Assessment and Evaluation of the Effect of Natural Disasters on Critical Power and Communications Infrastructures (2005-2012)

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EXECUTIVE SUMMARY

The U.S. power system infrastructure is traditionally considered to include transmission and distribution components of the utility grid. The actual system, however, is best characterized with at least four distinct networks: the transmission grid, the electrical distribution system, the telecommunication power infrastructure, and generator sets used as backup systems.

The transmission portion of the utility grid is composed of high-voltage lines running from power generation stations to substations where the voltage is stepped down into the distribution grid. Cables mounted on poles (usually shared with telecommunication networks) distribute electric energy to consumers. Although under normal conditions the electric utility grid is reliable, it is vulnerable to storms. Hence, extended outages over a large area are common outcomes of hurricanes. In the case of Hurricane Katrina, about 700,000 customers in Louisiana and almost 200,000 in Mississippi lost power. More electricity users suffered outages in Alabama, making the total number of affected customers greater than one million by the time the storm passed through the Gulf Coast on August 29, 2005.

The telecommunication power infrastructure has long used a mix of utility power and local dc power plants to achieve high reliability and extended operation. The utility is connected to the dc system bus via rectifier circuits, both at central office (CO) locations and at local power units. When the utility feed is lost, batteries act to maintain power. There is no time delay for changeover to the backup energy source, since the rectifier architecture provides an *OR* function for the sources. Battery backup in the telecommunication system is designed to maintain full function after loss of ac power for intervals of a few hours. If batteries become discharged, the local source shuts off and communication is lost within a small area. At the CO level, there may be additional generation equipment to maintain operation as long as fuel sources permit.

Telecom power systems in most locations are protected with robust enclosures intended to withstand icing, salt spray, and other severe weather conditions. In the event of widespread and extended flooding, as occurred in New Orleans and other communities, enclosures cannot prevent water ingress. It is possible that battery systems will be destroyed in such a circumstance, along with rectifier circuits and other power interface hardware.

The fourth network is an *ad hoc* collection of local resources with purely local control and no coordination. In many instances, this network also failed after Katrina. In a typical installation, a diesel generator fires up automatically after loss of ac power. After a few seconds

when the engine is at speed, a transfer switch isolates the local power system and supplies power from the generator. The objective of the generator is to provide extended backup, although generator sets have much lower reliability than other resources, especially after operating for several hours. In many cases, these systems failed owing to water contact or physical equipment damage. A typical failure mode for permanent backup systems that survived the disaster, and temporary systems that were installed after the disaster, was simply running out of fuel following many hours or days of use. In these cases, restoration is a matter of refueling – a seemingly trivial task that is complicated by logistics, damage to highways, and post-storm access challenges. Many backup systems failed for lack of refueling because of flood damage, contamination, and shortages.

Damage to these networks was assessed a few weeks after the storm with an on-site survey along the Gulf Coast. After the survey, additional information was obtained from communication network operators, backup power suppliers, and public information resources through the press and government. This report describes survey results and places them in the context of information from other sources.

Bellsouth is the largest operator of traditional land-line telephony service in the area affected by Hurricane Katrina. The day after the eye of the storm made landfall almost 2.5 million lines were out of service. Of 33 COs that failed, two-thirds lost service due to lack of electric power caused mostly by fuel starvation of generator sets. The rest were destroyed by the hurricane's powerful storm surge. Wireless communication networks were also severely affected by the storm, although most of the switching centers escaped serious damage. Consequently, wireless network service was restored to an adequate level within a week, much faster than land-line services.

In general, the analyzed networks had similar geographical distributions of damage. Failure owing to direct infrastructure destruction by high winds or storm surge was found in Louisiana in Plaquemines Parish and the eastern half of St. Bernard Parish. Destruction also occurred along a 1 km strip of the Mississippi Gulf Coast between the Louisiana-Mississippi border and Biloxi Bay. Failure owing to flooding and security issues occurred in metropolitan New Orleans.

There is no single cause that explains Katrina's devastating effects on power and communication networks. Much of the primary damage was caused by storm surge. Although the winds were strong, the sustained wind speed at the time of Gulf Coast landfall had reduced to a strong category 3 on the Saffir-Simpson scale, compared to the peak category 5 level earlier in the Gulf of Mexico. The strong storm surge may explain why damage to electric substations and communication centers was far more severe than in other hurricanes. Although distributed portions of the networks were also severely damaged, wind effects were not out of the ordinary for a hurricane of the size and strength of Katrina.

The duration and severity of the outages was also caused by the Bellsouth wire network being a common transmission means for many communication networks and systems, including wireless networks and 911 services. The shared use of infrastructure, such as poles by electrical and communication networks, introduced a common point of failure that reduced the overall reliability and contributed to outages. Availability was reduced by relying on generator sets to provide backup power for long periods. Damaged roads and fuel supply disruptions made fuel delivery difficult or impossible and led to failure at several sites. Construction not suitable for hurricane-prone zones was another reason for extended outages. Examples of vulnerable construction were found in generator fuel tanks and in ground-level layouts of some sites in areas at risk of flooding or close to the coast.

Although effects of Hurricane Katrina were severe, many sites did not lose service. Two factors explain why. The most important was the dedication of network operator employees who showed remarkable commitment towards keeping the system running. A second was good fortune. Sometimes a few meters made the difference between a site being flooded or not.

Several recommendations can be implemented to mitigate damage from future storms as severe as Katrina. Some can be carried out in a short time, but others will take many years to implement. Mobile communication network transmission capacities and interconnection points between operators need to be increased to provide architectures that are more diverse. In the short term, links can be realized using microwave radios. Restoration means for destroyed COs need to be improved. Switch-on-wheels designs are a better option than digital loop carrier systems. The use of digital loop carrier systems to replace COs and damaged cables had the disadvantage of making the land-line network more vulnerable to future storms in the area affected by Hurricane Katrina. Network diversity can also be improved by minimizing shared infrastructure among different networks.

There are a number of options to improve network reliability when using generators for extended periods. Expanded battery capacity may solve the problem for outages lasting several hours. However, when the electric power is out for several days, many sites need larger fuel tanks. Access points for these tanks should be located high above ground to avoid possible flooding of the tank. Using natural gas or flexible-fuel diesel and natural gas generator sets might ease logistical requirements after a storm. Fuel consumption and needs can be reduced dramatically by installing solar panels at COs and cell sites. Use of a highly reliable “power of last resort” could support limited energy for wireless repeaters and support communication needs of first responders after extensive network damage. A long-term solution may involve the use of distributed generation systems to reduce dependency on the electric grid.

Restoration plans should be coordinated in advance with security officials to define alternative routes for delivering generators and fuel to damaged sites. Collaboration among tower owners and wireless communication operators during the planning phase should be expanded with the objective of equipping each cell site with one generator instead of wasting resources by delivering multiple generator sets to supply each individual operator at a tower site. Coordination among communication companies should be improved to establish “best practice” design and construction for areas subject to hurricanes.

TABLE OF CONTENTS

1 Introduction

On August 29, 2005, Hurricane Katrina struck the Mississippi and Louisiana coasts with winds over 200 km/h and storm surges up to 9 m in some areas. Devastating effects on utility power and telecommunication networks hampered early rescue and relief efforts, making them almost impossible in some areas. The impact on power and communication infrastructures and the consequences of extended outages in the aftermath of the hurricane illustrate the need for further contingency planning. In the past, there has been limited research on disaster damage and restoration of telecommunication systems or on how the reliability of communication systems in extreme conditions is related to power supply. Research on primary causes of failure under such circumstances is also limited.

The impact of Hurricane Katrina on the U.S. Gulf Coast caused heavy damage to infrastructure networks. One of the most serious effects was complete loss of communication, caused both by direct damage and loss of electrical supply. Communication loss hampered rescue efforts, stymied attempts to coordinate early responses, and made calls for aid impossible from the hardest-hit areas. It was only by September 2, four days after the storm crossed the coast, when military-grade communication networks (often satellite-based) began to have an impact as substitutes. A parish sheriff from a particularly hard-hit area in Louisiana reported during a CNN broadcast that his biggest needs were drinking water and communication. A description of the effects of Hurricane Katrina was delivered by Lt. Gen. Russell Honore, the military commander in charge of recovery and relief operations [1]:

> "What this storm did was a classic military operation. The storm gathered strength, attacked the coast of Louisiana-Mississippi with overwhelming force. One of the things in a military attack you want to do is to cut the enemy's ability to communicate. It took out all cell phones and regular phone service. The other thing this storm did is to cut the road network. As the storm moved north it protected its left flank by leaving a flood. Again, classic military attack: take the enemy's eyes out, take his ears out, then fix him so he can't maneuver."

Clearly, in the U.S. communication networks have become essential tools for safety at many levels. There are many open questions about how communication system dependencies on power networks and power supply affect reliability under extreme conditions. In the future, communication dependence is likely to grow even more as broadband networks become common.

1.1 The storm

Katrina was an extraordinarily powerful and deadly hurricane that carved a wide swath of catastrophic damage and inflicted high loss of life. It was the costliest and one of the five deadliest hurricanes ever to strike the United States. Katrina first caused fatalities and damage in southern Florida on August 25, 2005 at about 6:00 p.m. local time as a Category 1 hurricane on the Saffir-Simpson Hurricane Scale. After reaching Category 5 intensity over the central Gulf of Mexico, Katrina weakened to a strong Category 3 storm shortly before making landfall on the northern Gulf Coast on August 29th at 5:00 am local time, near Buras, Louisiana. The central pressure yields an important indication of hurricane strength, with a lower central pressure indicating a stronger storm. Katrina's minimum central pressure of 920 mb is the lowest on record in the Atlantic basin for Category 3 hurricanes, and at that time was the third lowest pressure of any hurricane making landfall in the continental US. Hurricane Katrina was not only extremely strong but also extensive with a storm surge of 3 m as far as Mobile, Alabama and hurricane force winds extending 120 km eastward. New Orleans experienced sustained surface winds weaker than a Category 3 storm at ground level with increased wind speeds at higher floors of tall buildings [2]. Even so, the damage and loss of life inflicted by this massive hurricane in Louisiana and Mississippi were staggering. Significant effects extended into the Florida panhandle, Georgia, and Alabama.

Considering the scope of its impact, Katrina was one of the most devastating natural disasters in United States history. Estimates of the insured property losses caused by Katrina range between $20 and $60 billion. The American Insurance Services Group (AISG) estimates that Katrina is responsible for $38.1 billion of insured losses in the United States. A preliminary estimate of the total damage cost of Katrina is assumed to be roughly twice the insured losses, or at least $75 billion. This figure would make Katrina the costliest hurricane to occur in the United States. Even after adjusting for inflation, the estimated total damage cost of Katrina is roughly double that of Hurricane Andrew (1992). Normalizing for inflation and for increases in population and wealth, only the 1926 hurricane that struck southern Florida is on the same order as Katrina in terms of damage cost. The Insurance Information Institute reports that, mostly due to Katrina but combined with significant impacts from the other hurricanes striking the United States in the same year, 2005 was, by a large margin, the costliest year ever for insured catastrophe losses in this country.

1.2 On-site survey and project scope

This study extends the knowledge of catastrophic disaster effects on the electrical power supply and the impact on telecommunication power infrastructure including backup systems [3-5]. Information is presented from an on-site survey and other relevant sources. The on-site survey was conducted on October 17-23, 2005 in the area highlighted on the map shown in Fig. 1.1. This region follows the I-10 corridor between Mobile and New Orleans. It also includes areas adjacent to US 90 and Louisiana highway 39.

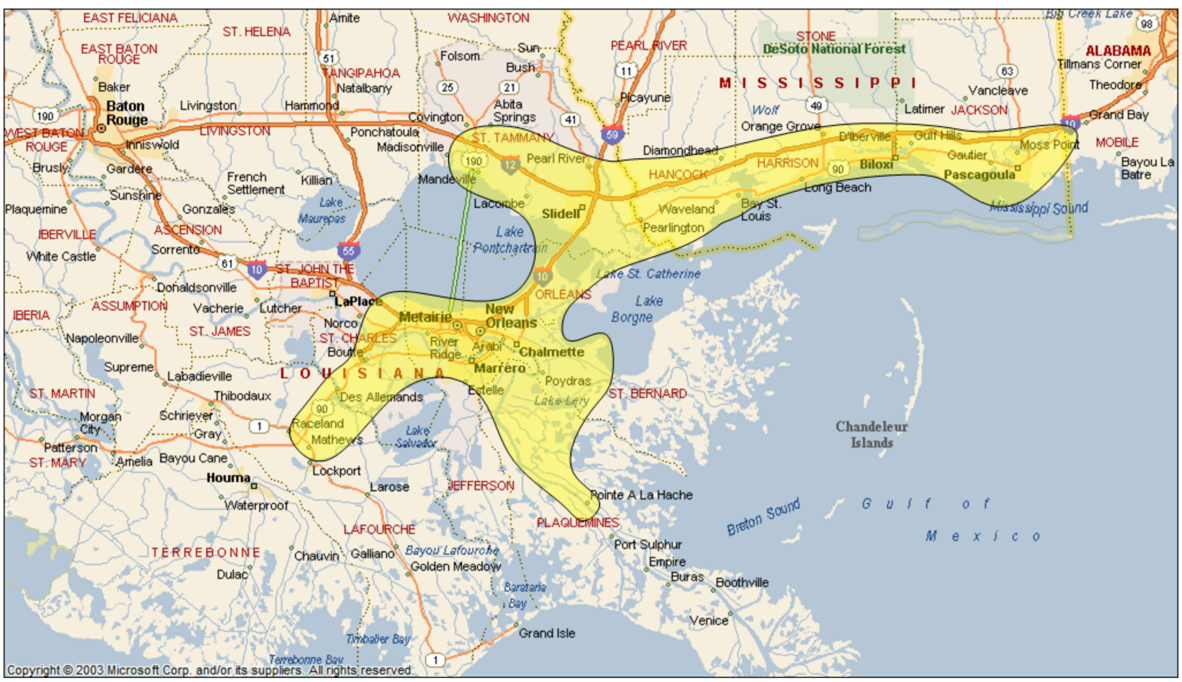

Fig. 1.1. On-site survey territory

The tasks carried out during the survey included:

- Determine the extent of restoration already in place, areas in which the process is in progress, and areas not yet in progress. Identify a suitable geographical sample of each type of area.
- Assess the status in each sample area. Identify working and non-working telecom and large backup power units
- Survey battery-based and fuel-based backup to determine the degree to which repair or replacement will be required in place of routine recharge or refueling.
- To the degree possible, gather spot data to support maps of the extent of telecom power outages.
- Use digital still and video images to record status of:
    - Cellular telephone sites
    - Fixed-line telephony central offices
    - Electric power substations
    - Electric power transmission and distribution
    - Emergency backup power systems

Two graduate students, Alexis Kwasinski and Wayne Weaver, both with industry experience, performed the on-site survey. As with everyone and everything affected by Katrina, logistical, transportation, communication, and housing were major challenges in carrying out the survey. Due to destruction, refugee housing, and emergency personnel housing, the closest hotel available was in Orange Beach, AL, almost 200 miles east of New Orleans. Transportation was an issue since many roads and bridges were damaged. For example, the I-10 bridge over Lake Pontchartrain, a major artery into the city of New Orleans, was heavily damaged in the storm. At the time of the survey the south bridge spans had been restored to working condition (see Fig. 1.2), but the north spans were still under repair. This caused extended delays in travel to and from New Orleans.

After the on-site survey was conducted, extensive data gathering was carried out via private companies such as Caterpillar, Alltel, Sprint, TMobile, Cingular, and BellSouth as well as from government agencies including the Federal Communications Commission (FCC), the US Geological Survey, the Federal Emergency Management Agency (FEMA), the US Army Corps of Engineers, the National Oceanic and Atmospheric Administration (NOAA), and the US Department of Energy. Satellite and aerial imagery [6-10] was used to determine the status of the affected area shortly after the storm had passed. Additional on-site data, network information, personal accounts and various other data have been gathered and integrated into this report.

Fig. 1.2. I-10 bridge over Lake Pontchartrain

2 Communication System and Electric Power System Background

Many communication networks operate within in a region. The networks of interest for this report are the public switched telephony network (PSTN), the mobile communication network, satellite communication networks, and broadcasting systems such as cable television (CATV), emergency services, and commercial radio and TV systems. New telecommunication means such as voice over Internet protocol (VOIP) or telephony over Internet are not analyzed, because they are not physical networks but rather services that operate over one of the networks mentioned above.

A natural disaster can affect the operation of these networks in many ways. A direct impact implies destruction or damage to one or more key network elements. An indirect impact implies that network operation is hampered because some necessary external factor has failed. This report focuses on the electrical power supply. To give a better understanding of communication network relationships with electrical power, possible failure modes, and recovery means, a description of communication networks and electrical power systems is presented next.

2.1 The public switched telephony network (PSTN)

The PSTN is the traditional landline telecommunication system in which subscribers with fixed telephones are interconnected through cables by a commutating element called the *switch*. Other names given to the PSTN are fixed-telephony network, wire-line telephony network and *plain old telephone system* (POTS) network. Companies that provide POTS services are called a *competitive local exchange carrier* (CLEC).

A switch is the most important element of a PSTN. The function of a switch is to link two network subscribers by commutating calls. The building that houses the switch is called a *central office* (CO). In many ways, a CO is analogous to a substation in an electric utility grid, serving as the primary connection point to consumers as well as an interconnection to bulk communication infrastructures. Each CO covers a portion of the CLEC territory. This geographical region is called a *CO area* and is determined based on the number of potential subscribers, geographic limitations and demographic characteristics. The location, usually a CO in the most populated zone within its area to minimize connection length to subscribers, must be close to important routes to minimize linkage distance to other COs.

The CO also contains other communication equipment, including transmission systems necessary to connect the CO to other COs. Fig. 2.1 shows the basic communication elements of a CO. Calls are commutated in the switch matrix. Copper cables to subscribers are terminated in vertical blocks in the *main distribution frame* (MDF). These cable terminations are connected with cross-connect jumpers to horizontal terminal blocks that are also located in the MDF. Several positions in the horizontal blocks of the MDF are then connected to switch line modules (LM) where the signals of some LMs are combined in multiplexing units (MUX) to produce a single signal in order to reduce the switch matrix complexity. The multiplexed signals are processed in interface modules (IM) that separate the MUX units and the switch matrix. The switch matrix is also connected through IM and de-MUX units to trunk modules where high capacity links are terminated in the switch. These trunks are then connected through the transmission distribution frame (TDF) to the transmission system, where most of the trunk signals are routed to other COs and communication centers. The entire system is controlled with process controllers and managed from administration terminals.

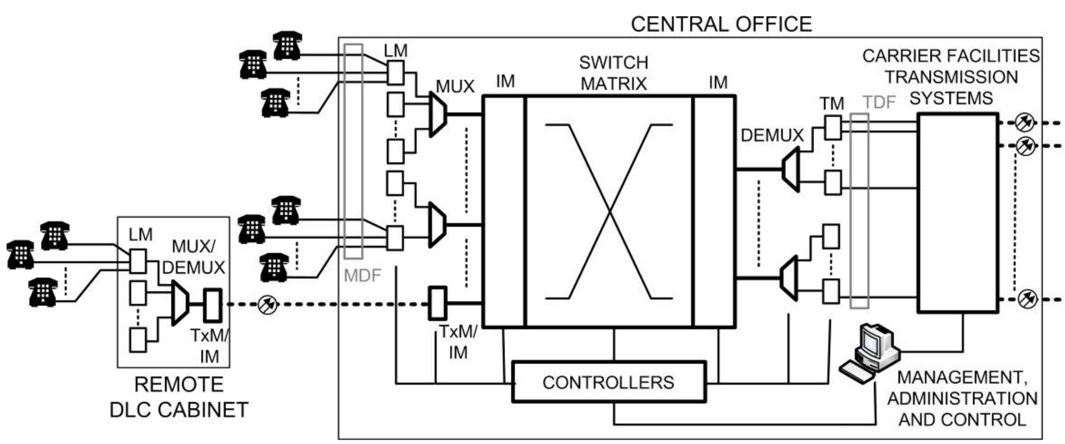

Fig. 2.1. CO main communication components with a remote DLC

Fig. 2.1 also shows an alternative to connect subscribers through a multiplexed remote terminal, a digital loop carrier (DLC) system. The DLC is placed away from the CO in metallic cabinets containing the line modules, multiplexing unit, and a transmission and interface module (TxM/IM), which connects the cabinet to the CO, generally using fiber-optic cable. While a copper wire connection between a subscriber and its CO cannot expand for more than 3.5 to 4 km, a fiber-optic cable between a DLC cabinet and a CO can reach lengths of 7 to 10 km. The most popular DLC systems, usually installed inside Type-80 cabinets, are the subscriber loop carrier SLC-96 and SLC-5 manufactured by Lucent Technologies.

Sometimes, a switch can be operated with its main processing unit located in another CO, shown in Fig. 2.2. In this configuration, it is said that the latter is the host switch of the former, called the *remote switch*. In case the host switch fails, the remote switch is 95 % self-sustainable [11] and can still process local calls. The main reason to use remote switches is to optimize the traffic within its serving area.

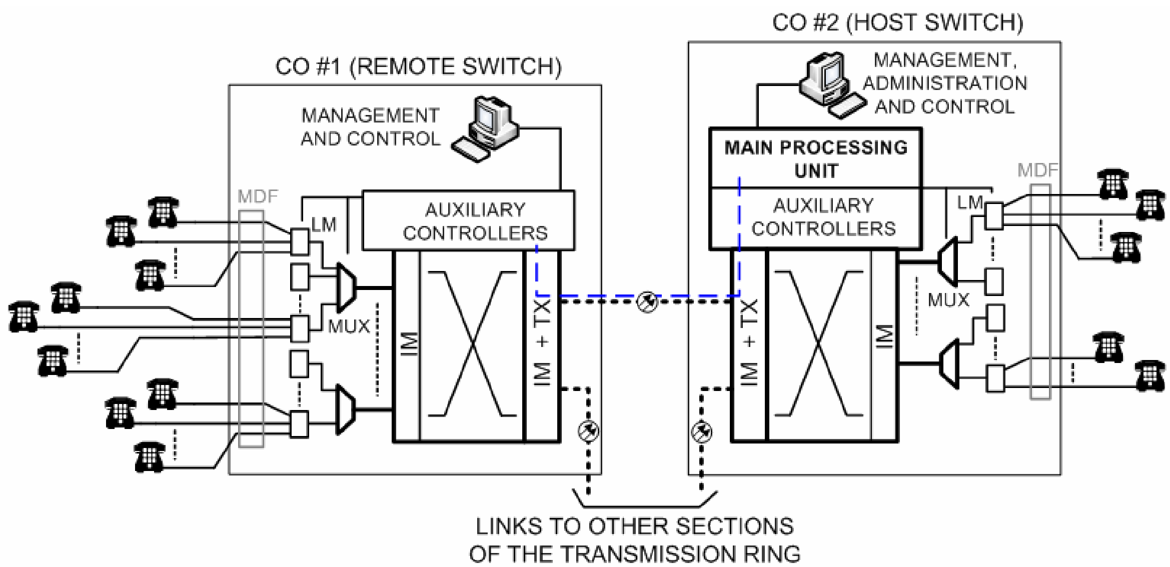

Fig. 2.2. Remote switch and its host architectures

The CO also contains all the ancillary services essential for the system to operate, among them, the direct current (dc) power plant. As shown in Fig. 2.3, the power plant receives alternating current (ac) electrical power and rectifies it into dc electrical power. It is distributed to a global power distribution frame (GPDF), the other system power distribution frame (PDF), and to inverters that feed the management terminals with ac power. The GPDF and PDF hold the fuses that protect the system in case of a short circuit in the equipment frames. The switch, transmission systems, and management terminals are the main power plant loads. The CO power plant also feeds subscriber telephones with copper wires when they are directly connected to the MDF. Fig. 2.3 also shows that the DLC cabinet requires a separate power plant that receives the ac power from a local connection.

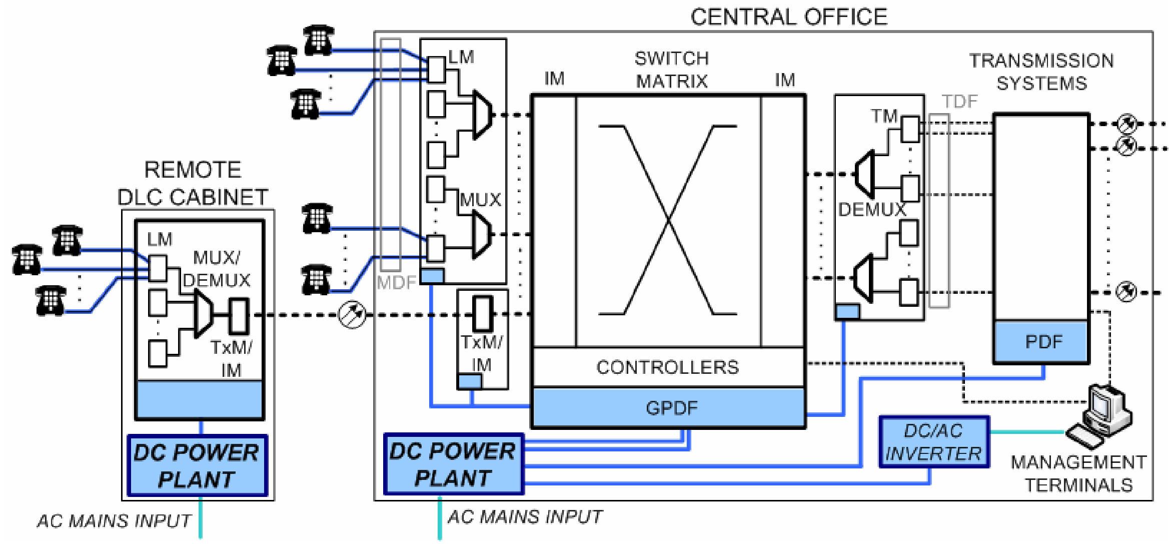

Fig. 2.3. CO and DLC main components showing the electrical supply scheme

One of the main functions of the power plant is to provide energy to the system even when there is an outage in the ac utility grid. This is accomplished by including batteries directly connected in parallel to the load and a combustion engine/electric generator set (genset) in a stand-by mode connected through a transfer switch to the ac mains input. Fig. 2.4 shows a basic scheme of a telecom switch power plant. During normal operation, the system is fed from the electric grid through rectifiers that converts the ac mains into dc power. The function of the batteries during an electric utility grid outage is to provide power to the system for a short time until the genset starts and the transfer switch connects the generator to the rectifier input. In this manner, as long as the genset has enough fuel and does not fail, the CO can operate normally until the electrical utility power is restored. In normal operation, DLC cabinets have the same power plant structure without the genset.

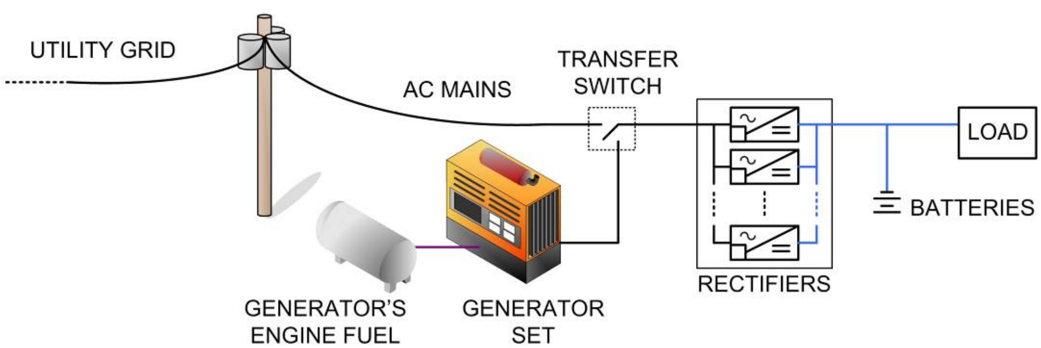

Fig. 2.4. Basic elements of a telecom power plant and connection scheme

One problem with batteries is their very high density – they are made with lead. A CO battery string may weigh well over 1 tn/m^2, a standard floor-loading value for dwellings. For this reason batteries are usually placed at ground level, where it is easier to reinforce the floor. Another problem is the difficulty of replacing batteries, as they need to be maintained charged while stored. If they are not, they eventually discharge and end up being permanently damaged. Thus, battery manufacturers keep only a small battery inventory. Lead times for large orders may reach up to 4 weeks. The rest of the CO equipment is mainly printed circuit boards and metallic frames, which can be easily stored and produced rapidly.

One of the most important characteristics of the PSTN is its extremely high reliability with downtimes, usually less than a minute per year. This has both commercial and emergency (911 system) implications. Fig. 2.5 shows a scheme of the enhanced 911 (E911) system with its three main elements: the PSTN, the public safety answering points (PSAPs), and the E911 offices. In the E911 system, the PSTN carries the call to the PSAP, as routed by the corresponding E911 office. Since CO areas do not generally coincide with PSAP areas, the system includes the E911 offices that route the calls to the corresponding PSAP center of the calling party. In Fig. 2.5, both party A and party B belong to CO X, located in PSAP area B. When party B calls 911, there is no issue because CO X, PSAP B and calling party B are all located within the same PSAP area. However, when party A, located in PSAP area A calls 911, the E911 office #1 routes the call through CO X to PSAP A. The system is also programmed to reroute 911 calls to backup E911 offices in case the primary one ceases to operate. For example, in Fig. 2.5, E911 office #2 is the E911 CO #1 backup.

In the PSTN not all the COs have the same importance. To reduce the cost in transmission links, the PSTN architecture has a radial configuration in which several COs are connected through another switch called a *tandem office*. Hence, tandem switches are more important than regular switches called *class 5 CO* or *local offices* (LO) that handle subscriber calls. Fig. 2.6 presents an example of how tandem offices interconnect class 5 COs. The figure shows that party D can talk to party C only through tandem office Y. In the same way, party E can talk to party A only through tandem office X. Moreover, party A and party B can only talk through tandem offices X and Y. When the traffic between two class 5 offices is high enough, they can be directly connected with high-usage trunks. For example, in Fig. 2.6 party F and party G can be connected without passing tandem office X. The importance of a tandem office becomes evident in Fig. 2.6. When tandem office Y fails, the subscribers of the five class 5 COs connected to it will only be able to talk to other subscribers of the same LO. Usually, tandem switches do not interconnect subscribers, but they do connect class 5 switches to other higher hierarchy centers.

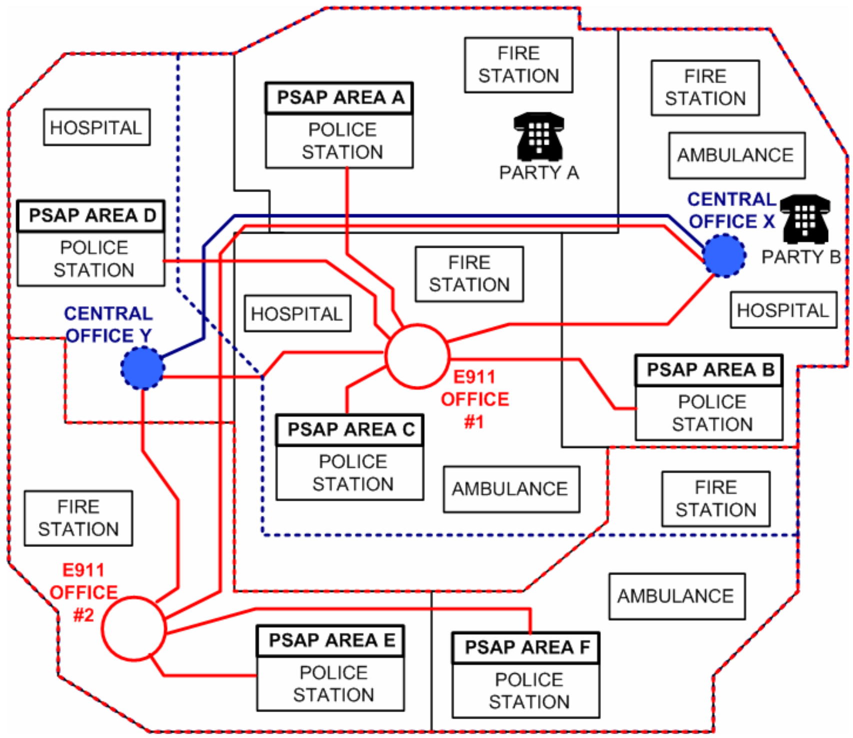

Fig. 2.5. E911 system representation

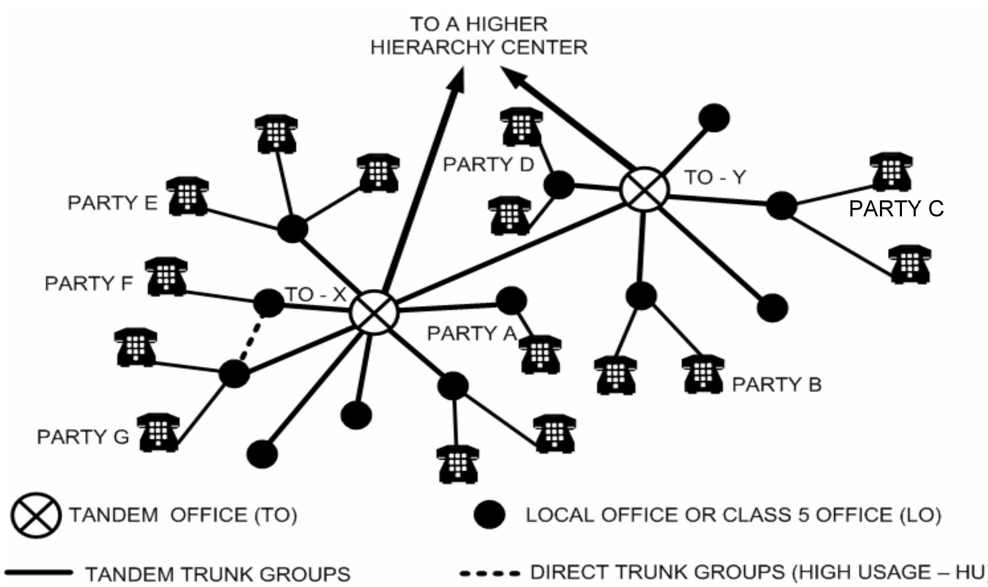

Fig. 2.6. Typical CO connections in a city

The elements of the PSTN within a CO area are divided into outside plant and inside plant components. All the elements located outside the CO up to the vertical blocks of the MDF are part of the outside plant. The remaining elements situated inside the CO are part of the inside plant. For historical reasons, sometimes transmission fiber-optic cables and microwave antennas are considered neither part of the inside nor the outside plant. The outside plant is extremely vulnerable to natural disasters and, for this reason, needs to be considered as part of any study of natural disaster effects on communication systems. The basic terminology used for outside-plant hardware is shown in Fig. 2.7: poles, manholes, a cable entrance facility, serving area interfaces, line drops, feeders, and distribution cables.

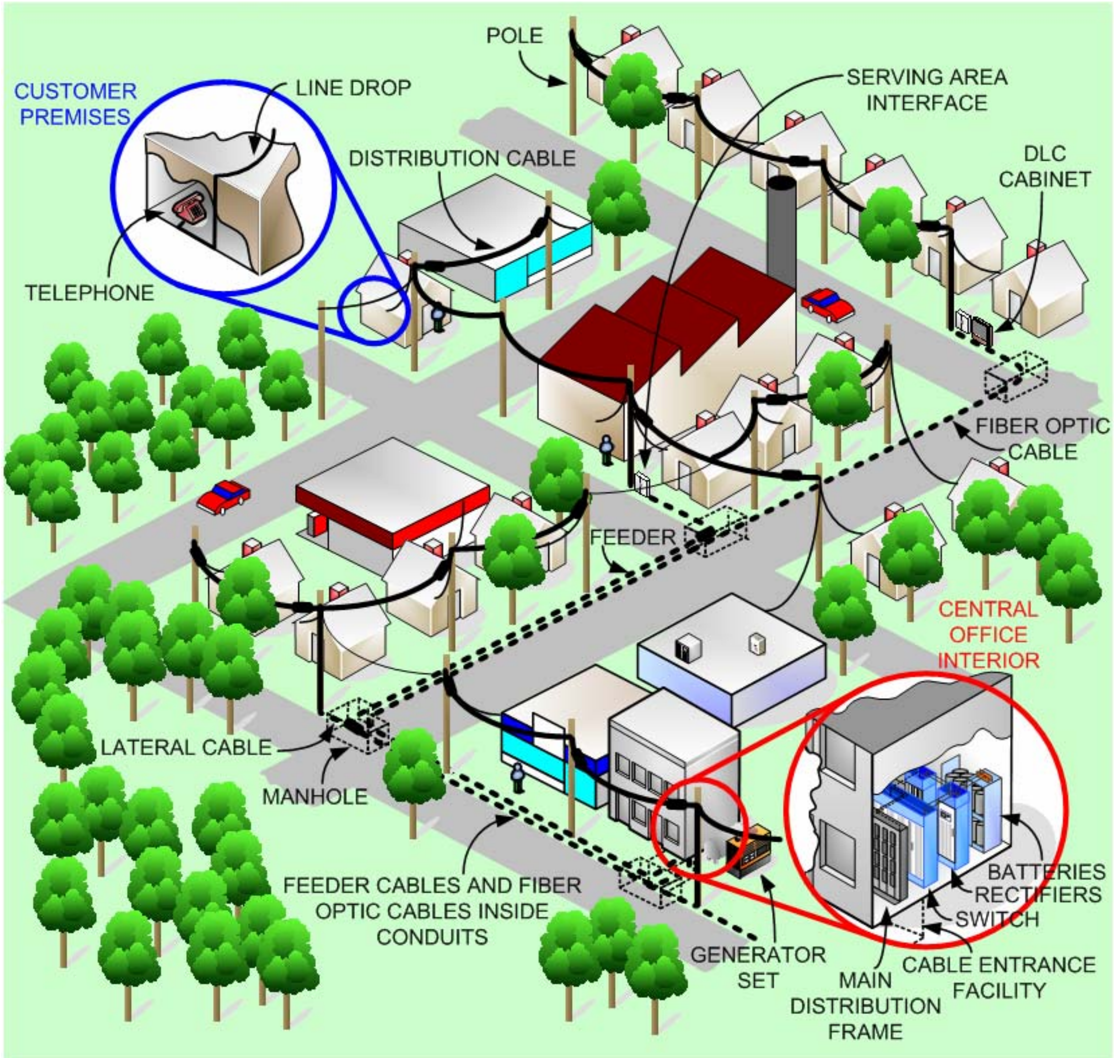

Fig. 2.7. Main outside-plant elements of a CO.

2.2 Mobile communication network

In a mobile communication network the fixed wire connection between the CO and the subscribers is replaced by a radio link. This radio link utilizes a frequency or a code assigned at the time of establishing the call. Once the call has ended, the frequency or code is freed and can be used by other subscribers. Another difference from a fixed-telephony service is that subscribers can still maintain a communication when they are moving. Other names for mobile communication networks are *cellular telephony, wireless telephony networks* or simply a *cellular network.*

Fig. 2.8 shows the main elements of a mobile communication network: the mobile telephony-switching center (MTSO) and the cell sites. The MTSO is also called a *mobile switching center* (MSC). A user will communicate through a radio link to a cell site, which in turn is connected to the MTSO with a fiber-optic cable, a microwave link, or, in special cases, a satellite link. Having a satellite link between the MTSO and the cell site is different from a satellite mobile communication, in which the satellite itself acts as a cell site. It is not very common to use satellite links in mobile communication networks and not all equipment manufacturers support this application. In the rare cases that it is used, the cell site is in distant locations that are very complicated to reach by land, such as very high mountains or Antarctica. The entire mobile communication network coverage area is divided into regions called *cells* that ideally have the form of a hexagon. Cell sites are located in the intersecting point of three cells. Each cell site covers the surrounding area, which is divided into 3 sectors, each of them corresponding to 1/3 of each of the adjacent cells to the cell site, as in cell site #10 shown in Fig. 2.8. Usually, the same location is shared by cell sites of different operating companies that install their base stations in different shelters or platforms and place their antennas in the same tower at different heights. Fig. 2.8 also exemplifies a typical call: When user A calls user B, the call goes through cell site #5 via a radio link and continues to the MTSO through a fiber-optic cable. Then the MTSO routes the call to cell site #8 using a microwave link, and the call connection is finally established via a radio link between cell site #8 and user B. A key characteristic of mobile communication is that users may move without having the call disconnected. This characteristic is represented with user C. In the figure, user C is driving through the south-north sector of cell site #1, represented in green, and entering the north-north sector of cell site #6. At this point, the network controllers transfer the call path from cell site #1 to cell site #6 in a process called *handoff*.

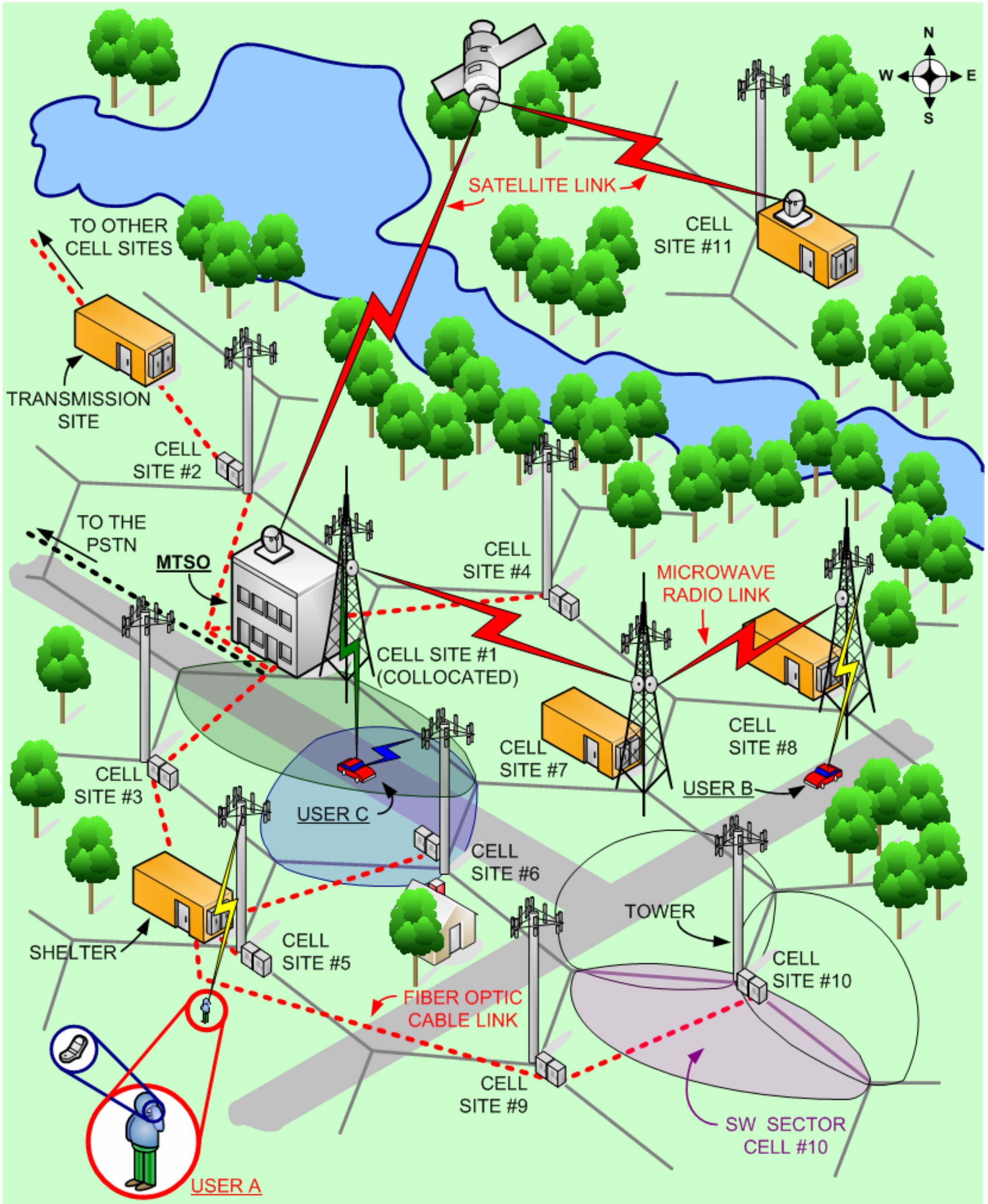

Fig. 2.8. Mobile-communication network scheme

A mobile communication switch is similar to those used in the PSTN, as shown in Fig. 2.9. One difference is that in MSCs, switches do not have line modules since all the links to other COs and to the cell sites are through trunks. Another difference is that MSC switches incorporate a cell site controller that manages the calls between the MTSO and the cell sites and in between cell sites. One of the cell site controller functionalities is, for example, the handoff. The customer database in also dynamically handled differently so that the system can keep track of the user locations to allow incoming calls to be routed to the appropriate cell. Fig. 2.9 also shows that in some ways a cell site and a DLC cabinet are alike in the sense that both act as fixed remote subscriber concentration nodes. Yet, while DLC cabinets have a fixed connection to the subscriber using copper wires, cell sites have a flexible connection using radio links. Fig. 2.9 also shows that the cell site electronic equipment and its housing are called a *base station* (BS).

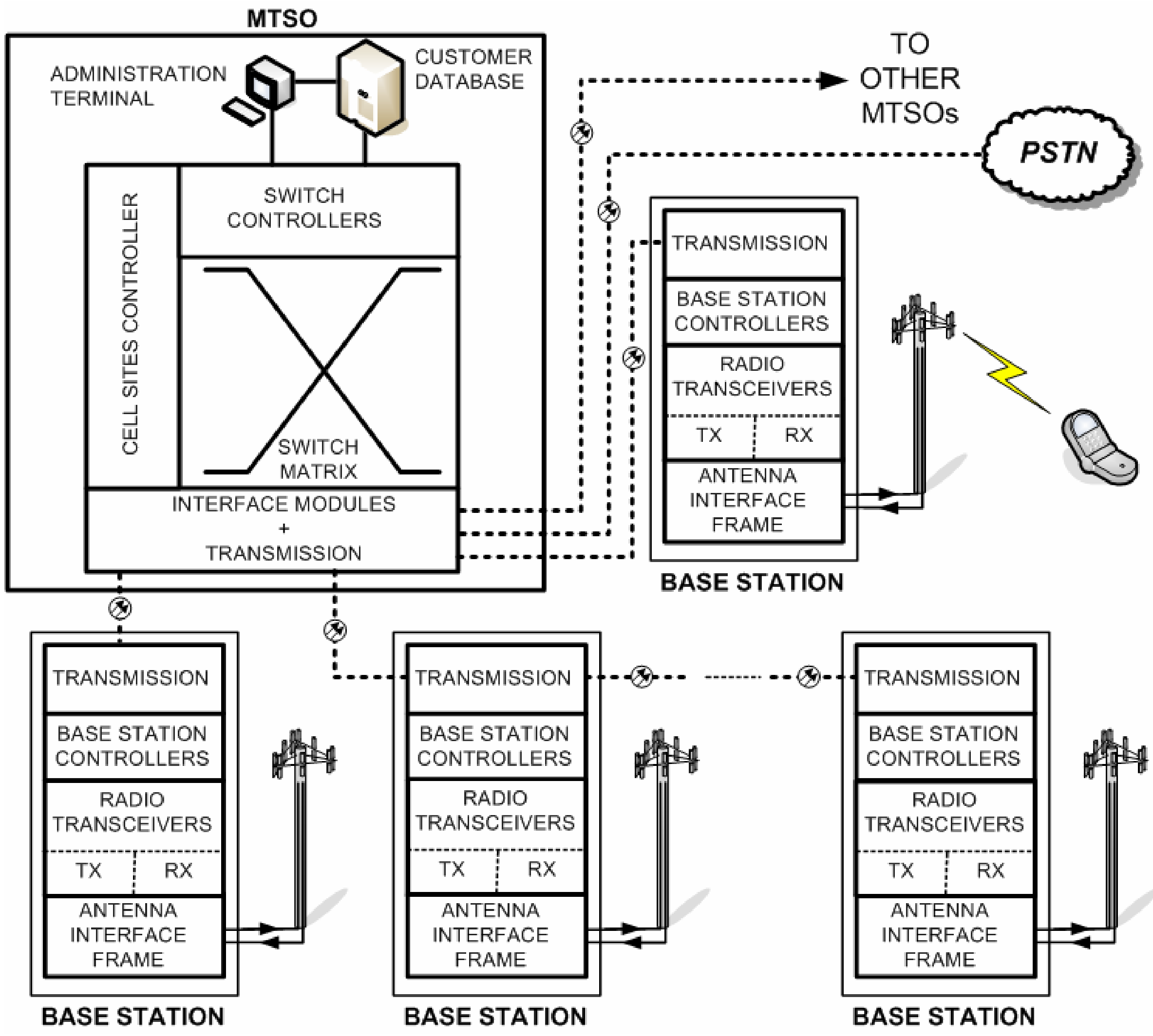

Fig. 2.9. MTSO and cell sites main communication components

The electrical power supply of MTSOs and cell sites is also very similar to PSTN systems. As Fig. 2.10 shows, the only difference in the electrical power distribution in a MTSO when compared with a PSTN switch is that subscriber telephones are no longer fed directly from the CO. For this reason, cell phones need to have their own batteries. The basic elements of an MTSO power plant and its connections are the same as already shown in Fig. 2.4. Base stations also have the same power plant architecture, although many cell sites do not include a permanent generator set.

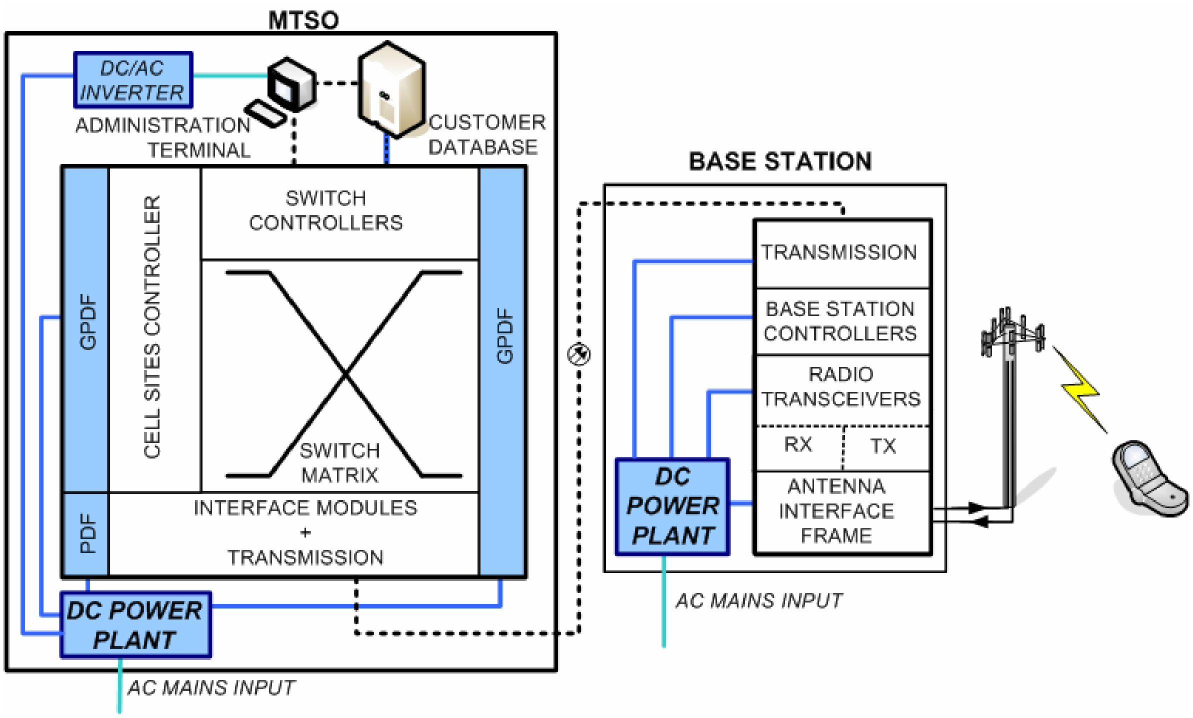

Fig. 2.10. Mobile communication network scheme

Fig. 2.11 shows the basic architecture of a cellular network including two full MTSOs, A and B; 5 remote switches (RS), A1, A2, B1, B2 and B3; and several cell sites represented by hexagons. The cellular network remote MSCs are equivalent to those of the PSTN, but the host switches add functions to the main processing ones: the host controls its respective remote switches' cells as well as performing the main processing unit functions. For example, in Fig. 2.11 the cell sites in the light-yellow area are controlled by MTSO B, but each switch performs the commutation process within its corresponding area bounded by a doted line. Since a host switch concentrates some of the functions of a remote switch, the loss of service in the former is more critical than an outage in the latter.

Fig. 2.11 also shows a common characteristic of communication networks called *network diversity*, which implies that there is more than one path linking two nodes. For example, cell sites B21, B22, B23 and B24 are connected with RS B2 in a ring, so there are two paths linking RS B2 with any of the four cell sites. RS B3 also has two paths to MTSO B: one passes through cell site B31 and the other through cell sites B32 and B22 and RS B2. In some cases, network diversity cannot be implemented. For example, cell site A23 has only one path to RS A2 passing through cell site A22. If for any reason cell site A22 fails, the area covered by cell A23 will also lose service. The same situation is observed with RS B1 connected to its host switch, MTSO B, using the PSTN transmission links.

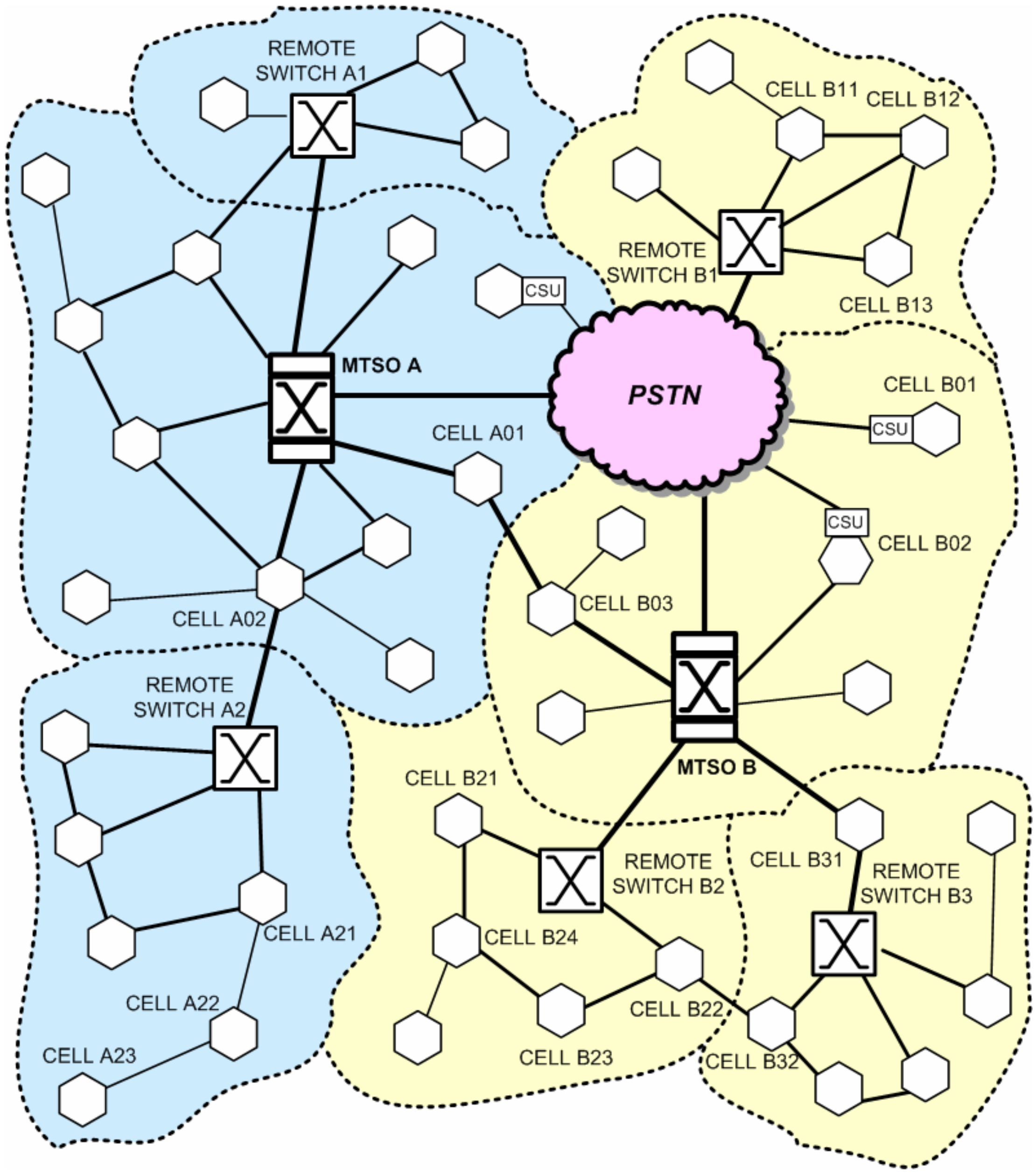

Fig. 2.11. Mobile communication network scheme

The cellular network has several connection points to the PSTN called *channel service units* (CSU). Mobile communication networks need to have links with the PSTN to make calls possible between a wireless phone and a wire-line telephone. However, some of the connections are necessary just to link cell sites and switches with the rest of the mobile communication network. One example of such a connection is the one already mentioned in RS B1. Another example is cell site B01. Hence, the PSTN is a critical point of failure for the entire communication system. If the PSTN fails, not only wire-line subscribers may lose service but also a significant portion of the wireless network may become isolated or even lose service.

As previously mentioned, satellite mobile communication is similar to regular mobile communication networks. The only difference is that the cell sites are replaced by satellites orbiting the earth and powered by solar energy and batteries. The switches are still located on land and are powered by the electric utility.

2.3 TV and radio systems

Traditional TV and radio systems broadcast signals from a main station using antennas. These antennas are quite vulnerable to high winds. However, if they fall, the transmission can easily be shifted to some other location within the broadcasting area with an appropriate antenna. Traditional radio and TV systems are useful during a disaster aftermath to broadcast messages of public interest, such as information about the location of food and water distribution centers. But public broadcasting systems only transmit information in one direction, so they have limited usefulness during disasters. Two-way private radio systems, such as those used by police and other emergency services, are more useful. As in all telecommunication systems, both the emitter and the receiver need to be powered, either by some local connection to the electric grid or with batteries.

More relevant for this report are cable TV (CATV) networks because most of such existing networks allow for bidirectional signal flow. Hence, it is possible not only to have TV signals or data broadcasted from the main transmission station to the subscribers but also to have data signals transmitted back from the subscribers to the transmission station. Thus, bidirectional CATV networks support several applications such as regular internet and internet phone services, commonly referred to as *voice over IP* (VOIP) services.

Fig. 2.12 shows the basic architecture and elements of a CATV network. The main transmission station is called the *head-end* (H/E). To support Internet-based applications, the H/E is connected to the PSTN though at least one fiber-optic link. The H/E is linked with the subscribers with fiber-optic cables up to optical nodes and then with coaxial cables. Since the signal loses quality as it moves along the coaxial cable, it needs to be improved by using amplifiers. Depending on the size of the coaxial cable, the number of subscribers and the topology, typically, in cities, the amplifiers are placed every few hundred meters.

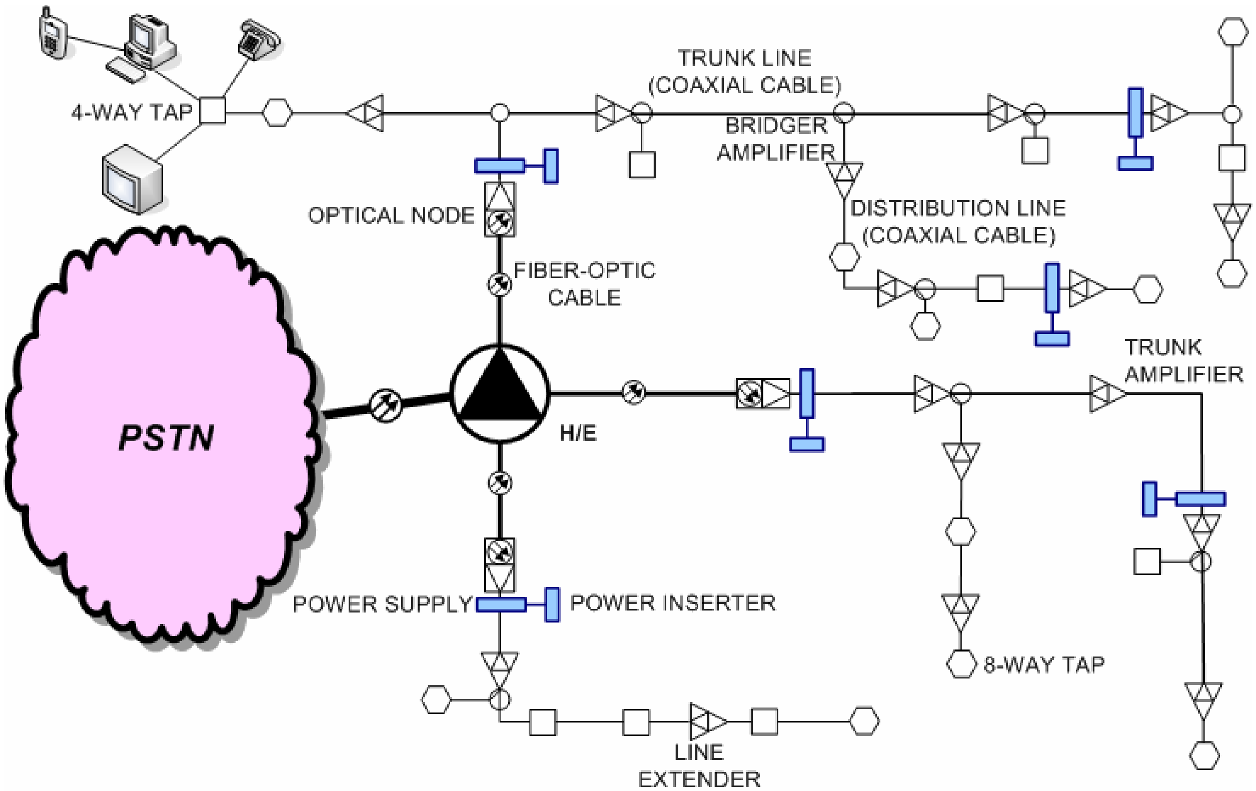

Fig. 2.12. CATV network schematic

The H/E, optical nodes and amplifiers require electrical energy to operate. Even though the H/E and the optical nodes require one power supply each, several amplifiers can be fed with one uninterruptible power supply (UPS). This is accomplished by injecting ac power into the coaxial cable, which is rectified for each amplifier. A UPS is a cascaded combination of a rectifier and an inverter with batteries connected at the rectifier output terminal to provide backup power for a few hours in case of an outage in the electrical supply. Usually, UPSs for individual amplifiers are placed in small cabinets mounted on poles, as shown in Fig. 2.13. Fig.

2.13 also displays the basic elements of a CATV network as well as broadcasting TV and radio stations.

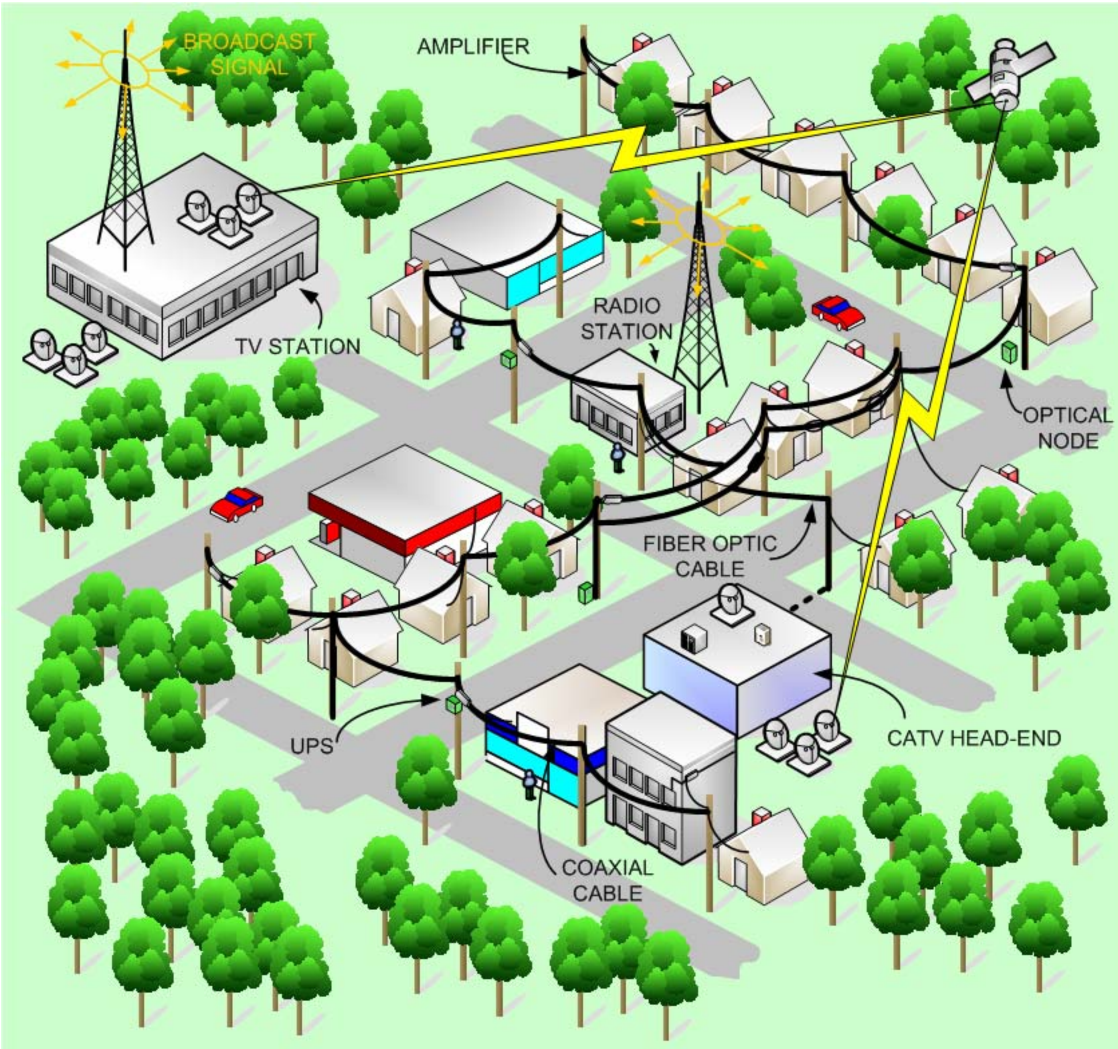

Fig. 2.13. TV and radio systems infrastructure elements

2.4 Electrical power systems

Fig. 2.14 presents a typical electrical power system with its main components. A power system has three main parts: generation, transmission and distribution. Electrical energy is generated in power plants and transmitted to substations close to the power consumption areas using high voltage (usually more than 110 kV) transmission lines. At the substation, the voltage is stepped down with transformers, and the electrical energy is distributed to individual consumers located close to the substation. The distribution involves at least one additional voltage transformation because the voltage output from a substation is usually 7.2 kV to 14.4 kV (medium-voltage) while the voltage at the ac mains drop of a typical small CO or cell site is 480 V, 230 V or 208 V (low-voltage). The medium-voltage conductors are called *primary* while the low-voltage wires are called *secondary*. The final voltage step down between primary and secondary conductors is performed in small pole-mounted distribution transformers with a power between 5 kVA and 200 kVA. Sometimes, the transformer can be located at ground level on a pad. In the case of large COs, the drop may carry voltages in the range of 1.2 kV to 4.2 kV. It is clear that most electrical systems include several transformation steps where the voltage is either increased or decreased.

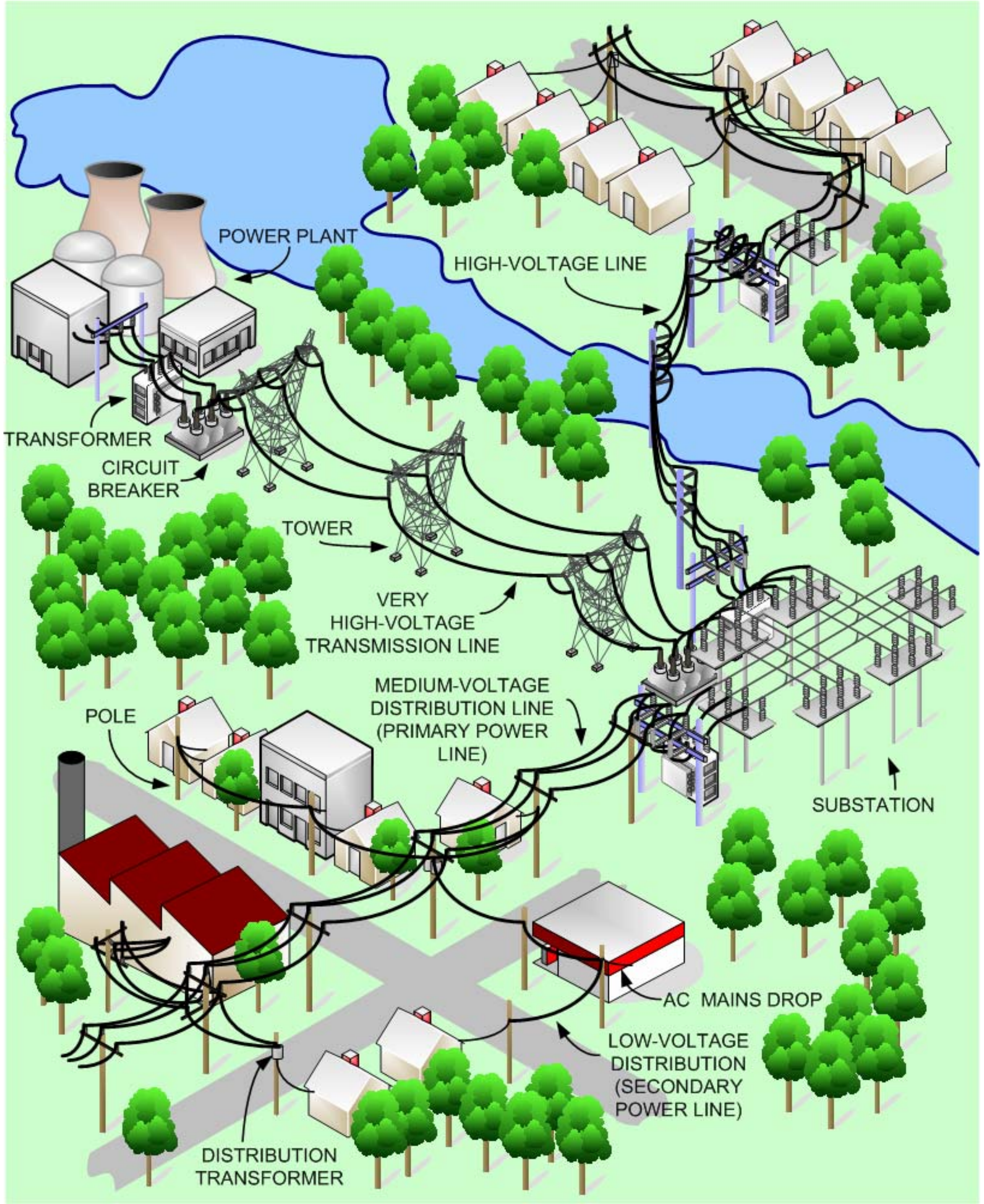

Fig. 2.14. Electrical power system components

2.5 *Electrical power system and communication network infrastructure*

The past sections have presented a short overview of existing communication networks and electrical power systems and provided a basic description of their infrastructure elements. Network infrastructure design is based on plans that foresee system requirements and parameters several years in advance. In the PSTN, the switch and transmission systems are designed for a 5-year future; the power plant and the outside plant, 10-year; and the CO building, at least 15 to 20 years in the future. Once the network is installed, it is extremely difficult and costly to rearrange all its elements. For example, relocating a CO building without disturbing service implies doubling the switching, transmission, and power capacity, as well as rerouting an important part of the feeder cables, the transmission links, the buried conduits and manholes. Thus, any analysis of the infrastructure needs to include a historical perspective using data from the geological, economical, social and political environment of that time. For example, barrier islands in the gulf and Louisiana’s wetlands, which are natural defenses against hurricanes, have eroded significantly since the last network designs were completed in the mid 1990s,

As previously mentioned, communication networks have common connection points between each other and the electric grid. Moreover, it is accepted practice in the US to have common elements for different individual network infrastructures such as utility poles. As Fig. 2.15 shows, the poles are shared by the electric grid, the PSTN outside plant and the CATV network. Even though this practice reduces costs, it provides a common point of failure for all the networks that, in turn, decreases their reliability. The higher risk of failure is observed not only during a disaster but also in the aftermath during the reconstruction period when it is not unusual that a contractor fixing one network ends up damaging another network element sharing the same pole.

Fig. 2.16 represents typical hurricane damage. A hurricane has several ways of producing damage: heavy rain, high winds and storm surge. While the effect of high winds and heavy rain can be noticed several kilometers inland, the effect of the storm surge is limited to within a few kilometers from the coast. In all cases, the northeast quadrant of the hurricane experiences the most severe effects. Both the heavy rain and the storm surge may flood large areas from the coast and inland. Electric power outages can also be caused by high winds or storm surge causing poles to break or fall, or by trees pushing down lines. Houses lifted from foundations and floating around during the storm can end up damaging a pole by crashing onto it. As poles are usually shared by other networks, the loss of service may be extended into the local portion of the PSTN and CATV network. Moreover, sharing cables in the same infrastructure increases the weight load and the stress on the poles making them more susceptible to damage during a storm.

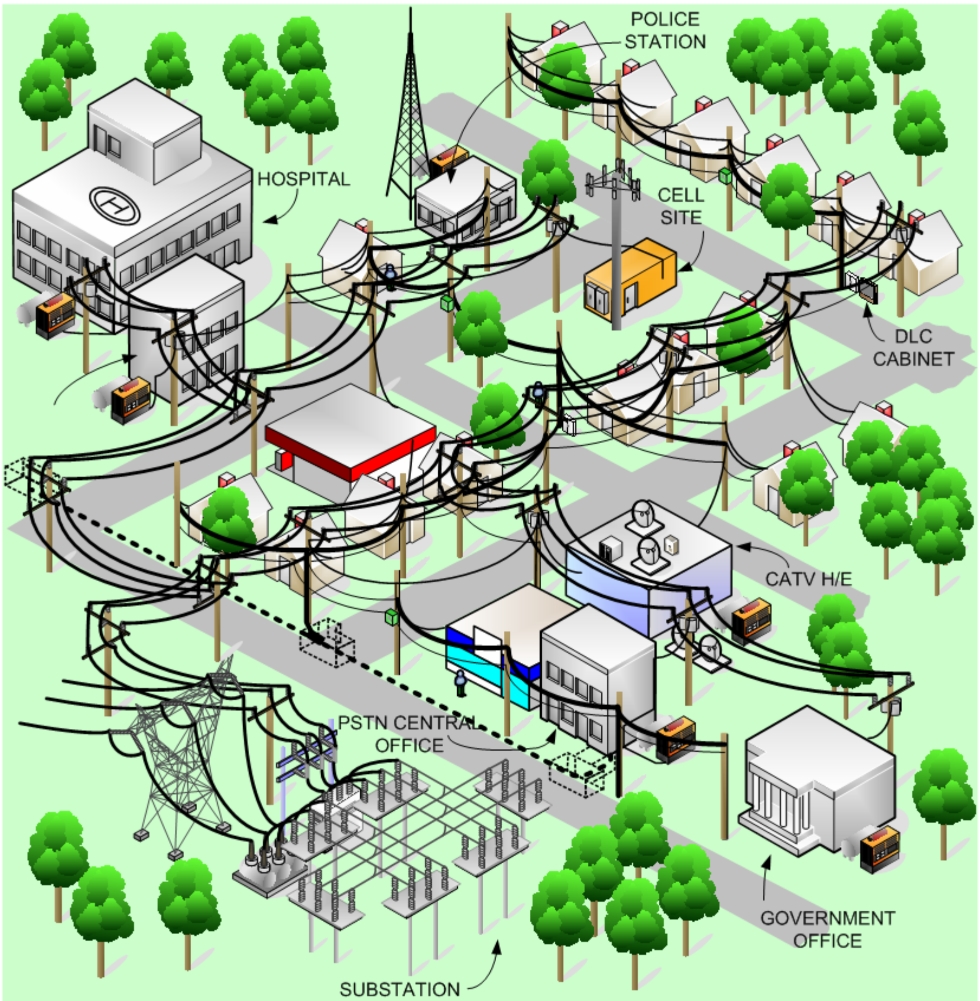

Fig. 2.15. Typical infrastructure in a US town

Floods can submerge manholes and the cables they contain, as shown in Fig. 2.16. Telecom copper cables can withstand submersions of short duration. Older cables are pressurized from the COs and newer cables are filled with gel that prevents water from entering the cable. However, when the pressurizing pump stops working due to lack of electric power or when the gel-filled cables are under water for a long time, the copper is corroded and the cable is destroyed. Thus, when COS are located in areas where flooding persists for several days, eventually all their feeder cables become permanently damaged and useless.

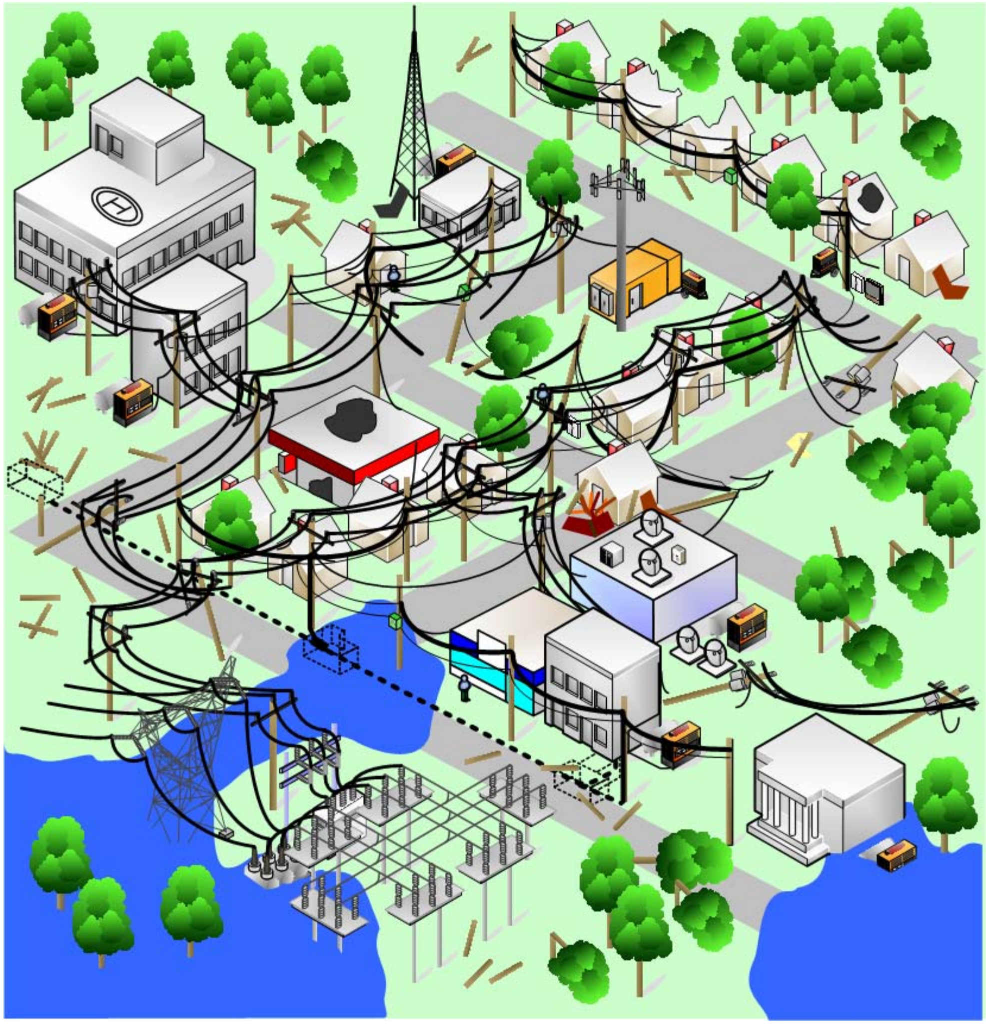

Fig. 2.16. Example of typical damage that a hurricane can cause in a town

Flooding and the storm surge can also affect the operation of backup gensets. All communication centers, government offices, hospitals, police stations and other buildings have permanent generator sets to provide electricity when there is a power outage. However, a storm may permanently damage the genset. The operation of gensets can also be indirectly affected by the presence of debris or flooding water in the streets that prevent reaching the site to refuel the generator. For example, in Fig. 2.16 the generators at the PSTN CO and the CATV H/E cannot be reached due to flooding and debris blocking all the roads. Not all the communication network elements, such as DLC cabinets and many cell sites, have permanent generators. During the initial hours of the electric grid outage, the DLC cabinets and cell sites without generators operate on batteries. When the storm passes, portable generators are taken to their locations, as is exemplified in Fig. 2.16. These generators also need to be refueled periodically, often daily.

2.6 Portable and backup power systems

Portable and backup power systems can utilize a variety of technologies such as combustion engines, fuel cells, turbines and solar, to name a few. While many types of power systems offer high efficiencies, they are usually less portable, have long setup times, can have poor electric transient response, and use nonstandard fuels. For these reasons the most common type of backup power system consists of a reciprocating engine and a genset. Some of the most important factors with genset usage in the context of disaster relief are capacity, transportation and fueling.

Typically, genset capacities can range from tens of kilowatts (Fig. 2.17) to megawatts (Fig. 2.18) and are transported as a single unit over road. Caterpillar,Inc., a major manufacturer of portable and backup power systems, deployed over 230 megawatts of power to the gulf region in the aftermath of Katrina [12]. As of February 28, 2006, approximately 10-20% of that capacity remained in the region. Most of the rest was in a standby application and called upon only when there were disruptions in the utility grid. However, there were still areas where reliable utility power was available and portable power the primary source.

Fig. 2.17. Trailer genset being transported

Transportation and deployment of such portable power to needed areas in the aftermath of a disaster is another hurdle. Roads, railways and waterways can be damaged and impassable. In cases like Katrina with urban unrest, security checkpoints can delay genset delivery. Fueling also is an issue. Once the genset is delivered and operational, fuel must be transported to the site throughout its operation. Fig. 2.19 shows the refueling of a genset providing power to a cell site in Biloxi, MS. During the on-site survey we spoke with the woman running the fueling operation. She stated that she picked up fuel in Birmingham, AL, and delivered it to cell sites all along the Mississippi coast every day. Gensets typically run on diesel fuel, however alternative units exist that run on natural gas only, gasoline only, dual natural gas – diesel, and bi-fuel.

Fig. 2.18. Caterpillar portable power trailer

Fig. 2.19. Refueling the genset that provides power to a Biloxi cell site

The key factor in preventing loss of service at COs is to keep the genset running. This makes the emergency generator the single most important component at a site after the storm. Unfortunately, gensets have an availability of 0.85 when run for 24 hours [13], meaning that a communication network availability is reduced from approximately 99.99% before the storm to 85% a day later. One alternative proposed by [14] in case of flooding is to have larger battery backup time. Besides the higher cost, more batteries presents disadvantages of significant battery weight and increased risk of fire, because higher energy storage can produce more intense short-circuit currents.

3 Damage Produced to Common Infrastructure of Communication and Electrical Networks

Electrical and communication networks use common elements in their distribution infrastructure. Figs. 3.1-3.22 show damage typical to the common infrastructure of electrical and communication networks observed during the site survey. Even though the damage to these elements was severe, it was usually limited to specific areas of the affected region. For example, Figs. 3.1 and 3.2 show extensive damage to both the residences and the entire infrastructure in Biloxi. The same destruction is depicted in Point A La Hache (Figs. 3.3 and 3.4) and Delacroix (Fig. 3.5). However, areas a few hundred meters away were not so heavily damaged, as Figs. 3.6-3.11 attest. Since the damage caused to the outside plant was limited to specific areas, it can not be explained how outages in communication networks were so widespread. In addition, although the damage in Figs. 3.1-3.6 is severe, it is relatively easy to fix, as shown in Fig. 3.12. Thus, long durations of service loss in many CO areas cannot be justified by this damage.

Fig. 3.1. Severe destruction in Biloxi, MS

Fig. 3.2. Total destruction in Biloxi, MS

Fig. 3.3. Severe structural damage to houses and a broken pole with distribution transformer and telecom outside plant cables in Point A La Hache, LA

Fig. 3.4. Total destruction on Highway 15, LA

Fig. 3.5. Fallen cables and destroyed houses in Delacroix, LA

Fig. 3.6. Severe damage to houses but light outside plant damage in Biloxi, MS

Fig. 3.7. Severe residential damage; none to electrical and PSTN distribution cables in Biloxi, MS

Fig. 3.8. Light damage to poles amid total destruction to buildings in Biloxi, MS

Fig. 3.9. Total destruction to houses but light damage to electrical infrastructure near Point A La Hache, LA

Fig. 3.10. Severe damage to construction but light damage to electrical and communication networks in Delacroix

Fig. 3.11. Severe damage to construction but light damage to electrical and communication networks in Delacroix, LA

Fig. 3.12. PSTN outside plant being repaired

In some areas, the infrastructure was damaged by houses, loosed from their foundations by the storm surge, floating until they hit a pole, as in Fig. 3.13. Yet, in similar cases, presented in Figs. 3.14-3.17, boats and houses that floated away did not damage the infrastructure.

Fig. 3.13. House crashed on a pole on Highway 15, LA

Fig. 3.14. Damaged pole and hanging wires on Highway 15, LA

Fig. 3.15. Crashed house on a pole on Highway 15, LA

Fig. 3.16. House lifted from foundation, boat, and undamaged poles in Slidell, LA

Fig. 3.17. Electrical and communication infrastructure in good condition on Route 90 northeast of New Orleans

Scattered damage, as shown in Figs. 3.18-3.22, was encountered during the site survey in most of the area affected by Hurricane Katrina. Although this damage was not severe and was relatively simple to repair, being dispersed in a large area, it demanded considerable resources that, otherwise, may had been used to restore more seriously damaged zones. This damage affected only a small number of subscribers and was not the cause for the extended and severe loss of communication in the storm’s aftermath. Critical outages were related to other causes including destruction of centralized communication nodes, such as COs, and electrical power failures. These will be discussed in the following sections.

Fig. 3.18. Damaged line on Route 11 south of Lake Pontchartrain, LA

Fig. 3.19. Broken pole and remains of telephone distribution cable in Slidell, LA

Fig. 3.20. Broken electrical pole in Biloxi, MS

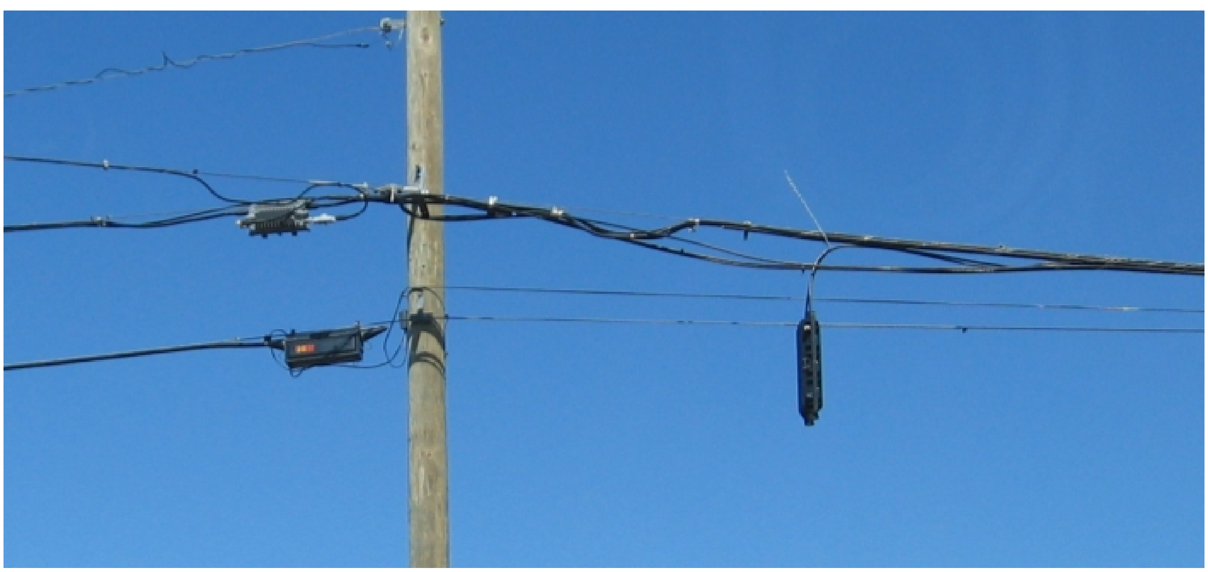

Fig. 3.21. Damaged CATV fiber-optic cable

Fig. 3.22. Hanging damaged PSTN outside plant distribution cable

4 General Damage to Communication Networks

A particular effect of Hurricane Katrina was its centralized nature, implying that communication interconnection points, such as COs, and electrical nodes, such as substations, suffered an unprecedented level of destruction. Damage to the cell sites, PSTN outside plants and electrical distribution grids was also severe but not significantly different from results of other strong hurricanes. Figs. 4.1-4.7 show typical damage caused by Hurricane Katrina in a communication center. As the figures indicate, the site was immersed in salty seawater that corroded all the equipment and destroyed the place. As will be discussed in following sections, such damage happened in several COs, long-distance switches, MTSOs, transmission sites and other communication nodes along the Mississippi coast, in New Orleans and Plaquemines Parish.

Fig. 4.1. Damaged switch (left). The rectifier bay is in the background, MDF on the left behind the switch. Notice the debris on the cable-racks.

Fig. 4.2. Inverter with mud

Fig. 4.3. Part of the switch on the left and two rectifier bays on the right

Fig. 4.4. Transmission-system power-distribution frame showing corrosion caused by immersion in sea water

Fig. 4.5. GPDF back side. Like the PDF in Fig. 4.4, it shows corrosion due to water immersion.

Fig. 4.6. Batteries on the left and rectifier bays on the right, both covered with mud

Fig. 4.7. Detail of two battery cells covered in mud. The green-colored interconnection bar is corroded copper.

5 Hurricane Katrina's Effects on the PSTN

BellSouth is the largest CLEC in the affected area, with a total of 4.9 million lines and thousands of kilometers in fiber-optic links. Thus, the focus of this report will concern Hurricane Katrina's effects on the BellSouth PSTN. Some analysis about transmission networks of other companies is included at the end of this section.

On August 30, 2005, the day after Katrina made landfall in Louisiana, 2.475 million BellSouth lines were out of service due to damage to the outside plant and outages in COs [15]. From the beginning of the storm, BellSouth lost service in 33 COs, 29 in the most severely impacted area of the Gulf Coast region shown in Figs. 5.1 and 5.2. Among the affected COs, nine were destroyed and two more severely damaged, an unprecedented level of destruction.

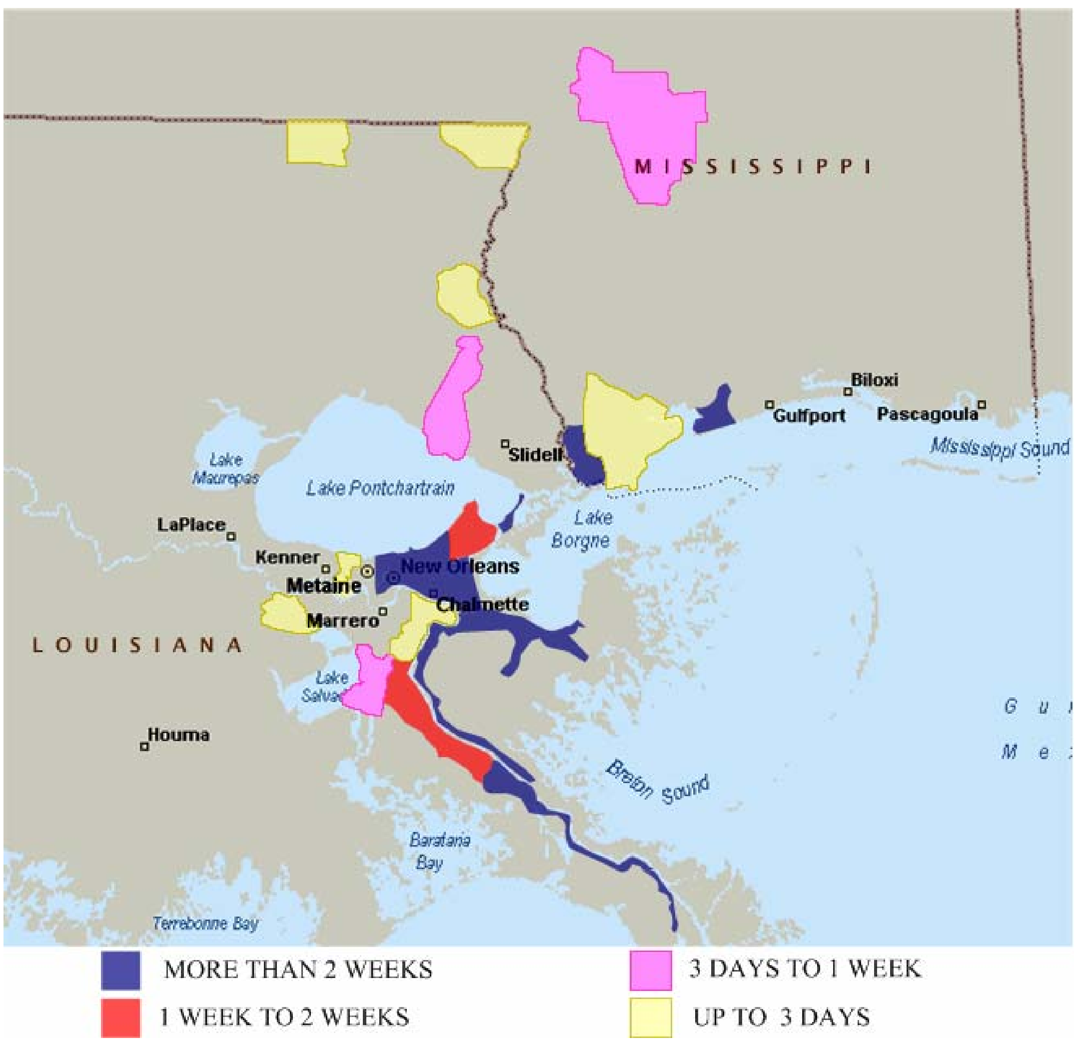

Fig. 5.1. Failed BellSouth CO regions and outage severity

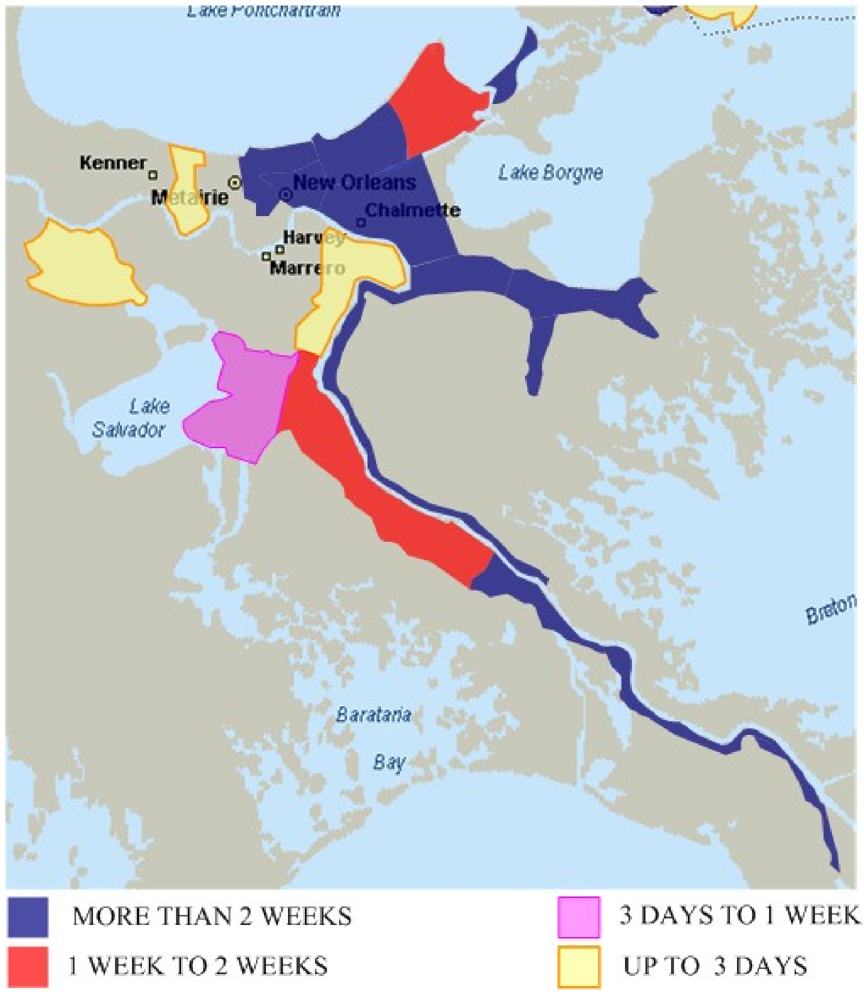

Fig. 5.2. Failed BellSouth CO regions in New Orleans and outage severity

Figs. 5.3 and 5.4 show causes for CO outages. Destroyed CO regions are shown in red. These are COs where all the equipment was ruined by the storm surge and, in many of cases, the building itself was destroyed. Blue areas indicate CO regions that failed due to water damage of the genset or lack of genset refueling but did not sustain equipment damage. The combined failure of a CO due to lack of electric power and partial equipment damage is indicated in yellow. Loss of service due to genset engine fuel starvation is shown in purple. In these cases, disruption of local diesel suppliers and obstruction of delivery capabilities due to impassable or damaged roads played a crucial role in many of the outages. Some of these COs also may have been subjected to flooding in buried fuel tanks but sustained no damage to the inside plant. It is also likely that damage in the outside plant may have accompanied the power-related outages. Damage to the outside plant may have directly affected a dedicated line or an important trunk, such as one connecting the PSTN to a mobile communication network element. Isolation of a remote switch from its host when the link between them was severed was another possible effect of outside plant damage.

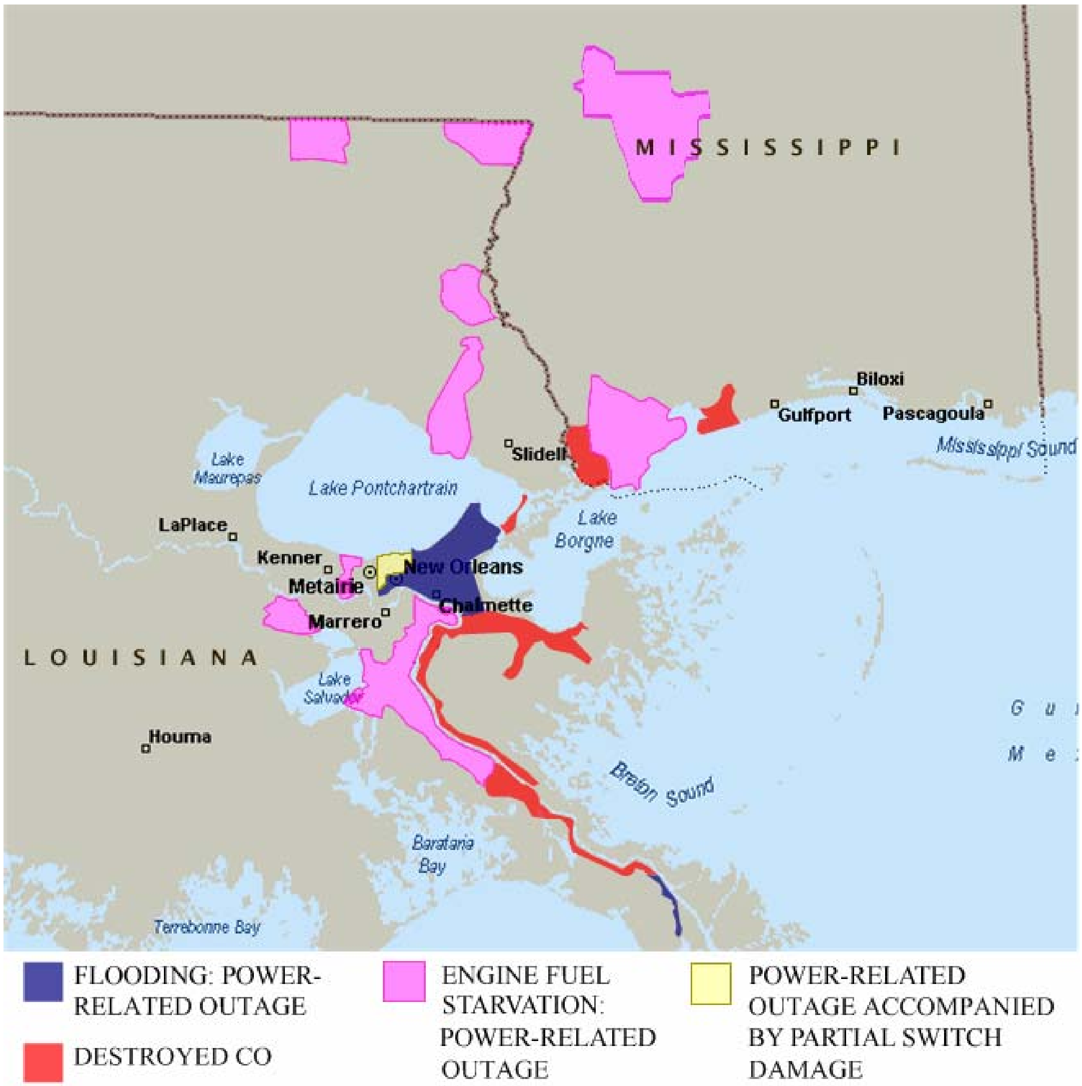

Fig. 5.3. BellSouth failed CO regions indicating the outage cause

Electric power outages influenced many more COs than those indicated in red in Figs. 5.3 and 5.4. Fig. 5.5 shows the status of the COs in the affected area on September 12, almost two weeks after the storm. Besides the existence of COs that were out of service due to power-related causes, Fig. 5.5 shows many more switches operating on emergency generators due to the lack of electric power.

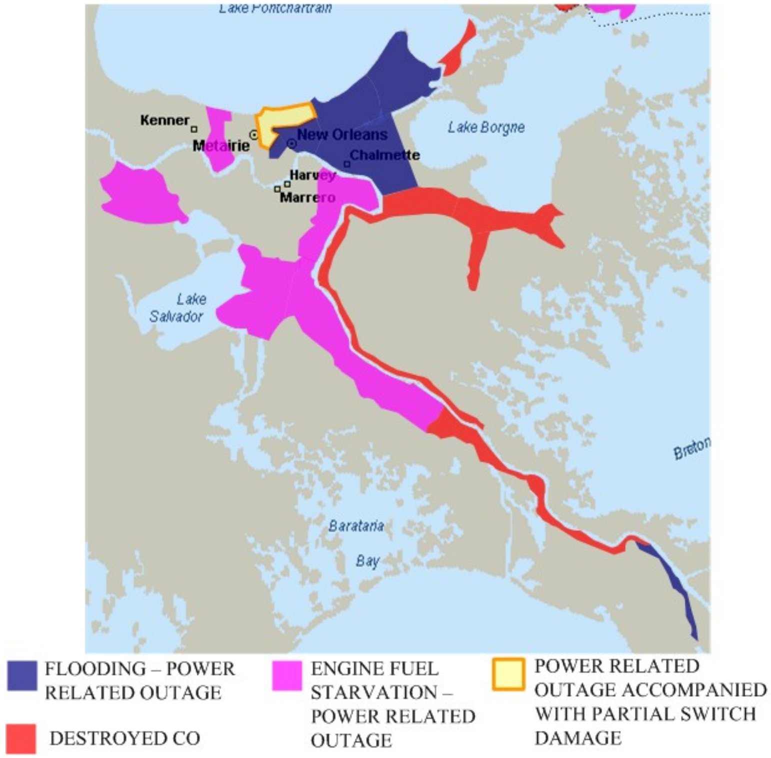

Fig. 5.4. BellSouth failed CO regions around New Orleans

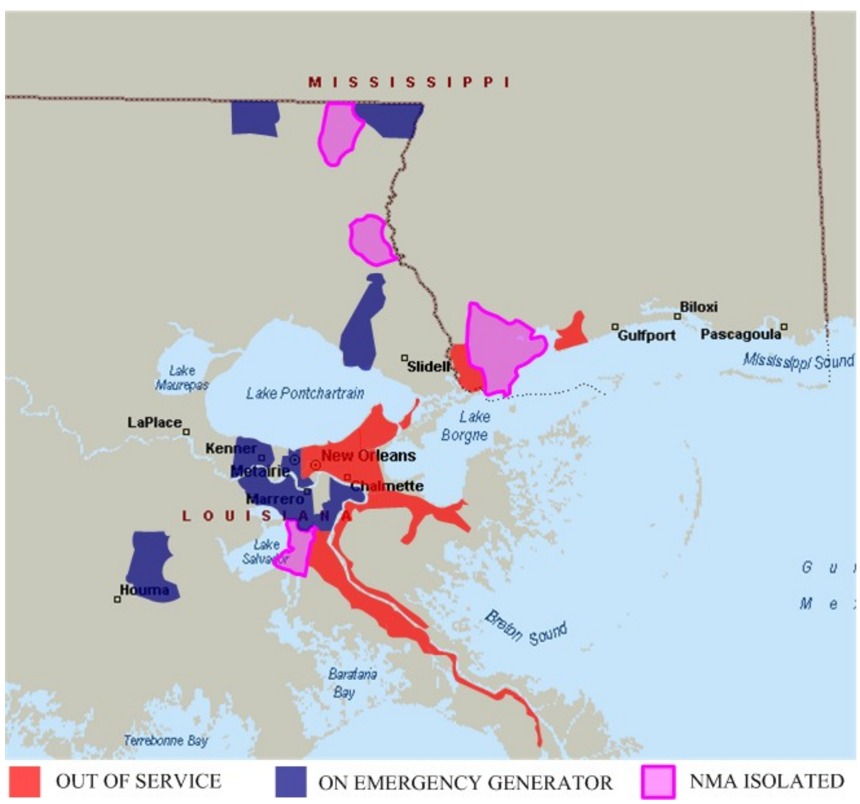

Fig. 5.5. CO status on September 12, 2005

E-911 centers were severely impacted by Hurricane Katrina both directly, when a PSAP or an E-911 was destroyed, and indirectly, when E-911 calls could not be routed due to PSTN failure. In Mississippi, service was affected in 43 out of 138 E-911 centers. All these 43 centers, many of which required re-routing of the traffic, were back in service by September 4th. In Louisiana, 35 of 91 E-911 centers failed. However, unlike Mississippi, service restoration took much longer due to the severity of the PSTN damage. By September 25th, almost one month after Hurricane Katrina landfall in Louisiana, 5 of the 35 E-911 centers in Louisiana, were still out of service.

Destroyed COs are always very difficult to replace. Fig. 5.6 shows two COs in normal operation while Fig. 5.7 exemplifies BellSouth's solution to replace destroyed COs. In Fig. 5.7 it is assumed that CO #1 has been destroyed while CO #2 still operates normally and has enough idle capacity to take over some of the CO #1 traffic. In order to provide service to CO #1 priority lines, a DLC system is placed beside the CO #1 building. Next, the DLC is connected to CO#2 using the existing fiber-optic cable link between CO #1 and CO#2 or by installing a new link. Finally, if the CO #1 feeder cables are in good condition, the DLC output copper pairs are spliced to feeder pairs. In this way, specifically selected CO #1 subscribers may receive normal service from CO #2. Fig. 5.8 displays the basic component of BellSouth's restoration tactic and telephone lines in the CO #1 area that may receive service through the DLC cabinets, including police stations, government buildings or emergency calling centers. Emergency calling centers (also called *phone banks*) seen during the site survey are shown in Fig. 5.9. The phone banks were used by evacuees to call the Federal Emergency Management Agency (FEMA) to obtain relief information. The fact that the output of the DLC is connected to feeder cables at the MDF or at the cable entrance facility is a clear indication that the outside plant is in fair enough condition to allow communication along part of the distribution cables and the feeders. One disadvantage of using DLC cabinets in a disaster aftermath is their batteries have a relatively short backup time. Hence, a portable genset is needed to provide an adequate service level.

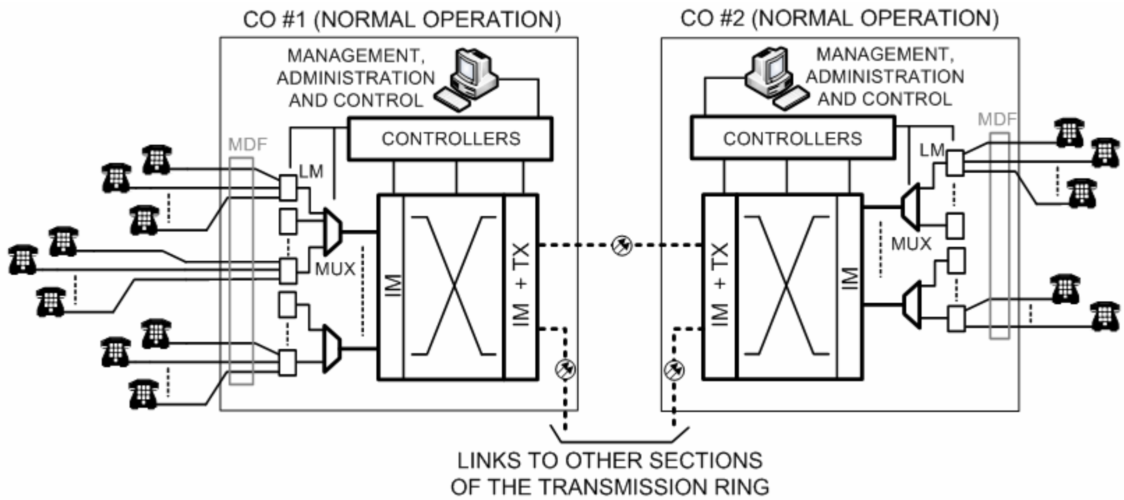

Fig. 5.6. Two COs in normal operation

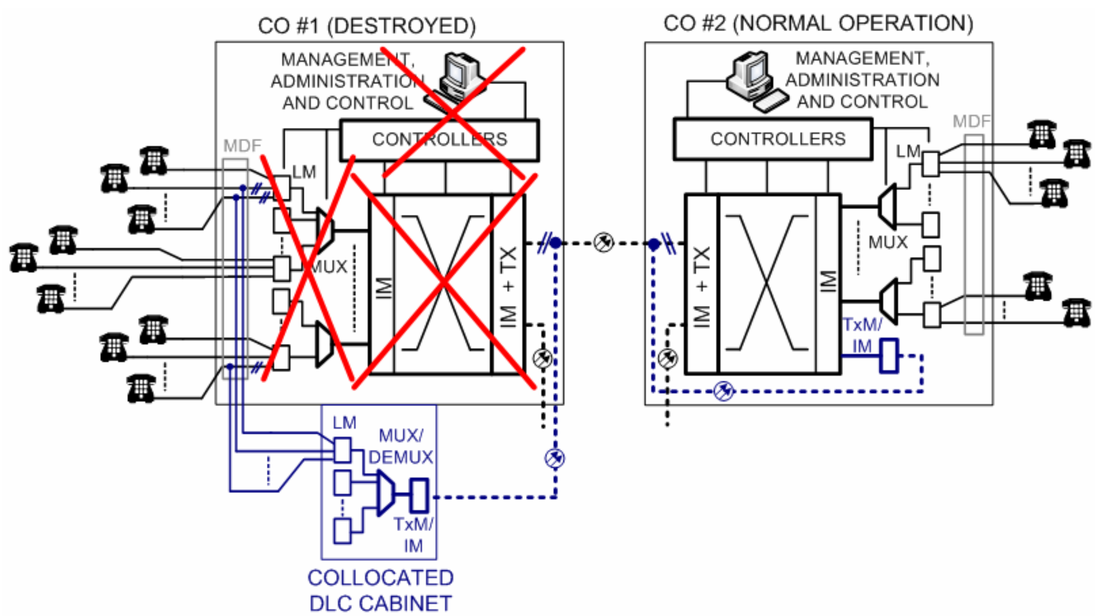

Fig. 5.7. Scheme showing BellSouth's solution to replace destroyed COs

A better alternative to DLC systems that was not used by BellSouth is to deploy a switch on wheels (SOW) to replace damaged COs. SOWs are truck-carried containers that house complete small switches, a power plant and transmission systems. These systems have already been used in rapid-deployed networks with new wireless networks and in countries with an extremely fast increase in POTS demand [16]. SOWs have two important advantages over DLC systems: they provide better functionality when connecting trunks, a requirement for cellular networks links, and they reduce potential congestion points by alleviating traffic of switches that otherwise will be hosting DLC systems. A disadvantage of SOWs is economic, as they are maintained idle for long periods without generating revenue. During this time, the SOW depreciates financially, while the batteries need to be maintained charged. Some authors [17] have suggested employing used parts to restore damaged COs. But they do not consider that legacy batteries are almost surely at the end of their life and cannot be used. Then the problem shifts into getting new batteries in a short time, which generally is not possible due to manufacturing constraints already cited.

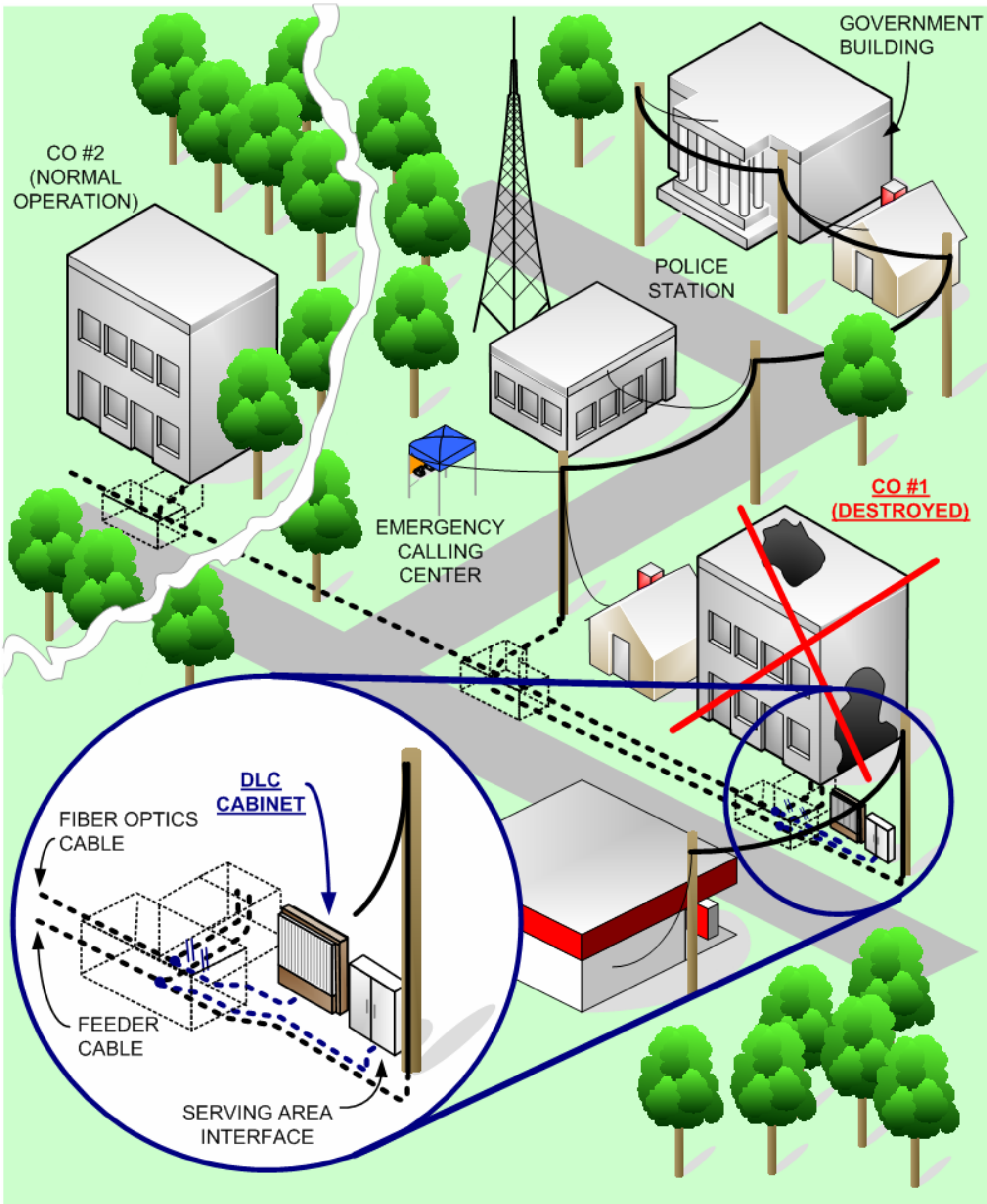

Fig. 5.8. Representation of the CO restoration tactic

Fig. 5.9. Phone banks

Restoration of the outside plant networks also involved using DLC systems. Water in manholes or along conduits from Hurricane Katrina flooding destroyed copper feeder cables in many COs. In case of very long immersion, fiber-optic cables also may have been slowly degraded until they were no longer operational. One important problem in planning outside plant restoration is that feeder cable capacity is calculated on, at least, a 5-year demand. However, mass evacuations and uncertainty about how and when the destroyed areas would be repopulated made it virtually impossible to calculate the demand and plan the installation of replacement feeder cables. While for a given copper, cable capacity is fixed and given by the number of pairs in that cable, for a given fiber-optic cable, capacity is not dependent on the cable itself but on the transmission equipment. Hence, from an outside plant-planning perspective, it makes more sense to replace the damaged copper feeders with fiber-optic cables connected to DLC cabinets, because the fiber-optic cables provide more flexibility to adapt to an uncertain demand. Fig. 5.10 shows an example of this method to replace damaged feeder cables implemented by BellSouth. The output of the DLC transmission equipment is connected to the feeder side of a serving-area interface that can be embedded in the DLC enclosure or located in a separate box beside the DLC cabinet. Within the service area, interface feeder pairs are connected with jumpers to distribution pairs, depending on where an existing or a new subscriber appears.

One important disadvantage of using fiber-optic cables and DLC cabinets to replace feeder cables is that DLC systems require local electric supply. Even though DLC cabinets have batteries which provide backup electricity for up to 4 hours, they need a portable genset to ensure there is no loss of service after that outage. Electric outages that last more than 4 hours are not uncommon, even with storms weaker than Katrina. Hence, deploying many DLC systems to replace damaged feeder cables creates logistical issues, since a portable genset needs to be deployed for each DLC cabinet. Moreover, for extended outages, the portable generators need to be refueled daily. Even worse, DLC enclosures are very vulnerable to flooding unless they are placed on top of poles. However, batteries placed on poles must be smaller than ground-mounted batteries thus reducing battery backup time to only a few minutes. So even though using DLC systems to replace feeder cables makes sense from a planning perspective, it has serious reliability issues.

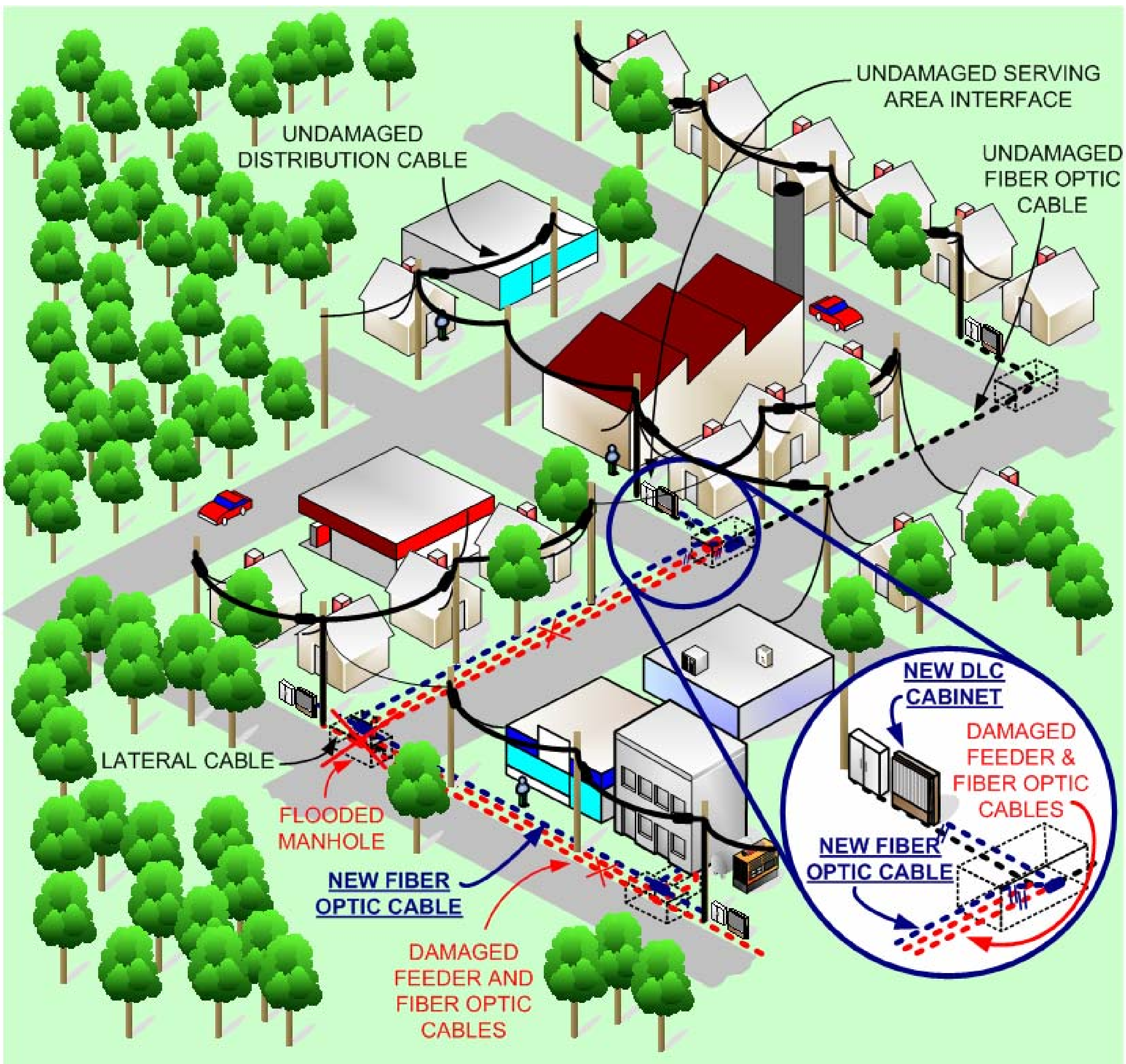

Fig. 5.10. BellSouth's solution to restore damaged feeders

5.1 COs that did not lose service

Even though a high number of COs lost service due to Hurricane Katrina, others maintained normal operations throughout the storm. Many of the surviving COs did not lose service thanks to remarkable efforts by BellSouth employees to keep gensets refueled and running. The New Orleans Main CO is a good example of a CO that survived unharmed both because of BellSouth employees and good fortune. The BellSouth Main CO entrance, shown in Fig. 5.11, is located on Poydras Street in New Orleans. This is the most important communications building in the affected region, because it houses several class 5 switches, a tandem switch, an AT&T long-distance switch and many important transmission terminals. Three factors affected operations in this CO during and after the storm: loss of electric power from the utility grid, flooding, and security issues related to public violence and looting. As Fig. 5.12 illustrates, the CO is situated in the heart of downtown New Orleans, halfway between the Convention Center and the Louisiana Superdome, an area that suffered extensive vandalism. Fig. 5.13 highlights the proximity to the Superdome, which explains why security was such an important factor in building operations.

Fig. 5.11. New Orleans Main CO entrance

Fig. 5.12. Aerial view of downtown New Orleans [8]

Fig. 5.13. Louisiana Superdome and the New Orleans Main CO

The best explanation of how New Orleans Main CO maintained service in Katrina's aftermath can be found in the testimony of Bill Smith, BellSouth's Chief Technical Officer, before the Senate Committee on Commerce, Science, and Transportation [18]. In that hearing, he said:

> "Our experience in the New Orleans Main Central Office at 840 Poydras Street gives a sense of the situation on the ground. BellSouth employees began staffing an Emergency Operations Center (EOC) on the 12th Floor of the building on Sunday, August 28th. The office lost power and engaged generators when the storm hit on Monday, but occupants breathed a sigh of relief that there was no flooding. Then, the levee broke and conditions rapidly deteriorated on Tuesday. Technicians and engineers in the office were trying to re-establish service and maintain power by keeping the generators fueled and running. As the situation in New Orleans deteriorated with violence and looting, the New Orleans police and the Louisiana State Police told us to evacuate the building. There was gunfire in the area and we were told it was unsafe for our employees to remain. At 3:00 p.m. CST, the Louisiana State Police arrived and provided us with an armed escort so we could leave the building. We moved to Baton Rouge and, concerned for the security of the building, we arranged for FBI agents to take occupancy of the building at approximately 9:00 that evening. By Friday morning, the Louisiana State Police and the FBI occupied the building. At that time, we began armed and escorted caravans to the building to bring fuel for the generator, water for the chillers, BellSouth personnel, as well as personnel from other carriers (at BellSouth's open invitation). In spite of these harrowing facts, this key switch, which serves as a regional hub for multiple carriers, remained in operation."

This testimony highlights the critical importance of the power system operation and the logistic issues that appeared due to flooding and looting. However, good fortune played a role as well. As Figs. 5.14 and 5.15 attest, flooding reached within a few meters of the CO front door. If the flooding had been slightly worse due to a small change in the Hurricane path, strength or timing, the CO generator set would have been even harder to refuel and the switches may have lost service.

Overall network performance was degraded, even though both the tandem switch and AT&T's long-distance switch maintained full operation, because, due to the limited capacity of these switches, they could not take all the traffic rerouted from failed COs. Cut transmission links, both to the east and to the west, interrupted most of the traffic going in and out of the CO.

Thus, communication congestion appeared which restricted calls despite the fact that the electric power supply was maintained and service was never lost.

Fig. 5.14. Aerial view of New Orleans, August 31, 2005 [6]

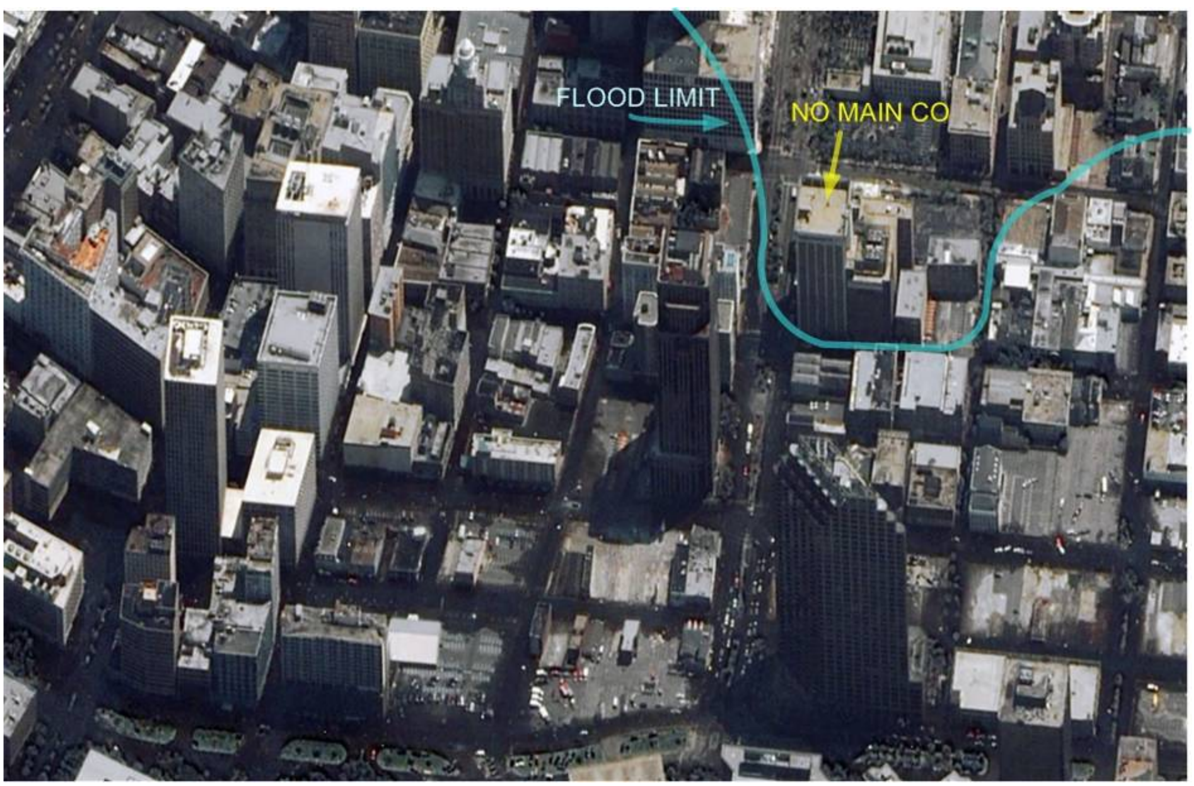

Fig. 5.15. New Orleans, August 31, 2005 [8]

Good fortune and efforts to keep gensets working played an important role in continuing service in other BellSouth COs. As Fig. 5.16 illustrates, many COs are located at sea level or below. Any small change in how Katrina impacted the coast may also have taken any of these COs out of service. Among these COs, Carrolton, shown in Fig. 5.17 is the one that was closest to being flooded with a few centimeters of water covering the streets all around. Even though the inside plant was not affected, many feeder cables were damaged and needed to be replaced by fiber-optic cables and DLC systems. In addition, floodwaters likely hampered the refueling of the emergency generator that provided electric power to the switch. Metairie and St. Charles (Fig. 5.18) are two other nearby COs that experienced flooding. The damage to their outside plants was less significant than in the case of Carrolton, but flooding may also have been an issue for refueling the gensets, especially for the St. Charles CO.

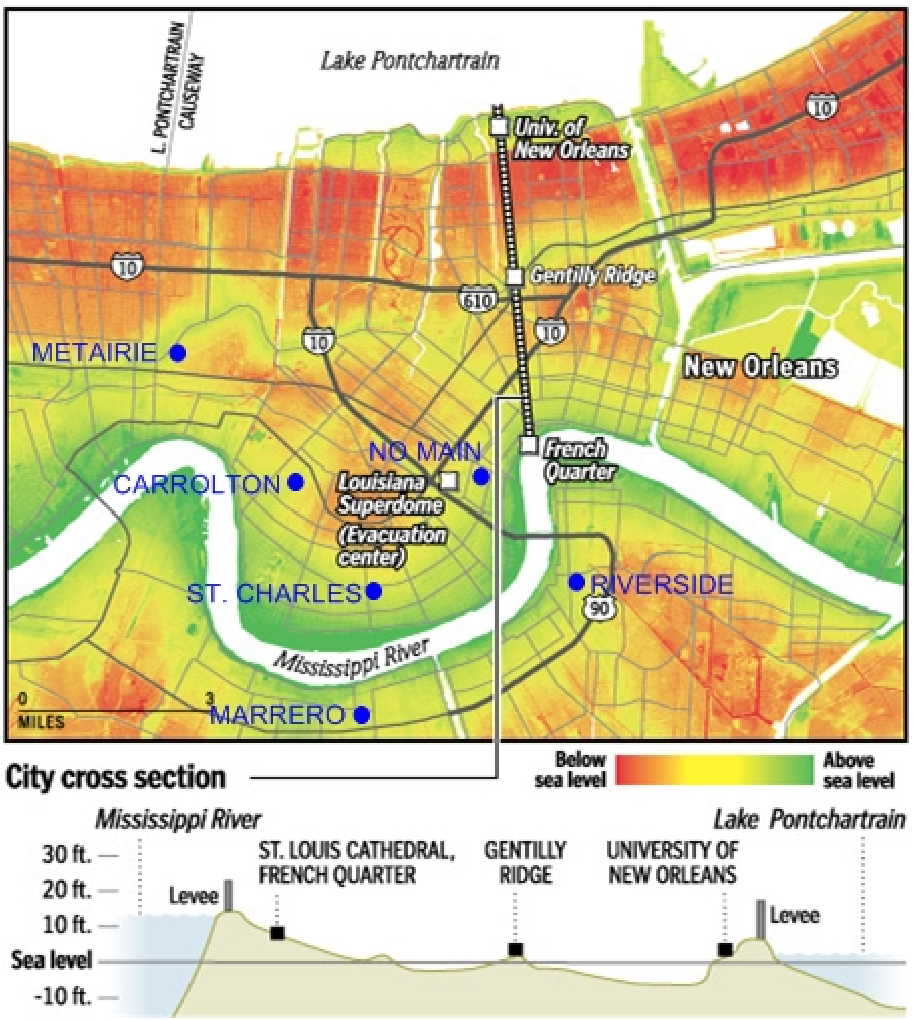

Fig. 5.16. COs that did not lose service and New Orleans area topographic map [19]

Fig. 5.17. Aerial view of Carrolton CO [10]

Fig. 5.18. Aerial view of St. Charles CO [6]

Slidell CO did not lose service even though it is adjacent to two COs that were destroyed, Lake Catherine and Pearlington. Nevertheless, Slidell CO (Fig. 5.19) did not avoid damage completely; some of the feeders needed to be replaced by DLC systems. Good fortune also helped to keep Slidell CO operational. During the on-site survey, we saw signs of flooding with water 20 cm high just 100 m south of the CO building. Although Slidell CO is not in a vulnerable location, it is only 7 km north of the Lake Pontchartrain shore with numerous waterways nearby, as seen in Fig. 5.20. As Fig. 5.19 shows, if the flooding had been worse because Hurricane Katrina has taken a westerly path, the genset fuel tank may have been damaged because it was placed almost at ground level. Most access to Slidell is from the north. Routes 11, I-10, I-59 and I-12 were not blocked or damaged, which surely helped keep the CO genset refueled.

Fig. 5.19. Slidell CO

Fig. 5.20. Aerial view of Slidell CO [10]

COs along the Mississippi Coast were also saved from losing service by efforts of BellSouth employees to maintain operation of the genset. The most remarkable example is Gulfport CO, shown in Fig. 5.21. This is a relatively important CO, since its switch is host to other regional remote switches. Bill Smith's testimony to the Senate [18] highlights the critical importance given to the electric power and how the hard work of BellSouth employees maintained the switch.

> "On September 3rd, a brick wall protecting the main generator keeping the central office alive started to give way. Nine workers from that central office ran from the basement, where they had been working while riding out the storm, to the rooftop room and fortified the walls with whatever they could find – plastic tarps, plywood and even the cardboard from a science project of one worker's son. The main wall in the office collapsed, yet their efforts to protect the switch were successful."

Fig. 5.21. BellSouth Gulfport CO

During the on-site survey to Gulfport on October 22nd, we were unable to identify damage to the wall of the Gulfport CO, probably because it had been repaired. Collapsed walls are not evident in either Fig. 5.22 or 5.23, although some likely spots of damage are suggested in Fig. 5.23. Fig. 5.23 also indicates the storm surge inflow and the railroad tracks, which protected the CO from serious damage. As seen in Fig. 5.22, the railroad tracks pass 1 meter above the street level forming a levee that stopped most of the storm surge.

Fig. 5.22. Gulfport CO on August 31 or September 1, 2005 [7]

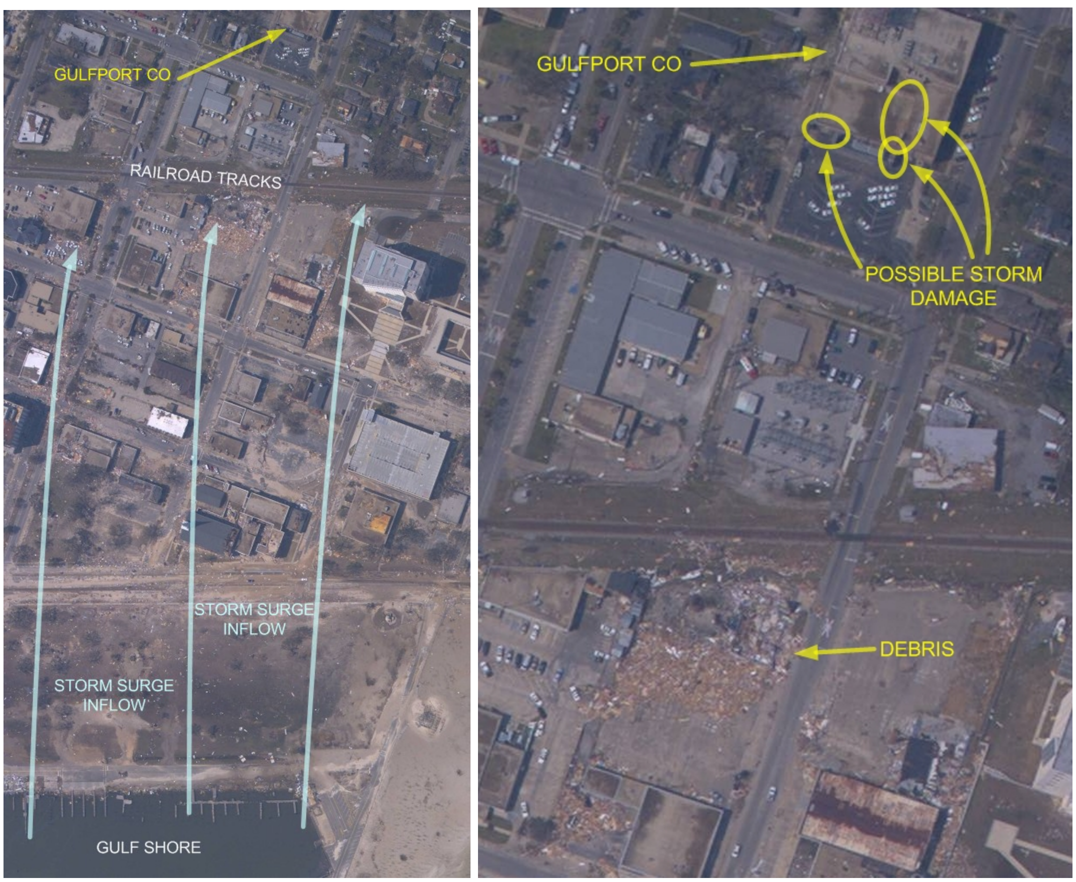

Fig. 5.23. Aerial view of Gulfport CO, August 30, 2005 [6]

Like the Gulfport CO, the Biloxi CO (Fig. 5.24) did not lose service even though it is located south of the railroad tracks. Good fortune played a role in averting an outage at this site, because the CO was built at an elevation high enough to avoid the storm surge (Figs. 5.25 and

5.26). Had Katrina taken a course a few miles more to the east, the Biloxi CO almost certainly would have suffered catastrophic damage. The unblocked access to I-110 (Fig. 5.27) may have also kept the genset refueled and operating.

Fig. 5.24. Biloxi CO

Fig. 5.25. Biloxi CO, August 31 or September 1, 2005 [7]

Fig. 5.26. Aerial view of Biloxi CO, August 30, 2005 [6]

Fig. 5.27. Aerial view of downtown Biloxi and CO [6]

Other COs in the Mississippi Gulf Coast, such as Edgewater, Gautier, Ocean Springs and Pascagoula, escaped damage and never lost service. With no outages in Gulfport and Biloxi, the service restoration time was shorter than in Louisiana. Nevertheless, Mississippi did have COs destroyed.

5.2 Destroyed COs

Fig. 5.28 shows the nine COs destroyed by Katrina, all by the storm surge. The presence or lack of electric power was not an issue when evaluating the cause of failure.

Fig. 5.28. Destroyed COs

Two of the destroyed COs were in Mississippi: Pass Christian and Pearlington. The Pass Christian CO is shown in Fig. 5.29. Storm surge damage is clearly visible. The reason Pass Christian CO was destroyed can be understood by looking at Figs. 5.30 and 5.31. The building was just 300 meters from the shore, an extremely vulnerable location. Strangely, the building was not constructed on pilings although it was located so close to the shore, meaning that even a small storm surge would have destroyed the switch. The emergency DLC system to replace the

CO was hosted by the Gulfport CO. Fig. 5.29 shows that the outside plant was in relatively good condition, which made possible the use of DLC systems. As was mentioned previously, using a DLC system to replace destroyed COs hints that the outside plant was not as seriously damaged as the CO itself. At the time of the on-site survey on October 17th, the DLC system had no genset to provide extended backup power in case of an electric grid outage, a common event during recovery operations.

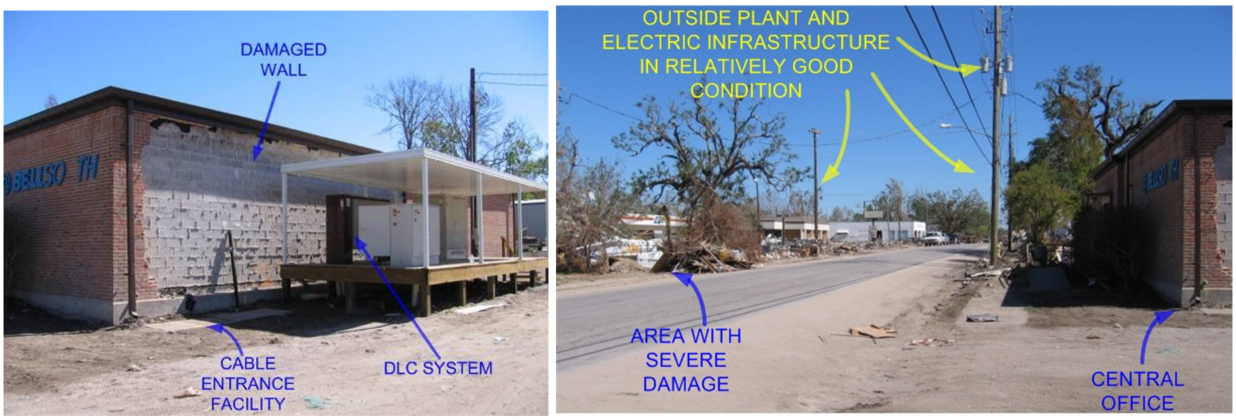

Fig. 5.29. Pass Christian CO

Fig. 5.30. Pass Christian MS, August 31 or September 1, 2005 [7]

Fig. 5.31. Aerial view showing vulnerable location of Pass Christian CO, August 30, 2005 [6]

The other destroyed CO in Pearlington, Mississippi, unlike Pass Christian, was located 8 km inland, not a vulnerable position. However, the CO, shown in Figs. 5.32 and 5.33, was destroyed when it was covered by more than 2 m of water from the storm surge. None of the pictures indicates a genset. As with the Pass Christian CO, the DLC that replaced the switch had no generator to extend the battery backup, which may have negatively affected PSTN reliability in that area. In addition, like the Pass Christian CO, the Pearlington DLC was hosted by the Gulfport CO. During the on-site survey on October 20th, work was being done on the outside plant, probably to connect the output of the DLC. This implies that the area recovered POTS service around that date.

Fig. 5.32. Pearlington CO

Fig. 5.33. Aerial view of Pearlington CO, September 2, 2005 [6]

The northernmost destroyed CO in Louisiana, Lake Catherine, was located 17 km to the southwest of Pearlington. However, Hurricane Katrina's effects on the Lake Catherine CO were more severe than in Pearlington, or any other CO. As Fig. 5.34 shows, the Lake Catherine CO was obliterated; only the building's supporting pilings survived.

Fig. 5.34. Remains of Lake Catherine CO [20]

The rest of the destroyed COs are located in Plaquemines Parish and south St. Bernard Parish. Two, Yscloskey (Figs. 5.35 and 5.36), and Delacroix (Figs. 5.37 and 5.38), were small remote switches constructed on pilings. Fig. 5.39 indicates that both buildings were better built than the surrounding houses with the objective of withstanding hurricanes. Unfortunately, they did not seem to have been designed for a hurricane as strong as Katrina. The photos in Fig. 5.40 show that the gensets of both COs were located outside at the same level as the switch. At the time of the on-site survey on October 18^{th}, both COs had been abandoned with no DLC system because their operational areas were unpopulated. On November 7^{th} the emergency DLC replacement systems hosted by the Chalmette CO were put into service in both Delacroix and Yscloskey COs.

Fig. 5.35. Delacroix CO

Fig. 5.36. Delacroix CO

Fig. 5.37. Yscloskey CO

Fig. 5.38. Yscloskey CO

Fig. 5.39. Aerial view of Delacroix and Yscloskey CO, September 7, 2005 [6]

Fig. 5.40. Gensets: Left – Delacroix, Right – Yscloskey

South of Delacroix and Yscloskey is the Point A La Hache CO which was also destroyed by Hurricane Katrina. While the area suffered severe damage, the building, (Fig. 5.41) showed no significant structural damage. However, the switch and all other equipment inside the CO were destroyed when a storm surge of approximately 2.5 m overtook the site. Some of the resulting flooding is shown in Figs. 5.42 and 5.43. The height of the storm surge was verified by the debris seen in Fig. 5.44. As in many other COs, the genset fuel tank was located in a vulnerable spot at ground level. Thus, even if the storm surge had not reached the level of the CO floor, the switch still would have gone out of service because the fuel tank would have been flooded. At the time of the on-site survey, there was no electricity in the entire area and no sign of people returning to their homes. There were also no indications of DLC enclosures to provide emergency telephone service to the area while the switch was not working. However, BellSouth's notices of network changes announced that a DLC system hosted by the Marrero CO was to be installed at the site by November 7th [21].

Fig. 5.41. Point A La Hache CO, October 18, 2005

Fig. 5.42. Aerial view of Point A La Hache CO [20]

Fig. 5.43. Aerial view of Point A La Hache, September 3, 2005 [6]

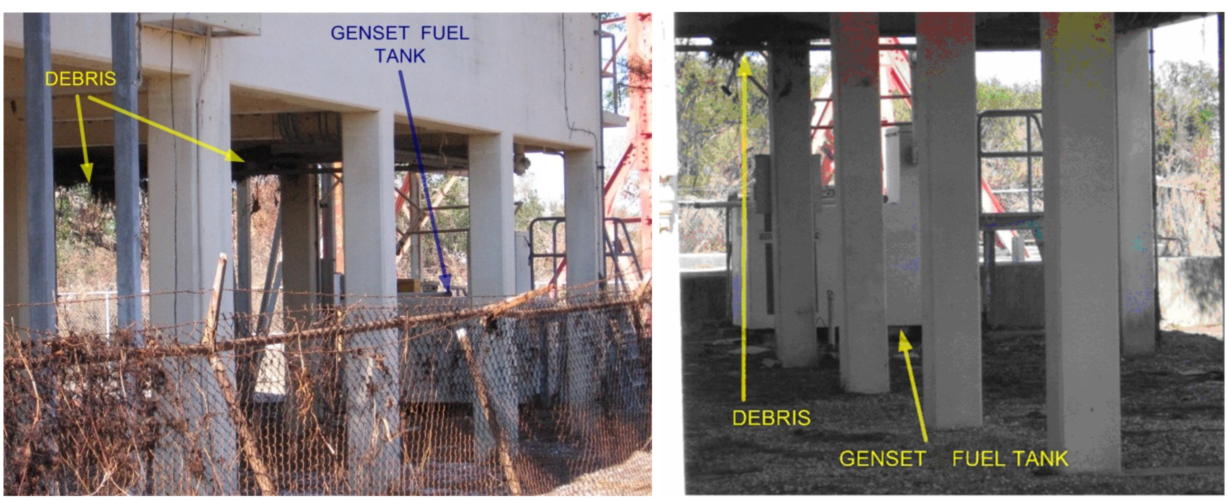

Fig. 5.44. Point A La Hache CO genset fuel tank.

The same issue encountered with the Point A La Hache CO genset fuel tank was also seen in the St. Bernard office located about 30 km to the north. The St. Bernard CO construction implies an even riskier condition because, as shown in Fig. 5.45, the building was not constructed on pilings, even though the area was at risk of flooding. Even a small amount of flooding, as indicated in Fig. 5.46, could cause serious damage and take the switch out of service. A similar problem was also noted in the Pass Christian CO, but in this site the building was not destroyed. At the time of the visit on October 22nd, contractors were finishing cleaning the interior from mold and mud. As in other sites, there was no indication of a DLC system, but there were also plans to install one, hosted by the Marrero CO, by November 7th.

Replacing destroyed COs with DLC cabinets leaves the PSTN in a very vulnerable condition if a strong hurricane hits the area again during the 2006 hurricane season. All of the last four analyzed COs were replaced by DLC systems hosted by the Marrero CO, one of the COs located at sea level shown in Fig. 5.16. Even worse, Marrero is a remote switch hosted by the Schrewsbury CO, located below sea level, which failed during Katrina. Hence, the Marrero-Schrewsbury link constitutes a single common point of failure for a very large area.

Fig. 5.45. St. Bernard CO

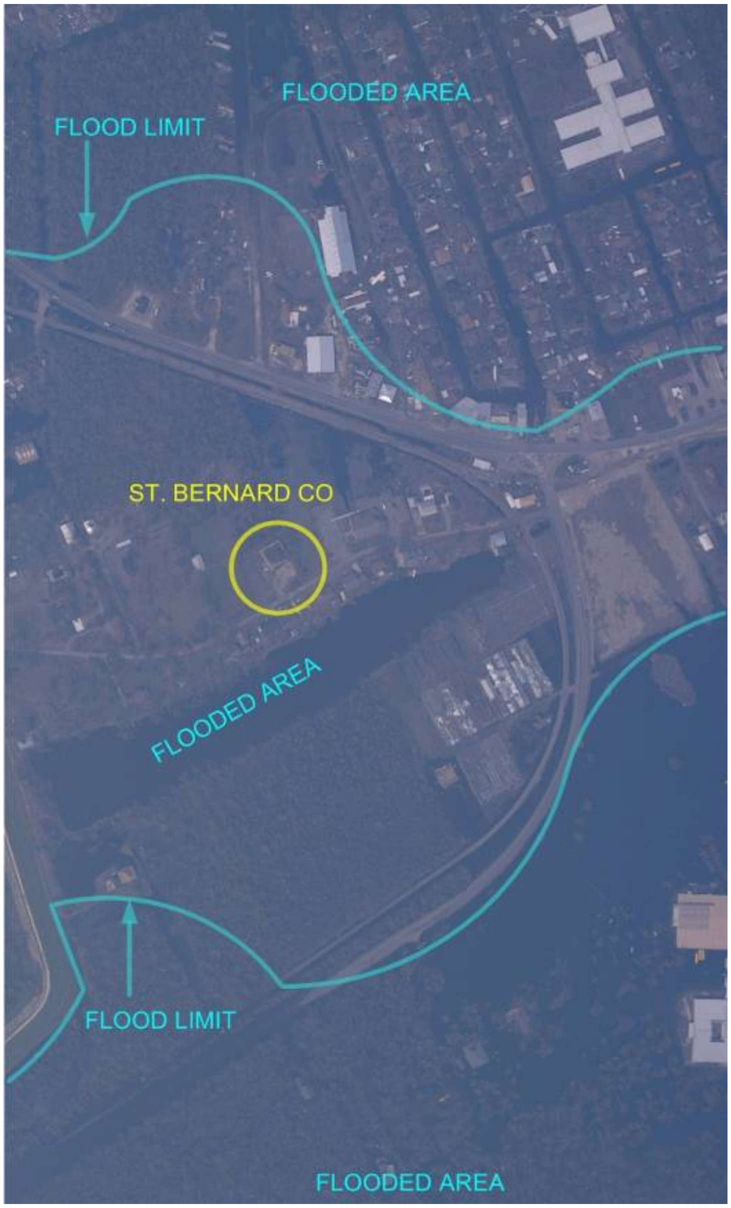

Fig. 5.46. Aerial view of St. Bernard, September 3, 2005 [6]

The remaining two destroyed COs are Buras (Fig. 5.47), and Port Sulphur (Fig. 5.48). Both COs were built similarly to Point A La Hache and experienced similar damage from the storm surge. Like Point A La Hache, the Buras genset or its fuel tank seems to have been located at ground level. Also, like Point A La Hache, the area around the COs experienced catastrophic damage, some of which can be seen in Figs. 5.49 and 5.50. Both switches were replaced on November 7th with DLC systems hosted by the Aurora CO. In addition, all the feeders were destroyed and replaced by DLC enclosures during the first quarter of 2006.

Fig. 5.47. Aerial view of Buras CO [20]

Fig. 5.48. Aerial view of Port Sulphur CO [20]

Fig. 5.49. Aerial view of Buras CO, September 3, 2005 [6]

Fig. 5.50. Aerial view of Port Sulphur CO, September 3, 2005 [6]

5.3 COs that failed due to lack of electric power caused by flooding

The most common outcome of any hurricane is the loss of electric power in a large region lasting days and, in some cases, weeks. Hurricane Katrina was no exception; all the affected area shown in Fig. 5.3 lost power. However, an electric power outage does not necessarily imply that a CO will lose service. Given periodic refueling, the on-site backup genset can maintain the switch for extended periods. The main difference between Katrina and other hurricanes is that the densely populated area depicted in Fig. 5.51 was flooded when the levees failed. Even though this is a small area, it contains several of the largest switches. Thus, a major percentage of the lines that went out of service belong to this area.

The flood created three problems:

1) Direct water damage to power plants, gensets or fuel tanks but not to most of the communication equipment
2) Loss of service from lack of refueling a CO genset because the water depth made reaching the site impossible
3) Loss of service from lack of refueling a CO genset because of civil unrest, looting or curfew

These problems caused CO outages due to lack of electric power. Six of the seven COs with these power-related outages are displayed in Fig. 5.52. Two, Lake and Mid City, suffered partial damage of communication equipment, including the switch. Mid City also had damage in the power plant located in the basement. As Bill Smith commented in [22]:

> "…In New Orleans, we've had water into some of the power facilities and power rooms but to the best of our knowledge, in the survey process, the majority of equipment has remained dry. We expect our challenge there will be to restore the power equipment with batteries and generators. … The switch was positioned on upper floors of the CO building precisely to avoid flood waters."

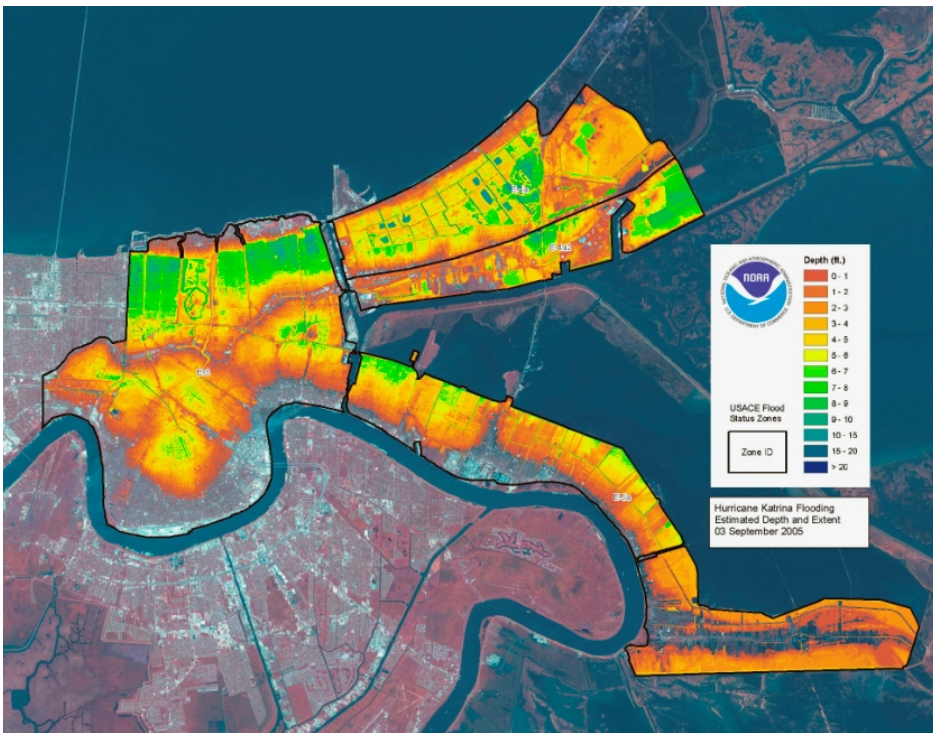

Fig. 5.51. New Orleans flooded areas with the estimated water depth [NOAA]

Bill Smith's comments show the importance of protecting the power plant in the same way that the switch is protected, by locating it on floors above sea level. They also explain why flooding and power-related outages are considered as the same failure cause. As Fig. 5.53 indicates, five of the COs shown in Fig. 5.52 are located below sea level in locations that were prone to flooding. Most of these COs were built some decades ago when design methodologies were not as comprehensive with respect to hurricanes. However, modern design guidelines place all CO critical systems, including the entire power plant, above sea level.

Fig. 5.52. New Orleans flooding with related failed COs in yellow and levee breaches indicated in light blue. Background satellite picture from [23]

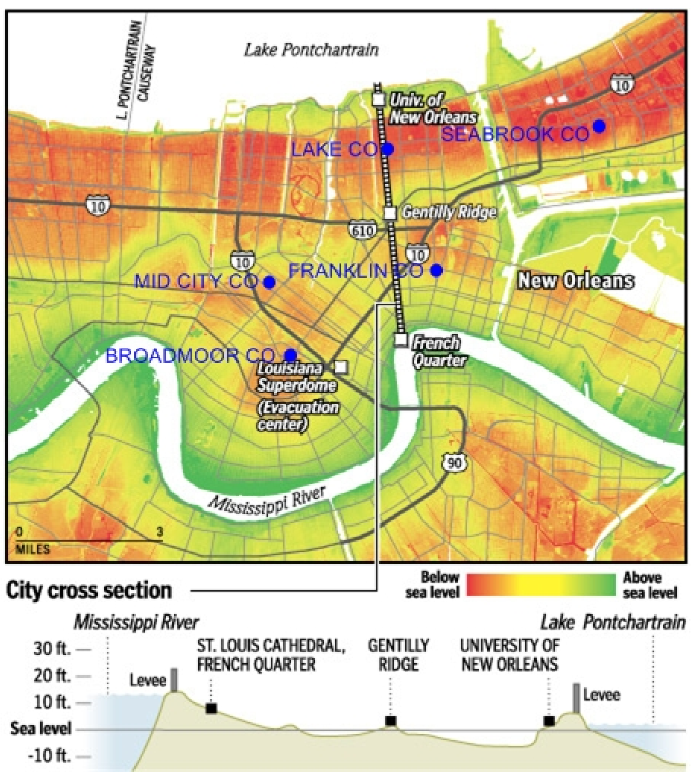

Fig. 5.53. New Orleans topographic map [19] with power-related CO outages.

Among the eight COs with power-related outages, Lake suffered the highest floodwaters. As Fig. 5.54 shows, the floodwaters reached a depth of more than 3 m. Besides being in one of the lowest points in the city, Fig. 5.55 shows that the building is located 300 m from the London

St. Canal levee, which breached 800 m southwest of the CO. The high floodwaters caused the destruction of the oldest switch in the building [24]. A newer switch was undamaged and used to restore service to subscribers of the older switch. Although the damaged switch was not replaced by a DLC system, several DLC enclosures were used to replace the entire destroyed feeder facility.

Fig. 5.54. Aerial view of Lake CO [20]

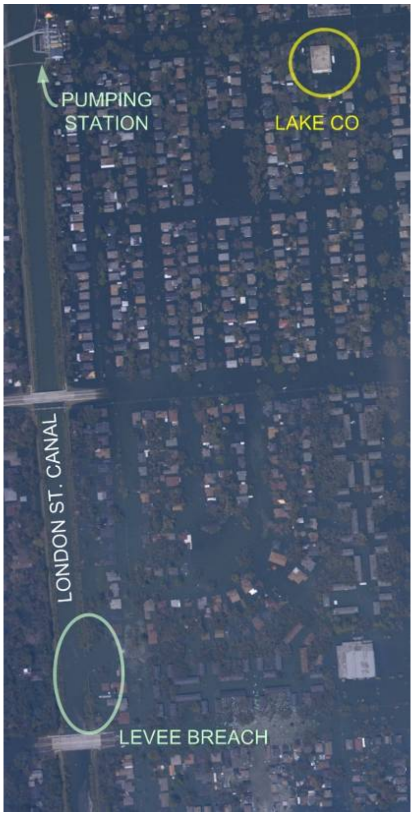

Fig. 5.55. Aerial view of Lake CO, August 31, 2005 [6]

Mid City is another of the COs that suffered damage to its switch. Fig. 5.56 shows that flooding was not as severe as in Lake; likely the switch was located at ground level. It is unclear how much damage the switch received, but probably it was not totally destroyed. The fact that it was an old switch may have contributed in the decision to replace it with a new one [25]. However, the power plant located in the basement was destroyed. Fig. 5.57 depicts the flooding around the CO. Even though the building was less than 500 m away from an exit on I-10, the flooding was significant enough to prevent reaching the site. Like the Lake CO, all copper feeders facilities were destroyed and will be replaced by fiber-optic and DLC systems.

Fig. 5.56. Aerial view of Mid City CO [20]

Fig. 5.57. Aerial view of Mid City CO, August 31, 2005 [6]

Broadmoor is another CO that suffered damage in the feeders and lost service due to lack of electric power (Fig. 5.58). During the on-site survey, on October 21st, the genset at the back of the CO was running, indicating that the electric utility grid was not providing power. This hints that the power plant was not damaged. Fig. 5.58 indicates that the flooding at this site was not severe and that there is a chance that the genset and other equipment located at ground level may have narrowly avoided damage. It is certain that the switch in this site was not damaged. However, part of the copper feeder facility was destroyed and needed replacement by DLC cabinets and fiber-optic cables. Fig. 5.59 reveals that the CO is located very close to I-10, but flooding may have prevented refueling the genset, inducing a switch outage.

Fig. 5.58. Broadmoor CO, Left: Front, Right: Back

Fig. 5.59. Aerial view of Broadmoor CO, August 31, 2005 [6]

Not all the COs that suffered severe flooding were damaged. Venice CO, shown in Fig. 5.60, is the most remarkable example. This is Louisiana’s southernmost CO, located near the mouth of the Mississippi River and about 15 km west from where Hurricane Katrina made landfall on August 29th. Despite its extremely vulnerable location and that the area surrounding the CO was catastrophically destroyed by the storm surge, as depicted in Fig. 5.61, there were no reports of damage in the CO except the genset. The only road access to Venice is Highway 23 from the north. It passes through one of the most severely affected areas by the storm, which surely prevented any genset refueling efforts by land. The building houses a remote switch hosted, before the storm, by the Buras CO. Since the Buras CO was destroyed, Venice is now hosted by the Jesuit Bend CO. There are no current reports of feeder damage.

Fig. 5.60. Aerial view of Venice CO [20]

Fig. 5.61. Aerial view of Venice CO, September 3, 2005 [6]

Seabrook, shown in Fig. 5.62, is another CO that experienced severe flooding but no damage to the CO or feeder cables. Fig. 5.62 indicates the CO was without a power supply. The genset may have been damaged and its fuel tank flooded. Even if the genset had not been damaged, it could not have been refueled since, as depicted in Fig. 5.63, this site had no direct access to dry land. Thus, the CO went out of service due to lack of electric supply. Fig. 5.63 suggests that one alternative to refuel the genset could have been to use boats like those employed in rescue missions.

Fig. 5.62. Aerial view of Seabrook CO [20]

Fig. 5.63. Aerial view of Seabrook CO, August 31, 2005 [6]

Franklin CO, depicted in Fig. 5.64, was another of the COs in New Orleans that lost service due to lack of electric power because refueling was impossible. Hence, although there was no damage to the power plant or any other equipment, the genset could not be refueled. Thus the switch lost service due to lack of power. In addition, there are no reports of extensive damage in the feeders. Since Franklin acts as an important center for routing E-911 communication, the outage in this CO had a severe impact on emergency calls. BellSouth’s solution was to reroute E-911 calls to Carrolton until Franklin regained full service.

Fig. 5.64. Aerial view of Franklin CO [20]

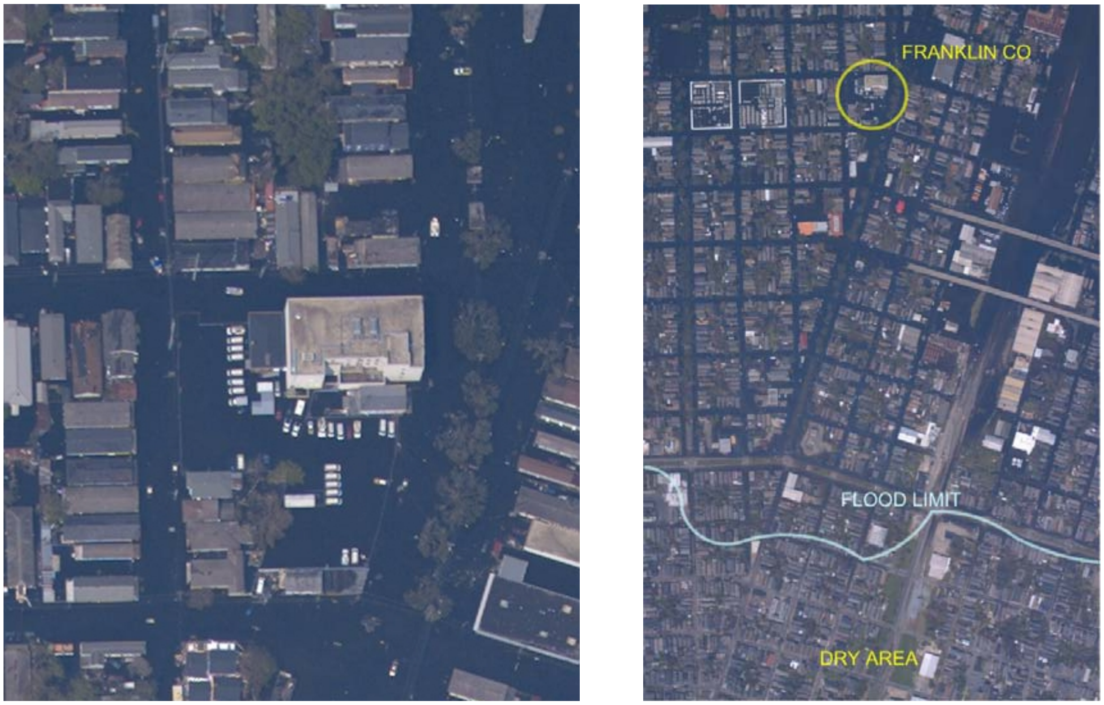

Fig. 5.65. Aerial views of Franklin CO, August 31, 2005 [6]

The Lower 9th Ward was one of the New Orleans' most severely flooded neighborhoods. Chalmette CO is located 7 km southwest of the Industrial Canal levee breaches that inundated that area of the city. Fortunately, the CO, shown in Fig. 5.66, was located on slightly elevated terrain and received only 1 m of water. During the on-site survey, on October 18th, we were informed at the site that no equipment was damaged but that the utility grid electric power had been out since the storm. They were expecting to have electric power restored from the grid before the end of October, as the work shown in Fig. 5.67 attests. By the time of the visit, they had no refueling problems. However, as Fig. 5.68 reveals, while the flood persisted, the CO was surrounded by high water that isolated the site and negated any refueling possibilities. Security issues may have also played an important role. During the on-site survey, we observed a sign on the front door by the police guard post reading, *BellSouth Fort Apache*. Hence, because of flood and security issues, the switch failed when it was impossible to deliver fuel to the genset.

Fig. 5.66. Aerial view of Chalmette CO [20]

Fig. 5.67. Chalmette electric drop being repaired

Fig. 5.68. Aerial view of Chalmette CO, August 31, 2005 [8]

Michoud CO experienced the same conditions as Chalmette: There was no damage to the equipment but flooding prevented fuel delivery to the genset. During the on-site survey on October 17th, local employees confirmed to us that there had been no damage to the equipment but that they suffered a long outage from the electric utility grid. Like Chalmette, the building is constructed on terrain slightly higher than its surroundings, as shown in Fig. 5.69. Additionally, the lowest floor is approximately half a meter above ground. These two factors may have assisted in avoiding equipment damage. However, the building was isolated when all the access routes became impassable due to the flood.

Fig. 5.69. Aerial view of Michoud CO, September 3, 2005 [6]

5.4 COs that lost service due to genset engine fuel starvation

Disrupted local diesel supply and obstructed roads are two possible primary causes for all the remaining CO failures. Contrary to previous cases, in these COs the flood waters receded quickly. Three COs that fall into this category, Bush, Lumberton and Bay St. Louis, may have also experienced damage to the outside plant that isolated them from the rest of the network, as Fig. 5.5 seems to indicate.

The Bay St. Louis CO is the most interesting of these three. As shown in Fig. 5.70, this CO area is on the coast, between two destroyed COs, Pearlington and Pass Christian. The CO contains a remote switch hosted by Gulfport CO and linked by a fiber-optic cable running along the coast and passing through Pass Christian CO. Other possible links connect Bay St. Louis CO with Pearlington to the west and Bayou Laterra to the north. The Bay St. Louis main link to Gulfport was interrupted when the bridges on Bay St. Louis were destroyed by the storm. Alternative links may have been interrupted due to storm surge damage in the town of Bay St. Louis and along Highway 603. The Bay St. Louis CO outside plant also received considerable damage, and plans to replace most of the feeders by fiber-optic cables and DLC cabinets were carried out at the end of 2005. As Fig. 5.71 shows, there is no indication of damage or flooding in the CO itself. However, the destroyed bridge on Route 90, flooding in a section of Highway 603, and catastrophic damage west of Bay St. Louis in Waveland likely delayed any effort to refuel the genset. As a result, the remaining fuel was consumed and the genset ceased operating.

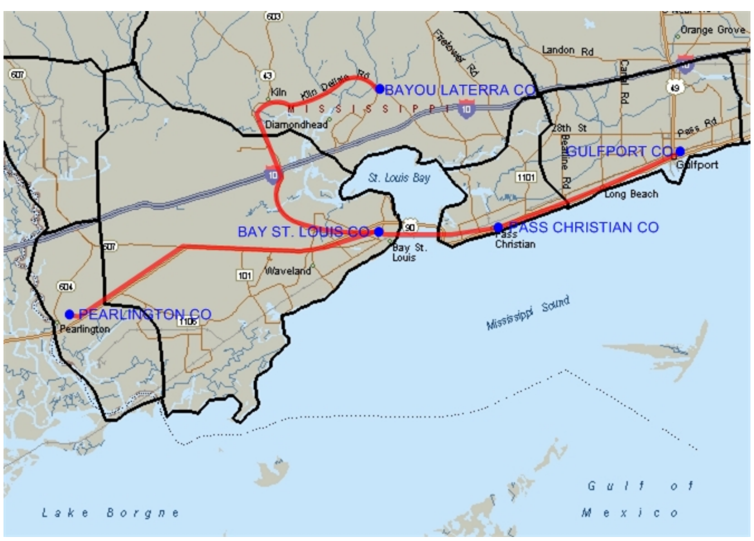

Fig. 5.70. Map of Bay St. Louis area with likely transmission paths indicated in red

The rest of the COs that lost service from fuel starvation are Mount Hermon, Angie, Lacombe, Schrewsbury, Harahan, Aurora, Luling / Boutte, Jesuit Bend and Laffite. Disruption of the local diesel supply may have caused lack of fuel for the gensets at Mt. Hermon and Angie. These COs are located almost 100 km north of New Orleans, where extensive damage and flooding was unlikely. Among the nine remaining COs, the most interesting are Schrewsbury and Aurora.

Fig. 5.71. Aerial view of Bay St. Louis CO, August 31, 2005 [6]

As Fig. 5.72 indicates, Schrewsbury CO is a host switch situated below sea level. Moreover, Fig. 5.73 shows that there is a canal less than 200 m north of the building. Thus, Schrewsbury CO is located in an area that may be easily flooded during storms. The genset or its fuel tank possible location, as pointed out in Fig. 5.73, is at ground level, which implies that it may be damaged even in light flooding. Schrewsbury CO is an extremely vulnerable node in the PSTN network because, as was mentioned earlier, it hosts Marrero, a CO that, in turn, hosts DLC systems that replaced destroyed COs in St. Bernard Parish. The low-lying terrain where Schrewsbury CO was built is at risk of flooding from levee breaches in the canals around Metairie and Kenner west of the Lake Pontchartrain causeway. If this disaster occurs, the PSTN outage area may be more extensive than that created by Katrina.

As Fig. 5.74 shows, the Aurora CO is similar to Schrewsbury; it is built below sea level near canals. In fact, Aurora's location is even more vulnerable than Schrewsbury, being so close to Norman Canal, as shown in Fig. 5.75. This figure displays more signs of flooding than

Schrewsbury and also reveals that the genset and its fuel tank are probably at ground level, an extremely exposed spot when flooding occurs. If the area is hit by a hurricane similar to Katrina, the Aurora CO is very likely to fail again. However, since it is now hosting the DLC systems that replaced the destroyed COs of Buras and Port Sulphur, the affected zone will be larger.

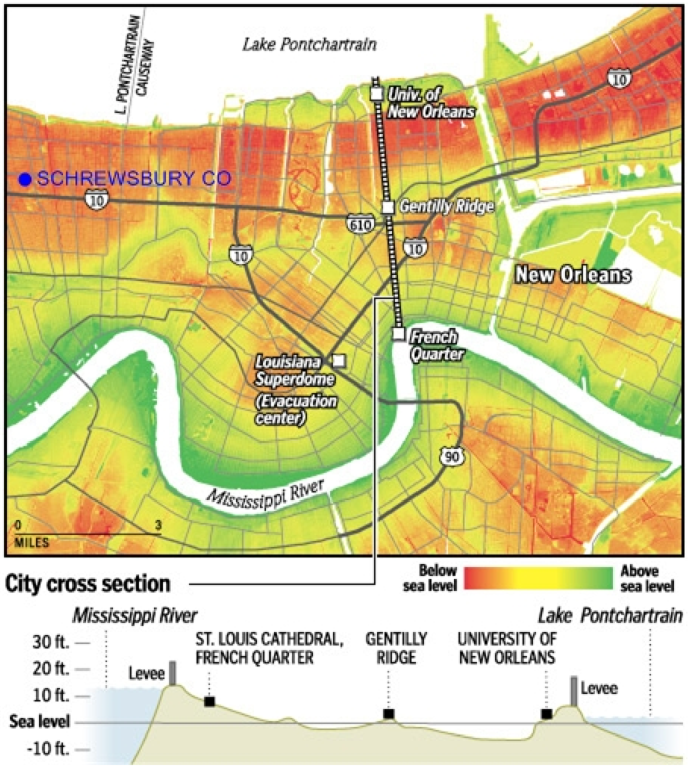

Fig. 5.72. New Orleans topographical map [19]with Schrewsbury CO location

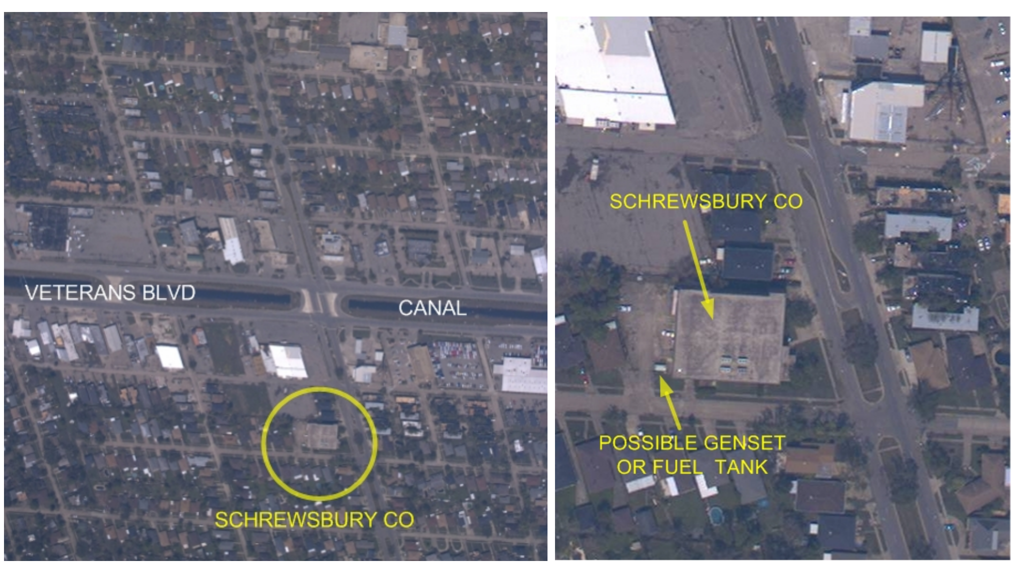

Fig. 5.73. Aerial views of Schrewsbury CO, August 31, 2005 [6]

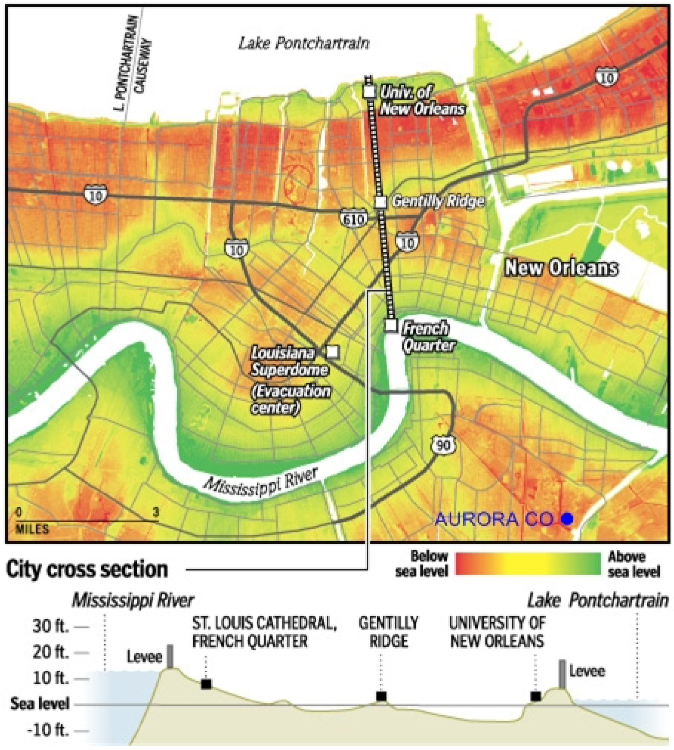

Fig. 5.74. Aurora CO location and New Orleans topographical map [19]

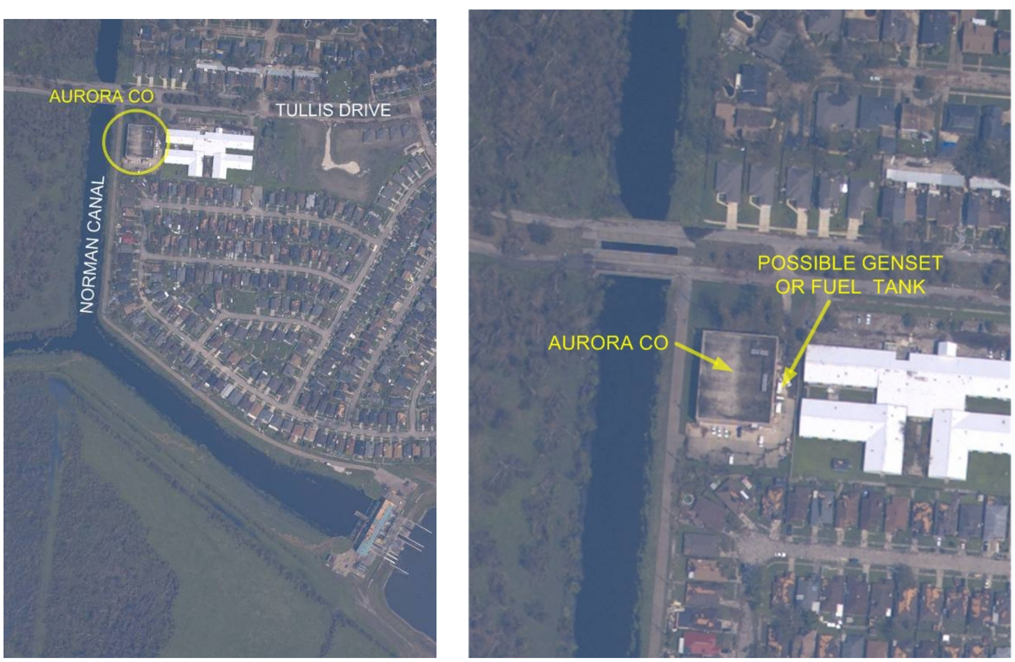

Fig. 5.75. Aerial views of Aurora CO, September 5, 2005 [6]

Natural gas provides a means to alleviate the genset engine fuel demand in some of these sites. In many disasters, utility gas outages are not usually as widespread as electric grid failures.

For example, during Katrina the city of Mobile lost most of the electrical supply but natural gas provision was not affected [26]. In hurricanes, natural gas supply is not generally interrupted inland, allowing the opportunity to reduce fuel delivery constraints by using natural gas or dual natural gas/diesel genset engines instead of the more common diesel ones. Natural gas engines have the additional advantage of not requiring a fuel tank that can be flooded during intense storms. The most reliable option is to use dual natural gas/diesel engines, since it will always leave open the possibility of using truck-delivered diesel in case the natural gas supply is interrupted. Logistical efforts can be eased when COs located further inland, not necessarily exposed to hurricanes, are equipped with natural gas genset engines; they release resources (trucks, gallons of diesel oil, people) to take care of the most compromised COs.

Larger and less exposed fuel tanks are other solutions to ease logistics requirements and reduce the risk of outage due to engine fuel starvation. As Fig. 5.76 indicates, other CLECs in the Gulf Region with capacity similar to those of Bellsouth seem to have larger fuel tanks for COs. For example, while Ybor City CO has an 8000 gallon fuel tank, Slidell CO has only 3000, as shown in Fig. 5.19. Hence, observations around the Gulf Coast seem to indicate that Bellsouth design practices require less genset autonomy than others CLECs in equally hurricane-exposed areas. Bigger fuel tanks have the additional advantage of higher access points, which makes them less prone to damage due to flood waters.

Fig. 5.76. Verizon CO fuel tanks on the Gulf Coast, Left: Sarasota, Florida,
Right: 8000 gallon tank of Ybor city CO, Tampa, Florida

5.5 Communication transmission networks

Sprint was the long-distance carrier suffering the most severe damage in its network, including the total loss of two key facilities – a switch in New Orleans and a POP in Biloxi [27]. When these two facilities failed, all the sites between them along the coast were cut off, affecting not only the transmission network but also the links between mobile communication cell sites. New Orleans' failed long-distance switch is shown in Figs. 5.77 [28] and 5.78. As the figures show, severe flooding damaged the equipment inside the building, thus causing the outage. In this case, availability of electric power had no relevance, because the primary cause of failure was equipment damage.

Fig. 5.77. Aerial view of New Orleans Sprint long-distance switch taken on September 1, 2005 [28]

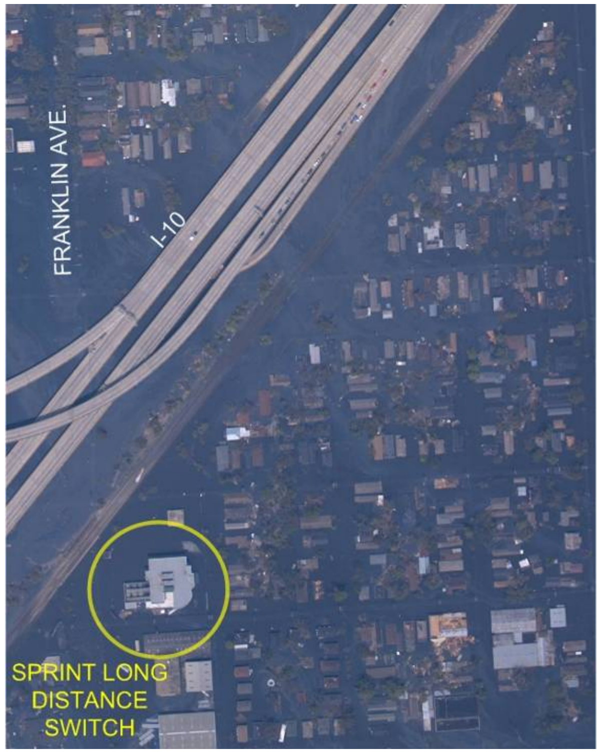

Fig. 5.78. Aerial view of Sprint switch in New Orleans, August 31, 2005 [6]

Neither did loss of electric power play a role in the single outage reported by AT&T, a flooded regeneration hut near New Orleans. The damaged hut reduced AT&T transmission network capacity by 5%. Lost capacity was restored by redirecting traffic using software that automatically reconfigured transmission equipment and by installing a new fiber-optic cable. The deployment of portable gensets to sites that did not have fixed emergency generators and keeping the main AT&T switch in New Orleans working were key factors in maintaining most of the AT&T traffic. As was mentioned, the AT&T switch in New Orleans is collocated with the BellSouth New Orleans Main and Tandem switches at 840 Poydras Street and was kept operating mainly due to employee effort and good fortune. Still, many calls were blocked due to congestion caused by other network failures.

Fig. 5.79 depicts another AT&T regeneration site, this one in Gulfport, MS. The figure shows that while the building is elevated 50 cm, the genset is located at ground level. During Hurricane Katrina, this facility did not fail. It was not flooded (Fig. 5.80) as it is located 2 km inland. However, a stronger hurricane passing closer to Gulfport could create flooding significant enough to damage its genset.

Fig. 5.79. AT&T regeneration site in Gulfport, Mississippi

Fig. 5.80. Aerial view of AT&T site, September 4, 2005 [6]

Level3 Communications has a transmission network that acts as the Internet backbone. One of Level3's regeneration sites along Route 90, south of Pearlington, Mississippi, was visited during the on-site survey. The site is depicted in Fig. 5.81 on October 17th. There were two gensets. However, Fig. 5.82 shows no generators at this site four days after Katrina made landfall in Louisiana. Although there are no reports of outages in Level3 networks, lack of gensets in an area where utility-grid power was out for several weeks after the storm is a strong indication that the site shown in Fig. 5.81 lost service due to power-related causes. Other outage causes such as equipment damage or severed fiber-optic links are highly unlikely because, as Fig. 5.83 depicts, the site was built on a slightly elevated terrain. This protected it from flooding and there were no signs that the fiber-optic cable was affected.

Fig. 5.81. Level3 Communications transmission site south of Pearlington, Mississippi

Fig. 5.82. Aerial view of Level3 transmission site, September 2, 2005 [6]

Fig. 5.83. Level3 transmission site showing its location on elevated terrain

MCI, another long-distance carrier with light damage to its network, reported loss of capacity due to some "water issues" in regeneration sites and a severed fiber-optic cable east of New Orleans [29], probably running along the I-10 bridge over Lake Pontchartrain. No power-related outages were reported by MCI.

5.6 DLC applications in outside plant

DLC cabinets existing when Hurricane Katrina struck the Gulf Coast created a logistical challenge in the aftermath, because the enclosures required extended backup to avoid running out of power. The DLC cabinets have local embedded batteries that provide power backup for only a few hours. Therefore, BellSouth had to deploy one portable genset for each DLC enclosure, as shown in Figs 5.84 and 5.85. Most of the DLC systems observed during the on-site survey belonged to the Bay St. Louis CO and Bayou Laterra CO. All of the portable generators at these sites were still working at the time of the visit. As mentioned, new DLC systems are being installed to replace destroyed copper feeder facilities. Most have been added to COs where, previously, there were no DLC systems, thus dispersing into a much wider area the sites that will require the deployment of portable gensets after a hurricane. It is clear that adding DLC systems to replace feeders will further complicate the logistical efforts in future hurricanes and reduce overall network reliability.

Fig. 5.84. SLC-96 DLC systems in Bay St. Louis and Bayou Laterra

Fig. 5.85. Two views of a DLC system in Waveland, Bay St. Louis CO

6 Hurricane Katrina’s Effect on Mobile Communication Networks

Over 3000 cell sites in the area were affected by Hurricane Katrina. Half of them are located in the hardest hit areas of the Mississippi coast, New Orleans and Plaquemines Parish, shown in Fig. 6.1. The extent of Katrina’s effect on mobile communication networks varies with geographic area and company. The three main reasons for cell site outages are:

1) Damage due to high winds

2) Damage due to storm surge or flood

3) Failure due to loss of power

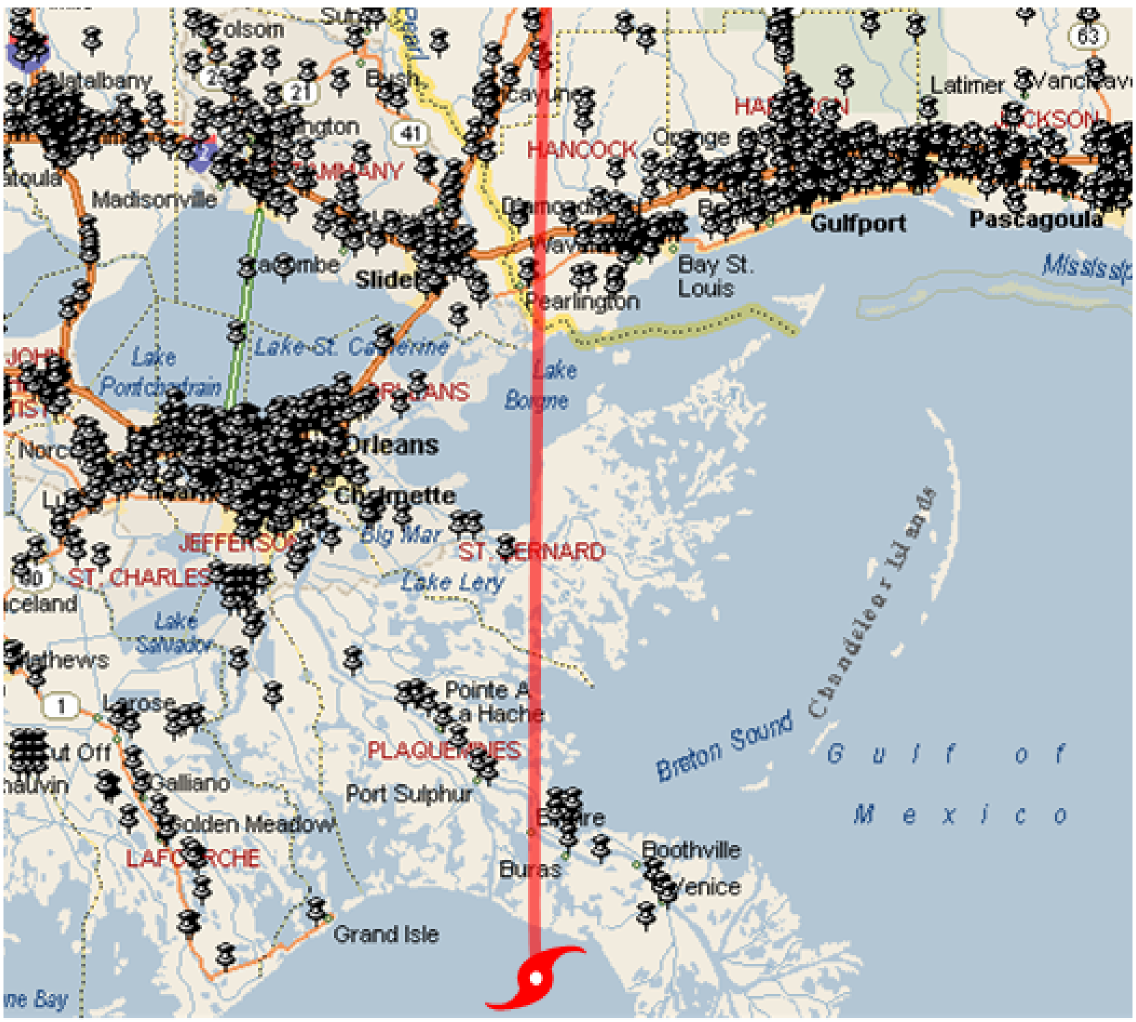

Fig. 6.1. Cell sites located in the affected area and path of Hurricane Katrina

Causes 1 and 2 concern failure due to critical damage in all or part of the communication-related components, including the antenna and base-station communication cabinets. For these causes, it is more useful to identify failure severity than failure origin. Power-related outages occurred when the power plant or the genset failed due to flooding, damage or lack of refueling.

Another possible indirect cause of failure is cell site isolation due to a PSTN failure. It occurs when a fiber-optics cable is damaged or a CO in the transmission path is destroyed. When the PSTN fails, the links between cells sites and remote switches with their host MTSO cease to operate. This failure cause is only relevant for sites where none of the other failure causes occurs. Unfortunately, identifying which cells failed for this reason requires highly detailed, proprietary network architecture information not typically provided by the service providers. Hence, it was only possible to mark the possible failure area.

Fig. 6.2 shows the most common solutions implemented by the mobile communication providers to restore their networks. Cell sites without electric power and no permanent genset were equipped with portable gensets, as in cell site # 11 of Fig. 6.2. All fixed and portable gensets require constant refueling, usually once a day, which presents important logistics issues. Hence, in preparation for the storm, portable generators need to be staged in places where they are not at risk from the storm but are close enough to their assigned sites so that they can be quickly deployed after the storm. Taking the genset to a site is usually complicated, because roads may be damaged or filled with debris and bridges may have been washed away. Security checkpoints and areas closed during rescue activities add more complications to portable power distribution. The same logistic issues usually persist during the refueling period that may take from a few days up to several weeks. Another problem after the storm is to replace destroyed cell sites. Cell site #8 in Fig. 6.2 exemplifies how damaged cell sites can be replaced by cells-on-wheels (COWs), base stations mounted inside a truck or a trailer. In some cell sites with platform-mounted outdoor cabinets, the site functions were entirely replaced by COWs. When possible, interrupted transmission paths were reestablished by using MW links, as shown with cell sites #9 and #10 in Fig. 6.2. Another alternative to restore transmission links was to reroute the path, shown with the PSTN link in Fig. 6.2. When an MTSO is damaged, its functions and subscriber database are transferred to another MTSO, although higher traffic in the backup switch may limit the number of calls in the damaged MSC area.

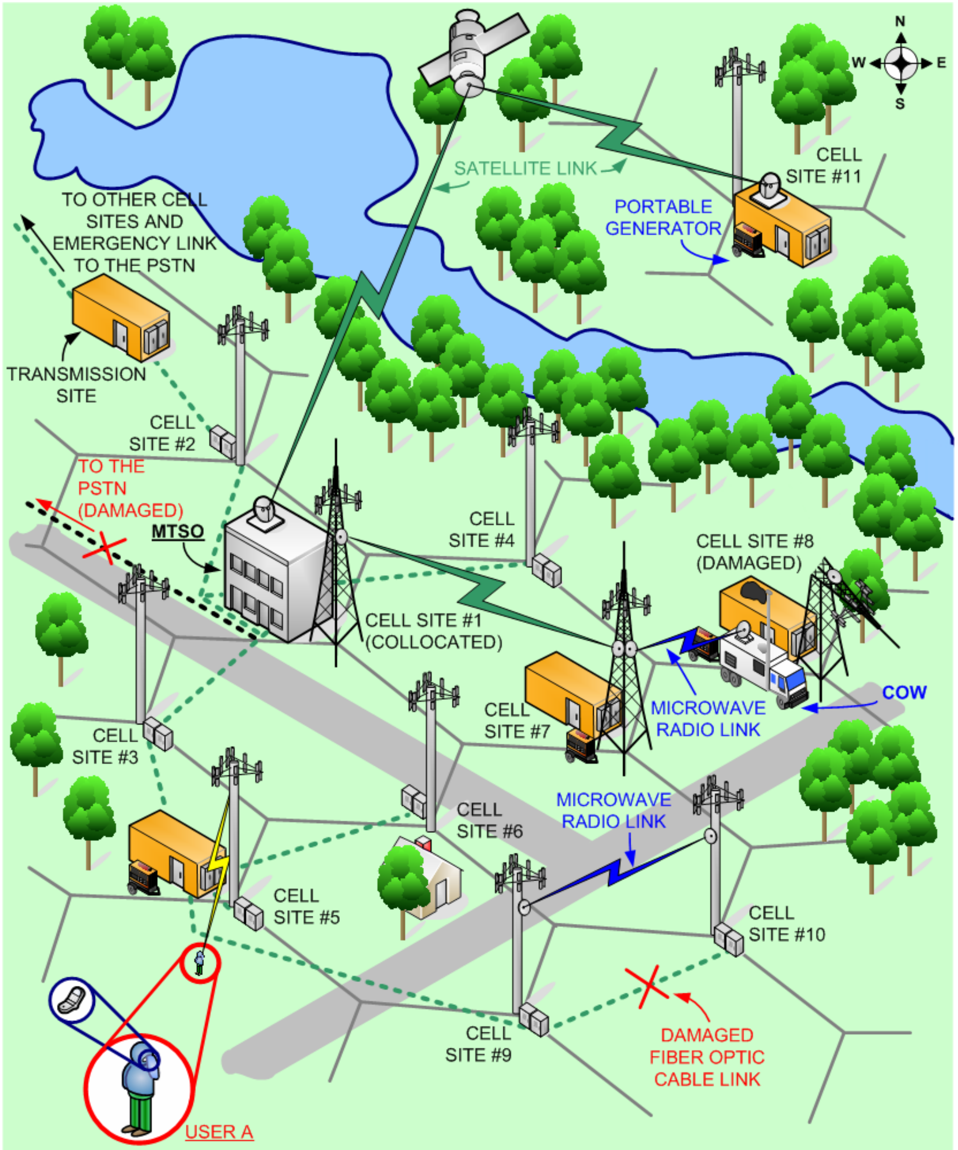

Fig. 6.2. Scheme of the mobile communication network restoration solutions

Cellular telephony companies made extensive use of these solutions in Hurricane Katrina's aftermath. Cingular deployed approximately 500 portable gensets and 30 COWs [30]. Verizon, Sprint-Nextel, Cellular South and T-Mobile also stated they used hundreds of gensets and dozens of COWs. Since MTSOs do not need to be as close to the demand center as PSTN switches, not many MSCs were damaged. Cingular lost of one its two switches in New Orleans due to flooding [30] and, as was discussed previously, Sprint-Nextel operations were affected by flooding in the long-distance switch [27]. The T-Mobile switch in New Orleans never lost service [31] due to employee efforts to refuel the switch genset and good fortune. Verizon switches did not need good fortune to maintain full operation during the storm, since they were located further inland in Baton Rouge, LA and Covington, LA[32]. All mobile communication providers lost connection to the PSTN due to flooding in New Orleans and severed fiber-optic cables, one of which is located on the I-10 bridge over Lake Pontchartrain [33].

Because of efforts of all mobile companies during the restoration process, a week after Katrina hit the coast cellular telephony networks were almost fully operational along the Gulf Coast and partially operational in New Orleans and Plaquemines Parish. The mobile communication network proved to be more flexible and resilient to natural catastrophes because of its modular architecture and the lack of fixed connection to the subscribers. Wire-line networks were more complicated to restore than wireless networks because of the PSTN fixed outside plant and, especially, the lack of flexibility introduced by the MDF in the CO. Another advantage of cellular telephony networks over fixed telephony networks is that COs do not need to be close to the demand center. Thus they can be located further inland in less vulnerable locations, as proved by Verizon.

A small sample of cell sites was surveyed in order to map the effect of Hurricane Katrina on mobile communication networks. These sample sites and failure causes are shown in Fig. 6.3. The red zone represents an area where a majority of the cell sites experienced equipment destruction due to wind, flood or storm surge. Yellow indicates partial equipment damage due to wind, flood or storm surge. Blue shows that the majority experienced power-related failures. Green and white striped zones represent areas where some cell sites may have been isolated from their MTSOs due to PSTN failure. The green area indicates regions where a large percentage did not fail. Circles mark the position of cell sites with a confirmed known condition after the storm. Cell site locations indicated with squares imply that the condition after the storm is estimated with a high degree of confidence. COWs are marked by truck icons, while sites where the genset was operating at the time of the site survey are showed with flags.

The blue area (where cell sites failed due to power-related causes) is the smallest, but it includes approximately half of all the affected cell sites. A map detailing these New Orleans cell sites is displayed in Fig. 6.4 with the analyzed sites marked on Fig. 6.5. Another area where cell sites are more concentrated is around Gulfport and Biloxi, Mississippi. Fig. 6.6 shows a detail of the all cell sites in this region and Fig. 6.7 displays the cell sites studied.

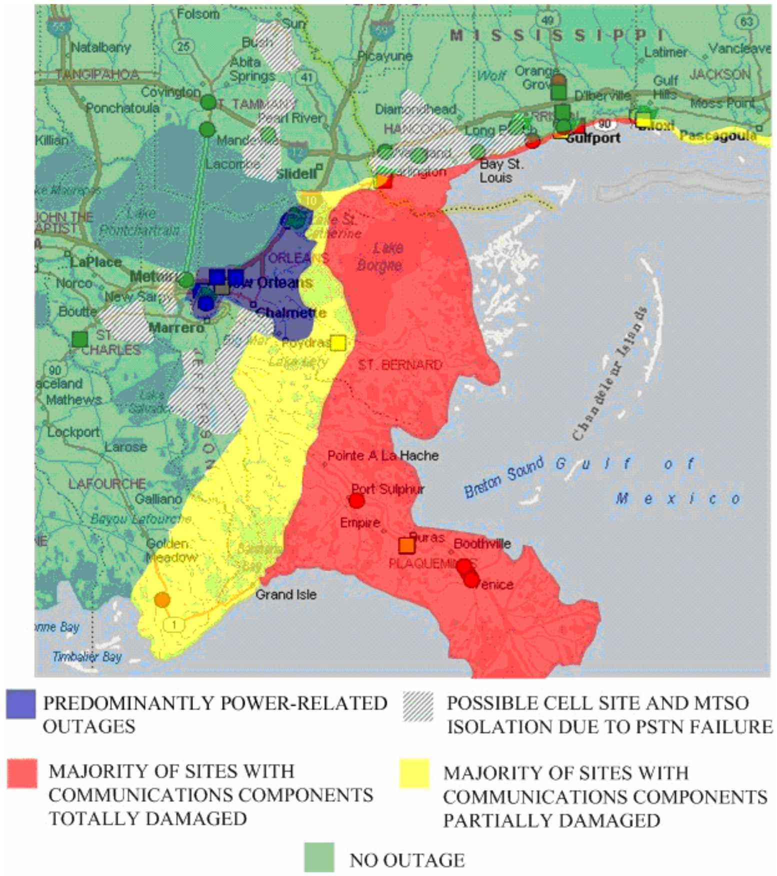

Fig. 6.3. Analyzed cell-site locations with predominant cause of failure

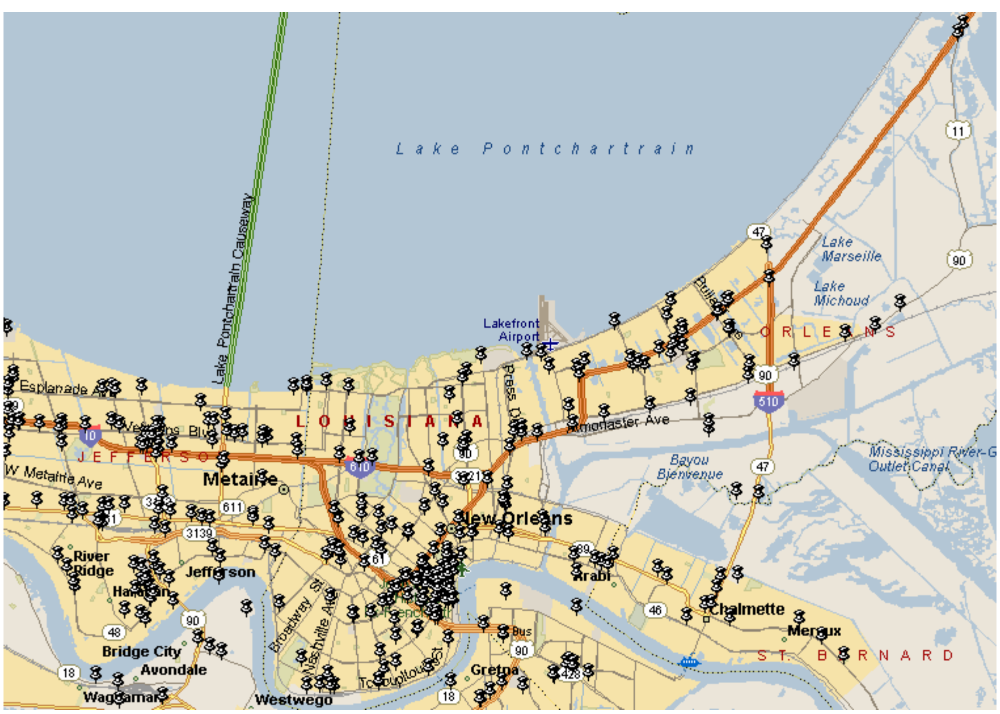

Fig. 6.4. Cell sites in New Orleans

Fig. 6.5. Analyzed cells in New Orleans.

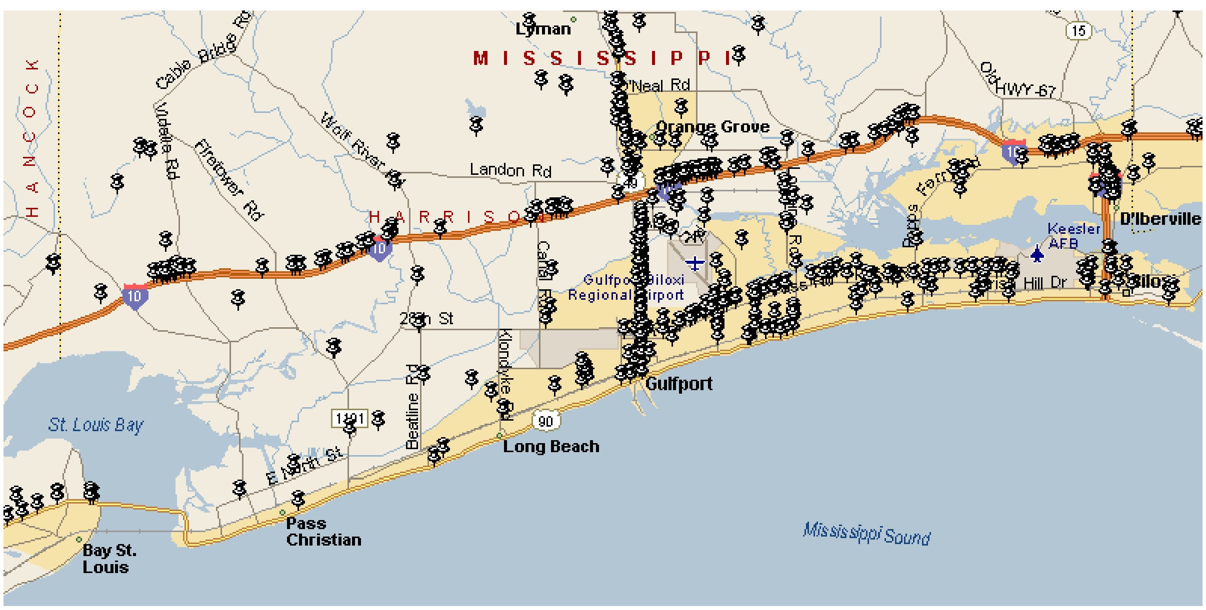

Fig. 6.6. Cell sites around Gulfport and Biloxi, MS

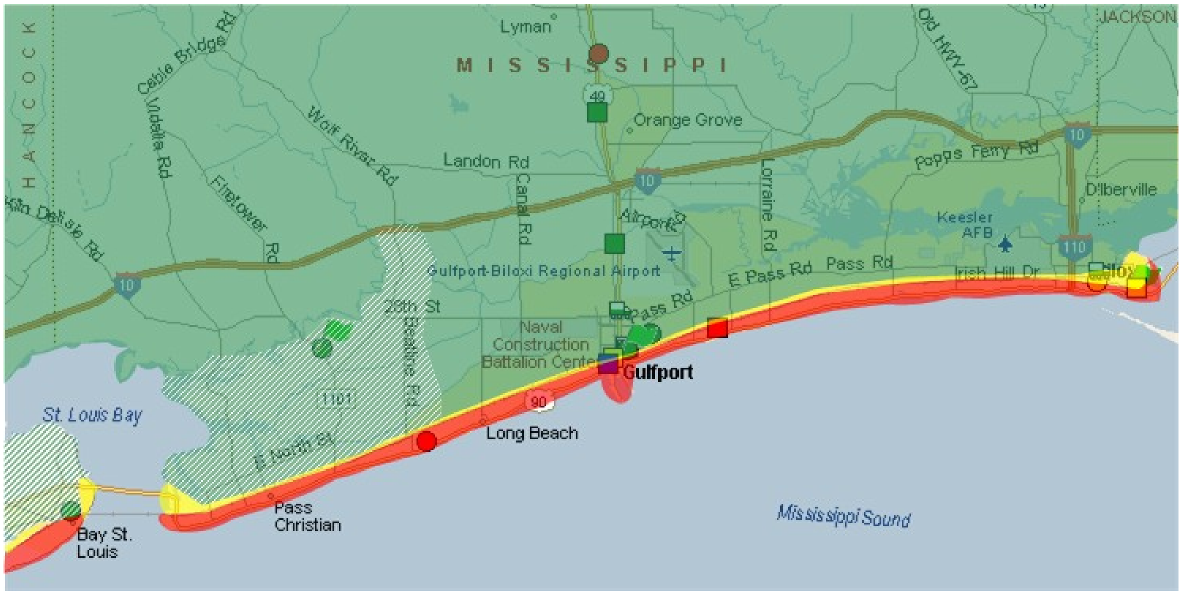

Fig. 6.7. Surveyed cell sites around Gulfport and Biloxi, MS

This work continues with an analysis of each of the sample cell sites along with a discussion of failure cause for each of the zones shown in Figs. 6.3 and 6.7.

6.1 "Red Zones": Areas where a majority of cell sites experienced total equipment destruction due to wind, flood or storm surge

Most of the cell sites in these areas were destroyed by Hurricane Katrina. Fig. 6.3 shows that this zone corresponds to the path of Katrina's eye and around 50 km to the east. It includes Plaquemines Parish and the eastern half of St. Bernard Parish, as well as a 1 km wide strip of the Mississippi Gulf Coast between the border of Louisiana and Mississippi and Biloxi Bay. Even though this zone covers a large region, it includes less than 1% of all the cell sites in the affected region.

Figs. 6.8 and 6.9 show two cells destroyed when different ships carried inland by the storm surge crashed on to the antennas. Fig. 6.9 shows that the two sites are close together in the southernmost populated area of Venice located on the Mississippi River Delta. Neither cell site appears to be adequately constructed for such an extremely vulnerable location; the shelters sit on low platforms in an exposed and unprotected position.

Fig. 6.8. Aerial view of destroyed cell sites in Venice, LA [34]

Fig. 6.9. Aerial view of destroyed cell sites in Venice, LA [6]

Figs. 6.10 and 6.11 show more destroyed cell sites in Venice, LA. The cell site in Fig. 6.10 is located 2 km north of the cells in Fig. 6.9; those in Fig. 6.10 are close to the BellSouth CO. These three cell sites suffered damage from wind and the storm surge. Their towers fell to the northwest, an indication that they may have fallen before Katrina made landfall. The aerial picture in Fig. 6.11, taken on September 3, 2005, clearly shows that water level was over the cell site platforms, with the storm-surge maximum level reaching even higher. It is unclear whether or not there were design guidelines for the platforms. However, it is certain that they were not designed for such a strong hurricane, either in terms of wind intensity or storm surge levels. In none of the three sites did electrical power supply play a role in their failure.

Fig. 6.10. Aerial views of destroyed cell site in Venice, LA [34]

Fig. 6.11. Aerial views of destroyed cell site in Venice, LA [6]

Figs. 6.12 and 6.13 show another destroyed cell site located in Port Sulphur, LA. As in previously analyzed sites, this one was destroyed by strong winds bringing down the tower and the storm surge flooding the entire site. The aerial picture displayed in Fig. 6.13 shows that the site is near the Mississippi River, as were the other cell sites discussed. However, the shelter and outside cabinet platform are located almost at ground level, implying a lack of uniform design guidelines in cell-site infrastructure design. As shown in the Venice site (Fig. 6.8), the fixed generator was also destroyed because of its vulnerable location.

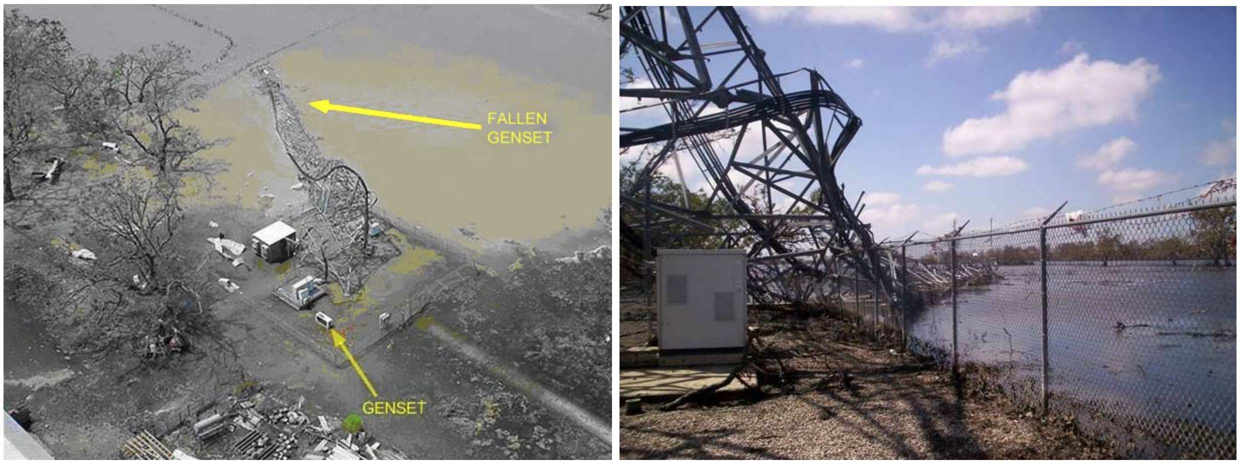

Fig. 6.12. Destroyed cell site in Port Sulphur, LA Left: [34]Right: [35]

Fig. 6.13. Aerial view of destroyed cell site in Port Sulphur, LA September 3, 2005 [6]

The lack of uniform cell-site design guidelines was verified by inspecting the sites displayed in Figs. 6.14-6.16. These are located in Buras, Louisiana, where Hurricane Katrina’s eye made landfall. Even through the hurricane’s strongest winds, their towers did not fall. It should be noted that the cell site west of the BellSouth CO is located on higher ground with all the base station shelter and cabinets on high platforms. It failed due to lack of power. However, it is difficult to evaluate how much damage this site received, though it may have been less than other sites. It is also unclear how much damage the cell site collocated with the BellSouth switch received (Fig. 6.16). Even though the BellSouth Buras CO was flooded by the storm surge, the cell-site platforms are higher than the CO floor. Thus these cell sites may have suffered only partial damage. However, since the storm surge reached higher levels than those indicated in the pictures, it is still possible that the storm surge may have damaged all three sites.

Fig. 6.14. BellSouth Buras CO showing the collocated cell site [20]

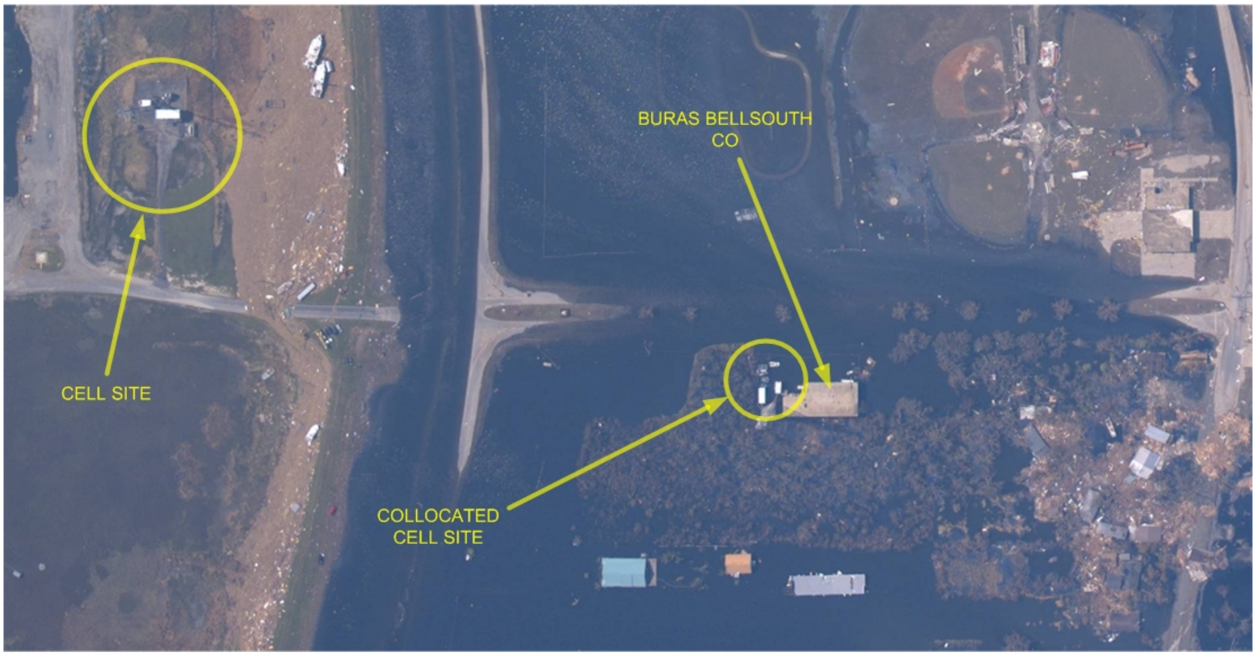

Fig. 6.15. Aerial view of the area around the BellSouth Buras CO, September 3, 2005 [6]

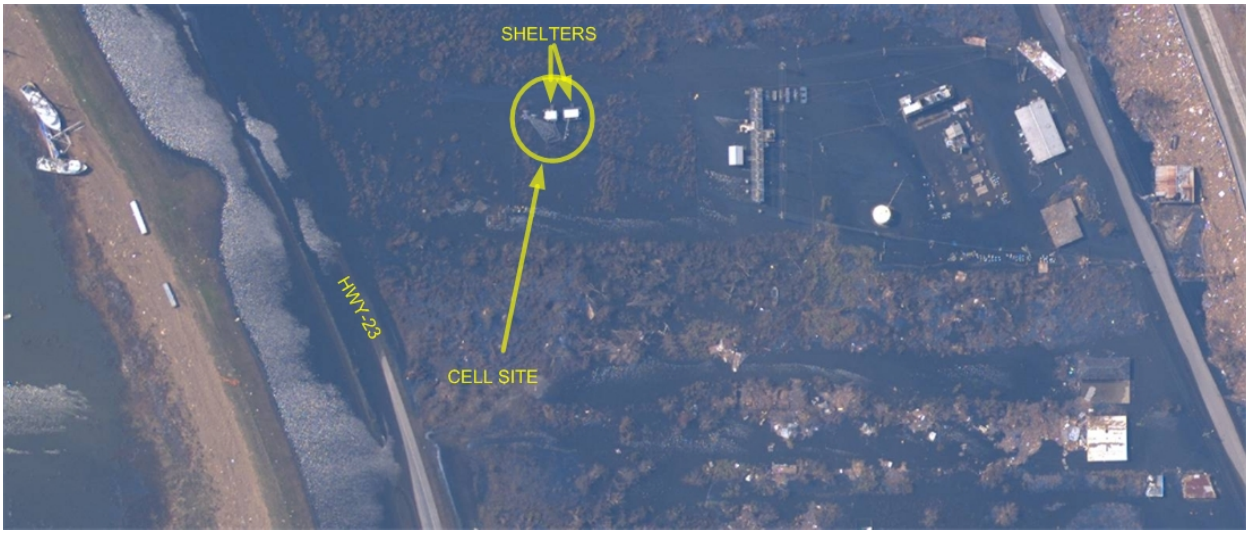

Fig. 6.16. Aerial view of the area around the BellSouth Buras CO, September 3, 2005 [6]

Cell-site destruction due to the storm surge also occurred on the Mississippi Gulf Coast. Figs. 6.17-6.19 show a base station in Long Beach destroyed by the storm surge. Only the tower remains standing. The aerial pictures presented in Figs. 6.18 and 6.19 indicate that the cell site was located in an extremely vulnerable spot. As Fig. 6.19 shows, the railroad tracks prevented the storm surge from further progress inland and thus protected the area to the north from catastrophic damage. Hence, the railroad tracks mark the northern limit of the zone where the majority of the cell sites were destroyed. Needless to say, the site failure was not power-related.


Fig. 6.17. Remains of a cell site in Long Beach, MS [36]

Fig. 6.18. Aerial picture showing the destruction of a cell site in Long Beach, MS [7]

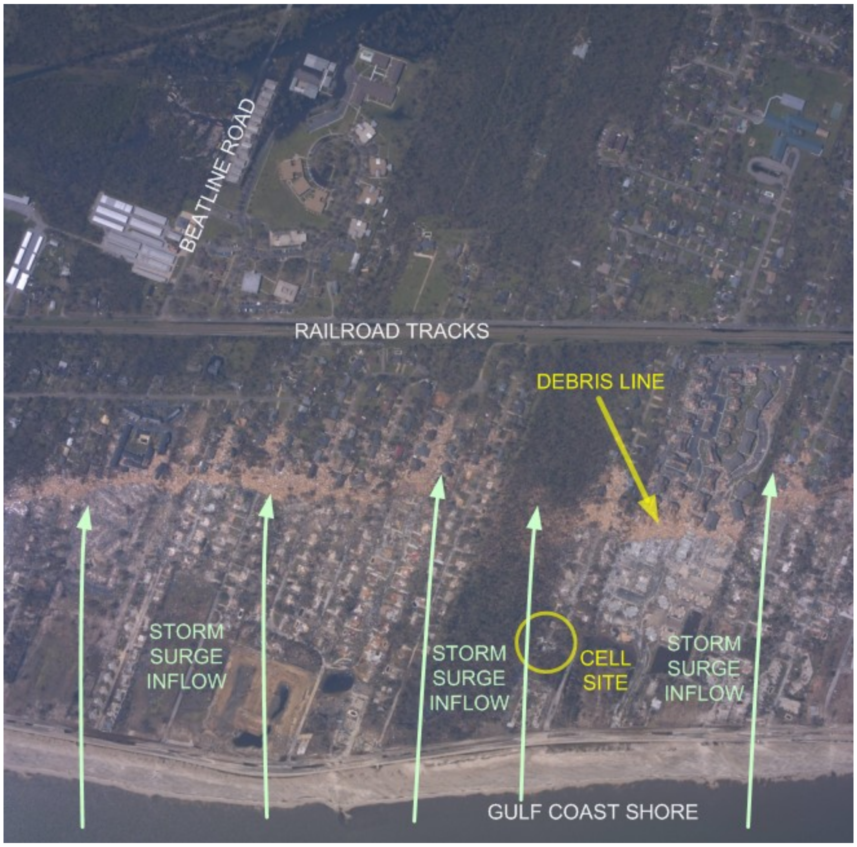

Fig. 6.19. Aerial view of the area around the cell site in Long Beach, MS [6]

In some cell sites, water towers are used instead of standard structures. Fig. 6.20 shows one cell site located east of Gulfport, MS, where the antenna is mounted on the water tower. Unfortunately, like the site in Fig. 6.17, this site was located just south of the railroad tracks and was probably destroyed by the storm surge. Figs. 6.20-6.22 display significant difference in the amount of damage north and south of the railroad tracks and show the role that the railroad tracks played in preventing serious damage to the north.

Fig. 6.20. Cell site located east of Gulfport that uses a water tank as tower [7]

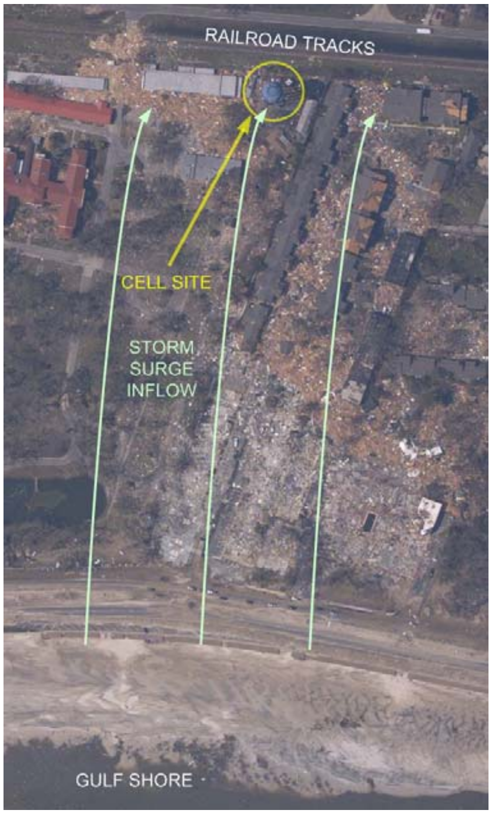

Fig. 6.21 Aerial picture showing the storm surge inflow near the cell site at the water tower [6]

Fig. 6.22. Damage next to water tower cell site [9]

Near the Mississippi/Louisiana border, the storm surge moved further inland, reaching up to 1.8 m in the town of Pearlington. Figs. 23-6.25 show two cell sites in the southern outskirts of this town: Fig. 6.23 toward the north, Fig. 6.24 to the east. Even though the cell sites are only 500 m apart, their construction is different. While the northern one has an elevated platform and shelter, the eastern one has a shelter at ground level. Fig. 6.24 shows a COW deployed at this site. The communication equipment was probably destroyed as equipment was at ground level and the storm surge reached at least 1.5. This site was without commercial electrical supply for about 3 weeks after the storm had passed.

Fig. 6.23 shows a common occurrence in many visited cell sites: the deployment of more than one portable genset to a single site. Usually, each cellular network operator deployed its own generator and refueling to each site. Thus, a significant number of cell sites received multiple gensets. It is clear that logistical burdens may have been eased if companies had coordinated their efforts so that only one genset was deployed to each site to power all the base stations located there. In fact, the site in Fig. 6.23 had three generators at the time of the visit on October 17, 2005 – two operating portable ones and one fixed unit not in service. Several factors indicate that the equipment on this platform was damaged including remains of equipment packaging, debris in the surrounding fence, a fixed generator replaced by a portable one and the fact that the storm surge height in Pearlington exceeded the platform height. However, since the portable generator feeding the shelter was working and the shelter floor was higher than the metallic platform, it is reasonable to assume that the equipment inside the shelter was not damaged. Thus, this cell site may have suffered only partial damage. Fig. 6.23 shows that portable gensets were deployed after September 2nd. Likewise, Fig. 6.24 shows that the COW was also taken to the assigned site after September 2nd. These figures set a time frame for network recovery in this area and confirm the estimated one-week recovery time.

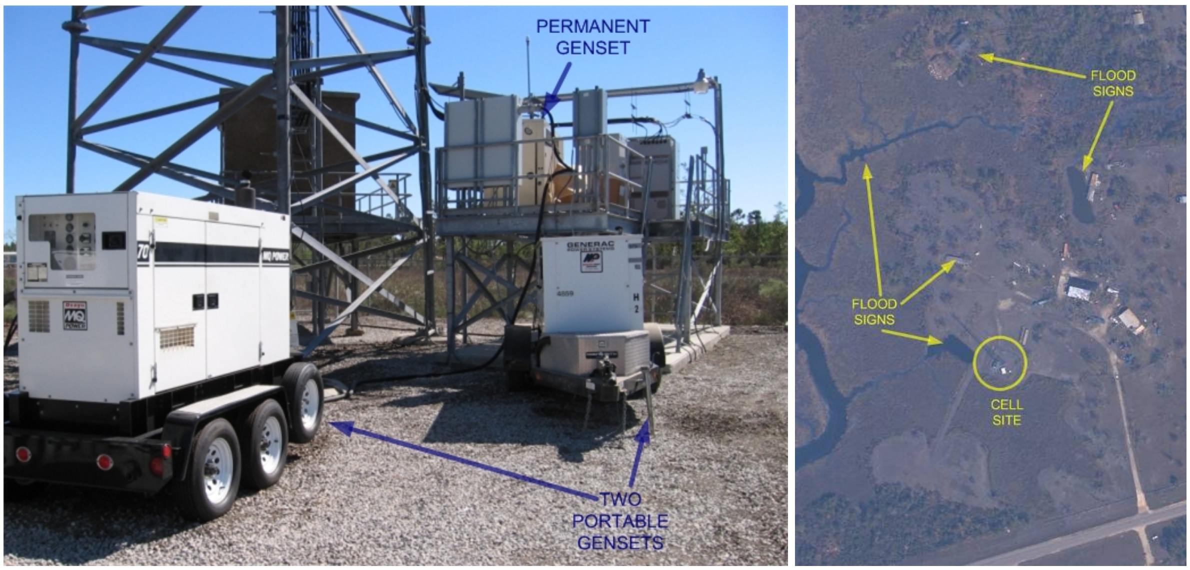

Fig. 6.23. Cell site located north of Pearlington, MS, September 2, 2005, Right: [6]

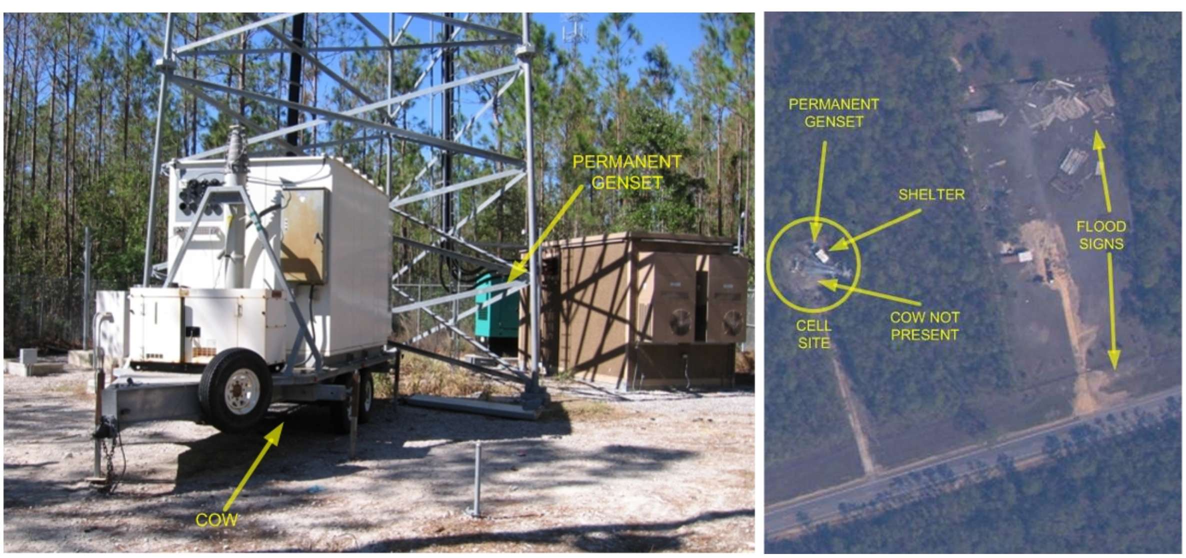

Fig. 6.24. Cell site located south of Pearlington, MS, September 2, 2005, Right [6]

Fig. 6.25. Aerial pictures of cell sites located around Pearlington, MS, September 2, 2005 [6]

6.2 *"Yellow Zones": Areas where a majority of cell sites suffered partial damage due to wind, flood or storm surge*

In these areas some of the cell components may have been damaged. In cases where there was more than one base station, not all were damaged. Fig. 6.3 shows that the largest yellow zone covers the south part of Jefferson Parish, the northern portion of Plaquemines Parish, a small strip of St. Bernard Parish east of Chalmette, and the southern coast of Slidell. Another small area includes a 200 m strip located approximately 500 m inland from the Gulf Coast. A 500 m strip of the Mississippi Gulf Coast, east of Biloxi Bay and extending to the border with Alabama, is also considered a yellow zone. Figs. 6.2 and 6.3 show that less than half of one percent of the total number of cell sites in the area affected by Hurricane Katrina fall into yellow zones.

Figs. 6.26-6.29 show examples of cell sites with partial and likely unseen damage. The site in Fig. 6.26 is located in Biloxi and operated by several mobile communication companies. Fig. 6.28 shows that this cell site is situated in a very vulnerable location, as it received storm surge inflow from two directions. Even though the site itself presented clear damage only to the perimeter fence, the surrounding area suffered catastrophic damage. Hence, it is almost certain there was some damage. This site also had remains of equipment packaging, which further supports the idea of some site damage and repair. Based on observations and storm-surge data, it was concluded that this site might have received partial damage to the platforms with the outdoor base station cabinets but not to the shelter in the back. A significant observation for Figs. 6.27 and 6.27 is the five generators (shown with red and white arrows) deployed after the storm, one of which is not portable. None of these generators was present when the picture in Fig. 6.29 was taken on August 31, 2005. However, a truck with equipment is seen in Fig. 6.28 parked in front of the cell. Both of these pictures suggest that the networks were operational again within approximately one week after the storm.

Fig. 6.26. Cell site in Biloxi, MS

Fig. 6.27. Cell site in Biloxi, MS

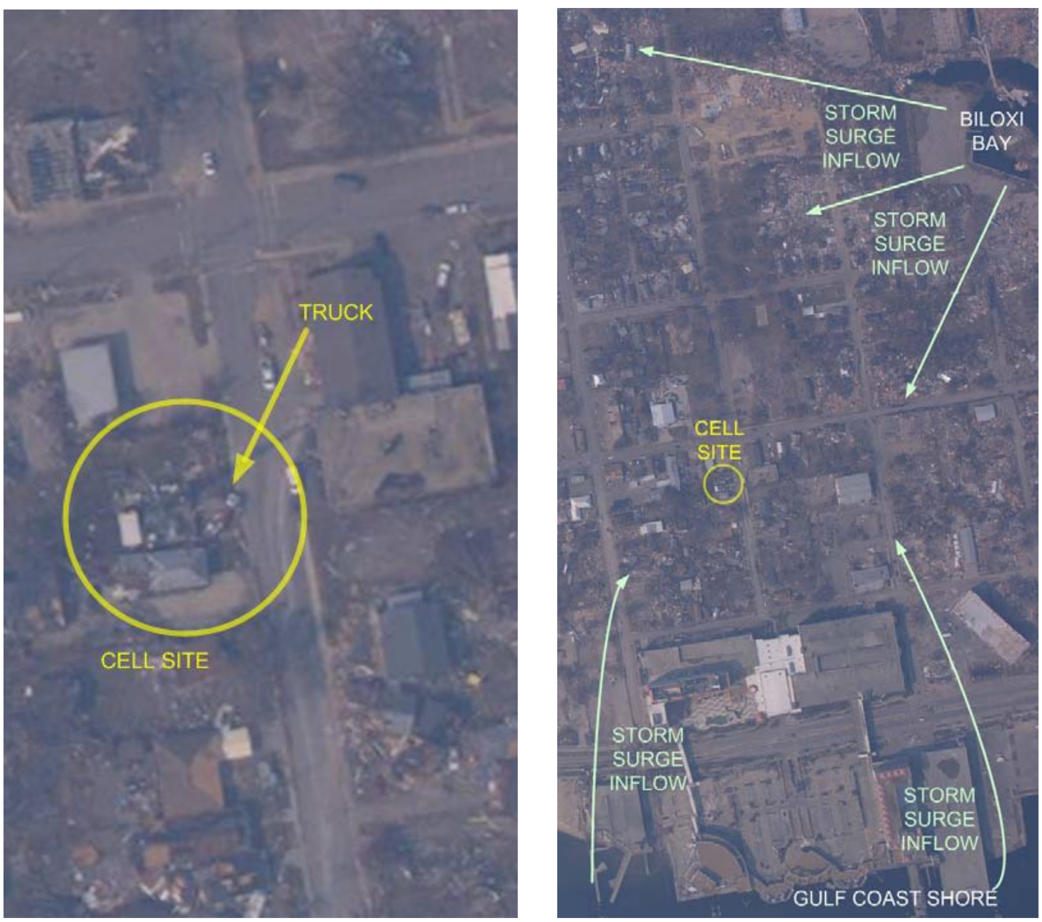

Fig. 6.28. Aerial picture of the cell site in Biloxi, MS. Note the parked truck. [6]

Fig. 6.29. Aerial picture of the cell site in Biloxi, MS, August 31, 2005 [8]

Biloxi had another cell site that experienced only partial damage. Figs. 6.30 and 6.31 show this cell site, which is situated approximately 400 m from the coast. Fig. 6.30 shows a general view of the cell site with a fixed genset that was not operating on October 17th, since the electric supply to this location had already been restored. An Alltel COW was also at the site, very likely to replace damaged equipment in a small shelter that was already removed by the time of the site survey. The small shelter, shown in Fig. 6.31, can be observed in a picture taken the day after Katrina made landfall. The COW was powered by a 45 KVA portable genset that was refueled every day. There were no indications of further damage in the cell site, and local residents informed us that the storm surge barely reached the cell site. Thus, this site received only partial damage to the (removed) small shelter.

Fig. 6.30. Cell site in Biloxi showing a COW and a missing small shelter

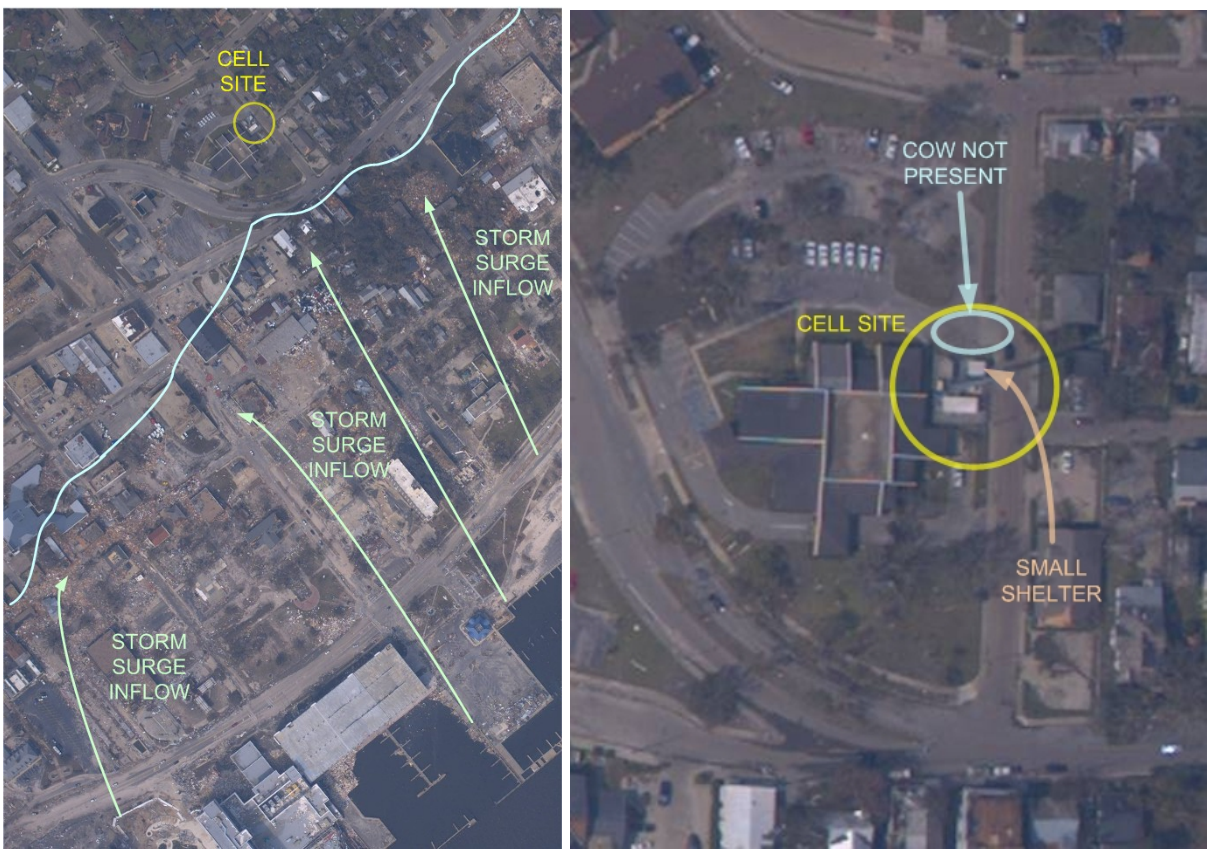

Fig. 6.31. Aerial pictures of cell site in Biloxi, August 30, 2005 [6]

Figs. 6.32 and 6.33 depict a cell site located 3.5 km north of Yscloskey in St. Bernard Parish that potentially suffered partial damage. During the survey, this is the only area in which there was no signal on our cell phones. Fig. 6.32 shows a platform with debris on top from the storm surge and a portable generator. An aerial picture taken on September 7, 2005 shows no sign of this portable genset. However, it does display a fixed yellow genset on the platform that was missing at the time of the survey. Fig. 6.32 also indicates the conduits used to pass the cables from the fixed genset into the shelter, with part of them left on the ground after the generator was removed. Fig. 6.33 (b) shows the destruction caused by the storm surge around the cell site. In this location, the storm surge was approximately 2 m deep. All these facts point to the possibility that the fixed genset was removed because it was damaged. This also implies that additional base-station components inside the shelter may have been damaged. Hence, it is more likely that this site failed from partial damage to its base station components than from a power-related cause.

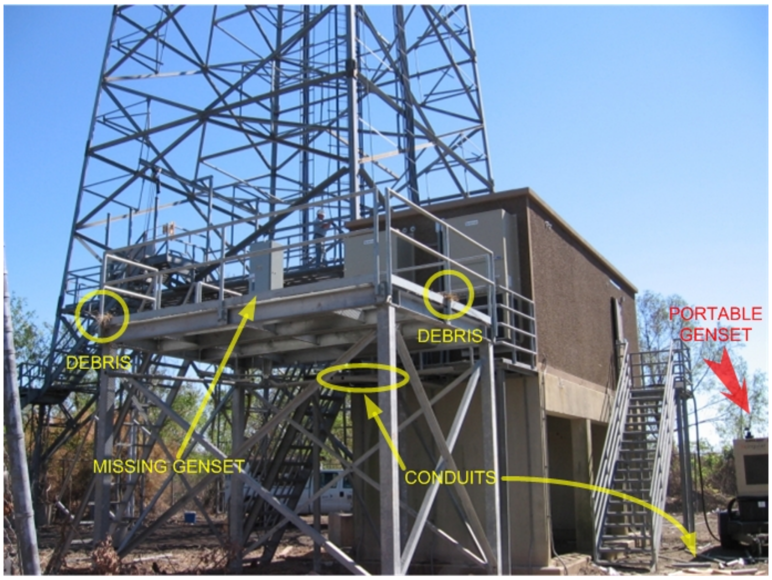

Fig. 6.32. Cell site on highway 46, St. Bernard parish

Fig. 6.34 shows a cell site in Gulfport which failed due either to power-related causes or to partial damage in its communication components. Interestingly, the picture shows two shelters and two gas tanks but only one genset, implying that another genset was missing. The aerial picture in Fig. 6.35, taken on August 30th, shows no sign of another genset, which means that the site had only one during the storm. Hence, if it was not damaged, one of the shelters may have failed due to lack of electric power. As Fig. 6.36 indicates, the cell may have received strong storm-surge inflow. If that was the case, part of the base station equipment may have been damaged because both shelters are at ground level. Remains of equipment packaging seem to support this possibility. Their vulnerable locations and shelter elevation show, once again, a lack of uniformity in cellular infrastructure design.

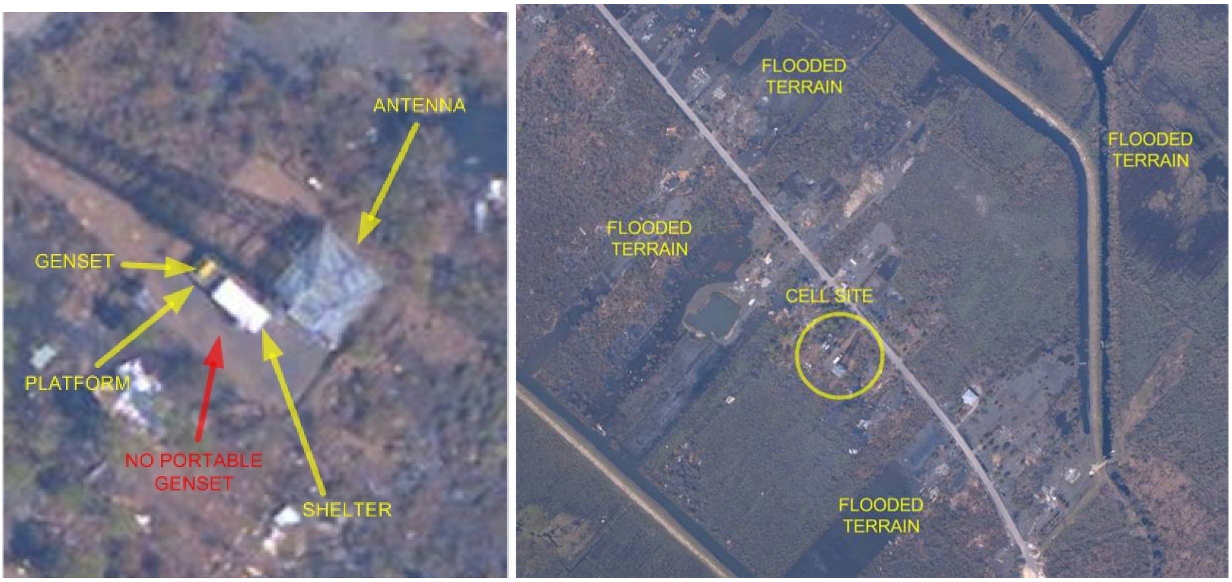

Fig. 6.33. Aerial pictures of cell site on Highway 46, St. Bernard parish [6]

Fig. 6.34. Cell site in Gulfport

Fig. 6.35. Aerial view of cell site in Gulfport [6]

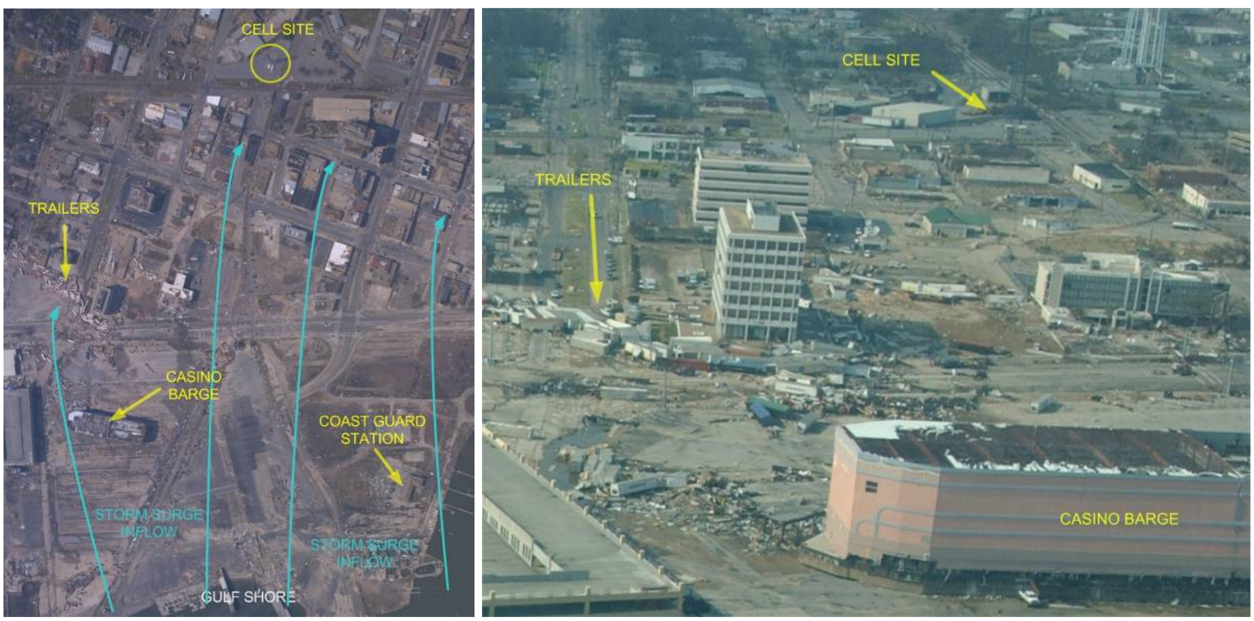

Fig. 6.36. Views of the destruction of Gulfport, Left: [6] Right: [7]

Figs. 6.37 and 6.38 show an exception to the type of damage in yellow zones. The cell site in these figures, located on the southern edge of Leeville, Louisiana, suffered catastrophic damage from the storm. The site tower fell, even though Leeville is east of the hurricane path where winds were less intense. Some towers nearby suffered no damage, which seems to indicate that the fallen tower may have had structural issues before the hurricane brought it down.

Fig. 6.37. Fallen Tower in Leeville, LA [36]

Fig. 6.38. Aerial view of the cell site with the fallen tower in Leeville, LA [10]

6.3 "Blue Zones": Areas where a majority of cell sites experienced power-related failures

In these areas, most of the cell sites were isolated by the flood. They could not receive portable gensets or existing gensets could not be refueled. In some cases, the base station power plant may also have suffered damage, but the communication portion of the equipment was not affected. Fig. 6.3 shows that this zone corresponds to the portion of New Orleans east of the 17th Street Canal and the neighboring northern portion of St. Bernard Parish. Nearly 50 % of all the sites affected by Hurricane Katrina are in this zone.

Figs. 6.39 and 6.40 present a cell site located on the Irish Bayou. As seen in Fig. 6.39 (b) there were multiple generators present: 3 portable gensets and 1 permanent one. All four gensets were operating at the time of the survey on October 21st. The site construction also indicates a lack of common design guidelines. Figs. 6.39 and 6.40 show that this cell site had the equipment placed over 3 m high, which prevented damage. Even though there was considerable damage in the surrounding area, the site only lost some side panels of the shelter platform. Fig. 6.41 displays an aerial picture taken on August 31, 2005, with this site being identified as the south cell site. It is clear that this area was severely flooded, with the storm surge reaching 2 m high, as indicated by the missing side panels of the shelter platform marked with yellow arrows in Fig. 6.40 (b). The flood prevented deployment of portable generators and refueling of any existing genset. Thus, when the electric power went out at this site, the base station was operated from batteries. When the batteries were exhausted, the cell site ceased operation.

Fig. 6.42 shows the north cell site indicated in Fig. 6.41. The shelter of this cell site is slighter lower than in the cell site in Fig. 6.39, approximately 2.5 m high, proving once again the use of different design guidelines from site to site. Yet, the shelter height was enough to prevent damage to the base station components. Fig. 6.42 also shows the deployment of multiple portable gensets in each cell site. In this case, there were two portable generators, indicated by yellow arrows in Fig. 6.42 (b). As with the south cell site, all the gensets were running during the site survey, indicating that this site also failed due to lack of electric power. Flooding prevented transporting portable gensets to the site.

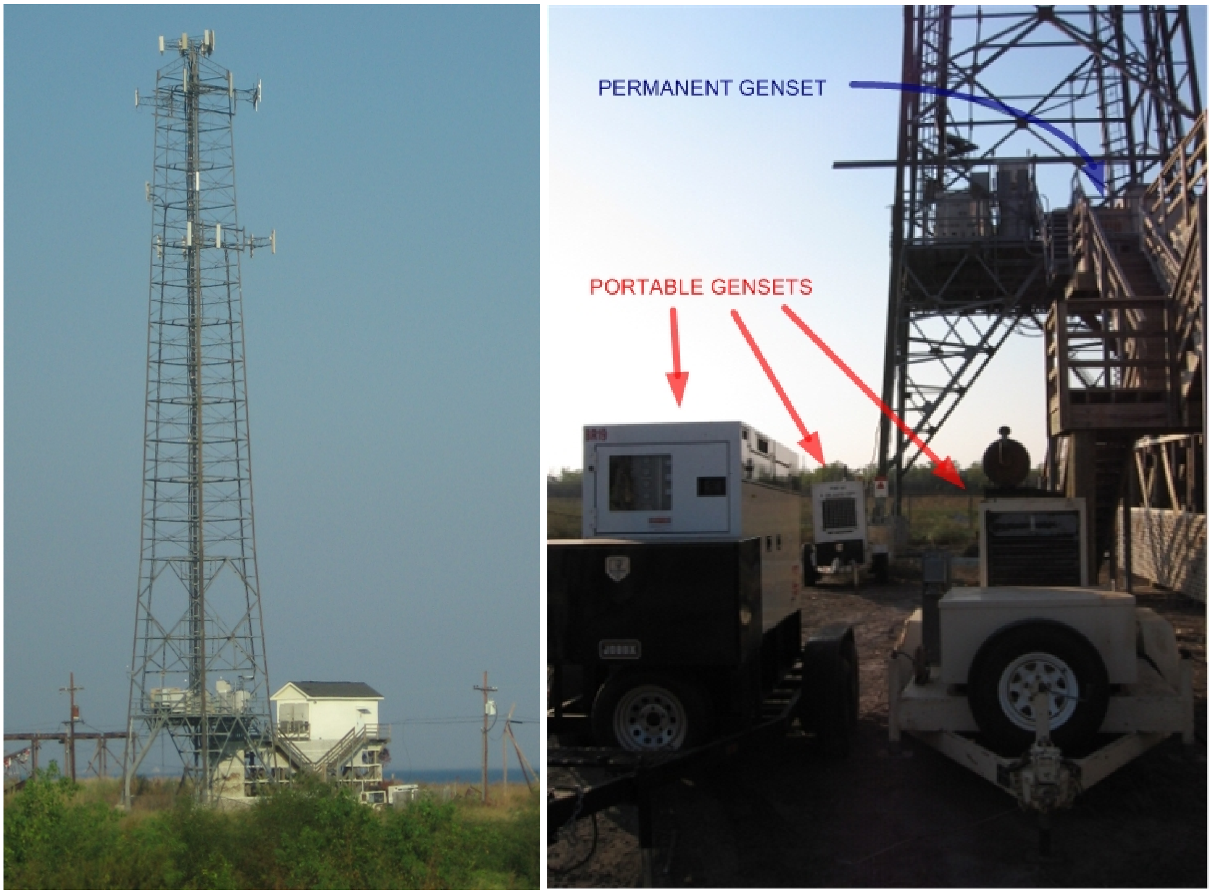

Fig. 6.39. Cell site in Irish Bayou

Fig. 6.40. (a) North side of cell site in Irish Bayou, (b) South side of the same site with arrows indicating the maximum height reached by the storm surge

Fig. 6.41. Aerial view of cell sites in Irish Bayou taken on August 31st [6]

Fig. 6.42. (a) General view of the north cell site in Irish Bayou, (b) Closer view of the same site with two portable generators indicated by yellow arrows

Fig. 6.43 presents a cell site in a flooded area of New Orleans, as shown in the aerial view displayed in Fig. 6.44. Even though the site was flooded, there was no damage to the base station communication equipment inside the shelter, as the flood level never reached the shelter floor shown in Fig. 6.43. The site survey on October 21, 2005, revealed that the generator was new and had not yet been connected. Since Fig. 6.44 clearly shows that a generator set was present during the flood, it can be concluded that the original genset was damaged during the hurricane and needed to be replaced. In addition to this damage, flooding and security issues prevented the network operation personnel from reaching the site to keep the electric power on. Hence, this site clearly failed due to power-related causes.

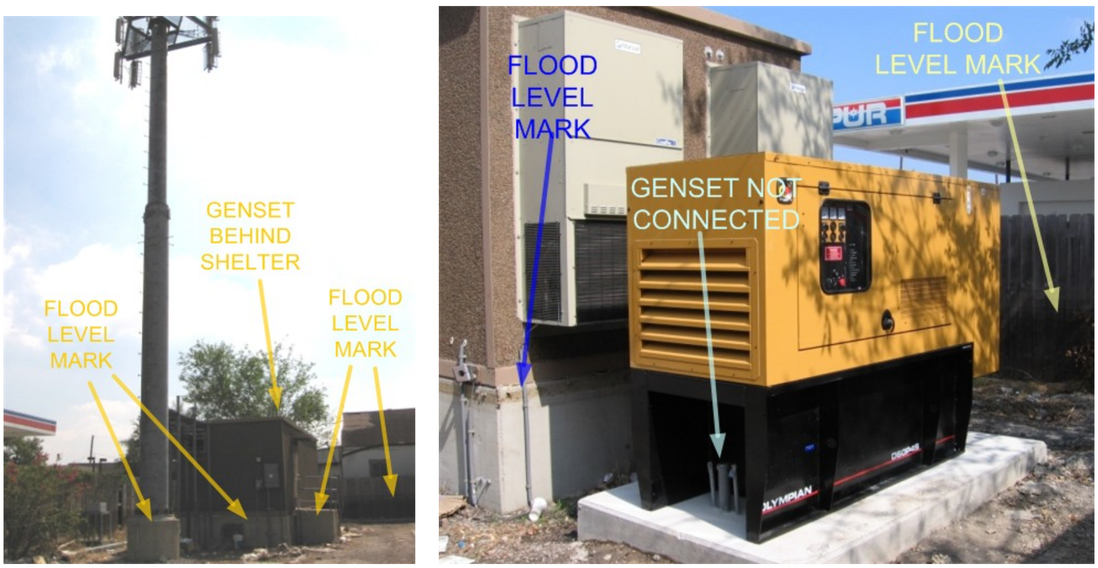

Fig. 6.43. Cell site with permanent genset in Broadmoor district

Many times cell sites in cities are placed on rooftops. For example, the base station in Fig. 6.45 was installed on a building located on I-10 and Chef Menteur Highway in Orleans Parish. Gensets are not usually placed on the rooftop because they are difficult to refuel and leaking fluids may damage the building. Using natural gas instead of diesel as the genset engine fuel reduces this problem. However, it is more expensive and seldom used. Instead, gensets for rooftop sites are usually placed on the ground by the building, making them vulnerable in case of flooding. This site did not seem to have a fixed genset, rather it had a portable generator connected to the base station with cables running outside the building, as shown in Fig. 6.45. The picture in 6.46, taken on August 31st, shows no portable genset outside the building and no evidence of flooding in the area around the building. However, the site was isolated by flooding in surrounding areas. This flooding may have prevented reaching the site to install a portable genset to power the base station until the water receded. Hence, the most probable cause of failure in this cell site is lack of electric power.

Fig. 6.44. Aerial picture of the cell site in Broadmoor district showing flooding in the area [6]

Fig. 6.45. Cell site located on the rooftop in Orleans Parish

6.46. Aerial picture taken on August 31st showing the building location of the cell site in Orleans Parish [6]

Fig. 6.47 shows a standard cell site installation located by I-10 south of Louisiana State Charity Cemetery. The aerial picture of the cell site in Fig. 6.48 shows that the area was flooded. However, the water-level marks in the picture in Fig. 6.47 indicate that the base station equipment was mounted high enough on a platform inside a shelter to avoid flooding. Hence, the base station was probably not damaged but failed due to lack of power.

Fig. 6.47. Cell site in New Orleans, northwest of downtown

Fig. 6.48. Aerial picture of a site northeast of downtown New Orleans

Some cell sites in New Orleans were collocated with BellSouth COs that failed. Fig. 6.49 shows one where the antenna can be seen on the rooftop of the Lake CO. Whether or not the base station equipment was damaged depends on the floor where those systems were located. The only certain cause of failure is the lack of power caused by the flooding. Another example of a collocated cell site is at the Broadmoor CO shown in Fig. 6.50. In this case, it is clear from the marks in the figure that the water did not reach the base station cabinets. However, the flooding shown in Fig. 5.59 prevented delivery of fuel for the cell site genset, causing a failure due to lack of electric power.

Fig. 6.49. Collocated cell site inside BellSouth Lake CO [20]

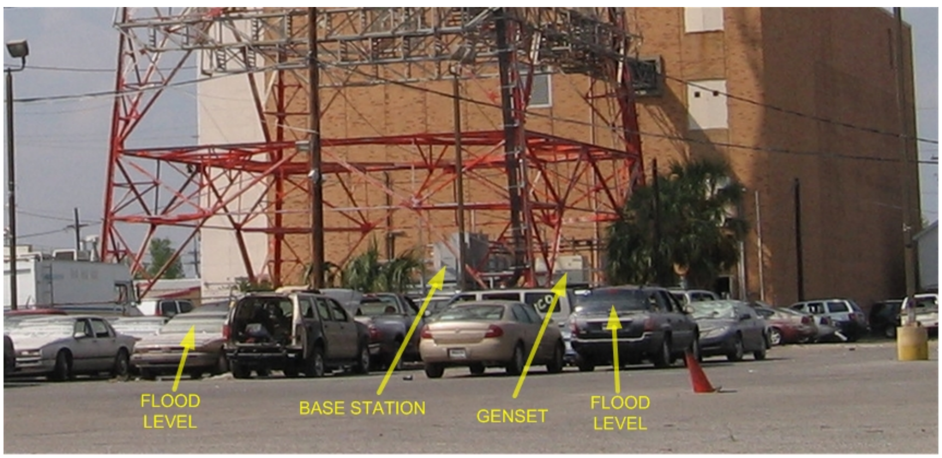

Fig. 6.50. Collocated cell site on a platform outside BellSouth Broadmoor CO

Fig. 6.51 shows a cell site that may have experienced partial damage to the equipment located inside one of the shelters. This site is situated 500 m south of the damaged Sprint long-distance switch of Fig. 5.77, near the intersection of I-10 and I-610 northeast of downtown New Orleans. As the aerial picture in Fig. 6.52 indicates, water covered the wooden fence in front of the site but did not reach the floor of the north shelter. Hence, the base station in this shelter probably lost electric power. However, inconsistent design guidelines led to an almost certain flooding of the south shelter and the outdoor platforms; their floors were not as high as the north shelter. As a result, all the base stations except the one inside the north shelter likely were damaged. The possibility of damaged equipment at these parts of the site is supported by the existence of a cardboard box by the north shelter stairs, probably containing replacement equipment for the damaged base stations. Thus, even though this site is in a blue zone, it is considered to have failed due to damage in one of the base-station communication components.

Fig. 6.51. Cell site northeast of downtown New Orleans

Fig. 6.52. Aerial picture of cell site northeast of downtown New Orleans, August 31, 2005 [6]

6.4 "Green Zones": Areas where the majority of cells sites stayed in service after the storm

The green zones cover the areas affected by Hurricane Katrina that were not included in the other regions. In a green zone most of the cells sites operated after the storm without major problems, implying that portable gensets could be delivered to the site and that repaired and portable gensets were regularly refueled. However, some of the cell sites in these zones may have been isolated by a PSTN failure.

Fig. 6.53 shows a cell site in Bay St. Louis spared from damage because it was located north of the railroad tracks, which provided a storm-surge break. The site had a permanent genset with no need of a portable one. As Fig. 6.7 indicates, the only reason this site might have failed was by being isolated by a PSTN outage.

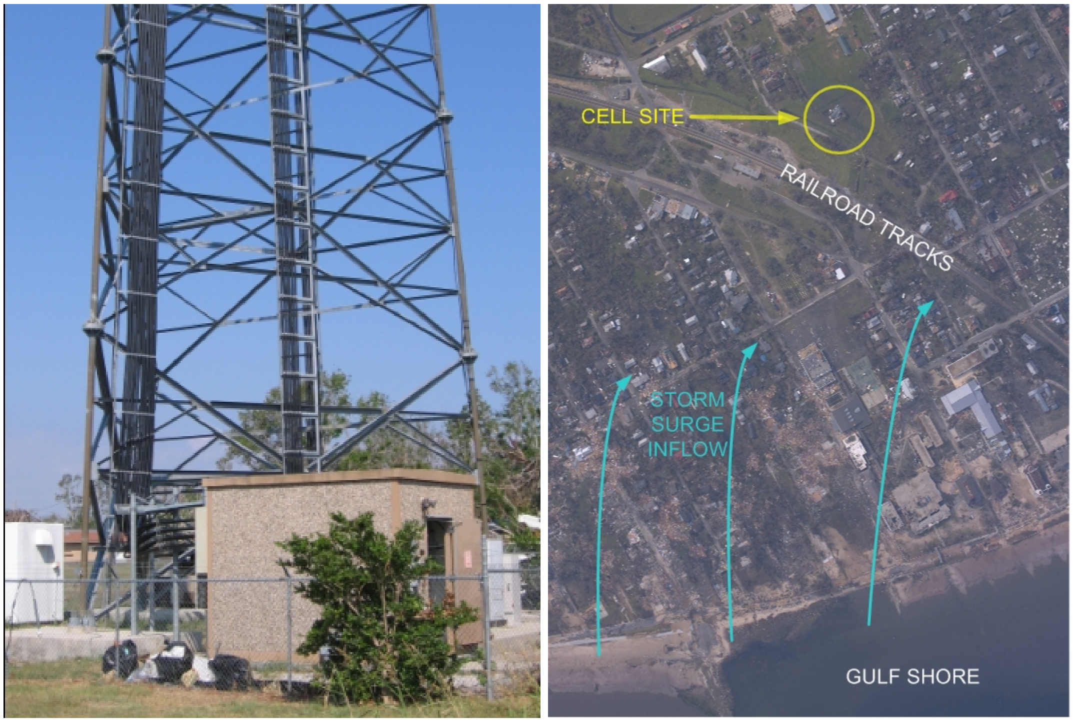

Fig. 6.53. Views of cell site in Bay St. Louis. Aerial picture taken on August 30th [6]

Fig. 6.54 shows a cell site located on Route 607, approximately 500 m south of I-10. Fig. 6.54 (a) shows two of the three fixed gensets marked with yellow arrows. These gensets were not operating at the time of the site survey on October 17th, indicating that electricity was already restored. Fig. 6.54 (b) shows that this site is next to two substations and that the site and surroundings suffered no damage. Thus, we surmise that this site did not fail.

Fig. 6.54. Cell site on Route 607, off I-10 showing two of the three gensets with yellow arrows. Aerial view [6]

There were other cell sites in a similar situation. Figs. 6.55 and 6.56 show two cell sites located side by side at the intersection of Routes 90 and 607. The electric power was on at both sites. However, at the site shown in Fig. 6.55, the remains of a power cable indicates that by the time of the site survey on October 17th, a portable genset had already been removed. The portable generator can be observed in the aerial picture taken on September 3rd and displayed in Fig. 6.56 (b). As with the cell site in Fig. 6.54, there were no indications of damage or failure of any kind. The dissimilar design criteria previously observed in other cell sites is also noticeable in the cell site of Fig. 6.55 in which some of the equipment was placed on a platform 2 m above ground and the rest was installed inside a shelter at ground level.

Fig. 6.55. Cell site located at the intersection of Routes 90 and 607

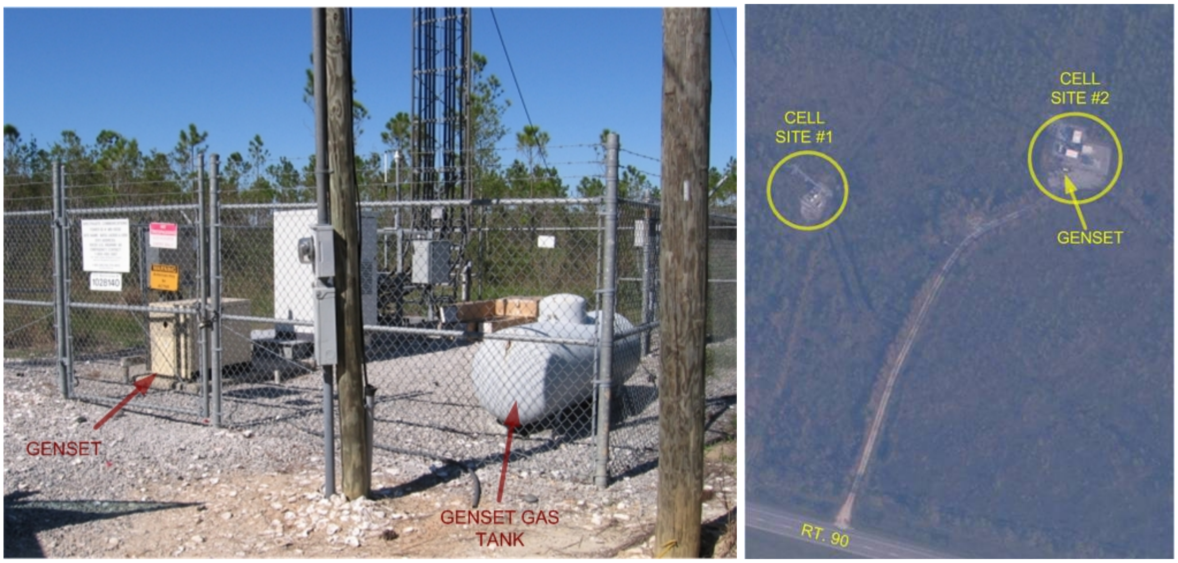

Fig. 6.56. (a) Left: Cell site located 100 m west of the one shown in Fig. 6.55, (b) Right: Aerial view of the cell sites in Fig. 6.55 (cell site #2) and in Fig. 6.56 (a) (cell site #1) [6]

Figs. 6.57 and 6.58 show an interesting cell site located northeast of Gulfport harbor. It has a permanent satellite link to its network, even though there are fiber-optic cables terminated at the site. The reason for this configuration is unknown. This was located at a safe distance from the shore site and showed no damage. However, one shelter was removed between the time the picture in Fig. 6.58 was taken and October 22nd. This cell site had three fixed gensets, which is enough to power the entire location. Since there was no sign of damage or information to the contrary, it is reasonable to assume that neither of the base stations lost service. The electric power had been restored by the date of the site survey.

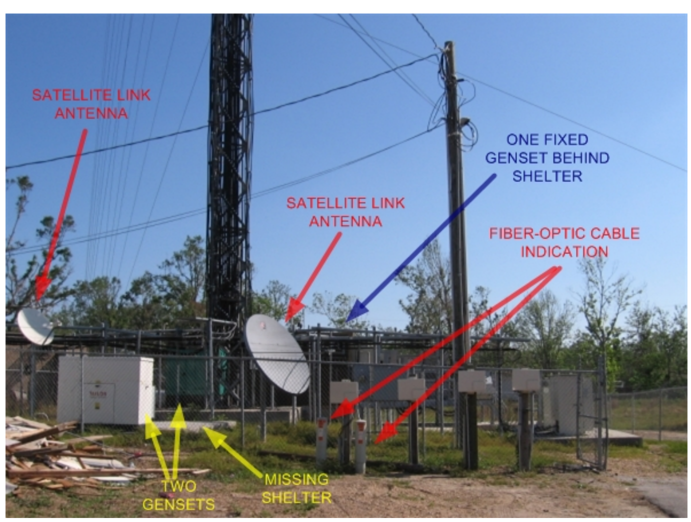

Fig. 6.57. Cell site in Gulfport with satellite-link antennas

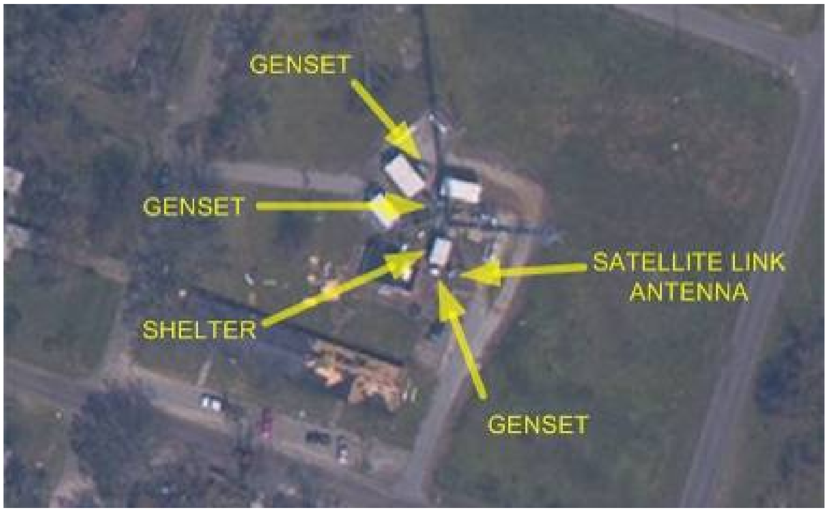

Fig. 6.58. Aerial view of cell site in Gulfport, August 30, 2005 [6]

Fig. 6.59 shows a cell site, located by a Lake Pontchartrain Causeway tollbooth, which had no damage and likely never lost service. This is an important cell because it covers a vital segment of the causeway, one of the few remaining points of access to New Orleans after the storm.

Fig. 6.59. Cell site next to Lake Pontchartrain Causeway Toll

Another site situated in an important location was the T-Mobile New Orleans MTSO and its collocated cell site. Fig. 6.60 (a) shows a picture of the MTSO obtained during the on-site survey. This place was very important during the rescue and relief operations because it was located by a main staging area west of New Orleans. Figs. 6.60 (b) and 6.61(a) show the helicopters and ambulances used to evacuate people after the storm. The location also helped T-

Mobile to coordinate with local law enforcement and genset refueling personnel. The T-Mobile MTSO avoided damage by good fortune. The blue dot Fig. 6.61 (b) indicates the MSC is located below sea level and 3 Km west of the 17th Street Canal. If the 17th Street Canal levees had breached to the west instead of to the east, the T-Mobile MTSO would have been flooded and destroyed, as happened to one of the two Cingular MSCs in New Orleans. Thanks to good luck the MTSO operated normally throughout and after the storm.

Fig. 6.60. (a) Left: T-Mobile MTSO picture obtained during the site survey,
(b) Right: Picture from FEMA showing the staging area next to the T-Mobile MSC,
indicated in the background with a red arrow [37]

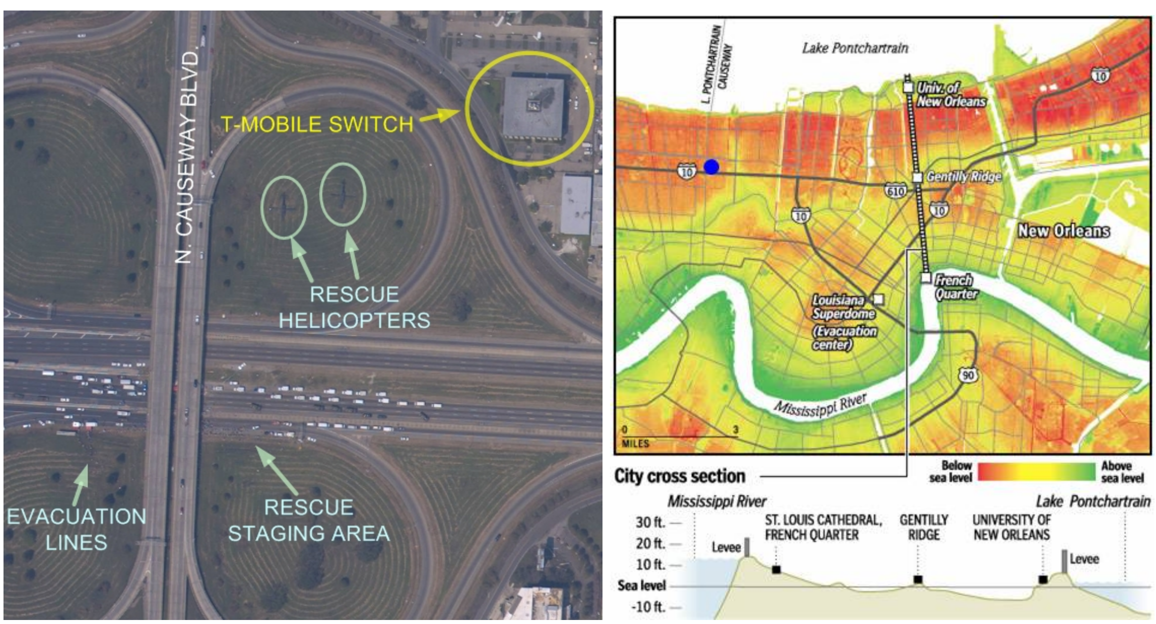

Fig. 6.61. (a) Left Aerial picture taken on August 31st showing the T-Mobile MTSO and rescue staging area [6], (b) Right: New Orleans topographic map [19].
The T-Mobile MTSO is marked with a blue dot.

Fig. 6.62 shows a cell site located north of Pass Christian that may have failed due to lack of electric power. As Fig. 6.62 (b) indicates, the site did not have a genset by September 4th. During the on-site survey on October 17th the portable generator deployed there was operating, indicating that the electric power from the grid was still off. The cell site showed no sign of damage and for that reason we considered it likely did not fail.

Fig. 6.62. (a) Left: Cell site located north of Pass Christian, (b) Right: Aerial picture of the cell site in Fig. 6.62 (a) taken on September 4th [6]

During the site survey, many COWs were found in Gulfport. The most interesting is shown in Figs. 6.63 and 6.64. This COW belonged to Sprint Nextel and was installed next to an AT&T transmission site on Highway 49 and 30th Street, north of Gulfport. The site is interesting because of a microwave transmission repeater that was installed next to the COW. As was mentioned previously, the Sprint-Nextel transmission network was interrupted when the Sprint long-distance switch in New Orleans, along with the POP in Biloxi, were destroyed. Likely, the site in Fig. 6.63 acted as part of a temporary link that replaced the severed transmission path between New Orleans and Biloxi. The aerial picture in Fig. 6.64 was taken during the site installation and shows the raising of the tower for the northeast link. Hence, Fig. 6.64 sets a period for the Sprint-Nextel network restoration. The picture was taken on September 4th. Therefore, it is safe to assume that it was roughly one week after the storm before the network was restored.

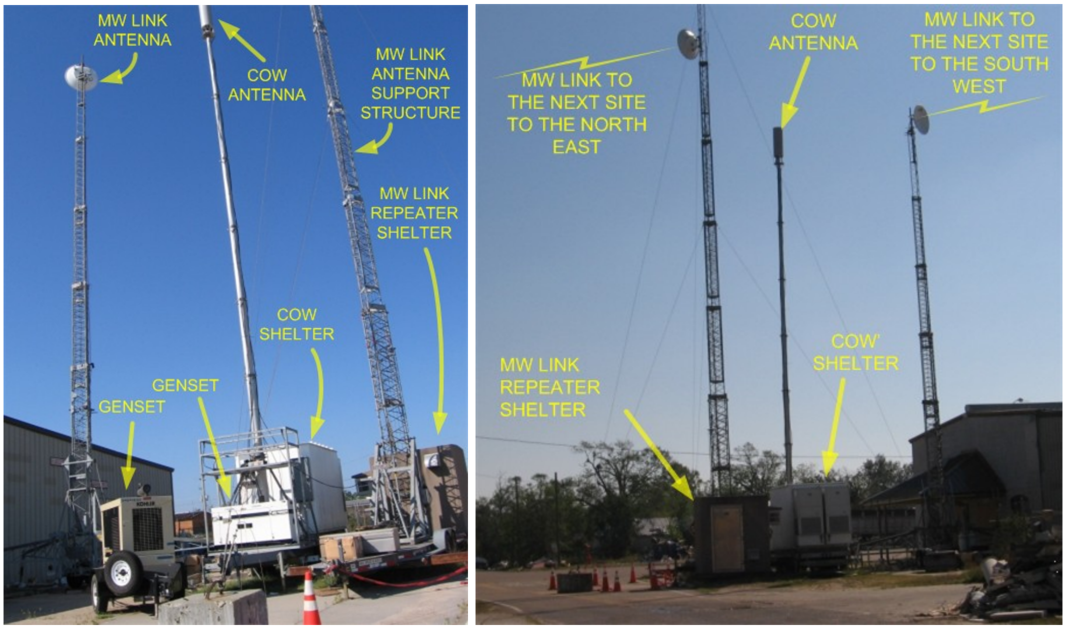

Fig. 6.63. (a) Right and (b) Left: Sprint Nextel COW and emergency transmission repeater

Fig. 6.64. Aerial shot of Sprint Nextel COW and emergency transmission repeater, September 4th [6]

Fig. 6.65 shows another COW found one block northwest of BellSouth CO in Gulfport. The picture on the left was taken during the site survey on October 22nd while the aerial picture on the right was taken on August 30th. The latter shows that the COW was not installed at that time, the day after Katrina made landfall.

Fig. 6.65. (a) Left: COW in Gulfport, (b) Aerial picture taken on August 30th of the area where the same COW was installed [6]

Fig. 6.66 shows a COW mounted on a truck in Gulfport. This COW was set up in an alley next to a BellSouth CO. The cables that connect the base station with the PSTN are visible in the picture. The genset that powers the COW is located behind the truck.

Fig. 6.66. COW behind BellSouth Gulfport CO

Figs. 6.67 and 6.68 show two damaged cell sites within the green zone. Fig. 6.67 shows a broken tower at a cell site located on the Jackson State University campus in Jackson, Mississippi. The tower may have had structural damage before Hurricane Katrina, since the winds in Jackson were not strong enough to topple the tower. The tower broke at a reinforced section, which is usually added when more antennas are included on a tower. So it is possible that the structural damaged was caused during the retrofitting process or because of the addition of the reinforced sections. Fig. 6.68 shows an aerial picture taken on September 4th of another cell site with a fallen tower. In this case the cell site was located about 15 km north of Gulfport, on Route 49. Like the tower in Jackson, there must had been preexisting structural damage before Katrina, because many other cell sites closer to the coast and on the same route did not suffer such catastrophic damage.

Fig. 6.67. Broken cell-site tower on the Jackson State University campus [38]

Fig. 6.68. Aerial picture of a fallen monopole tower north of Gulfport, MS [6]

7 Damage to Radio & TV

Even though radio and TV allow for communication in only one direction, they help during disasters by providing rescue and relief-related information. A radio is always recommended as an item for storm kits. Radio and TV studios and transmitters experienced damage similar to the mobile telecommunication networks.

Most of the transmitters close to the Mississippi Coast and in the southwestern half of Plaquemines Parish and St. Bernard Parish were destroyed. Fig. 7.1 shows one located in Delacroix, Louisiana. The storm surge destroyed the transmitter although the antenna remained standing. Even though the genset was located on a high platform (Fig. 7.2), it was damaged. Other site antenna towers were toppled by the wind. Such was the case with WLOX-TV in Biloxi, as shown in Fig. 7.3. Fig. 7.4 shows that while the railroad tracks may have protected the station from the storm surge, high winds brought the tower down.

Fig. 7.1. KQLD-FM Radio transmitter and tower in Delacroix, LA

Fig. 7.2. KQLD-FM radio transmitter genset

Fig. 7.3. WLOX-TV antenna tower [36]

Fig. 7.4. Aerial view of WLOX location in Biloxi [6]

Other sites in New Orleans were destroyed by flooding. One of those was WVUE-TV. As Fig. 7.5 shows, the channel was knocked off the air by severe flooding of the transmitter located next to the studio. Other TV stations that suffered transmitter flooding were WDSU and WGNO located in Chalmette. Figs. 7.6 and 7.7 show these two transmitters suffered extensive flooding. The studios of WDSU in downtown New Orleans were not flooded, as Figs. 7.8 and 7.9 show, but the building was evacuated and the transmission moved to Florida. The WGNO approach to regain service was different from WDSU. WGNO restored service in its transmission site by replacing the damaged equipment with truck-mounted equipment. Other transmitters damaged were WYES and WVUE TV.

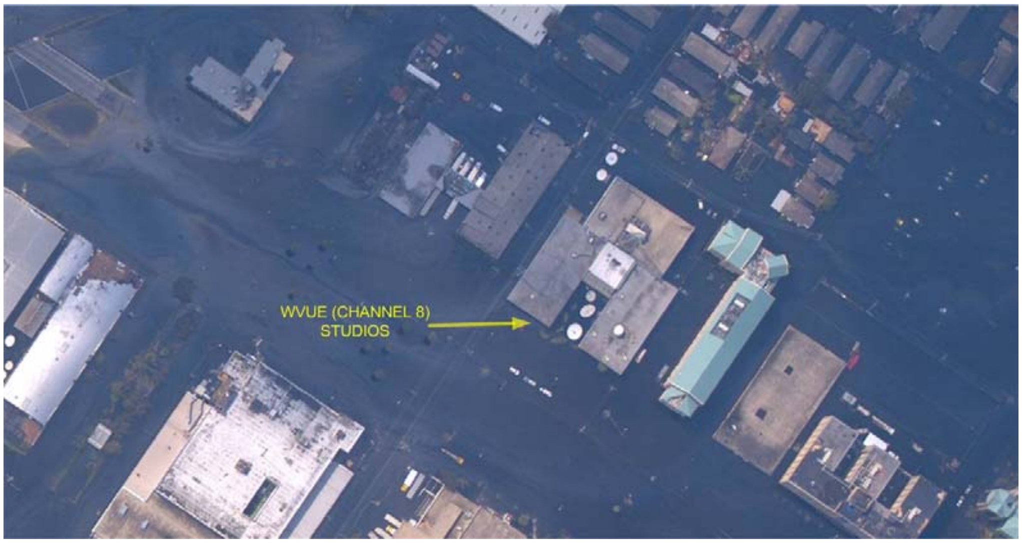

Fig. 7.5. Aerial picture of WVUE-TV studios in New Orleans, August 31st [6]

Fig. 7.6. Aerial view of WDSU transmitter, September 3rd

Some destroyed transmitters were replaced by a new site located in downtown New Orleans owned by the American Tower Company. This transmitter was the new home of WPL, WUL-DT, WHNO, WQUE, WYLD, WEZB, WTKL, WLMG, and WWNO. It also transmitted the signals of several government agencies, including the US Coast Guard, the FBI, the IRS, and the DEA. Clear Channel Communications, owner of some of the radio companies using the site, refueled the genset from Orlando and later from a FEMA deposit in Baton Rouge.

Fig. 7.7. Aerial view of WGNO transmitter taken on September 3rd. Other towers correspond to WYES and WVUE TV and some FM radio stations [6].

In none of the previous sample sites was the primary failure cause power-related. However, power-related outages did occur in other sites. The transmitter for WWL radio is located in Estelle, south of Marrero. This area was not flooded and suffered no significant damage. The transmitter had a 12000-gallon fuel tank for the genset, more than enough to sustain operations for several days. However, the WWL radio signal went off the air when the transmitter genset had a failure and provided only half of its rated power. As a result, the WWL radio broadcast was moved to the WWL-TV transmitter located in Gretna.

Fig. 7.8. Aerial view of WDSU studios in New Orleans taken on August 31st [6]

Fig. 7.9. Oblique aerial view of WDSU studios taken on August 31st [8]

WWL-TV transmits from a hurricane-hardened building equipped with a 1 MW generator and up to 11500 gallons of fuel stored in two tanks. Nevertheless, the WWL-TV staff was moved to Baton Rouge, and the WWL-TV signal was never lost. Refueling the genset was a complicated operation that required a delivery escorted by security guards armed with semi-automatic weapons.

Cable TV companies faced additional problems because the CATV outside plant is more vulnerable. Yet, during the site survey, we did not observe more significant damage than what was seen in the PSTN outside plant. Although serious damage occurred, especially in the coastal areas of Mississippi, most pole-mounted UPSs, such as those showed in Fig. 7.10, seemed to have been undamaged. These UPSs were able to operate for a few hours until the batteries were exhausted. After that, service was only recovered when the electric grid was restored.

Fig. 7.10. Pole-mounted CATV UPS

During the on-site survey, we also noticed that pedestal-mounted UPSs seemed to have received more damage than pole-mounted units. Pedestal UPSs are located at ground level, a vulnerable configuration. Fig. 7.11 shows a case of two UPSs, one pole-mounted and the other pedestal-mounted. The pole-mounted unit seems to be undamaged, while the pedestal UPS was destroyed.

Fig. 7.11. Pole-mounted and pedestal-mounted CATV UPSs.

8 Damage to Electrical Networks

This project is primarily focused on issues in telecom-related infrastructure. However, since the terrestrial electric grid is the primary power source of most telecom equipment, a brief overview with observations on the electric grid is presented here. Additional information can be found in studies and reports focused more on the grid [39-42].

8.1 Generation and transmission

In the transmission network, the physical infrastructure is large, relatively sturdy, and configured in direct point-to-point fashion. While there are disastrous failure modes – conductor failures have toppled miles of towers in previous cases, dead-end towers and sturdy foundations help keep damage local. Repair is relatively straightforward since right-of-way access is usually part of the initial design.

Like all damage from Katrina, high winds and flooding were the root cause of most electrical outages. Mississippi Power is the primary utility for the Mississippi gulf coast region. The Watson Electric Generating Plant, shown in Fig. 8.1, is a critical generation plant for the Mississippi coast. As Fig. 8.2 attests, the power plant suffered minor damage during the storm.

Fig. 8.1. Mississippi Power, Watson Electric Generating Plant

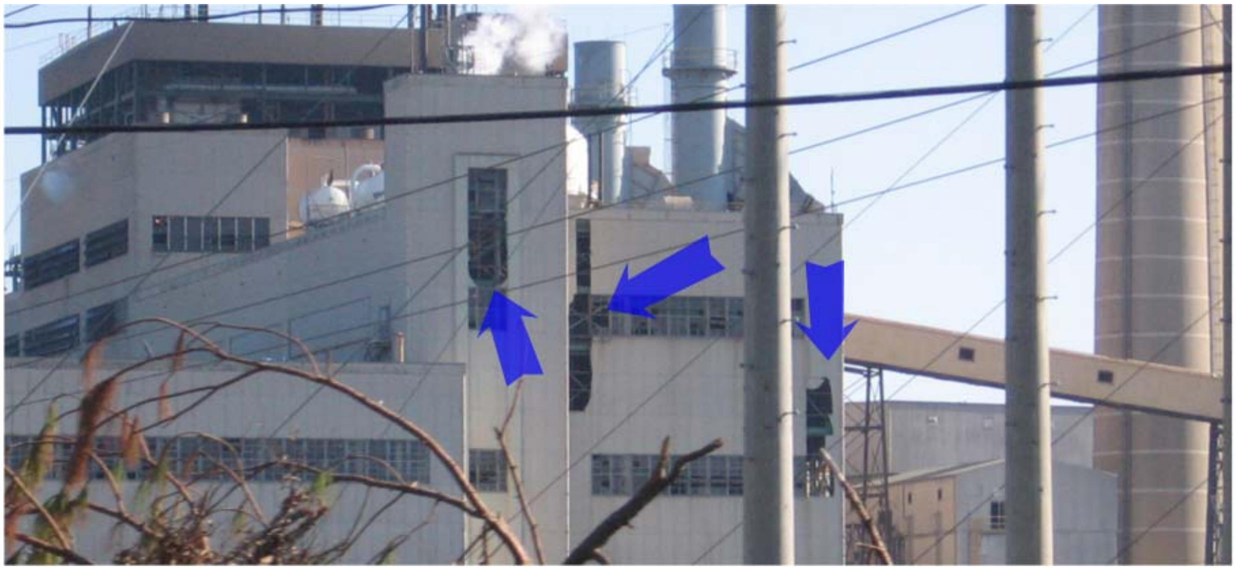

Fig. 8.2. Blue arrows indicating damage to the Mississippi Power Watson Electric Generating Plant

After Katrina, all 195,000 Mississippi Power customers lost power, nearly two-thirds of the transmission and distribution system was damaged or destroyed, and all but three of the company's 122 transmission lines were out of service. More than 300 transmission towers were damaged, 47 of them metal towers in the 230-kV bulk power system. In the distribution system, about 65 percent of the facilities were damaged; 9,000 poles and 2,300 transformers were lost; and 23,500 spans of conductor were down [43]. Louisiana suffered similar damage. Even though only the eastern half of the state was affected, 63 percent of the customers (678,850) remained without power as of September 3rd (Fig. 8.3).

8.2 Substations

Substations are a localized point of failure in the electric power grid. In the areas affected by Katrina, substations were most damaged by flooding and debris. The concentration of live, exposed conductors in a substation made outage from storm waters and debris a high likelihood. However, because of the low-wind profile of most substation equipment, wind damage is not often significant. For example, the substation in Fig. 8.4, off Louisiana Highway 39 near Belair and adjacent to a levee of the Mississippi River, sustained substantial flooding and debris damage from the storm including a control structure with the foundation indicated in Fig. 8.4. Figs. 8.5 and 8.6 depict other substations that were also damaged by the storm surge. Flooding took most of the New Orleans substations out of service. Two of those are shown in Figs. 8.7 and

8.8. At the time of the on-site survey, most observed substations were cleared of water and debris and were operational. An exception is the Biloxi substation, full of debris, with broken conductors and control panel doors hanging open, shown in Fig. 8.9. However, if we consider that most customers were incapable of receiving service at this time, it is reasonable that Mississippi Power had allocated resources to more critical areas.

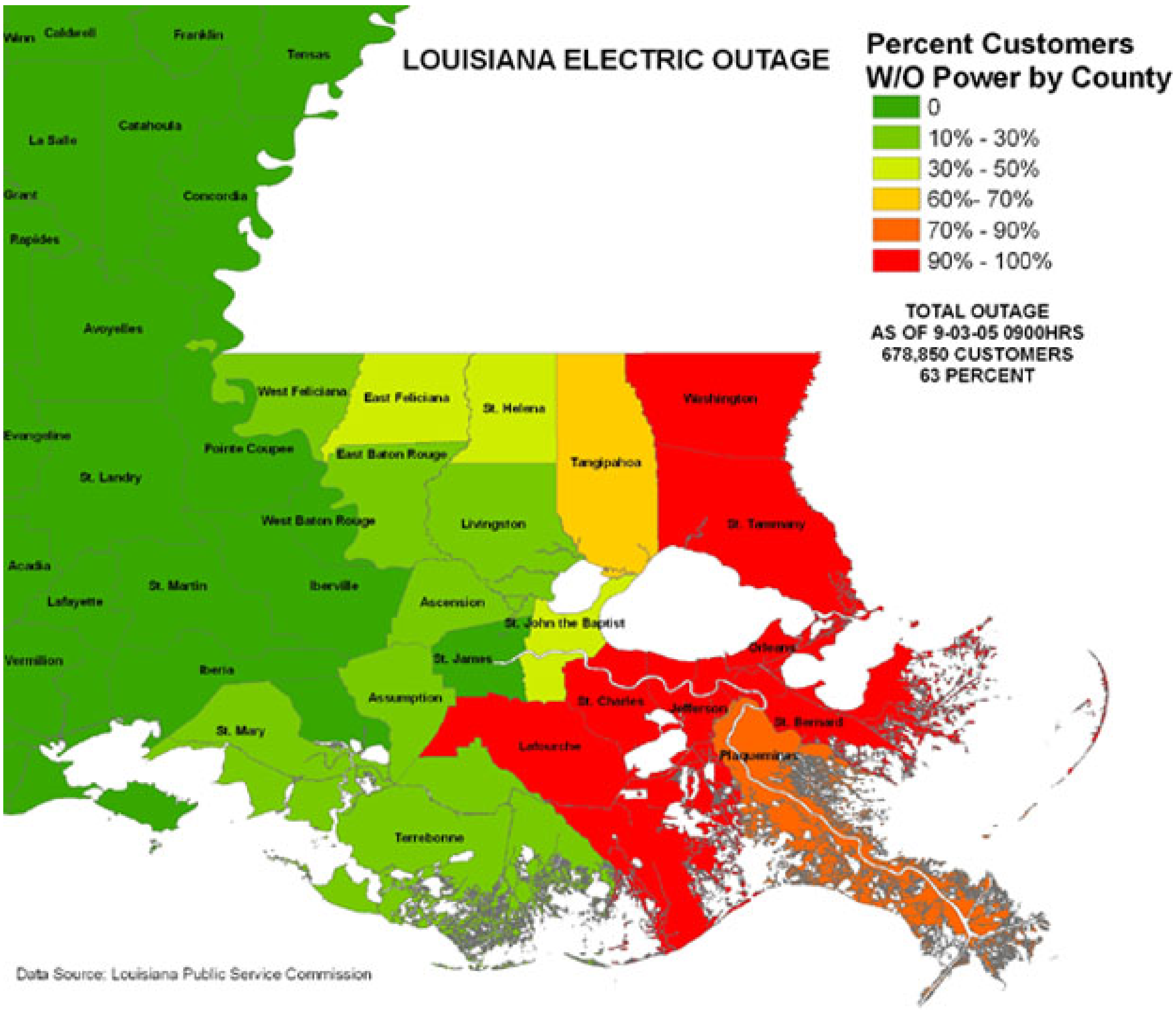

Fig. 8.3. Electric-outage severity map in Louisiana as of September 3, 2005 [44]

Fig. 8.4. Entergy 66MVA Substation near Belair, LA

Fig. 8.5. Damaged substation on Route 603, northwest of Waveland, MS

Fig. 8.6. Substation in Waveland, MS

Fig. 8.7. Debirgny Substation near Louisiana Superdome in New Orleans

Fig. 8.8. Substation northwest of downtown New Orleans. Aerial view on the right taken on August 31, 2005 [5]

Fig. 8.9. Mississippi Power substation in Biloxi, MS

8.3 Distribution

In the distribution network, the physical infrastructure is vast, and the sheer number of connections makes restoration a long and labor-intensive effort. In a situation like Katrina where a substantial fraction of structures sustained heavy damage, power restoration is coupled to structure restoration and the process can take months to years. Costs are likely to be high since heavy damage may require near-complete rebuilding of the distribution infrastructure in the hardest-hit areas.

Figs. 8.10 and 8.11 show damaged distribution infrastructure including lines and poles. The broken pole shown in Fig. 8.10 highlights the susceptibility of multiple networks succumbing at a single point of failure. This pole supported a common distribution transformer and power lines as well as telephone and cable television lines. The picture in Fig. 8.11 shows a repaired distribution line near Pearlington, LA with damaged and discarded equipment on the ground. The photograph in Fig. 8.12 shows an example of a staging area for replacement distribution transformers at a substation. These substation staging areas were often observed throughout the affected areas during the on-site survey and are examples of effective distribution of resources by the power companies.

The restoration strategy of a distribution system needs to take into account the customer base in an affected area. For example, a large area may be without service, but if most customers within the area were evacuated or incapable of receiving electric service due to site damage, then restoration resources would be best served in a smaller, but still populated area. However, priority should be given to service restoration in areas that contain key telecommunication sites, such as PSTN COs, transmission sites, and large cellular sites.

Fig. 8.10. Damaged pole

Fig. 8.11. Damaged lines in Pearlington, MS

Fig. 8.12. Staged distribution transformers

9 Additional Electric Power Issues

Hurricane Katrina also affected operation of security and health centers. Many were destroyed when Katrina made landfall, while others suffered electrical outages and failure of the PSTN. These effects are described in sections 9.1 and 9.2 to convey a sense of the importance of electrical supply to the operations of vital human services. Finally, a short analysis of alternative methods to solve the problems caused by lack of electric power in a disaster aftermath is given in section 9.3. Although such methods of producing electrical energy could improve electric supply, the site survey did not reveal their extensive use in the aftermath of Hurricane Katrina.

9.1 Electric power backup in police stations and other security offices

Communication networks for security forces failed because of damage produced by Katrina at the communication centers and by failure in the PSTN. Direct damage produced by the storm occurred in most of the stations located on the Mississippi Gulf Coast and in the City of New Orleans. In New Orleans, two primary tower sites were lost while police and fire centers had to be evacuated due to flooding. Fig. 9.1 shows one of the fallen antennas in Gretna, south of downtown New Orleans. Direct damage to the US Coast Guard (USCG) station in Gulfport, MS is obvious in Figs. 9.2 and 9.3. Lack of power was not the main cause of failure in these sites. Other centers destroyed by the storm were the Bay St. Louis Police Department, the Hancock County Emergency Operations Center, the Jackson County Sheriff's Department PSAP and several other PSAPs along the Jackson County Coast. During the site survey, we visited the Jackson County Emergency Operation Center in Pascagoula where additional gensets and communication systems had been installed (Fig. 9.4). An added genset was also installed at a public safety building in Biloxi, MS, shown in Fig. 9.5. Provisional communication services were restored by September 1st, using equipment provided by the Florida Department of Law Enforcement and a military communication unit with a satellite link. In Hancock County, E-911 service over the PSTN was finally restored by September 19th. Harrison County experienced only the destruction of the Pass Christian PSAP. However, most of the PSAPs along the coast lost service when the PSTN failed.

Fig. 9.1. Fallen antenna in Jefferson Parish sheriff office building [45]

Fig. 9.2. USCG station in Gulfport, MS [7]

Fig. 9.3. USCG station in Gulfport, MS [9]

Fig. 9.4. Jackson County Emergency Operation Center in Pascagoula, MS

Fig. 9.5. Public safety building in Biloxi, MS

9.2 Electric power backup in hospitals and other health centers

Hospitals and other health center operations were affected similarly to security offices and police stations. According to [46], in New Orleans, the Chalmette Medical Center, Charity Hospital, the Children's Hospital, Lindy Boggs Medical Center, Memorial Medical Center and St. Charles Specialty Hospital suffered damage from flooding and were evacuated shortly after the storm. However, West Jefferson Medical Center and East Jefferson General Hospital were not damaged and their gensets worked without problems allowing these hospitals to maintain relatively normal operations throughout the storm and its aftermath. Health Centers close to the Mississippi Gulf shore suffered extensive damage. Figs. 9.6 and 9.7 show a nursing home in Pass Christian, MS that was destroyed by the storm surge. As Fig. 9.7 attests, the genset in this site was destroyed as well.

Fig. 9.6. Destroyed nursing home in Pass Christian, MS

Fig. 9.7. Destroyed genset at nursing home in Pass Christian, MS

9.3 Alternative sources of energy

Although alternative sources of energy may facilitate restoration efforts by reducing site logistical requirements, the site survey revealed that they were rarely used. AT&T was the only communication company that reported using backup systems other than gensets. In [47] AT&T said they used fuel cells in a few sites to generate electricity for extended periods. There was no further comment about use of fuel-cell technologies. However, unless a fuel cell includes a natural gas reforming unit, there would be no reduction in site refueling needs. Even with a reforming unit, a fuel-cell system needs to be installed where gas utility service has not been lost, unless the fuel cell is refueled regularly using portable containers.

Diversified fuel sources and use of local generation to construct a microgrid may provide a better long-term solution. Use of distributed generation resources such as reciprocating engines, microturbines and solar panels may be more reliable than traditional power plants [48]. Fuel cells with hydrogen sources could be used and be more convenient than traditional gensets. Microgrid-based telecom power plants would also reduce energy storage requirements using alternative energy storage devices such as fly-wheels and ultracapacitors, which are lighter than batteries.

Some distributed generation solutions, such as solar panels used as a microsource, can be implemented short term. Solar-powered systems reduce logistical requirements by decreasing the load on a site genset, thus cutting fuel consumption. During the night, power may be provided by a battery bank or a genset. Even though deploying solar-powered systems in communication sites is potentially advantageous, there are no reports that any communication company used solar-powered systems in Katrina's aftermath. However, during the site survey, we found a solar-powered portable water purification unit, shown in Fig. 9.8. Similar units can be adapted for use in communication sites and deployed after a storm to cell sites, MTSOs and COs to reduce genset fuel consumption. In the case of COs, having a solar energy source allows the use of the site genset with an extended autonomy without modifying the size of the genset fuel tank. In this way, network operators have more time to deliver fuel to the site, thereby lowering the risk of an outage due to genset fuel starvation. If solar-powered units are permanently installed in communication sites equipped with larger battery strings, the number of portable gensets needed to be deployed after a storm can be reduced significantly. In addition, utilizing solar power in cell sites throughout the year can significantly reduce expenses owed to an electric utility company, because less electric power will be consumed from the electric grid.

Fig. 9.8. Portable solar-powered water purification unit

9.4 Power of Last Resort

Solar-powered units offer an alternative for battery charging in CO locations. Communication failures following Katrina were extreme, however, and first responders may need a functional backup that operates even when extensive infrastructure damage occurs. One possibility is a network of low-power low-capacity radio repeaters, designed to support several channels of mobile communication. If a network of this type could be overlaid on the existing infrastructure, it could provide basic radio communications for first responders even in the midst of a storm. The intent is a low-power backup system – up to only a few watts per location – that functions entirely on its own without other external energy.

"Power of last resort" arrayed in this manner would have to be implemented as a maintenance-free standalone unit rugged enough to survive almost any disaster. Individual units would have to be adaptable for installation on buildings, power poles, highway structures, cell towers, or other structures likely to survive a storm. Such a network offers a possible alternative to satellite-based communications and could be suitable for use by local responders during a crisis. A set of projects initiated by the U.S. military [49] is seeking to develop battery-free, maintenance-free power devices for communications energy. The outcomes have potential impact as a worst-case communications alternative.

10 Conclusions

10.1 Causes of communications failure

Why did communication networks fail in such a severe way from Hurricane Katrina? As with any disaster there is no single explanation. One important reason was Hurricane Katrina's unusual strength made evident by the height and extent of the storm surge. Even though the winds were strong, Katrina made landfall only as a category 3 hurricane on the Saffir-Simpson scale. Given that a category 3 hurricane can produce severe damage, there have been many category 3 hurricanes that hit the continental US without producing catastrophic damage. Hence, response planning based on the Saffir-Simpson category may yield misleading results.

Although the storm surge was the most important destruction factor affecting, primarily, sites in Plaquemines Parish, the eastern half of St. Bernard Parish and a 1 km strip of the Mississippi Gulf Coast between the Louisiana border and Pascagoula, flooding due to broken levees in New Orleans affected more sites and originated many failures from lack of electric power. Katrina's effect was more centralized than distributed. Several substations were severely damaged, while not many high-voltage transmission lines were affected. Eleven switches were destroyed but, even though in some areas the outside plant suffered significant damage, only a few cell sites were destroyed. This destruction pattern was more favorable for mobile communication networks than for the PSTN.

Another important reason that explains the severe communication network outage in the aftermath of Hurricane Katrina is the existence of three common points of failure: in many areas the PSTN acted as a single transmission backbone for most of the networks, shared infrastructure (poles), and the telecommunication sites' power feed. The BellSouth network not only transmitted POTS but also interconnected many cell sites and remote MSCs with their respective MTSOs. Moreover, the entire E-911 system is based on the PSTN network. Thus, when the PSTN COs lost service, the transmission links and access points passing through failed COs were interrupted. In the cases where the switch could be maintained, as in the New Orleans Main Tandem switch, rerouted traffic from failed COs was higher than the available capacity, creating congestion points that reduced the network functionality. Thus, the PSTN failure was a major contributor to the breakdown of the entire system.

An unavoidable common point between communication and electrical networks is the power feed. Besides the direct destruction of sites caused by the storm surge, the main reason for CO and cell site failure that accounts for the majority of outages was loss of electric power. In some COs in New Orleans, the primary failure cause of the power-related outages was flooding that prevented deploying portable gensets or did not allow refueling. Disruption of the local diesel supply and the impossibility of delivering fuel due to damaged roads also played an important role in areas where COs lost service even though the initial flooding subsided in a few days. In some COs, flooding damaged fuel tanks buried below ground level while the rest of the equipment was unaffected. Even though the area affected by flood-related power outages was relatively small, it held the highest density of communication systems.

The fact that many outages were caused by lack of electric power highlights the importance of securing communication sites' electric supply during and after storms. It also emphasizes how dependent telecom networks are on electric power and, especially, on continuous genset operation after a storm. The site survey revealed that all networks relied almost entirely on gensets to provide extended backup power. However, generators are relatively inefficient when required to operate for more than few hours. This suggests that from a reliability standpoint, the connection between the electric grid and communication networks is a weakness.

Vulnerable construction practices may have been a factor in the failure of some sites. We observed many examples that attest to this. For example, the Pass Christian CO, located a few hundred meters from the coast, was built at ground level. Sometimes the existence of a vulnerable construction is seen as a lack of uniform design guidelines, such as having the same cell site base stations on platforms of different heights. Reasons for these contradictory designs are unknown. But they should be analyzed with a historical perspective, since many of the infrastructures were constructed several years ago. As with numerous issues related to infrastructure design, solutions may also take many years.

Having analyzed the reasons why the communication networks failed in such an unprecedented way with Hurricane Katrina, one can ask the question, "What factors prevented the outcome being worse?" Certainly, good fortune played a crucial role in some cases. And hurricane preparedness was adequate based on pre-Katrina criteria. The single most important factor that prevented further damage was the remarkable effort, amid extremely difficult conditions, of communication and electrical company employees. Flexibility to adapt to the new conditions and ease of implementing alternative, on-the-spot solutions to clear outages showed extraordinary experience levels from these employees.

10.2 Proposed solutions

A first lesson that can be learned from Katrina is that communication companies must base their hurricane-restoration plan not only on the wind-speed forecast, but also on other hurricane parameters such as the forecasted storm-surge height and extension. Future research on the effects of strong storm surges versus extremely intense winds on telecommunication infrastructure is needed to support contingency plans. Hurricanes where wind speed is more important than storm-surge strength may produce more distributed damage instead of affecting centralized elements of the communication network.

Common points of failure among the networks can be addressed in a variety of ways. One approach for decreasing the risk of a major system break-down due to PSTN failure is to increase mobile communication transmission capacities and provide architectures with more network diversity. These include increasing direct connections between wireless communication networks. A short-term, relatively inexpensive solution is to create microwave links between cells and MSCs currently connected to its network through the PSTN. On the PSTN side, destroyed switches could be replaced by SOWs instead of DLC cabinets. SOWs are more expensive than DLC enclosures, but they are more reliable, provide better functionality for trunks, and reduce congestion nodes by allowing better distribution of traffic. Yet, the majority of the damaged PSTN COs were replaced by DLC systems, which were mostly hosted by the Schrewsbury and Aurora COs. These COs were built on terrain located below sea level and close to canals. Thus, they and the PSTN network in New Orleans were at a high risk of failure. Another factor that added to the higher PSTN failure probability, even with moderate strength storms, was the replacement of damaged feeder facilities by DLC cabinets.

A shared infrastructure is both less costly when built and less reliable in a disaster. While sharing poles is accepted in the United States, in many countries it is an exceptional case or prohibited. Even in countries where all the networks belong to the State, higher reliability and improved safety receive priority over lower costs, leading to separate infrastructures. Hence, it is advisable that to increase network diversity and improve overall reliability, infrastructure should not be shared among different networks.

A third point of failure, the connection between the electric grid and a communication network, is a weak point in the infrastructure. Site failure from lack of power can be reduced if the communication network dependency on the electric grid is minimized by providing local sources of energy with improved reliability. Gensets, the widespread solution in Katrina's aftermath, have a relatively low availability when used for more than a day. Genset reliability can be improved if logistics and fuel delivery are enhanced in two ways: first – diversify the fuel supply by using dual natural-gas or diesel gensets for COs close to the shore, and second – reduce fuel distribution by using natural-gas engines at inland sites. A direct method is to increase the electric energy stored at each site, i.e., increase the number or capacity of battery strings. Another way is to employ alternative sources of energy, especially solar power to provide electricity to the communication system during the day. Solar-assisted power plants can be installed in a relatively short time, easing genset fuel demand. Distributed generation resources, such as reciprocating engines, microturbines and fuel cells may provide a long-term increase in availability by making the site independent of the electric utility grid.

Power-related outages could also be reduced by revising and improving restoration plans based on several different disaster scenarios. Plans need to consider three equally important factors: resource availability after the storm, resource deployment, and response timing. The objective of the plan should focus on the common good with an emphasis on avoiding outages. Commercial competition between companies should be set aside. As a first milestone, resources need to survive the storm. Then steady distribution needs to be ensured after the storm and during restoration. Inland staging areas with good access to the coast have to be identified and prepared before the hurricane season begins. Emergency diesel fuel and portable gensets can be stored there. Living arrangements for personnel working on restoration should also be made in advance. Plans should be coordinated with local law enforcement officials to ensure access to the affected area after the storm without interfering with rescue operations. After the storm, fuel should be delivered in a timely fashion through routes previously agreed upon by security officials. Plans should consider alternative routes to the main sites and alternative means of fuel transportation, including helicopter and boat.

A recovery operation group should be defined before the hurricane season starts. The group should use personnel within the affected area and have a well-defined structure including a liaison with other communication companies, the FCC and law enforcement officials. Plans of BellSouth and other companies that provided for housing and relief of the affected employees and their families were extremely useful and productive because they improved an otherwise extraordinarily difficult working environment. Resources need to be administrated wisely. The logistical effort of deploying and refueling generators can be reduced if all operators of a same cell site agree on one genset supplier for that location instead of each providing its own genset. This alternative way of delivering gensets can be implemented in a very short time well before the start of the hurricane season. Mobile communication networks were restored much faster than the PSTN. However, the restoration time could have been even shorter if there had been coordination to provide just one genset per site. The impact of this recommendation may extend beyond the communication industry; fewer deployed gensets implies fewer trucks on the road, which will reduce traffic and support rescue and relief efforts. Finally, the plan should include a clear restoration order, giving the highest priority to E-911 centers and law enforcement and emergency response offices with lower priority to communication network connection points.

Vulnerable construction can be avoided at the network design stage. In the communication industry there are design guidelines for areas at high risk of earthquakes. Similarly, communication companies might agree on common design guidelines in coastal areas at high risk of hurricanes. These guidelines should include a unified code for infrastructure design and construction. They could be extended to add improvements in network architecture and interconnections. For example, the guidelines should define not only the recommended height at which communication systems are constructed, based on their geographical location and topographical data, but also the required structural strength depending on proximity to the shore. Topographical characteristics of the coast should also be taken into consideration. In addition, the design guidelines should be coordinated with city planner decisions. For example, levee strength and network survivability objectives may influence new CO construction. Plans to reinforce CO buildings should include expected flooding. Better ways of sealing the interior of a CO from flooding waters should be developed. Doors can be strengthened to keep water from entering the building. Conduit seals that prevent water from easily inundating manholes and cable entrance facilities already exist on the market, implying that this solution can be rapidly implemented. Power-plant components should be given the same importance as any other element of the communication network, such as the switch. Gensets located outside, in sites close to the coast, should be considered destroyed after even moderate hurricanes. Emergency generators, engine fuel tanks, pumps and other ancillary components also should be placed inside at an adequate height with respect to sea level. Having larger fuel tanks to provide extended autonomy may be an adequate solution for sites where alternative energy solutions cannot be implemented.

10.3 Follow-up commentary

One team member, P. Krein, visited New Orleans in July 2006 and observed evidence of the reconstruction process. He toured a residential area near the 17th Street Canal levee breach where there had been nearly three meters of flooding for more than two weeks after Katrina. While most residents evacuated, some took refuge in attics. There were fatalities. Today the neighborhood is a disquieting mix of abandoned churches and homes, un-repaired houses for sale, structures being readied for demolition, houses in early stages of heavy restoration work, and a very few fully recovered houses. As a rough estimate, about 10 per cent of the houses have been recovered. A higher percentage does not appear to have been touched since the storm.

The electrical and communications infrastructure is generally restored. Cell telephone service is normal. Even at this late date, most of the houses have not been sufficiently repaired to permit grid reconnection and thus do not have electrical or telephone service. Fig. 10.1 illustrates part of this issue. It shows damage in a residential area and abandoned cable infrastructure in the vicinity of the 17th Street Canal in July 2006. Fig. 10.2 shows a nearby house with a large tree yet to be removed. Fig. 10.3 shows an apparently abandoned home in this formerly affluent neighborhood. The visible high-water line in the image is about 1.9 m above grade. Neighbors reported that the water level reached about 2.4 m, and traces are more evident in the interior of many structures. In these areas, many distribution network repairs seem to be temporary or incomplete, but this is probably justifiable since the load is only a small percentage of pre-storm demand.

Fig. 10.1 Abandoned cable run and residence damage in an alley a few blocks east of the 17th Street Canal, Orleans Parish, July 2006. Photo courtesy of D. Dickey.

Fig. 10.2 Residence that still shows heavy storm damage from Katrina, July 2006. Photo courtesy of D. Dickey.

Fig. 10.3 Abandoned home east of 17th Street Canal, July 2006. Photo courtesy of D. Dickey.

To the west, in Jefferson Parish (this canal breach was on the east side, toward Orleans Parish) recovery appears to be essentially complete. To the south, along Canal Street toward the central city areas, there are long stretches where businesses and other facilities remain closed. Outside plant infrastructure seems to be complete, but damage to structures obviously has overwhelmed the ability to carry out repairs. Farther south, near downtown areas, most businesses seem to have re-opened and recovery is progressing. While a few buildings downtown are still under repair, most seem to be in normal operation. Downtown and in the French Quarter, most of the people on the streets and customers in businesses appear to be out-of-town work teams from churches and various charitable groups.

New Orleans and other sections along the Gulf Coast continue a long recovery process from Hurricane Katrina (in some areas exacerbated by later effects of Hurricane Rita). While most of the power and communications infrastructure has recovered and is in operation, some of the repairs used temporary fixes and will need to be addressed again as restoration continues. Neighborhoods subjected to extensive flooding will not recover fully for many years.

10.4 Afterword

Communication companies should not be blamed for the extensive outage that followed Hurricane Katrina's landfall. They implemented plans based on hurricanes such as Camille, Hugo and Andrew which were more intense than Katrina; some of these past storms also flooded New Orleans. On the night of August 28, one could ask the question, "If the PSTN has survived so many hurricanes in the past, why should Katrina be different?" If events are analyzed with a historical perspective, the answer to this question is, "Nothing should have been different." A possible mistake among communication planners was a failure to recognize the evolving nature of land, communications and electrical networks. Some of these changes have been relatively recent, so they were difficult to identify in a timely manner. One example is the high dependency on a PSTN that was designed a decade or more ago, before the installation of mobile communication networks. In addition, various published scenarios suggested that a hurricane with the strength of Camille with an unfavorable landfall point would cause extensive flooding as actually occurred from Katrina. Soil erosion along the Louisiana coast in recent years has weakened natural barriers to strong hurricanes, and other known effects have altered the potential impact of large storms in this region.

We now know that a series of incidents caused the unprecedented outage in communication after Hurricane Katrina. Now is the time to act to prevent such a disaster from reoccurring. Some of the strategies discussed in Section 10.2 and elsewhere in this report can be implemented in the short term. These will alleviate certain effects a future hurricane similar to Katrina might produce. Other strategies will require planning, financing, and more time, even years, as for any major infrastructure change. Until long-term changes are carried out, military-type communication systems or last-resort repeater networks need to be ready to support rescue and relief efforts after a disaster like Katrina.

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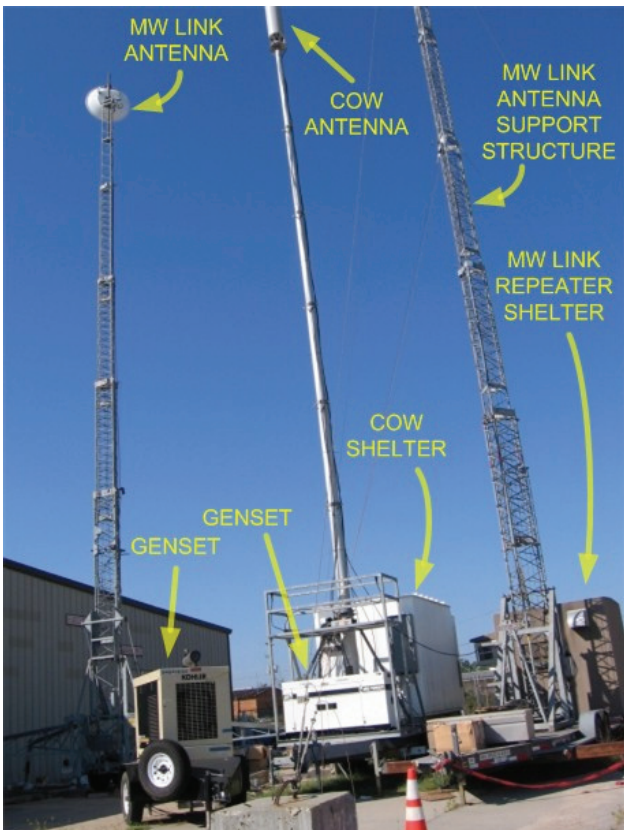
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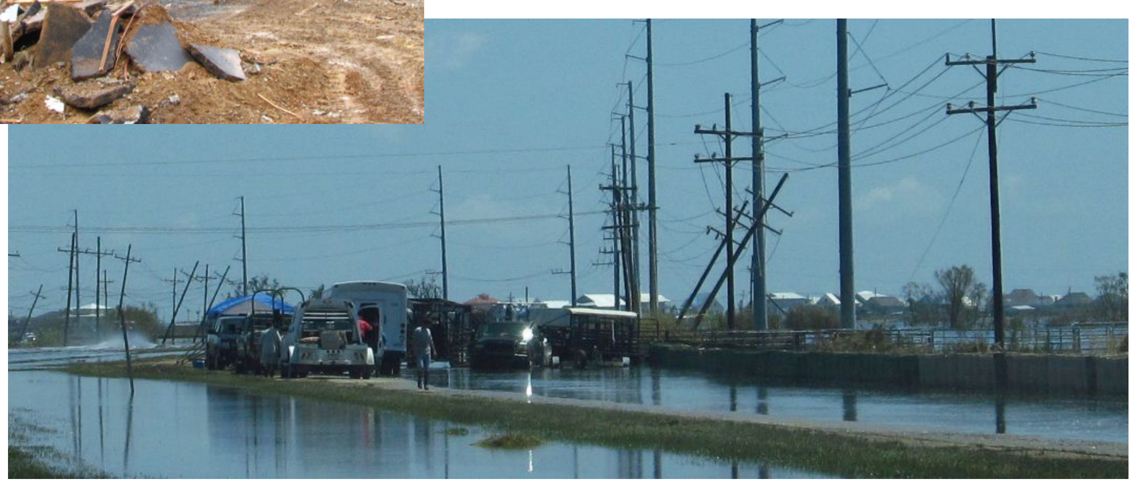

U.S. Gulf Coast Telecommunications Power Infrastructure Evolution since Hurricane Katrina

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Abstract

This paper studies the evolution of communication networks infrastructure in the U.S. Gulf Coast region from late August 2005 when it was affected by Hurricane Katrina to recently. Focus is placed on power supply within the particular planning constraints existing in the area after such a critical event. The discussion is supported by extensive photographic evidences from site surveys performed a few weeks after Hurricane Katrina and more recently in 2008 and 2009.

1 Introduction

This paper describes how telecommunications power infrastructure in the U.S. Gulf Coast evolved from the time the area was affected by Hurricane Katrina. It also comments how these changes relate with the U.S. Federal Communications Commission (FCC) mandate [1] and with the recommendations made in INTELEC 20006 by an independent research team [2]. When Katrina struck the U.S. on August 29, 2005, it originated an unprecedented telecommunications outage that restricted the recovery and restoration efforts. At the time, there were two main analyses of the effects of the hurricane on telecom networks: one conducted by the FCC [3] and the other conducted by university researchers [2]. Although both studies identified lack of power as one of the main failure causes, [2] presented a more detailed and insightful analysis on both technological and operational aspects. In addition to lack of power, other outage causes mentioned in [2] included logistical limitations and inadequate construction practices. The discussion in this paper has a network and infrastructure planning perspective which necessarily includes demographical transformation in the affected area. Thus, the analysis included here explains how demographical changes in the affected area affected the communication networks infrastructure restoration; i.e., the description of the infrastructure evolution since Hurricane Katrina also tells the history of the entire region since the storm. Therefore, this study provides valuable lessons not only in terms of technical aspects but also in terms of a human perspective, which eventually is the basis and driving force for infrastructure deployment decisions.

This paper resumes the discussion where [2] ended. Since the reason for the more complete analysis in [2] as compared with FCC's study [3] may have been the different methodology based on field information, the proposed paper maintains the same methodology used in [2] and supports the analysis by presenting large photographic testimonial from on-site surveys performed after 2005. Firstly, this paper summarizes the observations and lessons in [2]. Secondly, it provides a planning background necessary to provide context to the descrition in the next parts. Thirdly, the evolution of the power infrastructure for different types of communication networks, such as the public switch telephony network (PSTN), wireless networks, and cable TV (CATV) networks, is discribed. Finally, this paper summarizes the analysis and reviews the validity of the sugestions in [2].

2 Historical and planning background

2.1 Hurricane Katrina effects on the U.S. Gulf Coast

Hurricane Katrina made landfall on the U.S. Gulf Coast South of New Orleans near the town of Buras along the Mississippi River. Although Katrina's winds were not particularly strong, its storm surge—an influx of water carried inland by the hurricane's wind and low pressure center—was. The storm surge destroyed nine of Bellsouth's central offices along the coast of the state of Mississippi and the lower Mississippi River delta. Six central offices lost service when the levees that protected New Orleans failed and the city flooded. As Fig. 1 shows, a large portion of the city of New Orleans is below the levels of surrounding water bodies, such as Lake Pontchartrain, the Mississippi River, small ships and other canals, and the Gulf of Mexico, with only a few meters high concrete or compacted soil walls separating the water and the city. Additionally, eighteen central offices lost service due to engine fuel starvation or other type of genset failures. Evidently, Hurricane Katrina affected Bellsouth's (now AT&T) centralized network elements more severely than other storms. In wireless networks lack of power was also an important cause of failure particularly in the distributed network

Figure 1 Intersection of I-10 and I-310 showing the water level above the street level in the direction of New Orleans

elements, i.e., the base stations. As explained in [2] only a few cell sites were destroyed, although damage to some of the base stations in a given location was not uncommon. Power was also an issue in CATV outside plant networks.

The study in [2] discusses several issues relates with the restoration efforts and network design practices that influenced outage occurrence and duration during Hurricane Katrina. One relates with service restoration of damaged infrastructure by using digital loop carrier (DLC) systems. These systems were used both as a temporary replacement to destroyed central offices, and as a substitute to damaged outside plant cooper feeders. Another point made in [2] refers to inconsistent cell sites construction practices, highlighting the fact that in many cell sites not all the base stations were located over the flood plane. Yet another observation points out that infrastructure on poles seemed to be more resilient to hurricane actions than that at ground level. Additional, more general suggestions indicate the benefits of using natural gas instead of diesel to power generators, the need to have less deployable gensets to each cell site, and the advantages of developing microgrid systems to power telecom loads in such circumstances.

2.2 Planning background

One very complicated aspects of any restoration process after a disaster, such as Hurricane Katrina, in which significant damage occurs, is to reconcile the immediate repair needs with the long term network planning goals. Communication networks infrastructure plans are usually made, at the least over, a 5 to 10 years horizon. These planning activities typically includes all the outside plant (OSP) elements, buildings, and cooling and power systems. Lead acid batteries are a typical example of long term planning infrastructure components because they are amortized over at least 10 years. Thus, a significantly important initial task of any planning process is to estimate the demand into 5, 10, or even more years into the future. This is when planning difficulties immediately after a disaster and during the few weeks long restoration and network rebuilding process start. The reason for these planning difficulties is that during this period the focus is on restoring service to an area where the future demand that would drive decisions on network elements deployment and capacity is mostly unknown.

The network evolution after Hurricane Katrina in and around New Orleans and along the state of Mississippi Coast is an example of these problems. A survey of this region reveals large areas that remain frozen in time from the time Katrina made landfall. As it is exemplified in Figs. 2 and 3, in many New Orleans neighbourhoods many houses remain as they were when their owners evacuated the city as the hurricane approached: boarded up and abandoned. In the most severely flooded areas north and east of downtown, more than half of the houses remain abandoned. This observation is in agreement with repopulation estimates by the end of 2008 of 56 % described in [4], and calculations for the entire city of 74 % contained in [5] but with many neighbourhoods still below the 50% level 3 years after the storm [6]. Some of the areas, particularly the elevated ones around downtown and the French Quarter, actually have today up to 20 % more population than 3 years ago, when Hurricane Katrina struck New Orleans [6]. Many areas where most dwellings were extremely damaged or destroyed, such as in the Mississippi River delta, the state of Mississippi Coast, and the region east of Lake Pontchartrain were partially repopulated with mobile homes, as shown in Figs. 4 and 5. Demand estimation for such a large deployment of mobile homes is a very difficult task because of its rapid and largely unpredictable changing nature. Hence, in order to meet both immediate restoration needs and future planning requirements, network elements need to provide enough flexibility to adapt to potentially fast and/or unpredictable demand changes.

Most electronic based elements of communication networks do not entail a significant planning issue because demand can be followed within relatively wide limits by

Figure 2 Mostly abandoned houses in New Orleans.

Figure 3 Homes behind AT&T's Lake CO in New Orleans.

Figure 4 View from the former location of Bellsouth's Delacroix CO.

Figure 5 A DLC and mobile homes in Bayou Sauvage.

adding or taking out printed circuit boards cards from a frame. For example, in wireless networks lack of demand can be adjusted by relocating base stations electronic cabinets into higher demand areas, increasing surrounding cells coverage, reducing capacity in the respective MTSO by removing cards in the switch, and adjusting the network database accordingly. This flexibility can be achieved because wireless operators do not typically own the cell site tower and other infrastructure that is not scalable, as exemplified in Fig. 6 where the cell site capacity was reduced by eliminating a base station antennas and other hardware.

Traditional wireline communication networks are not so flexible, particularly in the case of entire copper networks because of the unique point-to-point connection between subscribers and the switch. Some flexibility can be gained if the wireless network architecture is mimicked by placing more electronics in the outside plant and linking these electronics to the switch with fiber optics cables. This is the reason why Bellsouth/AT&T made such an extensive deployment of DLCs as part of the restoration and rebuild process after Hurricane Katrina.

3 Power infrastructure evolution

Since Hurricane Katrina struck the U.S. Gulf Coast, AT&T, the largest fixed telephony operator, made an extensive deployment of DLC systems. Digital loop carriers were used to restore service to destroyed central offices, replace damaged copper feeder cables, and to provide the outside plant with enough flexibility to accommodate an extremely difficult to forecast demand. Although such an extensive use of DLCs is justified by the particular planning issues that are observed after a disaster such as Hurricane Katrina, network availability can be negatively impacted. One reason is that since DLCs carry less traffic than other more critical network elements, such as a switch, then DLCs are designed with a smaller target availability [7]. Another reliability issue is that central offices hosting several DLCs may become a reliability weak point. In the particular case of using DLCs to replace destroyed central offices, the central office that hosts those replacement DLCs becomes a single point of failure of an extensive area. Additionally, according to FCC's Katrina Order [1], back up times in the DLCs used to replace central offices is one third than that required in central offices. Thus, indirectly the FCC Katrina Order may lead to areas where network availability is less than before Katrina, as central offices requiring 24-hours of back up are replaced by less reliable DLCs needing at least 8-hours of back up.

Figure 6 A comparison of the same cell site in Irish Bayou few weeks after Katrina and in July 2008.

Power supply is a significant issue for DLCs particularly after a disaster. Since DLCs are usually connected to the central office through a fiber optic cable, DLCs require their own local power supply. The conventional power supply configuration present before Hurricane Katrina in almost all DLCs in the Gulf Coast includes a local rectifier plant with batteries for a few hours of back up. Extended operation during long power outages with this conventional configuration requires deploying a portable diesel genset. However, during hurricanes unsafe weather conditions to deploy gensets usually last longer than the back up time provided by the batteries. Hence, most DLCs with a conventional power configuration usually loose service during hurricanes. Another disadvantage of portable gensets is that the generators need to be refuelled regularly. As the number of DLCs increases, so does the logistical needs and the probability of failure due to genset failure, engine fuel starvation, genset burglary, or human error.

One of the alternatives that were implemented to address these power issues in some of the DLCs installed after Hurricane Katrina is exemplified through the DLC installed to replace Saint Bernard destroyed switch. As Figs. 7 and 8 show, extended operation of the DLC without power from the electric grid is achieved through a natural gas-powered genset. This is a good solution for hurricane prone areas as zones with natural gas service outages are much smaller than those affected by an electric power outage [2]. Unfortunately, the same solution cannot be implemented in earthquake-prone areas because natural gas service is automatically interrupted during earthquakes to prevent fires to occur. Although the use of DLCs to replace destroyed central offices may have been originally considered a temporary solution, in most of the destroyed central offices, the solution was permanent. As Fig. 7 shows, this was also the case in St. Bernard central office, where the original building was abandoned and only a DLC was left operative. Fig. 7 also shows that at the time when hurricane Katrina struck the area, the central office had a fuel tank to provide back up operation with a diesel genset for more than the 24-hours later required by the FCC. Thus, the FCC Katrina order did not addressed the root cause of failure in this and other central offices in the region already at the time in compliance with the later order. Another central office that failed due to Katrina's damaging

Figure 7 Former Bellsouth's St. Bernard Central Office.

Figure 8 Detail of the DLC at the former St. Bernard Central Office location.

actions but also at the time in compliance with FCC's 2007 order is Pass Christian. In the case of Pass Christian central office, shown in Fig. 9, although the DLC used to restore service remained operational 3 years after the hurricane, the central office building was rebuilt after it was completely flooded and severely damaged by Katrina's storm surge. Still, the fundamental vulnerability of this site—its close location to the Gulf Coast—remains. Hence, a 24 hour back up requirement as ordered by the FCC will not improve the outage avoidance probability at this site.

Figures 10 and 11 show the past and present condition of two other destroyed central offices: Delacroix and Yscloskey. Nowadays, the remains of the building that used to contain those switches have disappeared and only a DLC is found at each site. In reality, those switches were replaced by a number of DLCs distributed over what used to be each of the central offices areas. As Fig. 4 exemplifies, the decision of eliminating these central offices areas could be explained from a planning perspective by the unpredictable demand in these severely affected areas. Yet, widespread use of DLCs may lead to network availability issues, particularly because many of these new DLCs, such as the ones in Figs. 10 and 11, lack a permanent genset as the one in Fig. 8, so each of them would require the deployment of a portable genset to support operation during long power outages. Furthermore, their vulnerable location in easy to flood areas that can be accessed by only one road—Louisiana's Highway 46—from relatively distant genset staging and distribution centers imply that FCC's 8-hour energy back up requirement is certainly insufficient to prevent a loss of service in case of future hurricanes. Debris and some damage to the fences in the recent photos in Figs. 10 and 11, likely caused by 2008 hurricanes Gustav and Ike, suggest that those DLCs are placed at an insufficient height to prevent damage in case a hurricane at least as severe as Hurricane Katrina struck the area again.

Figure 9 Pass Christian's Central Office just after Hurricane Katrina struck the Gulf Coast and in July 2008.

Figure 10 Delacroix central office site just after Hurricane Katrina and approximately 3 years later.

Figure 11 Yscloskey central office site just after Hurricane Katrina and approximately 3 years later.

Many more DLCs can be found in the area, either in sites already existing before Hurricane Katrina affected the region (Figs. 12 and 13) or in new sites installed to meet an uncertain demand or to replace damaged copper feeder cables (Figs. 5 and 14). As Fig. 12 indicates, some DLCs were replaced by newer ones, sometimes a few meters from the original location, and were equipped with permanent natural gas genset to eliminate the need of a portable diesel one after a hurricane. Although the DLC in Fig. 14 was also equipped with a natural gas genset some new DLCs, such as the one in Figs. 5 and 13, do not have any permanent genset. The one in Fig. 13 is a particularly interesting example as the DLC is located besides Waveland's provisional locations for emergency services. One common observation from Figs. 12 and 13 is that both original DLCs were replaced by newer DLCs of smaller capacity. Additional fully new DLCs were located nearby in order to absorb the potential demand that the smaller DLCs cannot meet. Although this planning choice has a higher cost it may improve network availability by distributing potential failure points at the DLCs. Another common observation in Figs. 12 to 14 is that all DLCs, even those originally at ground level, are installed on elevated platforms. This practice was not maintained away from the most severely affected areas by Hurricane Katrina, likely due to costs and schedule constraints. In addition, although many of these platforms seem to have an adequate height, some DLCs, such as the one in Fig. 5 may still be not high enough to prevent damage from a very high storm surge.

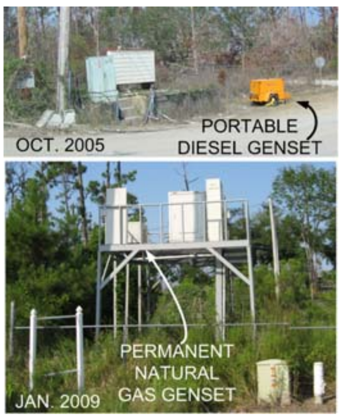

Figure 12 A DLC in Mississippi on Highway 43.

Figure 13 The same DLC site in Waveland, MS.

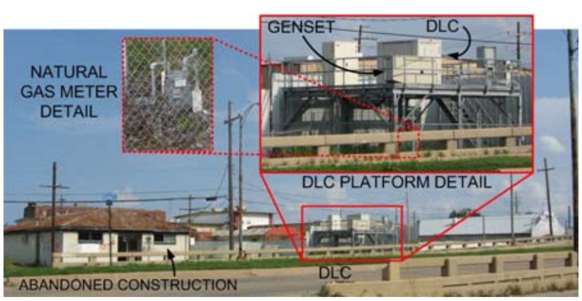

Figure 14 A DLC installed after Hurricane Katrina located in New Orleans at 2801 Franklin Av. Photo taken in Sept. 2009.

Inconsistent construction practices in terms of communication equipment platform heights are more noticeable in the case of wireless cell sites. This is one of the main issues not identified in [1] but mentioned in [2] and exemplified through the top photo in Fig. 15. Flood waters at this particular cell site reached approximately the fence height. Hence, only the base station on top of the elevated shelter escaped damage. Of course, meeting the 8-hour minimum back up time would not have prevented an outage in most base stations at this site. Although the more recent photo shows that there has been some improvement in raising all base stations in all cell sites above the flood plane, the improvement is very limited. Many other cell sites in the region, such as the one in Fig. 3 co-located at AT&T's Lake central office, still show base stations located below the flood plane. One other recommendation in [2] was to install more permanent gensets at cell sites in order to avoid multiple portable genset deployments at each location. Although there is not a significant additional number of new permanent gensets at cell sites, a noticeable percentage of the permanent gensets are now being fuelled from propane tanks. Some of them are new gensets, such as the one on

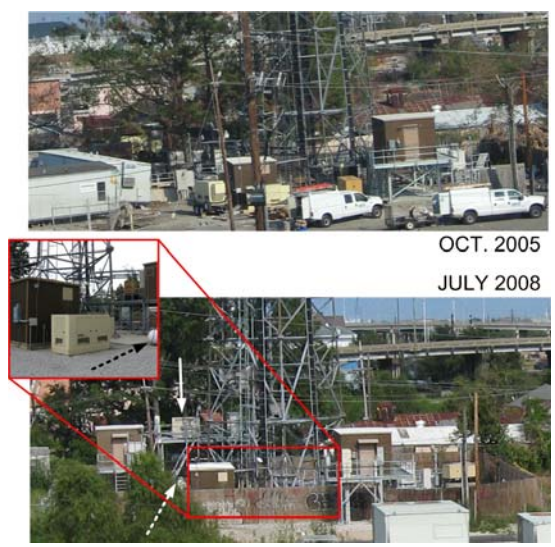

Figure 15 Cell site in New Orleans located near the east intersection between I-10 and I-610. The detail shows a permanent propane fuelled genset located at ground level. The solid arrow indicates a new base station on a platform. Dashed arrows indicate propane tanks.

the new elevated platform in Fig. 15, but others, such as the one in Fig. 16, are propane fuelled replacements of the ones existing when Katrina made landfall. A similar infrastructure solution is observed in a radio transmitter shown in Fig. 17. In it, the infrastructure was hardened and expanded, and propane fuelled gensets replaced the one damaged by Katrina. One particular concern with infrastructure elements located at ground level, such as propane tanks and natural gas meters, is that they are vulnerable to the storm surge action, as it was exemplified in [2] through the CATV UPS shown here in Fig. 18. As the figure indicates, the destroyed UPS was never replaced and only the undamaged pole mounted UPS was left in place. Still, some fire codes and local regulation prevent elevating some infrastructure elements, and, in the case of the pole-mounted UPS, it is difficult to address the issue of maintaining operation during long outages without having to rely on many portable gensets that need to be deployed to several widespread sites.

Figure 16 A closer view of the cell site in Fig. 6.

Figure 17 KQLD-FM Radio transmitter in Delacroix, LA.

Figure 18 CATV infrastructure north of Yscloskey, LA

4 Conclusions

This paper described the evolution of communication power infrastructure in the U.S. Gulf region since Hurricane Katrina. It explained that uncertain demand and network flexibility requirements led to a widespread use of DLCs, most of them located on elevated platforms. In order to maintain operation during long outages some DLCs were installed with natural gas gensets. Use of propane fuelled gensets has become more common in wireless communication cell sites. Although improvements have been made, telecom networks still have many vulnerabilities, particularly in terms of power supply. Other mostly unaddressed issues include inconsistent construction practices with many network elements still below the flood plane or at risk from storm surges.

5 Acknowledgements

Many of the photos from 2005 were also included in [2]. All the photos from 2005 were taken as part of an University of Illinois at Urbana-Champaign project funded by the U.S. National Science Foundation (NSF) under award number ECS-0554090.

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Effects of Notable Natural Disasters from 2005 to 2011 on Telecommunications Infrastructure:

Lessons from on-site Damage Assessments

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Abstract— **This paper discusses lessons from notable relatively recent disasters that had significant impact on communications infrastructure. The discussion will be based on field damage assessments and will be supported by extensive photographic evidence. In particular, the following disasters are discussed: from 2005, Hurricane Katrina; from 2008, hurricanes Gustav and Ike, from 2010 Chile's earthquake and tsunami, from 2011 New Zealand's earthquake in Christchurch, and the Great Earthquake and Tsunami in the Tohoku Region of Japan. This paper perspective focuses on basic questions addressed during field damage assessments that lead to identify potential ways for improving power supply availability during extreme events. Main failure modes are discussed, and similarities and differences observed from all these extreme events are commented. Predominant restoration strategies are also examined. Finally, this paper concludes with a summary of recommendations, including potential use of micro-grids as a powering option for communication sites in such extreme events.**

Keywords-Natural Disasters; Power Conversion; Power Availability; Hurricanes, Earthquakes; Failure Modes; Lifelines; Communications Power Plants.

I. Introduction

This paper discusses lessons from notable relatively recent disasters that had significant impact on communications infrastructure. In the past few years, several natural disasters have attracted significant public attention. Perhaps, the two most notable examples of such events are Hurricane Katrina in 2005 and the recent March 2011 M_w9.0 Great Tohoku Earthquake and Tsunami in Japan. In many of these disasters ,significant communication outages occurred. Then, understanding the reasons of these effects is important not only from the technical point of view of network operators but also from a societal view as a whole. Available communications are not only important when the disasters is happening and in its immediate aftermath. During the service restoration period after a disaster, communications are important for many other infrastructures that rely on public networks to coordinate their logistic operations. Furthermore, communication-supported services, such as the Internet, and financial and banking operations, are also important in order to support communities to recover. In the past, there has been very few works studying the effects of natural disasters on communication systems based on damage assessments. One of those is a comprehensive study of the effects of Hurricane Katrina [1]. Evidently, at the time of evaluating lessons from disasters it is important to consider which method is used in order to study the effects of such disaster and how those lessons were drawn. Any suitable method needs to be objective and, for this reason, scientific approaches are desirable. The most common of the scientific approaches is to rely on data from telecommunications network operators and/or regulatory government agencies. However, in most situations these data is incomplete and inexact because of normal confusions during such extreme events. One relatively uncommon approach in electrical engineering is to perform field damage assessments a short time after the disasters happens. Although this approach has been applied more widely in other engineering disciplines such as in Civil engineering studies of transportation infrastructure or building performance after earthquakes, performing such forensic studies after a disaster is uncommon in the electrical engineering field. This paper bases its discussion in this empirical approach of relying on field observations that is used to validate quantitative data from various sources. The discussion discusses the following events: from 2005 Hurricane Katrina; from 2008, hurricanes Gustav, and Ike; from 2010, Chile's Earthquake and Tsunami; from 2011 Christchurch, New Zealand Earthquake, and the Great Tohoku Region Japan Earthquake and Tsunami.

The discussion section following this Introduction is structured in the following way: first, the general approach for the analysis methodology is presented. Secondly, the aforementioned disasters are discussed within the context of methodology presented in the first part of Section II. This paper concludes with a summary of its main points.

II. Discussion

A. *Analysis Methodology Approach*

The analysis is based on field damage assessments. During these field reconnaissance trips data about communication network performance is collected and documented through photographic means. These data is also used to validate information obtained from network operators and government regulatory agencies. The goal is that the combination of both sources of information allow for an accurate description of the effects of the natural disaster under study. During the field damage assessment, the goal is to answer two sets of questions:

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a) What infrastructure elements failed and what did not fail? Why?

b) In the cases when the infrastructure element under observation failed and/or was damaged, how was operation restored?

Answers to these questions can be translated in ways for improving power supply availability in communication sites subject to natural hazards. Consider that availability is

$$A = \frac{MUT}{MUT + MDT} \quad (1)$$

where *MUT* is the mean-up time and *MDT* is the mean-down time. The set #1 of questions aims at learning primarily how to achieve higher *MUT*s during extreme events, whereas the set #2 of questions targets at identifying ways used to reduce the *MDT*. The next portions of this paper answer questions a y b for notable recent disasters with a focus on communication infrastructure issues. Some other sources of failure in communication networks, such as network congestion due to increase traffic, are out of the scope of this work and, thus, are not discussed here. Hence, failure modes to be explored in this paper and that are related with communications infrastructure includes:

A) Lack of permanent onsite gensets and battery exhaustion (mostly occurring in cell sites and outside plant remote terminals).

B) Permanent onsite genset failure. Some potential causes include failure to start, fuel starvation, or other causes. In this case, overheating due to cooling failure is, typically, the next fault event to occur before batteries are discharged.

C) Power plant damage but communications equipment (e.g. switch fabric) undamaged. This failure mode is typically observed when part—e.g., batteries or diesel tank—or all of the power plant placed at ground level is affected by flood waters, storm surges, or tsunamis but the water level do not reach the communication equipment placed on higher floors

D) Communications site damage—i.e., power plant and communication equipment are damaged.

E) Other failures in communications infrastructure, such as severed cables or damage to transmission links.

B. 2005: Hurricane Katrina [1]

Hurricane Katrina made landfall on the morning of August 29 as a strong Category 3 hurricane near the town of Buras, in the state of Louisiana. Although Katrina's winds were strong, its most significant damage action was its storm surge which in some points in the Mississippi Gulf Coast reached almost 30 ft. high. This storm surge destroyed nine of Bellsouth's central offices (Fig. 1); five of them were restored with DLC systems with priority circuits hosted by a neighboring undamaged CO (Fig. 2). Six other central offices lost service when the levees that protected New Orleans failed and the city flooded. Additionally, eighteen central offices lost service due to engine fuel starvation or other type of genset failures. In total, about 2.5 million conventional PSTN lines lost service, representing about half of the total lines in the north Gulf coast area. Evidently, Hurricane Katrina affected Bellsouth's (now AT&T) centralized network elements more severely than other storms. These failures in the PSTN also led to loss of service in wireless networks because the latter often rely on former for call routing. A positive development was keeping New Orleans Main CO and tandem switch operational thanks a special delivery of diesel for the genset and water for the air conditioners with an armed-guarded convoy.

Distributed network elements, such as cell sites and digital loop carrier (DLC) remote terminals (RTs) were also certainly affected, but only 34—a relatively small number—of these distributed sites were damaged. Outages at most of these sites were also caused by power issues. In part, but particularly for DLC RTs, these power issues at distributed network elements were originated by lack of a permanent power onsite genset at the site. The solution implemented to power these sites was to deploy portable gensets. Yet, as it was found during the site survey, lack of coordination among different wireless network operators led to having at several cell sites multiple portable generators, each powering a different base station (Fig. 16.b in [1]). This lack of coordination in genset deployment led to ineffective resource management that translated into additional traffic in already congested roads during the immediate aftermath, and in extra logistical requirements. Another important issue observed during the damage assessment was lack of consistent construction practices for base stations, with sites having part of the infrastructure above the flood plane and part of the infrastructure below it. This is an important observation because most of the few damaged base stations among the 3,000 in the area affected by Hurricane Katrina, were located below the flood plane, and, thus, were damaged when flood waters reached the site. Also some towers at a few cell sites collapsed, but this was an occurrence affecting only a very small percentage of all wireless networks distributed locations. In order to restore service to damaged cell sites, network operators relied heavily on cell-on-wheels (COWs) or cells-on-light trucks (COLTs).

Other failure modes identified during the damage assessment was damage to outside plant copper infrastructure, and severed transmission links. Of these damage infrastructure, flood damaged copper cables were restored by replacing them

Fig. 1. Yscloskey CO after Hurricane Katrina.

Fig. 2. The former location of Yscloskey CO after Hurricane Gustav.

by DLC systems, and severed transmission links were provisionally restored with emergency microwave links (Fig. 16.a in [1]). The damage assessment served to identify the storm surge as the most significant damaging action of Hurricane Katrina, followed by the related flooding. Hence, one of the damage assessment lessons was, wherever possible and in the area at risk of storm surge or flooding, to use pole mounted systems over ground mounted systems, because the field reconnaissance provided evidence of pole mounted systems surviving the action of Hurricane Katrina where ground located infrastructure was destroyed (Fig. 11 in [1]).

C. 2008: Hurricane Gustav

Hurricane Gustav made landfall 3 days after the third anniversary of Hurricane Katrina about 60 miles west of Katrina's point of contact with Louisiana's coast. Gustav's wind speeds where a little lower than Katrina's but still very similar [2]. The most significant difference between Gustav and Katrina was in the storm surge height. Gustav's storm surge was significant but less intense than that of Katrina and although some levees were just overtopped and a few breached, New Orleans did not flood. However, Gustav moved away from the coast much slower than Katrina originating some flooded areas and complicating restoration efforts due to persistent rain. Telephone outages affected close to 50,000 lines [3] in Louisiana with the peak occurring on September 4, 72 hours after Gustav made landfall. These data indicates that this delayed peak may have originated in power related outages in one or more central offices, because 72 hours is the typical storage time in central offices diesel tanks. Although there were no reports of such failure, damage assessments identified the central office (CO) in Fig. 3, where issues with its permanent genset are highly likely to have occurred as evidenced by a large portable genset and supplemental air conditioning system. The damage assessment was also able to identify fewer failures in fixed telephony outside plant distributed network elements than with Katrina. The reason for these fewer failures was that many DLC RTs were equipped with permanent natural gas gensets (Fig. 4). The damage assessment also identified that since Hurricane Katrina many of the DLC RTs located in areas vulnerable to storm surge and flooding had been placed on top of platforms (Fig. 5), thus, reducing the number of DLC RTs suffering direct damage from the storm. Avoiding such damage reduced the MDT even when in some of these sites, particularly those in the Mississippi River Delta where access is difficult and there is no natural gas distribution service, outages caused by lack of power occurred. Nevertheless, extensive deployment of portable generators prevented extensive outages in many other DLC RTs and wireless base stations not equipped with permanent gensets. However, power issues severely affected service of digital telephony provided by CATV operators, leading to ad-hoc solutions, such as the one in Fig. 8 in [2].

D. 2008: Hurricane Ike

Hurricane Ike made landfall in Galveston Island, in the northeast Texas coast on September 13th. Although Ike was not an extremely intense hurricane in terms of wind speed, its storm surge was comparable to Katrina's reaching 20 ft at some points of the Bolivar Peninsula [4] versus maximum heights of 28 ft produced by Katrina in Mississippi [5]. Although the outages caused by Ike on communication networks were not as extensive as Katrina's they were nevertheless significant. The fixed telephony outages peaked at close to 340,000 [6]. AT&T lost service in 5 central offices with one of them, Sherwood (Fig. 1 in [2]), been destroyed. Although the damage assessment allowed to identify Sherwood CO's failure mode as communication site damage due to storm surge waters—all the equipment at the site was located no more than a meter above ground level—the failure mode of the other central offices was not completely clear. Although water marks in Fig. 6 suggests that Port Bolivar's CO may have been affected similarly than Sherwood CO by storm surge waters, it was possible to observe during the damage assessment that the onsite genset was operating. Moreover, unlike Sherwood CO where it was possible to observe "switch-on-wheels" (Fig. 7) used to restore service at the site, no equipment that could be used to potentially restore service was found outside Port Bolivar CO. The most likely failure mode in the other sites was a power related issue; perhaps diesel genset engine fuel starvation. These other central offices were likely small remote switches, like the one in Fig. 8 near Crystal Beach, which did

Fig. 3. A large portable generator outside Goodwood central office in Baton Rouge, Louisiana, less than a week after Hurricane Gustav.

Fig. 4. A DLC RT with a natural gas genset located outside St. Bernard CO destroyed by Hurricane Katrina.

Fig. 5. A new DLC RT with a permanent genset installed on a platform after Hurricane Katrina next to another DLC RT installed on the ground before Hurricane Katrina.

not show any sign of damage observable during the field reconnaissance. Another possible cause of failure was isolation due to a severed transmission link, as suggested by the emergency microwave transmission system in Fig. 4 in [2] and seen on the background in Fig. 8.

Power issues were one of the most important causes of outages affecting distributed network elements. In the area affected by Ike, AT&T lost service in 551 digital loop carrier (DLC) remote terminals (RTs) due to lack of power [6] but fewer than 3 % of all the DLC RTs were destroyed, like those in Figs. 2 and 3 in [2]. Some of these DLC RTs were damaged even when they were placed on platforms due to the significant storm surge height. A notable example of such occurrence can be found in the DLC RT in Fig. 10 in [2] used to restore service after Hurricane Rita destroyed Sabine Pass CO in 2005. Verizon outside plant infrastructure was affected in a similar way, with 321 RT affected, mostly from lack of power. Windstream lost service in 7 switching stations and 237 remote terminals due to lack of power [6]. More power originated outages were reported by Eastex, which lost service in 2 central offices due to failed gensets, and in 82 DLCs due to lack of power [6]. Although the effects of Hurricane Ike on Cameron Communications infrastructure are not known in detail, the damage assessment was able to identify some sites where damage likely occurred, such as the one in Fig. 5 in [2]. Damage to some of Cameron Communications DLC RTs may have been avoided by placing them on platforms (Fig. 10.a in [2]). Time Warner Cable had almost three-quarters of its network affected by lack of power [6], too. Service to DLC RTs affected by power outages was restored by deploying portable gensets (Fig. 6 in [7]), whereas service to some damage DLC RTs were restored with new cabinets on pallets (Fig. 8.b in [7]) or on wheels (Fig. 8.a in [7]). Although some cell sites were destroyed (Fig. 6 in [2]) or base station equipment were damaged, most of the loss of service in wireless networks was caused by lack of power in distributed network elements, particularly in sites without permanent gensets. Like with Katrina, cells on light trucks (COLTs) and cell on wheels (COWs) were extensively used to restore service to damaged cell sites (Fig. 7 in [2]).

E. 2010: M_w8.8 Maule Region, Chile Earthquake and Tsunami

On February 27 the southern coast of Chile was shaken by a strong earthquake with epicenter located offshore about 105 km North-Northeast of Concepcion. Its offshore location caused an important tsunami that affected several hundred kilometers of the Chilean coast causing infrastructure damage. However, the most intense tsunami damage was confined to relatively small areas. Besides network congestion, the most significant cause of outage in Chile was lack of power, primarily in distributed network elements—wireless cell sites and outside plant DLC RTs—which in most cases were not equipped with permanent onsite generators. For example, one network operator had only a small percentage of its 1,000 cell sites and none of its 200 DLC RTs equipped with permanent gensets. Due to the difficulties in procuring portable gensets, network operators used the few portable gensets they already owned before the earthquake struck plus a few more they were able to add from different sources afterwards in order to restore

Fig. 6. Port Bolivar CO.

Fig. 7. Emergency mobile switches outside Sherwood CO after Hurricane Ike.

Fig. 8. A small switch facility near Crystal Beach after Hurricane Ike.

service to their main sites. Once power from the grid was restored to these sites, portable gensets were redeployed to other sites that did not receive gensets due to their lower importance. Nevertheless, service in some cell sites was only restored more than a week after the earthquake, when electricity from the power grid was once again available.

Another cause of failures in wireless cell sites—most of them located indoor, in shelters—was damage caused by the intense shacking due to improper anchoring of batteries, bended equipment frames, or some other type of vibration damage, such as the cell site in Fig. 9.a. Like in other disasters, service to damaged cell sites was restored with COWs, such as the one in Fig. 9.b. The damage assessment was also able to identify many sites where loss of service was caused by fallen or misaligned antennas. For one network operator about 50 % of its sites experienced this type of problems. Yet, cell tower damage was minor with only 2 of the towers of a major network operator collapsing. In one of these cases the failure was initiated by a fallen concrete water tank. The damage assessment was able to document a few cell sites where nearby walls collapsed on the base stations but none of these cases seemed to have led to site outages, corroborating information from network operators not including this failure mode as a cause for service interruptions. Nevertheless, some base

Fig. 9. a) Right: A damaged base station in Curico and b) Left: the COW likely used to restore service in its area. Notice the satellite link in the COW.

stations located on building rooftops needed to be relocated because of the severe damage suffered by the building where they were installed.

The damage assessment identified that infrastructure affected by fallen surrounding constructions was a cause of failure in conventional wireline telephony, especially with drops pulled down by fallen facades. However, many outages were avoided thanks to the use of concrete poles that withstand forces by fallen walls better than wooden poles used in many other countries. Still, lack of power was a failure mode that led to 150,000 wireline subscribers' loosing service; particularly in small remote switches with fewer than 5,000 subscribers because these sites did not have permanent generators. At least 3 larger COs lost service due to collapse walls or damage caused by tsunami waters. A few others sustained damaged, but this damage was not significant enough to prevent operation. At least another CO lost service due to high temperatures caused by air conditioner stopping to operate because the genset at this site failed, as verified by the provisional portable genset found during the damage assessment.

F. 2011: Feb. 22, Christchurch, New Zealand, Earthquake.

On February 22, 2011, Christchurch, New Zealand, was struck by a M_w 6.1 earthquake. Although the earthquake's moment magnitude may not seem as significant as other recent earthquakes, the shallow location of the hypocenter (5 km), soil and terrain characteristics, and the close location to the city, produced significant soil liquefaction areas and one of the most intense sackings ever recorded which in some points reached twice the acceleration of gravity. The earthquake occurred less than 6 months after another earthquake with a M_w of 7.1 affected the same area although with less significant effects. Despite the significant shacking and soil liquefaction observed in the Feb. 22 earthquake, besides network congestions, the most important communication networks failure mode for this disaster was lack of power affecting distributed network elements, particularly wireless communications base stations. Power outages originated in soil liquefaction caused extensive damage to buried cables of power utilities. In wireless networks these power problems were aggravated by extensive use of micro and mini-cells (Fig. 10) which are very rarely equipped with permanent gensets. Although the damage assessment allowed establishing that the area affected by the earthquake was small, the network architectures relying on many low capacity microcells implied both logistical issues and the impossibility of deploying portable gensets to all these sites. In order to prevent outages, important sites were originally designed with extended battery reserve time of up to 24 hours and at least 20 % of the base stations of each network operator received portable gensets immediately after the earthquake occurred. Yet, another potential problem of extensive use of microcells is that their outdoor cabinets are only generally cooled through heat exchangers leading, to more demanding environmental conditions that may affect battery lives and reduce their reserve time. Since the damage assessment was able to verify that outdoor cabinets are only cooled with heat exchangers (Fig. 10), reduced battery backup times is a possibility that may or may not be ruled out to have occurred in the aftermath of this earthquake, as it has been previously commented in earlier disasters, such as in [8]. Power outages not only affected distributed network elements of wireless communication networks but also of the public switched telephony network (PSTN). These PSTN distributed network elements were fiber to the node (FTTN) broadband cabinets. However, restoring power to these sites with portable gensets was in most cases not a primary concern because these cabinets provided data services to customers' computers that cannot operate without power.

Although shacking in this earthquake was extreme, important damage to infrastructure was limited to buried copper cables in areas where significant soil liquefaction occurred. Damage to base stations was very limited with less than a handful of them destroyed by nearby falling buildings or rocks, or because the building where they were located collapsed. Another small number of cell sites had leaning masts but no tower was found to have collapsed. Service to damaged cell sites was restored with COWs. A few COWs were also located at key sites, such as the Civil Defense Headquarters, in order to expand network capacity or to compensate lack of coverage from nearby cells that could not be accessed because, although they were not damaged, they were located on top of buildings at risk of collapse or were located inside the cordoned-out and powerless area of the Central Business District (CBD). Entrance and moving limitations in the CBD also affected operations in a key PSTN central office, which, although it was not damaged, its operation was limited by lack of power and water for its chillers. Although the damage assessment was able to establish some damage to COs, this damage was not critical. Power outages also affected COs, yet, the presence of onsite permanent diesel gensets.

Fig. 10. A minicell base station cabinet showing the door heat exchanger.

G. 2011: Mw 9.0 Great Tohoku Region, Japan, Earthquake and Tsunami.

On March 11, a powerful earthquake struck about 120 km off Japan's Sanriku coast—this is Honshu's island northeastern coast, i.e. the eastern coast of the Tohoku region. Although shacking in most inland areas was not extremely intense, the earthquake location at a subduction zone offshore generated a massive tsunami that affected many coastal towns. In many of these cities, tsunami waves reaching in some places almost 40 m high, overtopped and destroyed seawalls protecting cities and towns. This huge tsunami led to destruction of towns and infrastructure along a several hundred km long stretch of coast. Fires that broke up in several coastal towns due to tsunami-induced damage, added to the destruction. Moreover, the tsunami damaged backup generators at the Fukushima Daiichi Nuclear Power Plant (FDNPP) which were essential to cool nuclear fuel rods when the power grid feed at the site failed. Without cooling, nuclear fuel overheating led to at least partial meltdown in three of the six reactors at the site and explosions at 3 and likely 4 of the reactors, leading to substantial radiation release to the atmosphere and the ocean. As a result of this nuclear accident, the Japanese government declared a 30 km evacuation zone around the FDNPP, of which, the 20 km inner area was eventually completed vacated of residents. In addition to having the FDNPP going offline during this accident, several other nuclear power plants in the area were stopped during the earthquake. Furthermore, some conventional coal-fired power plants were also damaged due to the tsunami. All this significant generation capacity brought offline by the earthquake and tsunami created peak power generation issues that will continue to impact communication networks for months and even years to come. In the immediate aftermath of the disaster, extensive power outages caused by damaged power infrastructure due to shacking (inland) and the tsunami (coast) created significant problems not only to communication sites but also to logistic operations when gasoline stations ceased to operate due to lack of power. Lack of refueling sites added to damaged roads to cause significantly difficult logistical problems that in some areas persisted for up to 3-weeks. Yet, even after roads were repaired and power was restored to gas stations, significant traffic increase in the entire eastern half of the Tohoku region led to road transportation delays up to double the normal time.

Earthquake and tsunami impact on all communication networks in the affected area was significant. However, since NTT occupies a highly dominant market position in both the fixed and wireless communication markets, most of the description that follows next applies to NTT. Maintaining communication services during earthquakes is extremely important in Japan, not only because of well known reasons mentioned in Section I, but also because Japan has implemented an earthquake warning system that gives people a few life-saving seconds notice of a soon to happened earthquake. After an earthquake, maintaining service operation is important in order to send warning messages when strong aftershocks happen. In total, almost 1.5 million PSTN lines lost service during this disaster with the peak outage occurring on March 13th. By March 28th 90 % of these outage lines were restored. Initially, approximately 1,000 of NTT's 1,800 buildings in the region were affected in different ways by the earthquake; most of them affected by power outages. Initial issues affecting most of these approximately 1,000 buildings were soon addressed. However, on March 28th 55 buildings were still presenting issues. Sixteen of these 55 buildings were having minor damage, but the site was not under normal operation due to damage to the power plant but not to the switch fabric, or due to some other unknown reason. Two of these sites with potential power plant issues identified during the damage assessment include the COs at Miyako (Fig. 11) and at Ofunato (Fig. 12). Presence of mobile gensets despite the fact that the site has a permanent genset seem to indicate that the most likely failure mode at Ofunato was failure mode C, although some communication equipment was also affected. Having this failure mode in earthquake and tsunami areas is not uncommon because heavy batteries loading force building designers to place the power plant at low levels in the building in order to prevent structural issues. In Miyako the most likely failure mode was A. Service restoration at these sites involved deploying mobile generators, such as those described in [9] and shown in Figs. 11 and 12. In these cases, transportation infrastructure performance played an important role because of the need for rapid deployment of mobile gensets before batteries are discharged. In other sites, like in Otsuchi, or Yamada (Fig. 13), power was restored with more conventional portable gensets. In both of these sites, the field reconnaissance was able to identify good building construction practices because of the reduced damage received by the switching equipment despite the extreme damage observed around the COs. The damage assessment also documented the presence of water tight doors in the CO of Kamaishi (Fig. 14.a). These doors likely prevented further damage and reduced the MDT at this site, yet power issues, such as those in Miyako may have still occurred in this site. Likewise, watertight doors may not seem to have completely prevented damage to the power plant and communication equipment at Ofunato (Fig. 12). A potential way of further reducing buildings vulnerabilities to tsunamis is to extend water tight closings to windows or to eliminate completely all windows at COs. Still, the cable entrance facility (Fig. 14.b) may be a vulnerable point for water to flood a site. Another vulnerability when implementing this approach is the presence of conventional commercial offices at ground level, that would difficult sealing the building completely to external water actions. Although most of these 16 buildings are located in coastal areas affected by the tsunami, 5 of them are located a few kilometers inland, northwest of the severely affected town of Ofunato and the completely destroyed town of Rikuzentakata. In these 5 COs the failure mode is not clear because they were not directly affected by the tsunami. However, their most likely failure cause was power related. In general, power-related issues was an important failure mode as evidenced by the fact that the initial number of failed lines was a third of those observed at the peak which occurred between 24 and 48 hours later. This is an expected outcome because, as described in [9], many of the low capacity sites do not have permanent gensets and rely on deployment of mobile or portable gensets before batteries are discharged in order to avoid loosing service.

Although power issues were an important source of outages in the PSTN, direct damage caused by the tsunami also contributed to many line failures. Of the 55 buildings with

Fig. 11. Miyako CO powered by a mobile generator.

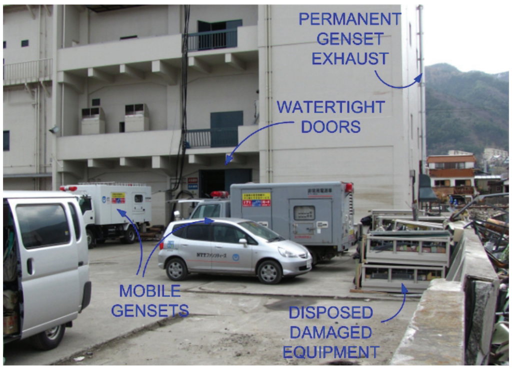

Fig. 12.Ofunato CO powered by mobile and portable gensets.

Fig. 13. Yamada CO powered by portable gnsets.

issues on March 28th, 26 of them had been destroyed by the tsunami or all of their equipment had been rendered useless by the tsunami. In some of these sites, including Onagawa (Fig. 15), Rikuzentakata (Fig. 16), and Shizugawa, the COs are one of the few remaining standing buildings in the town, which suggest an adequate CO building performance considering the tremendous magnitude of the tsunami—notice that the CO building in Onagawa has the remains of a home on its roof. Such adequate performance will certainly contribute to reduce the MDT. Service restoration in the areas served by some of these COs, such as Onagawa, were similar to those implemented after Hurricane Katrina, i.e., use DLC systems to provide circuits to government facilities and emergency response sites. In other sites, such as in Rikuzentakata, service was partially restored by hosting most of its switching services in a neighboring undamaged CO.

Other failure modes for PSTN COs include isolation due to severed transmission links. These links were interrupted when fiber optic links were damaged by the tsunami, usually by destroying bridges where the fiber optic cable had been installed. Of the originally 90 fiber optic links damaged, on

Fig. 14. a) Left: A water tight door in Kamaishi CO. b) Right: Cable entrance facility in Nobiru CO (as seen from the top).

Fig. 15. Onagawa CO with a house on its roof.

Fig. 16. Rikuzentakata.

March 28th there were still 4 COs with this problem. Service restoration involved repairing these fiber optic links. Of course, another source of PSTN failure was extensive damage to the outside plant in areas affected by the tsunami. Finally, of the 55 buildings still experiencing issues on March 28th, 9 of them were located in the forced evacuation area around the FDNPP where access was prohibited due to health issues associated to radiation exposure.

Wireless communication networks were also severely affected by the disaster. Although an appreciable number of base stations were destroyed by the tsunami, since most base stations lack a permanent genset, grid power outages were the origin of most base station failures. Once again, lack of power as a main cause of outages can be verified by the fact that on March 11th, 2,200 base stations were down, whereas 24 hours later, out of service base stations peaked at 6,720. Power issues affecting base stations could be examined based the on significant reduced network coverage inland, where the effects of the tsunami were not felt and where shacking was relatively minor. For example, on March 13th, NTT DOCOMO network coverage in Iwate prefecture was 50 % of normal levels inland and there was no network coverage on the coast. The same day, network coverage in Miyagi prefecture was almost non-existent except for the city of Sendai which was mostly covered. In Fukushima Prefecture and on this same day, network coverage on the coast was 0 %, and was about 10 % in the eastern half of the prefecture terrain, and 100% of nominal levels on the western half of the inland area. By March 22nd, service at all but 788 base stations had been restored either because grid power was once again available at the site or because a portable genset had been deployed to restore power. By March 28th, 307 base station had its service disrupted. Of them, 224 had issues with severed transmission links, 62 had been destroyed by the tsunami and 21 still needed to be inspected. By late April 59 base stations were still experiencing outages. It is also important to point out that 68 service affected base stations in the area around the FDNPP need to be added to the figures of March 22nd, March 28th and late April. Of the damaged base stations, the field reconnaissance documented cases of collapsed towers (Fig. 17), destroyed base stations after having been hit or carried away by the tsunami and debris (Fig. 18), and/or fires (Fig. 19). Notice in all these cases the vulnerable location of base stations at ground level. By finding collocated wireless network switching equipment and PSTN equipment, the damage assessment was also able to identify that another problem that affected wireless networks operation, particularly during the first days, was outages affecting PSTN exchanges. Service restoration to damaged base station involved some limited use of COWs (Fig. 20.b) , micro-cells (Fig. 20.b), equipment repair, or shifted coverage to neighboring cell sites with increased capacity and that were undamaged by the tsunami because they were on hill tops. Severed links were restored through repairing them or by installing temporary microwave links (Fig. 21) or satellite links (Fig. 20.b). Up to 870 satellite phone terminals were also used to restore wireless services in some key locations. Satellite phones were also used to support utilities restoration efforts in the aforementioned disasters, although in the case of Hurricane Katrina, their use was affected for a period of a few days when an intense solar storm interrupted satellite communications.

One final note of relevance is to mention the satisfactory performance of the microgrid site in Sendai that was presented in INTELEC in earlier years [10]. Thanks to the reinforced design of the natural gas feed for the generators and the agreement in place with the natural gas distribution company, natural gas to the microgrid was not interrupted, even when the rest of the city had its natural gas service stopped for several days. Although the generators went offline for a few hours onsite batteries kept the load at the high-power quality circuits powered. After the issue with the generators was addressed, they remained powering the high-power quality levels loads continuously. As expected, power to the standard-quality levels loads was off until power from the grid was restored.

III. Additional observations and recommendations

Consider once again the set of questions that are the target of the damage assessment studies and that were introduced in Section II.A. The set of questions #1 refer mostly to design and operational issues. For both failure modes A and B, one alternative approach is to utilize novel communication power plants based on micro-grids [11], such as the one tested by NTT in the city of Sendai. One of the advantages of micro-grids is enabling a more reliable power supply through functional diversity [11]. Moreover, they allow integration of renewable sources such as photovoltaics which do not depend on lifelines. As such, micro-grids become true sustainable power systems in the sense that they sustain operation amid extreme conditions. Furthermore, use of combined heat and power generation address issues due to air conditioners low power supply availability [12]. Other design approaches imply the use of extended local energy storage through fuel cells (Fig. 22) or alternative local power standby systems [7]. The set of questions #2 allow to address the aforementioned failure modes, too. In this case, in addition to design and operation issues, the MDT is also related with maintenance policies and logistical operations. For example, as already discussed, failure modes A and B are typically addressed through the deployment of portable generators. Failure mode C can be addressed by deploying mobile power plants. Unfortunately, in some severe events, Failure Mode D is inevitable (Figs. 15). In these cases, some of the discussed solutions include deploying digital loop carrier systems (Fig. 4) or containerized solutions (Fig. 23) or switch-on-wheels to restore a damaged central office (Fig. 7), or cell-on-wheels to restore service to damaged base stations (Figs. 20.a).

In all these recent disasters it was possible to find one or more COs that loose service. This outcome seems to exceed the effects of disasters of a decade or more ago. The question that remains to be answered is whether this difference is caused by new observations enabled by the damage assessments, or whether the failures of COs in recent disasters are originated in new communication technologies that make COs more vulnerable to natural disasters. Similar questions can be raised regarding entire networks. Have new technologies made them more vulnerable? One of such newer technological approaches already discussed in [7] is the increased use of locally powered distributed network elements, such as DLC RTs. For these network elements, wherever possible it is advisable to use central power from the CO using a split phase ±190V power distribution system using existing copper infrastructure. In some other few cases, use of renewable energy sources may reduce logistical needs even when it may not be possible to power the entire load. However, as pointed out in [7], it is still difficult to find a general solution for all cases.

IV. Conclusions

This paper has shown the value of conducting damage assessments after natural disasters as an extreme empirical approach to support learning about communication infrastructure availability, both in normal conditions and during extreme events. The damage assessments attempt to answer two set of questions through field collected data and information. The discussion is supported by describing relevant observations gathered from damage assessments conducted after recent disasters around the world. Common failure modes and practices both to reduce the mean down time and to increase the mean up time are discussed with the end goal of improving communications availability.

Fig. 17. A destroyed cell site near Rikuzentata.

Fig. 18. A destroyed cell site in Ishinomaki.

Fig. 19 A destroyed cell site by the tsunami and fire in Yamada.

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Fig. 20. a) Right: A COW in the town of Osawa. B) Left: A micro-cell used to restore service to the cell site in Fig. 17.

Fig. 21. An Emergency microwave transmission site in Otsuchi.

Fig. 22. A back up fuel cell for a base station in New Orleans.

Fig. 23. Shelters with switching equipment used to restore service to Shichigahama CO. Its original building was displaced 500 m by the tsunami.

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Field Damage Assessments as a Design Tool for Information and Communications Technology Systems that are Resilient to Natural Disasters

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ABSTRACT

This paper discusses how to perform field damage assessments after natural disasters as a systematic design tool to achieve information and communications technology (ICT) systems that are more resilient to natural disasters. Hence, damage assessments are analogous to performing forensic analysis, such as autopsies, in biological sciences. Yet, for ICT system designs, practical studies based on damage assessments have been used with a limited scope, and mostly oriented towards earthquakes only. The ultimate goal of the damage assessments is, hence, to build a permanent record of data and information that allows answering the two basic questions that are the focus of such forensic analysis: what failed and what did not fail, and how was service restored in the cases when ICT systems failed. Other alternative approaches more commonly used to attempt to answer these questions, such as inquiries, computer based modeling and simulation, or pure theoretical analysis, has been shown to yield limited and sometimes erroneous outcomes. This paper shows that damage assessments can provide valuable insights not generally gained through these other approaches. In doing so, this paper discusses planning and procedures involved in performing an effective damage assessment. Some of the discussed factors that influence damage assessment planning include geographic layout, meteorological or geophysical conditions of the disasters under study and ICT networks characteristics, both technically (hardware and software) and in terms of management (logistics, operations, maintenance, etc.). Since failures in ICT facilities may be originated in supplying infrastructures, evaluation and description of both types of interdependencies, physical and functional, are also explained. A practical example based on the March 2011 Japan's earthquake and tsunami is provided.

Categories and Subject Descriptors

B.0 [**Hardware**] General

General Terms

Management, Measurement, Documentation, Performance, Design, Reliability, Security, Standardization, Verification.

Keywords

Damage assessment, natural disasters, information and communication technology systems.

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1. INTRODUCTION

This paper describes how to do a systematic study of information and communications technology (ICT) systems performance during natural disasters in order to identify ways to make these systems more resilient to extreme events. The specific approach to conduct such studies discussed in here is field damage assessments. These damage assessments play an analogous role to autopsies as part of forensic studies and, hence, the discussion extends some practices used in biological sciences into engineering approaches for ICT network infrastructures and, in particular, their performance during natural disasters.

In the past few years, several natural disasters have attracted significant public attention. There are a few reasons for this increased attention, but one of those is that natural disasters show people that despite all the technological advances in the past century, Nature can still expose how fragile human societies are. These disasters also showed how dependent modern societies are to built infrastructures, particularly power grids and communication networks, and how vulnerable societies are to the effects that extreme events have on such infrastructures. This realization of such vulnerability has driven increased support for research for understanding the impact of natural disasters on critical infrastructures. Natural disasters may, then, be considered as extreme tests for such infrastructures that may allow detecting weaknesses that may not be identified through more conventional studies because of the inherent complex structure of these infrastructures and their interactions.

However, despite this increased interest in understanding the effects that natural disasters have on critical infrastructures and, in particular, ICT systems, have only lead to systematic studies in structure engineering for earthquakes [1]. Analysis of the effects of natural disasters on ICT systems have mostly followed non-systematic anecdotal approaches both through public inquires conducted by regulatory agencies or other government offices [2], or through news releases from ICT network operators [3]. That is, analysis of the effects of natural disasters on ICT infrastructure is at a similar stage than first forensic studies when investigators relied on witness accounts. In the ICT area, a more systematic approach also based on forensic science has been followed regarding analysis of software failures, cybercrime and security issues. A systematic approach to perform such studies has been outline in [4]. However, the focus is on data analysis and not on infrastructure issues. Hence, the goal of this paper is to extend the concepts detailed of [4] into performing systematic studies of ICT infrastructure performance during natural disasters. The core of the described approach is to perform field damage assessments that may or may not be complemented by information and data obtained from ICT network operators or other sources. Therefore, the proposed analysis approach implies that field damage assessments play a role in understanding the effects of natural disasters on ICT infrastructure analogous to the role that modern forensic pathology has in criminal sciences. The ultimate goal of understanding the effects of natural disasters on ICT networks infrastructure through a systematic approach is to gain formal knowledge of failure modes and system performance that will serve as the basis for network deployment best practices and for ICT system components design and operation.

This paper is organized in the following way: Section 2 discusses the proposed systematic forensic study of the effects of natural disasters on ICT systems by describing all its fundamental parts. Next, Section 3 presents a case study of a damage assessment performed by the author after the March 2011 earthquake and tsunami is presented as an example for the proposed approach. Finally, this paper concludes with a summary of the main discussed topics.

2. DAMAGE ASSESSMENT PROCESS

Damage assessments are conducted after a disaster affects a given area. In terms of evaluating the performance of ICT network infrastructures the questions that the damage assessment attempts to answer are:

a) What failed and what did not fail? Why?

b) In the cases when a given infrastructure element under study failed and/or was damaged, how was operation restored?

The set of questions (a) are analogous to the question of what tissue or organs show injuries or damage and how those injuries may have been done that are the core of forensic pathologies analyses. Evidently, since humans cannot be revived, question (b) is only relevant within the context of the study of ICT infrastructures discussed here.

In order to answer these questions, a systematic approach based on an established process need to be followed. The existence of a systematic approach with an established process is the fundamental difference between the proposed approach here based on field damage assessments and the most commonly approach based on anecdotes [3] or public statements that are part of an inquiry [2]. The information collected from the field though damage assessments are then fundamental empirical data that supports a scientifically based objective analysis framework. Such a systematic approach yields fundamental knowledge that can be used as part of an objective engineering design process or as part of the development of operations practices. By being objective, it also help to minimize issues found with other approaches that do not follow an objective scientific approach as it happened for example with the analysis performed by the Federal Communications Commission (FCC) about Hurricane Katrina [2] and the mandate that the FCC issued based on such study [5] [6].

Part of the existence of a systematic approach to study the effects of natural disasters on ICT networks is based on the fact that the damage assessment is performed within an established process. This process has a few steps and requirements. The steps are derived from those detailed in [4]. These steps are:

1) Data Collection
2) Data Examination
3) Analysis
4) Reporting

Evidently, such a damage assessment needs to be conducted by an independent party. Hence, although information from ICT network operators and from regulatory agencies could still be included as part of the study, only experienced people independent of these interested parties should perform the damage assessment. There are several reasons for this requirement but the obvious one is that only studies performed by independent parties can ensure its objectivity. Another reason is that interested parties, such as ICT network operators and regulatory agencies, have typically other priorities, such as service restoration, than collecting data. It is also not uncommon that during crisis operations marked by stressful and hectic activities environment that conflictive or erroneous reports can be inadvertently issued. More importantly, interested parties have rarely an established protocol to secure all information and data, such as the one publicly demonstrated during the Space Shuttle Columbia disaster [7], during natural disasters because operations during such events are exempt of those requirements based on the notion of operating under an act of god which frees interested parties of liabilities derived from such event. Although studies performed by independent parties avoid these issues, they may find the difficulty of not knowing important details of the network under studies. For this reason, it is very important that the professionals conducting the study have sufficient experience in planning and operating ICT networks and interdependent infrastructures so they can identify and interpret relevant data to collect. This section discusses next the four steps of the damage assessment process.

2.1 Data Collection

The data collection step can be separated in two phases: the preparation and planning phase and the execution phase.

2.1.1 Preparation and Planning

The preparation and planning phase begins when a disaster occurs or in the cases when it is possible to forecast the disaster in advance, such as hurricanes, when there is enough information for anticipating the approximate area and time when such a disaster will occur. As a general rule, the longer the time spent in this phase, the most effective time will be used in the execution phase and the safer the damage assessment trip will be. The final outcome for this preparation phase is a plan that lists activities and locations to visit each day with details about specific things to look at each location—e.g. through a checklist. In addition the plan should list logistical details and the intended schedule. Hence, two key decisions to be made as part of this phase are to organize the damage assessment trip logistics and determine its schedule. Another important task to be completed during this phase is to identify data sources and, if possible, start collecting information. For example, in case of hurricanes when it is possible to anticipate a few days in advance where and when they will strike a coastal area, data collection may begin early. Typically data collected at this early stage before the disaster strikes or in its immediate aftermath include outage information from various sources but, in particular, from ICT network operators and electric utilities. The latter data can be sometimes obtained from Internet sites displaying live actual outage data. Electric outage data is usually an important piece of information at the time of analyzing the data (step 3) because of the interdependencies between ICT sites and their necessary power supply. In addition, both electric and ICT sites outage data serve as one of the factors that will influence the selection of the areas to be surveyed in order to answer both questions (a) and (b) indicated above. During this phase, data is collected from all possible sources. The goal is to record all data, both the one identified at the time to relevant and useful and the one which at the time is not seen to be important. The general notion that drives this data collection process is that it is common that during disasters information is changed quite often without leaving old data publicly available. Hence, regular and often recordings contribute to save all of this volatile data which may become eventually useful for the analysis step.

The schedule of the damage assessment tends to be one of the most difficult decisions of the process because of the number of factors affecting it. The same factors listed in [4]—information value, data volatility, and effort—are also important in the planning phase of the proposed approach in order to prioritize the sites to visit in the damage assessment. Preliminary outage and damage information collected during the preparation phase serve to provide some good approximation about the value, volatility and effort associated with each piece of information that could be collected when visiting a given site. When planning the order of the site visits, it is desired to plan to visit the least damaged areas first in order to document any potential damage before it is repaired. However, a damage assessment that is performed too soon may find difficulties in order to obtain information from the most heavily damaged areas. Hence, other important factors influencing damage assessment scheduling include availability of information—e.g. closed areas during rescue operations—and safety limitations—e.g. after the earthquake and tsunami in 2011 in Japan, a large region between 19 and 50 miles around the Fukushima Daiichi nuclear power plant where the nuclear accident and nuclear radiation leak had occurred was open to travel but it was a region that according to the US government was not advisable to be visited due to safety concerns. Evidently, other factors that influence damage assessments scheduling decisions include geographic, ICT networks and disaster characteristics. For example, in the same way that anatomic characteristics may influence the order in which different organs are examined during an autopsy, geographic characteristics of the disaster zone influences scheduling decisions. Finally, a well designed plan should always allow for buffer times that can be used to address unexpected circumstances or to study a site with more detailed than previously expected or to examine locations not previously considered as part of the plan. That is, contingencies should also be considered within the plan.

A general rule of thumb is that for very intense disasters the damage assessment needs to be conducted between 3 and 6 weeks after the disaster occurred. The lower end of 3 weeks considers the time necessary to conclude rescue operations and have most of the disaster area open. The higher end of this period considers the time that it typically takes to observe ICT networks restoration activities in process but still conserving the chances of identifying most damaged infrastructure components. Evidently, for less intense disasters the damage assessments need to be conducted earlier. For example, for tropical storms and Category 1 hurricanes, it is desired to conduct the damage assessment within the first week when the disaster struck. Damage assessments duration also depends on the intensity of the disaster and the extent of the damaged area but it can be expected that a reconnaissance trip may last between a day for the less intense disaster to 10 days to the most intense and most extended disasters.

One of the fundamental aspects that influence the successful outcome of a damage assessment is the logistics involved with the execution of the field trip. Once the schedule of the damage assessment has been determined, it is possible to plan the routes for each day of the trip. Part of the factors affecting planning the routes for each day that are added to those listed in the previous paragraph include sunrise and sunset times—without proper illumination it is not possible to document damage and without photographic or video evidence, a piece of information may become part of a witness accounts that may no meet well the intended systematic approach of the proposed study method. Evidently, another important factor to consider is known road damages or delays caused by non-operating traffic lights. One general principle of the damage assessment planning is that anyone performing the study must not interfere with authorities—specially those performing rescue operations—and needs to be as much self sufficient as possible in order to minimize the use of resources of the people affected by the disaster. That is, anyone participating in a damage assessment should plan to carry its own sufficient rations of food and water. Selection of the right places where to stay is another important decision of the planning process. In order to make the best use of time it is desirable to stay as close to the disaster area as possible. However, lodging places near or on the disaster area may lack some services, such as electricity, or they may be occupied by utilities crews that came into the disaster area from other regions. In some cases evacuees may also stay as such convenient places. Even if none of these situations occur, other important services, particularly operating gas stations, may invalidate lodging places near the disaster area. For this reason an important desirable characteristic of any lodging place is to have good communication links. Many times a location somewhat distant from the disaster area may still be convenient if there are various fast and direct ways to access the zone affected by the extreme event. Of course, this discussion implicitly implies that a damage assessment planning process should identify operating gas stations in key locations. Finally, logistic planning should also consider all the equipment necessary to document the damage assessment findings and to support the field trip activities. Commonly used important equipment include GPS receivers for navigation and trip route logging, cameras, safety gear and clothes—e.g. reflecting vest, masks, hard hat, and steel toe boots— a notebook, enough batteries for electronic equipment and a car inverter. Other desirable items include a gasoline container to provide extended autonomy in cases where most gas stations are expected to be closed, and if possible an extra spare tire. In general, the person performing the damage assessment should not rely in plastic money means. The primary payment method should always be anticipated to be in cash.

As it can be interpreted from this discussion, preparing the damage assessment plan and completing the related tasks of organizing the damage assessment logistics, determining its schedule and identifying data sources involve the need of great amount of reliable information. The best of such source of information is local contacts. Evidently, interactions with local people need to be sensible of their difficult situation but in most cases local contacts are willing and personally motivated to provide support to damage assessments. News media may also serve as a source of information, but this information needs to be considered in the context of the type of work performed by these media outlets. That is, since the focus of reporters is going to be necessarily be on the most heavily damaged areas, relying on such information without considering a proper context may lead to the erroneous impression that a hugely vast area was completely obliterated by the disasters when almost always the reality is that intense damage is usually observed in very bounded and relatively small areas.

2.1.2 Execution

Although during the damage assessment execution phase it is convenient to be flexible in order to adapt to unforeseen circumstances, it is typically desirable to follow the realized plan in order to maximize the number of sites to visit. As mentioned, a well designed plan should still include some buffer times intended to be used to avoid these unexpected circumstances. The first desirable task of the damage assessment execution is to meet with ICT network operator's personnel or with engineers from other related infrastructures, such as electric utilities personnel, in order to collect information about potential locations to visit or to gain a general awareness of the situation in the field. These early meetings with network operators should set up in advance with the premise of being sensitive to the high likelihood that ICT network operators will have their attention focused on the infrastructure restoration process. The field damage assessment will typically follow these preliminary meetings and its execution will follow the plan and checklists detailed in the previous preparation phase.

There are two approaches for performing a damage assessment: one that could be characterized as a fast area sweep that maximizes covered area and visited locations by minimizing the time spent at each site, and the other that could be identified with a targeted focus in which fewer locations are examined but with each site evaluated in more detail. Evidently, in this last approach more time is spent at each site. The choice for which approach to use depends on many factors, such as characteristics of the disaster and the affected geographic area. Usually, the targeted focus approach is suitable for less intense and small affected areas. In cases with complex damage assessments involving an intense disaster affecting a large area use of both approaches in a sequential manner with the fast area sweep approach first followed by the targeted focus approach tends to yield a comprehensive record of the effect of the disaster under study.

Once at each location, the goal of the damage assessment is to document the condition of not only the ICT network infrastructure but also of other infrastructures that may influence the operation of ICT systems. Examples of these other infrastructures called lifelines include electric grids and transportation networks. In almost all cases documented records includes photos and videos paired with a written records of the observations. Of particular interest is to keep records of wireless communications networks coverage, gas stations operational conditions, and power outages location. It is also important to keep a record of both damaged and undamaged infrastructure, as well as general construction characteristics of affected infrastructures, such as areas with buried telephony and power cables or extent of use of digital loop carrier (DLC) systems for telephony networks or micro and nano-cells for wireless communications networks. The checklists prepared in the planning phase help to avoid forgetting to examine a given detail at a site. In many cases, finding specific sites within a general location area needs to be done on the field during the damage assessment. This is usually the case when trying to locate telephony central offices or electric substations. For the latter, the simplest approach is to follow overhead transmission lines. The same method allows finding power generation plants. In order to find central offices the general rule of thumb is to look for them within a couple of blocks around train stations. The reason is that in most countries towns grew from train stations outwards so other key infrastructure centers, such as telephony central offices, are found very near train stations. Both aerial cables and lines of manhole or buried fiber optic cables signs could also be used as guides to find relevant ICT infrastructure sites.

2.2 Data Examination

This step is dedicated to examine data by studying the collected photographic evidence and analysis of potential collected numerical data, such as electric or communications outage information. Following analogies with [4], the goal of this step is to extract relevant information from the evidence collected during the damage assessment trip. Thus, this step requires studying all photos for clues that would help to answer the questions (a) and (b) listed at the beginning of the Section 2. Hence, the examination of the photos needs to follow a critical approach focusing on the information that each individual photo provides and also the information that all photos as a whole provide—e.g. when many photos show a common issue then the relevant piece of information is not only the issue itself but also that the issue is observed at many locations. Examination of the photos tend to be a tedious work that demand considerable time because while examining each photos it is important to maintain considerable focus and attention in order not to miss any details.

2.3 Analysis

The objective of the analysis step is to answer the questions (a) and (b) listed at the beginning of this Section. The analysis makes use of the information extracted from the field damage assessment evidence in the previous step and evaluates both component level and system level issues in ICT network infrastructures. Analysis at a component level focuses on performance of a given site or part of a site as an isolated entity. A typical analysis at a component level may involve, for example, studying why a wireless communications cell site tower collapsed during an earthquake. A system-level analysis tends to study the performance of a site or ICT network element within the context of the entire ICT network or while interacting with other infrastructures. One of such analysis at a system level may involve assessing the logistical requirements and extent of deployment of portable generators used to power wireless communications cell sites or to power telephony DLCs.

The analysis of ICT systems performance while interacting with other infrastructures has various aspects to consider. Essentially, this analysis considers that ICT systems are interdependent with other infrastructures. These interdependencies may take different forms but the two most common interdependencies found for ICT system operating during extreme events are physical interdependencies and functional interdependencies. Physical interdependencies are found when two infrastructures share the same infrastructure. For example, in the US, Japan, and other countries electric distribution aerial cables share the same poles than telephony outside plant cables. In this type of interdependencies, both infrastructures fail simultaneously. Functional interdependency is found when an infrastructure requires in order operating adequately that another infrastructure operates well. That is, in the case of ICT infrastructures, functional interdependency is found with respect to the following interdependent infrastructures called lifelines: electric grid to power sites, water supply for cooling of large centers, and roads for delivering fuel for gensets and deploying portable gensets to distributed sites. In cases with functional interdependencies failures typically occur sequentially, with some delay between a given lifeline failure and an impacted ICT site outage. Both field information and numerical outage data may be used to identify these types of dependencies in ICT networks during disasters.

2.4 Reporting

The final step of the process is to prepare a report that details all the collected information and the process that was used to collect such information. The report also examines the collected data and presents the observations made from the analysis of the information. In most reports extensive photographic evidence should be presented. Mapping of the information is also an important technique that is usually necessary to apply to most reports. In order to realize such maps, it is highly advisable to use of GPS receivers in order to record all routes followed during the trip. In some cases, information needs to be excluded from public reports, usually because of security concerns or because the data was provided by ICT network operators that prefer to keep such information confidential. These commonly found situations highlight another important advantage of damage assessments: since ICT network operators cannot ask to exclude photos from sites that are accessible or can be viewed by the public, photos from the damage assessment can serve to provide a complete analysis of ICT networks performance during a disaster even when ICT network operators ask to keep information provided by them private.

3. CASE STUDY

The damage assessment performed after the March 11, 2011 Japan's Tohoku Region earthquake and tsunami can serve to exemplify the implementation of a damage assessment. Preparation for the damage assessment started immediately after news of the disaster occurred by initially collecting raw reports from news media. Data collection continued in the following days by establishing contacts with local collaborators from the Japanese communications company NTT and from universities colleagues. Eventually, the damage assessment was scheduled from April 17th to April 23rd. The main factors that influenced these dates were the need to wait until the situation at the Fukushima Daiichi power plant was sufficiently stabilized and that basic services, particularly gas stations, were operating again within a suitable distance from the disaster area. The schedule consider April 17th as a day to arrange local logistics, April 18th as a day to meet with NTT's engineers, and April 19th as a day to travel to the base of operations in the town of Yokote. This town was selected because it was sufficiently away from any potential radiation fallout (at the time of planning the damage assessment there was no clear information about radiation levels in Japan). Radiation concerns also influenced the decision of traveling to the affected area through the west coast so at all times during the damage assessment the traveled path remained at least 50 miles away from the damaged power plant. As an additional safety measure a sensitive dosimeter was carried all the time to verify radiation levels in different areas and in food and water supplies. Nevertheless, sufficient water and basic food supplies were taken from the US because of reported shortages after high radiation levels were measured in Tokyo's water supply [8]. These shortages were then verified to be over at the time of the survey.

The damage assessment in and around the disaster area were conducted April 20th to 23rd. The tracks taken each of these days along with other relevant trips are shown in Fig. 1—analogous to a diagram of incisions in an autopsy. As this figure shows the damage assessment started from the areas farthest away from the earthquake epicenter and move then closer, leaving the city of Sendai for the last day. The approach followed in this damage assessment was a fast area sweep because at the time there were firm plans for another damage assessment that would follow the targeted focus approach which was eventually performed in June 12th to 21st. One of the advantages of this dual approach is that some areas that were impossible to visit in the first damage assessment because of blocked roads or destroyed bridges, or continuing recovery operations due to the heavy sustained damaged were visited during the second damage assessment. The approach into the most heavily damaged disaster regions in the coast from inland areas allowed to document the good condition of infrastructures and to determine general ICT network practices, such as the use of small remote switches without permanent gensets, shown in Fig. 2. Hence, power outages may have led to communication failures, an hypothesis implying functional interdependence that is supported by the fact that most communication outages lagged power outages. Little damage inland seem to also support the hypothesis that power outages was an important source of gasoline sell disruptions. Little damage was also observed on power grids located inland, yet power outages were extensive. This situation indicating high fragility of power grids was also observed after other disasters. However, significant damage was observed in a narrow strip of terrain along the coast. Unfortunately, many towns are located just on the shore line so the tsunami affected many communities. In these heavily damaged areas, the fast sweep approach was valuable in order to identify different damage failure modes in ICT infrastructures, such as collapsed towers and destroyed shelter (Fig. 3) or combined tsunami and fire damage (Fig. 4). In some locations it was also possible to examine the interior of central offices verifying that damage was caused by tsunami water and not by earthquake shacking (Fig. 5).

The damage assessment study followed the aforementioned steps by using the data from this discussed first field trip to plan the second targeted focus damage assessment. Analysis and reporting steps are still under way. Their results and observations will be documented in a report to be issued by the American Society of Civil Engineers (ASCE) in the coming months.

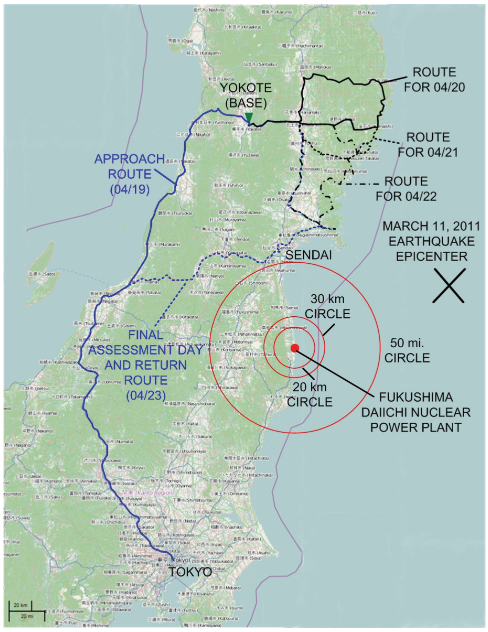

Figure 1. Map for a damage assessment conducted after the March 2011 earthquake in Japan (background © OpenStreetMap contributors, CC-BY-SA).

Figure 2. A small remote switch located 20 km east south-east of Morioka.

4. CONCLUSIONS

This paper has presented a systematic approach to study the effects of natural disasters on ICT infrastructure by following an analogous approach to that found in biological sciences forensic pathology studies. The systematic approach is a fundamental difference from most previously reported studies that follow a mostly anecdotal approach. The proposed approach follows the process detailed for digital data analysis as part of computer and network forensic studies. Based on this approach the basic steps that are enumerated and detailed are Data Collection, Data Examination, Analysis and Reporting. Here, the Data Collection step is divided in two phases: an initial phase for preparing and planning the field damage assessment trip and a later phase for executing such trip, which is the core of the presented approach for a systematic forensic study. Finally, this paper presents an actual case study based on a recently performed damage assessment after the March 2011 earthquake and tsunami in northern Japan as an example for the proposed approach.

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Figure 4. A cell site affected by the tsunami and fires in Yamada.

Figure 5. Main distribution frame of a central office that suffered both earthquake shacking and tsunami waves.

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Telecommunications Outside Plant Power Infrastructure: Past Performance and Technological Alternatives for Improved Resilience to Hurricanes

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Abstract — This paper discusses technological alternatives to achieve a more resilient power supply of telecommunications outside plant network elements during natural disasters. Outside plant powering alternatives are explored based on a description of past performance during 2005 Hurricane Katrina, and 2008 hurricanes Dolly, Gustav and Ike, and restoration options after those storms. Network planning implications are also considered. Power options including both backup and local generation units are evaluated using calculations based on actual field data of digital loop carrier systems of different capacity.

I. Introduction

This paper discusses telecom outside plant (OSP) power options to increase telecommunication networks resiliency to natural disasters and, in particular, to hurricanes. Since the 1970s power issues in the OSP have gain importance, when the first digital loop carrier (DLC) systems were installed. Initially, DLCs were used to extend a central office service area, usually into rural zones or new subdivisions at least 5 or 6 km. away from the central office (CO), or to provide feeders relief to, for example, areas with a fast growing demand and not enough infrastructure. In the 1980s and 1990s increased use of DLCs was motivated by the need of providing more broadband services requiring fiber optic links. During these years cable TV (CATV) networks also had increased needs for local power at thousands of OSP signal amplifiers. In recent years, both applications converged with the advent of voice-over-IP telephony in CATV networks, and the deployment of video services in traditional telephony networks. In all these applications, highly reliable power supply is an important requirement for active OSP network elements.

Digital loop carrier systems have been widely used for service restoration after hurricanes [1]. This application takes advantage of DLCs flexibility, which provides a quick way of restoring service without having to undergo the highly time consuming process of fixing the existing damaged infrastructure as it was before the storm struck. Hurricane Katrina provides a good example of widespread use of DLCs, initially restore service into areas where the CO was destroyed and, later, to replace damaged feeders due to water immersion in New Orleans [1]. Almost all these DLCs were permanently left operating in the networks [2].

However, DLCs limited energy backup and lack of local generation at most sites negatively impact their availability, particularly during disasters. Hence, widespread use of DLCs for service restoration that are subsequently left permanently installed may have a long term effect on network availability in disaster prone areas because their use to restore service during a disaster increases power issues when the next disaster affects the same area. In the next section, this paper describes power issues in OSP in past hurricanes. Implications of DLC deployment in terms of system availability are also discussed beyond the immediate restoration phase after a hurricane. The following section discusses power alternatives for enhanced resiliency in disasters. This paper concludes with a summary of the discussion presented throughout this work.

II. Past performance and Planning during hurricanes

During hurricanes, although there is always important damage in cables and serving area interfaces, lack of power in OSP's DLC cabinets for wireline telephony or in CATV enclosures for IP telephony accounted for many service outages. For example, in the aftermath of Ike (2008) an important number of outages for AT&T were caused by severe damage at Sherwood CO and failure of four other switches. Yet, more outages were caused by loss of service in 551 DLCs [3]. Of these, less than 3 % of failures were caused by equipment destruction, such as the remote terminals (RT) in Fig. 1. The rest of the failures occurred when the batteries were discharged before a portable generator set (genset) was deployed during the long power outages. There exist other examples of power failures in DLCs leading to many circuit outages in hurricanes. Statistics from Hurricane Hugo in 1989 [4] shows similar values than those with Ike in 2008 with 555 DLCs loosing power but only 10 destroyed. In 2003, approximately 800 DLCs lost power after Hurricane Isabel [5]. Many DLCs had power issues in 1992 after Hurricane Andrew when more than 1000 DLCs lost power, 722 of them in Miami [6]. Even in a more extreme case, such as in the Gulf Coast during Hurricane Katrina, when most outages were caused by destruction or loss of service in many COs, understanding the operational behavior of OSP powered elements during hurricanes is still important because many of the destroyed COs or damaged feeder cables were restored using DLCs [1]. Although the effect of Hurricane Katrina on wireline telephony networks was unusual in the sense that there was an unprecedented number of CO failures, the effects

Fig. 1. Destroyed DLC RTs by Hurricane Ike.

on the pre-existing DLCs in the Gulf Coast seems to be similar to what was observed in the other aforementioned storms: close to 1000 DLCs lost power after Katrina, but only 34 were destroyed [7]. Even in Florida where Katrina was much less intense, 825 DLC were affected by power outages and at least 37 of these failed [8]. Other storms causing significant effects on the OSP during 2005 include Wilma with Sprint's near 900 OSP remote terminals out of service and Bellsouth's 814 DLCs failures, and Dennis with Bellsouth's 300 DLCs affected by power outages with 82 of them failed [8].

In all these storms the large majority of DLCs were not equipped with permanent gensets so OSP RT require the deployment of a portable diesel genset, typically with a rated power of 10 kW, to sustain operation during the long power outages that often follow a storm. However, due to uncertainties in storms forecast and impact, and transportation constraints during evacuations, it is impractical to deploy the gensets before the storm. Furthermore, portable gensets should not be deployed to sites at risk of being damaged—e.g. those close to the coast—by an incoming storm because they will likely be destroyed along with the RT being powered. This situation led to difficult decisions during the 2008 Atlantic Hurricane Season, when Ike's storm surge poised an important hazard to gensets deployed to OSP sites in the eastern Louisiana Coast a few days before, after Hurricane Gustav. Outside plant sites power issues in Louisiana would have been more serious after Gustav hadn't been by the improvements implemented in that same area after Hurricane Katrina [2]. These improvements included placing the DLCs in elevated platforms (Figs. 2) and installing permanent gensets, most of them fueled by natural gas (Figs. 3) and some of these even directly connected to the dc bus (Fig. 4.a). Still, costs and space constraints limit the application of these alternatives to all sites, so most OSP sites still required a portable genset (Fig 4.b). Pole mounted systems is a cost effective alternative to systems installed in platforms when searching for more resilient options, as exemplified in Fig. 5.a. However, if the OSP local powered system is placed too high, it leads to operational and maintenance complications and to unsuitable and unsafe powering options after a disaster, as shown in Fig. 5.b. If it is placed lower, then complications are eased but it may not be protected enough, as shown in Fig. 5.c.

Other important issues with portable gensets are their theft risks and, in some cases, low reliability. For example, after Ike many DLCs were powered by small, off-the-shelf gensets, such as the one in Fig. 6.a, that may not be reliable enough for telecom applications. Such intuition may be confirmed by sites, such as the one in Fig. 6.b, where the genset failed. Widespread use of portable gensets also causes important logistical needs because they need to be refueled periodically. Still, the most important disadvantage of portable gensets is

Fig. 2. DLC cabinet on an elevated platform near New Orleans.

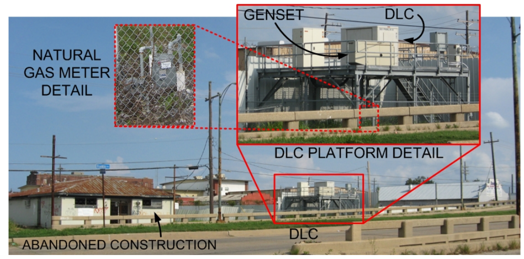

Fig. 3. DLC platform equipped with a permanent natural gas genset.

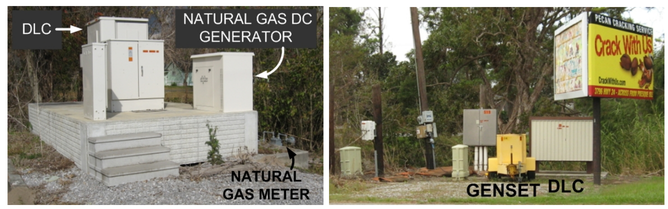

Fig.4. **(a) Left:** DLC powered by a natural gas dc genset.. **(b) Right:** DLC powered by a 10 kW portable genset after Hurricane Gustav.

that since they are deployed after the storm passed, they cannot prevent loss of service in most sites because battery backup times in most OSP RTs sites is not long enough to sustain operation from the time the mains power goes off to the time when the portable gensets can be deployed. One reason for this to happen is that, although outside plant cabinets are typically engineered to accommodate enough batteries to provide 8 hours of backup, environmental conditions—specially heat—limit batteries autonomy and life [9]. Another reason is complicated access road(s), as it happens with the DLCs used to replace Delacroix and Yscloskey COs. As Fig. 7 shows, there is only one road to access this area, which is often flooded after hurricanes. The only grid's sub-transmission line runs parallel to this road.

Considering the aforementioned consistent power related issues, it may seem contradictory that DLCs are used to restore service after a hurricane. However, DLCs have important advantages that make them a very good choice from a network recovery and infrastructure planning perspective. Besides expanding broadband capabilities to the traditional OSP infrastructure, DLCs can be deployed quickly after a disaster in order to replace damaged feeders. Sometimes,

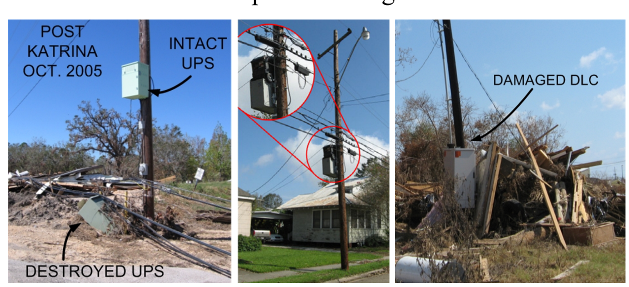

Fig. 5. **(a) Left:** An intact CATV UPS mounted on the pole and a destroyed CATV UPS installed on the ground**, (b) Center:** Genset on top of a pole-mounted CATV UPS after Gustav, **(c) Right:** Damaged pole mounted DLC

Fig. 6. DLC powered by small gensets. The one on the right failed.

DLCs were placed over platforms with wheels (Fig. 8.a) so they can be quickly moved to where they are needed. In some other cases, DLCs were placed over pallets (Fig 8.b) in seemingly temporary installations, although some of these DLCs were still operating in the same condition four months after Ike. From a long term planning perspective, DLCs are a very good alternative to unknown demand that exists in areas affected by a disaster. As explained in [2] through the effects of Katrina in New Orleans, repopulation of the area affected by a disaster creates planning issues because demand evolution is unknown and the alternative of repairing the infrastructure to the state prior to the disaster my lead to a large unused excess capacity at a high capital cost. In this context, DLCs' flexibility provides a way to reconcile the immediate repair needs with the long term network planning goals based on an uncertain demand. However, concerns related to power supply still persist in locally powered OSP elements, so a discussion about power alternatives is key in order to ensure meeting availability goals for any communication network. Moreover, this discussion is not limited to wireline telephony and CATV OSP networks. Common issues and opportunities for synergistic solutions also exist with the distributed portion of wireless networks, i.e., cell sites, and low-power inside plant telephony elements, such as small capacity remote switches. Next, this work addresses power issues in communication networks distributed elements by discussing powering alternatives in the OSP.

III. OSP POWER ALTERNATIVES

Different alternatives have been proposed in order to improve OSP power supply resiliency during hurricanes. Each of these options has their own advantages and disadvantages so their application vary from site to site. Some of these options, including permanent diesel or propane gensets, rely on locally stored energy storage, whereas others, including natural gas (NG) gensets, and photovoltaic (PV) modules, utilize an external source of energy. Suitability of power supply options are discussed with the power planning perspective suggested in [10] including the need for increased power resiliency in disasters through diverse a power supply based on flexible fuels that takes into consideration the dissimilar ways in which disasters affect primary energy delivery infrastructures. The analysis is supported by actual power consumption data indicated in Tables I in the appendix for some representative sites. As it suggests power consumption even for the same type of DLCs may vary significantly, particularly for those providing telephony services because power consumption depends on circuits' usage. As Table I displays some sites may have a combination of RTs, some times combining telephony and video services. In these sites, power can be saved during disasters by interrupting video services so telephony services carrying E-

Fig. 7. Map showing the present condition and former location of Ycsloskey and Delacroix COs and surrounding area.

Fig. 8. (a) Left: DLC on wheels, **(b) Right**: DLC on a pallet.

911 are prioritized.

A. Backup fuel cells

Fuel cells are one of the main options suggested as an alternative to batteries in OSP enclosures [11]. In its simplest configuration fuel cells are locally stored back up systems, because they operate fueled by hydrogen stored at the site in cylinders, tubes or bottles. Initially, the argument in favor of fuel cells was made by comparing their performance with that of batteries, particularly in hot environments. But FCC's "Katrina" order 07-107 [12] increased interest in fuel cells, particularly because of the extended backup time that can be obtained with standard configurations such as those specified in [13]. When comparing the data from Table I and the autonomy information in [13], it can be concluded that fuel cells can sustain operation of most OSP sites between 12 and 24 hours, minimizing the risk of outages that occurs in traditional battery-portable gensets configurations, as discussed above. Fuel cells also weight less than batteries, reducing the structural stress of DLCs placed on platforms. Although in recent years initial concerns over costs have been reduced, refueling fuel cells is still an important issue during critical situations, such as disasters, because hydrogen cylinders are not, yet widely available. This is an important limitation for using fuel cells in disaster prone areas which can be overcome by having a reformer to produce hydrogen from NG or propane locally. However, higher costs for this alternative limit its widespread application.

B. Natural Gas Gensets

As it was discussed, NG gensets are a good option to power OSP sites after hurricanes because they don't require periodic refueling and because NG outages are less widespread than electric power outages during hurricanes [1]. Hence, OSP sites with NG gensets are less likely to loose service that in those sites with the standard solution based on batteries and portable gensets. In terms of diversity, NG gensets have the extra advantage of being able to also operate with regular gasoline, which makes possible in extreme cases to also store energy locally by keeping a gasoline tank at the site in case the NG supply fails. Furthermore, there is in the camping market tri-fuel—NG, propane, and gasoline—generators that provide significant flexibility during disasters, although it can be argued that their design may not be reliable enough for long term operation in telecom application.

However, natural gas-only gensets is an inconvenient solution in places, such as in some areas in Florida, that lack NG distribution services. Natural gas gensets are also unsuitable for earthquake-prone zones, because NG supply is automatically interrupted in case of a seism. As shown in Figs 9, NG gensets has been installed in the area affected by hurricane Katrina in 2005. Most of these sites have 25 kW gensets, a power rating significantly larger than what is always required in all OSP sites, even in sites with multiple enclosures or huts. A better alternative is the 7.5 kW dc genset shown in Fig 4.a, although its rated power is at least 4 times the rated load at the site. This situation indicates a commercialization opportunity for small NG telecom-grade dc gensets with an output power in the order of 2 to 5 kW. This power range provides advantages in the choice of motor technologies because there already exists permanent magnet dc generators already developed for wind generation applications that do not have the reliability and maintenance issues found in traditional brushed dc machines—i.e. dynamos. Due to their flexibility, tri-fuel gensets may provide a better alternative and, hence, a better commercialization opportunity.

C. *Propane gensets*

Although propane (or LPG) gensets have more logistical needs than those fueled by NG, permanent LPG gensets are a suitable alternative for many OSP sites, specially for those where NG is not a suitable option. Propane gensets rely on local stored energy, which needs to be replenished periodically. However, logistical requirements are less demanding than other fueled-based options, such as fuel cells, because of the longer autonomy achievable for the same volume of fuel. For example, when compared with fuel cell systems, a 32 inches long by 27 inches wide by 28 inches high 6.5 kW genset equipped with a 46.3 inch high by 15.1 inch wide 100 pound LPG cylinder can support a 5 kW load—over all those exemplified in Table I—for about 40 hours. Other advantages of LPG gensets are that they tend to require less maintenance and last longer than equivalent diesel or gasoline generators because fuel is burnt in a cleaner way. In addition, LPG cylinders are usually more resistant than gasoline or diesel tanks. Hence, with a properly sized cylinder and placed on a protected spot, LPG gensets may prevent outages due to lack of power during the storm.

D. *Permanent diesel or gasoline gensets*

Although portable diesel or gasoline fueled portable generators were widely used to restore service in past hurricanes, and permanent diesel gensets are used in many cell sites and practically all central offices, their permanent use in OSP applications (Fig 10.a) is uncommon. One problem with this alternative is that diesel or gasoline gensets require periodic maintenance, so a widespread use of these gensets for OSP applications is impractical. Also, risk of theft adds to the practical limitations of their widespread use.

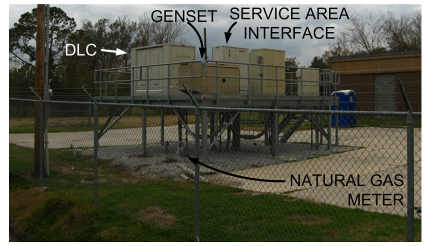

Fig. 9 A DLC platform with a permanent 25 kW natural gas genset.

E. *Distributed generation technologies*

Distributed generation (DG) technologies include a variety of local sources that are intended for continuous operation. Typically, systems with distributed generators—i.e. micro-grids—do not rely of local stored energy to power load but on an external energy supply. Other options for DG already discussed in this work include sources fueled by NG, such as generators and fuel cells with local reformers. Due to their long autonomy, permanent LPG generators with large tanks could be considered a DG source. Yet another DG option includes renewable energy sources: PV modules [14] and small wind generators. As discussed in [10] one of the advantages in terms of power resiliency during disasters of these sources is that they do not depend of another infrastructure to operate, so they are not significantly affected by disasters. In case of hurricanes, as Fig. 10.b exemplifies, PV modules and small wind generators are only affected by extremely strong winds which are only found in small areas within few kilometers from the hurricane eye wall or by tornados spun by the storm which only affect very localized and small zones. PV modules can also be affected by large hail which also occurred in very few localized small areas.

One advantage of powering OSP sites with distributed generators is that their use throughout the year can reduce electricity costs. This feature will very likely become more advantageous as electricity costs increase due to more congestion points in the grid, and new greenhouse gasses limiting policies. In this last sense, use of renewable energy sources could lead to network operators additional income related with a potential carbon derivative market that could be created by "cap and trade" policies currently under discussion at the U.S. Congress. But, in order for this last advantage to have any practical value, renewable energy sources should be used in most OSP sites. However, there are important limitations for widespread use of renewable energy sources in OSP sites. One that applies to all micro-grid based telecom power plants (with or without renewable sources) is high costs. Even with tax incentives and expected favorable energy costs evolution, use of DG is cost effective only for sites consuming several tens of kilowatts or more [15]. In addition,

Fig. 10. (a) Left: DLC platform with a permanent diesel genset. **(b) Right:** House with rooftop-mounted PV modules in Smith Point, TX.

many systems integrating renewable sources, and particularly PV modules, are site specific and without a modular or scalable design. This is an undesirable feature after hurricanes when it is desirable to be able to add or remove sources to follow an uncertain demand. In the case of PV modules this is also an even more important disadvantage because mixing different PV module models, as expected when replacing a damaged panel after a storm that occurred a few years after the panels were originally installed, reduce system performance. One solution that would overcome these issues is to integrate the DG sources through multiple-input converts [15], [16].

Still, there are other important practical issues that limit the application of renewable sources in OSP applications as suggested in [17], including aesthetics, shadowing, risk of theft, and, more importantly, large footprint. Although it could be argued from Fig. 4.b that PV panels are more aesthetic than the billboard, an example based on the DLC contained in an Emerson Mesa 2 cabinet used to replace Delacroix CO exemplifies footprint issues. Let's assume, then, that we want to power the site with PV modules. Although the maximum possible power consumption in this site is 2 kW, it is safe to assume based on the reduced demand that the actual power consumption in this site is 1 kW, a relatively average power consumption among all the sites in the appendix. Hence, the energy consume in a day is 24 kWh. Considering the month of September when the peak activity of the hurricane season occurs and that the PV modules are placed facing south with a tilt equal to the local latitude (30^o), the average total solar radiation is about 5 kWh/m^2/day [18]. Let's also consider that we choose to use 200 W Sanyo's HIT Power 200 modules with an efficiency of approximately 17 %. Hence, the effective average solar radiation is approximately 0.85 kWh/m^2/day, equal to 0.17 times 5 kWh/m^2/day. Hence, 28 PV modules are needed. In reality, it is desirable to add some more modules in order to compensate internal conversion losses and to provide redundancy. Thus, the final number of PV modules is about 32. Since each module measures 1.35 x 0.9 meters and they are tilted 30^o, the 32 panels occupy an area of 34 m^2. Due to the sun's trajectory in the sky, and PV modules orientation and fixed installation, the solar radiation used in the calculation is equivalent to about 5 hours of effective solar hours per day. Hence additional batteries to power the DLC when the sun is not effectively present are also required. Clearly this alternative is impractical and even when it could be implemented in sites such as Delacroix where there is enough space, it is not suitable for most OSP sites.

One compromise alternative is to install less PV modules than those needed. With less panels cost savings can still be achieved during the year by limiting the peak power when electricity cost more. After disasters, although the PV modules will not be suitable to fully power the load, it may still reduce logistical needs by reducing the power demand for a portable genset deployed at the site. Hybrid solutions such as the one represented in Delacroix in Fig. 11, combining limited PV generation and low power wind systems, can provide a better solution but due to space constraints, their application is still limited to some few specific OSP sites. Furthermore, during the time when the site is under the effects of a hurricane no power could be generated by the wind generators and the PV modules, so the likelihood of an outage due to lack of power is the same than that for the traditional solution.

Fig. 11. Depiction of a hybrid PV-wind system at the DLC installed at the former Delacroix CO location. PV panels could also be installed over the platform for additional cooling action due to shadow.

F. Centralized power

The last alternative is to power the OSP sites directly from the CO. For this purpose, solutions with ±190 Vdc has been proposed in the past [19]. Although this alternative avoids all the issues involved with having to provide local reliable power, it requires having copper wires running from the CO to all OSP sites. Hence, this solution tends to be costly and unless the power distribution cables are buried—implying further costs—it is likely that a number of sites may loose power due to damaged ±190 Vdc power feeders caused by, for example, fallen tree branches.

IV. Conclusions

Lack of power in OSP network elements originates many service outages in telephony networks after hurricanes. For this reason, although DLC systems have many advantages, it is important to identify more resilient power supply alternatives. One is to use backup fuel cells. However, limited availability of hydrogen tubes and high cost of reformers may limit this solution application. In many cases use of fixed natural gas or propane gensets might be a suitable solution. Yet, the former is inconvenient in some areas where there are no natural gas utilities. DG units are another option yet many times costs are excessively high. One related alternatives is to use PV modules or hybrid PV-wind systems to power the OSP element but large footprints makes this choice impractical in almost all sites. Powering from the CO with ± 190 Vdc is another option but it is unrealizable with fiber optic links. These conclusions can be extended to small cell sites and remote switches. The analysis suggests that there are both important challenges and opportunities in the development of OSP powering technologies.

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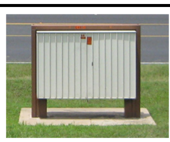
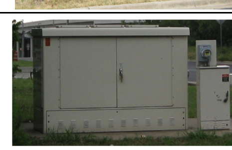
APPENDIX

TABLE I.A
POWER CONSUMPTION OF VARIOUS OSP REMOTE TERMINALS

	Cabinet type(s)[(1)]	Measured peak power
	Type 80A	0.5 kW
	Type 50	0.7 kW
	Type 50	0.25 kW
	Type 52	0.5 kW
	Type 52	0.75 kW
	Mesa 2	1.5 kW
	CATV UPS	1.62 kW

[(1)]Some model types are indicated for reference and are not the exact model.

TABLE I.B
POWER CONSUMPTION OF VARIOUS OSP REMOTE TERMINALS

	Cabinet type(s)[(1)]	Measured peak power
	Type 80 G + Type 82G + Type 52	3.5 kW
	LSC-2030 + Type 50	1.25 kW
	LSC-2030 + Type 52	0.75 kW
	hut	5 kW
	Type 82G	1.9 kW
	Type 80	1.5 kW
	Type 80	2.07 kW
	Type 80G	0.85 kW
	Mesa 6	2.8 kW
	Mesa 4	4.6 kW
	LSC-2030	2.7 kW
	LSC-2030	0.5 kW

[(1)] Some cabinet types are indicated for reference. They are not the exact model.

Technology Planning for Electric Power Supply in Critical Events Considering a Bulk Grid, Backup Power Plants, and Micro-Grids

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***Abstract*—This paper discusses a risk assessment approach to infrastructure technology planning aimed at improving power supply resiliency to natural disasters or other critical events. Cost as well as power supply availability are both fundamental decision factors considered in the study. The proposed planning process spans three phases during which the critical loads under study are subject to the effects of the extreme event: during the event, the immediate aftermath until potential infrastructure damage is repaired, and the long term aftermath until the load has recovered the same level existing before the critical event. The combined risk of these three phases is calculated considering likelihood of the critical event to occur, expected impact, and system vulnerability. This risk is then added to the system capital and normal operational costs to yield a lifetime cost that is used to compare technological options. Micro-grids are identified as a relevant technology with potential to achieve enhanced power supply during critical events. The analysis provides indications on how to better configure micro-grids in order to achieve high availability through diverse local distributed generation sources.**

***Index Terms*—Critical event, disasters, micro-grid, power supply, risk assessments, technology planning.**

I. INTRODUCTION

THIS paper presents a risk assessment planning framework to objectively determine suitable technology options for electrical power supply systems that are resilient to critical events, such as hurricanes. The systematic technology evaluation process proposed here considers costs resulting from the expected critical event effects on system operation and output. Although electrical power supply is a critical need when a disaster happens, traditional electric grids show little resiliency to external actions from such events. As it is exemplified with the effects of 2008 Hurricane Ike summarized in Figs. 1 and 2, grid outages may affect for a long period almost all or all customers in an extensive region where no more than 1% of the power grid infrastructure is damaged. These outages may jeopardize human lives and delay community recovery efforts by hindering many society critical services, such as financial, and health services. Communication networks are particularly affected by power supply deficiencies in these events as attested by the fact that most of their outages have power related causes [1]–[4].

Despite the recognized importance of improving power supply resiliency during critical events, few works seem to have been published focusing on this topic [4]–[10]. Although significant work, particularly in civil engineering—e.g., [11]—has been dedicated to study planning issues when extreme events may affect critical infrastructures, most studies rely on risk assessment methods after the infrastructure is installed [12] and not during the initial planning stages. In this sense, there seems to exist little past work addressing the issue of how to systematically and objectively plan new or replacement power supply infrastructure deployment in areas that are prone to critical events. One is [13], but it is mostly based on a qualitative analysis. In contrast, this paper presents a quantitative planning framework based on risk analysis with some similarities to that suggested in [14] in terms of considering system characteristics as an important part. Yet, many differences exist, such as the applied focus in here. Furthermore, although micro-grids—small electric distribution grids powered by local generation sources with a total capacity of a few MW—have been identified as a suitable technology to improve power supply availability [15], no past works focused on how to design micro-grids able to sustain operation during an extreme event. The risk analysis planning framework presented here allows determining not only if micro-grids are a suitable technology option, but also how to engineer them so they are more resilient to critical events.

II. PRELIMINARY NOTIONS

A. Power Supply Alternatives

The proposed framework supports evaluation of suitable technologies in order to achieve a resilient power supply for a given load confined to a limited physical space, such as a building—a data center or industrial campus—or an area with a maximum radius of 500 m, such as a neighborhood or part of it. This confined space with a given load defines a *service area* in which the load can be powered based on three *powering approaches* or *technology options* (TOs):

TO A) the traditional approach of using the bulk power grid without any local power backup alternatives (Fig. 3),

TO B) same as TO A, but with a local backup power plant with batteries and a diesel generator (Fig. 4),

TO C) a *micro-grid* with varying alternatives for the local distributed generation (DG) power sources (Fig. 5).

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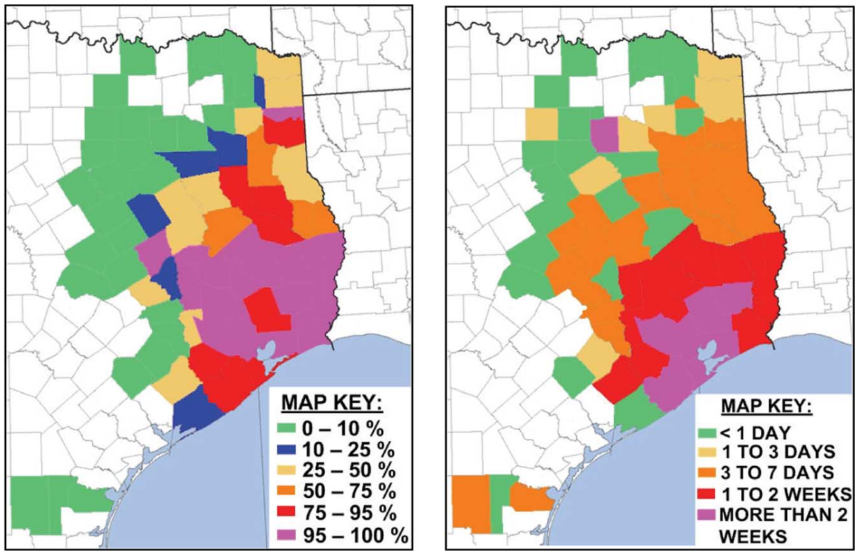

Fig. 1. Left: Power outage incidence caused by Hurricane Ike in Texas. Right: 95% restoration time for Hurricane Ike in Texas.

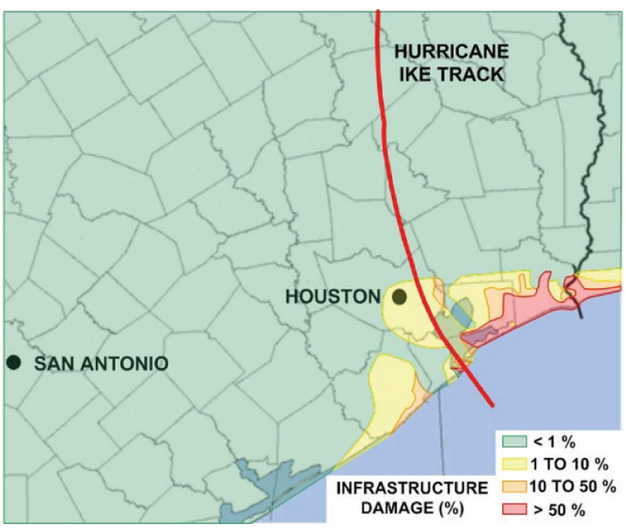

Fig. 2. Percentage of power infrastructure damage caused by Hurricane Ike.

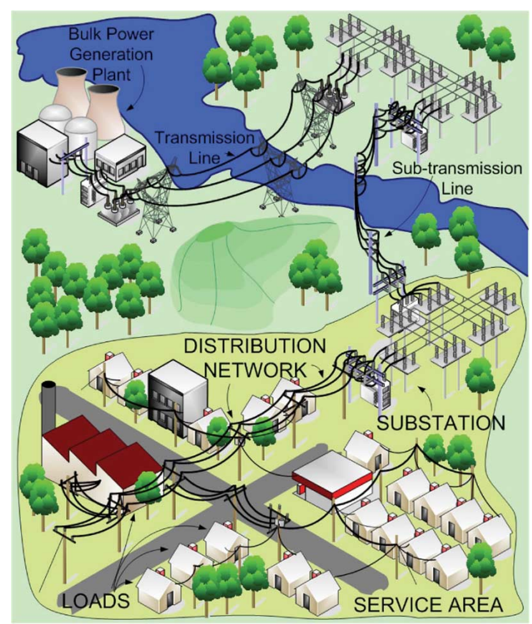

Fig. 3. TO A: electric supply from bulk power grid.

All TOs typically require some external source of energy that is delivered into the service area by one or more *primary energy supply infrastructures* (PESIs)—also called lifelines in earthquake studies nomenclature—in order to power the load. Typically, TO A systems have a substation that acts as the interface between the distribution network within the service area and the PESI formed by a sub-transmission line and the rest of the bulk power grid. The TO B, displayed in Fig. 4, adds a local power plant made of power electronic interfaces, batteries, and a diesel generator, that provides backup power when the grid looses service. This power plant acts as the interface between the local power distribution and the bulk electric grid. In addition to the power grid, the roads necessary to transport diesel fuel for the standby diesel generator are another PESI. Roads are still the PESI in TO B when backup fuel cells without reformers are used instead of diesel gensets. If natural gas gensets are used instead of diesel generators, then the natural gas distribution network is a PESI. In TO C, power is supplied primarily from local DG power sources through power electronic interfaces and supported by ancillary hardware, such as energy storage devices for short term load following. All these components form a local power generation and controlled plant that when combined with the local power distribution infrastructure and the load constitutes a *micro-grid*. The main bulk utility grid can serve as a secondary energy supply infrastructure in addition to the PESIs, such as a natural gas distribution network for microturbines, fuel cells with reformers, or some types of reciprocating engines. Some other DG technologies, such as photovoltaic (PV) modules and small wind generators, do not require any PESI. Micro-grids show promise to achieve improved power supply resiliency to critical events over TOs A and B because well designed micro-grids—i.e., micro-grids with diverse power supply from at least two distinct PESIs—eliminate the single point of failure encountered at the grid tie in TOs A and

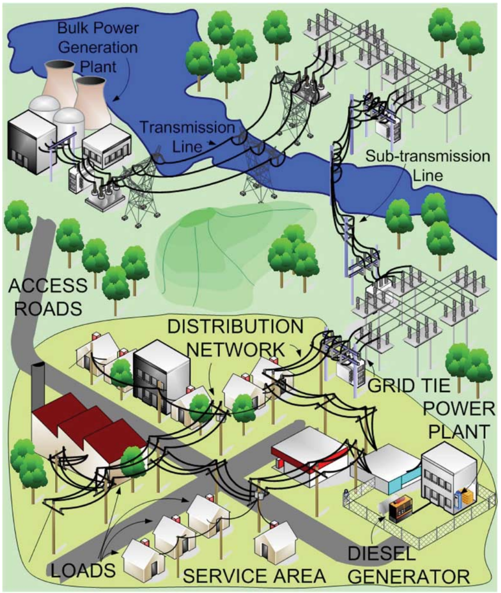

Fig. 4. TO B: electric supply from bulk electric grid with power backup from a diesel generator.

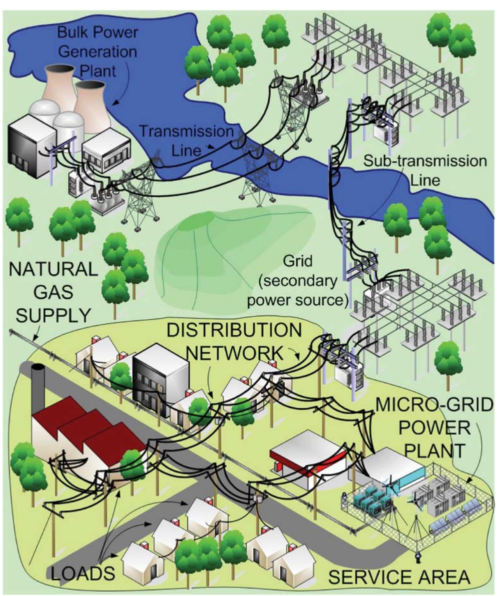

Fig. 5. TO C: micro-grid.

B [1]. Logically, in order to achieve high availability, it is desirable to select DG technologies for which their PESIs are affected by the critical event less severely than the electric grid.

B. Critical Event Timeline

The proposed framework considers that a critical event influences the power supply technology planning process in three phases shown in Fig. 6: *during the critical event, the immediate aftermath* of the extreme event, and the *long term aftermath* of the extreme event. For most critical events, Phase I—i.e., during the critical event—lasts for a relatively short time; at most for a few days. Phase II (immediate aftermath) starts when Phase I ends and is usually termed response, recovery and restoration phase. It typically lasts from a few days to several weeks, until 100% of the power infrastructure within the service area and its primary, and in some cases secondary, energy supply infrastructures have been repaired of all damage received during the critical event. At the end of Phase II power could be supplied to the loads in the same conditions that existed before the critical event occurred. However, some of this load may have disappeared due to the critical event actions. This significant effect of critical events is recognized in the last phase, the long term aftermath. It starts immediately after Phase II ends and lasts until the load is restored to the same levels existing before the critical event occurred. Hence, Phase III introduces in the planning process the fact that the service area load, and, hence, the local power supply infrastructure demand, may be severely affected by such events. Inclusion of this phase in the planning framework is an important difference from conventional critical events planning approaches that consider phases I and II but not the long term effects [16]. Yet, as Hurricane Katrina demonstrated, demand evolution plays a very important role in technology planning for critical events [17]. Phase III may last from a few weeks up to several months and even years.

III. Concept Definitions and Assumptions

The first concept that needs to be defined is that of the system under study. The system under study involves the local power supply infrastructure up to the demarcation points to the lifelines. Although these lifelines are not part of the system subject to eventual procurement decisions, their behavior when influenced by the critical event is a fundamental part of the risk analysis and planning framework. In effect, the selection of the most adequate TO, and the choice of local distributed generators technology for TO C, is heavily influenced by the PESIs availability at their demarcation point with the system under evaluation. In all TOs the system under study includes a local power distribution network. For TO A the system also includes the substation that connects the distribution network in the service area with the main power grid. For TO B the system adds a local power plant with backup generation. For TO C the system includes a local power generation and control plant, and the local power distribution infrastructure.

The service area for the system under evaluation is inside a larger region that may or may not contain other service areas served by the same power supply service operator. It is assumed that this region is subject to only one particular type of disaster to occur—e.g., hurricanes or earthquakes. If two or more type of disasters may occur, then the results of the study for each type of disaster could be compared in order to choose one of the solutions or to combine both solutions into one. Six other important definitions for the proposed framework are as follows.

1) Hazard [18]: "It is a potentially damaging physical event, phenomenon and/or human activity, which may cause loss of life or injury, property damage, social and economic disruption or environmental degradation."

Hence, the hazard is the originator of power supply disruptions to loads within the service area and not the means by which these effects are produced—as considered in [19]—which in here is called *damaging actions*. E.g., if the hazard is a hurricane, then its damaging actions are the strong winds, the storm surge, floods, torrential rains, and tornados.

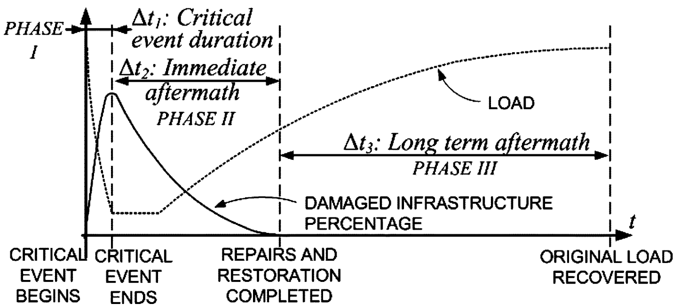

Fig. 6. Critical event timeline.

2) Hazard Probability (P_H)*:* It is the probability that a given hazard—i.e., a critical event—with a given intensity H_i will occur within some specified time interval.

Two important concepts are related with this definition: *hazard intensity*, H_i, and *time interval*. In the proposed framework, the time interval is the system under study total lifespan. Critical event intensity is a more complex concept for two reasons. One is that a given hazard may happen multiple times and with different intensities during the system lifespan. Thus, the evaluation process may involve choosing which hazard *scenario* to consider. One scenario may consider the most intense possible hazard. Another scenario may consider an expected intensity combined with its average occurrence frequency. Yet another scenario may compare different case studies each of them with a different value for H_i and corresponding return period. The second reason is that there could be different ways of characterizing H_i. In order to provide some basis for discussion and without pursuing a detailed analysis for being out of the scope of this work, let's consider that the hazard is a hurricane. The most common way of indicating hurricane intensity is with the Saffir–Simpson 5-category scale which is based on a 1-minute mean maximum sustained wind speed measured at a height of 10 m. However, this scale has been shown to be inaccurate when attempting to describe damage, as it happened with Hurricane Katrina [1], [20]. For this reason, there have been a number of publications suggesting different ways to measure hurricane intensity [20]–[22]. Yet, these measurements do not provide a clear indication of different intensities along the area affected by the storm. In order to provide an alternative way to measure hurricane intensity that can serve as a basis for the discussion, it is suggested to measure hurricane intensity with a local index, derived from the one proposed in [20], called *Local Tropical Cyclone Intensity Index (LTCII)* and defined as

$$(\mathrm{LTCII}) = \left(\frac{h}{h_0}\right)^2 \left(\frac{V_{\max,\mathrm{SW}}}{V_{\max,\mathrm{SW},0}}\right)^2 \left(\frac{A_{\mathrm{TS}}}{A_{\mathrm{TS},0}}\right) \left(\frac{T_{\mathrm{TS}}}{T_{\mathrm{TS},0}}\right) \quad (1)$$

where $V_{\max,\mathrm{SW}}$ is the maximum sustained winds at the studied location, A_{TS} is the area over land of tropical storm winds, and T_{TS} is the time period under tropical storm conditions at the studied site. For the latter, if the service area location is not likely to be under tropical storm winds, then T_{TS} is made equal to 1. The sub-index 0 indicates reference values. These reference values are $V_{\max,\mathrm{SW},0} = 74$ mph (the lower threshold for a category 1 hurricane), $A_{\mathrm{TS},0} = 35341$ mi^2 (the area of a semicircle with a radius of 150 mi—a typical average radius for tropical storm winds in a category 1 hurricane), and $T_{\mathrm{TS},0} = 12$ h (the time it takes to make 150 mi at 12.5 mi/h—a typical hurricane forward speed). The ratio h/h_0 equals 1 when the storm surge height h is less than 4 ft (the minimum typical storm surge height for a Category 1 hurricane). Otherwise h is the actual storm surge height and h_0 is 4 ft. In (1) both factors related to storm surge and wind speed are squared because storm surge or wind speed forces on buildings, columns, and poles, are squared functions of the storm surge height or the wind speed, respectively. Further explanation of the LTCII is out of the scope of this paper. Yet, the LTCII can serve to explain some concepts in the risk-based planning framework.

Implicitly, H_i also considers the *exposure* of a system under analysis at a given *location*;e.g., for a hurricane, a system on the coast is more exposed to high winds and storm surges than an equal system located inland. Since it is more likely to have higher LTCII near the coast, for the same LTCII the system on the coast have a higher P_H than that of the system located inland; i.e., the former is more exposed than the latter.

3) Hazard Impact (I_H)*:* It is the expected effect in terms of additional cost that a given hazard of a given intensity produce for a system under study when it is constructed, operated, or configured in a standard way.

This definition encompasses several concepts: an effect that can be monetarily quantified, a hazard with a given intensity, and a system that is constructed, operated, or configured in a standard way. The effects of the hazard under evaluation in each of the three aforementioned phases are different but they can all be measured in terms of a monetary cost. This is true even in the case of loss of life, such as when evaluating the effect a power outage at a hospital or a E-911 communications center, because loss of life due to power outages can be translated into an estimated cost of life [23] plus financial liabilities.

In some previous works [18], [24], [25] that use risk-based analysis, the notion of impact is equivalent to that of exposure as the total number of people, buildings or infrastructure elements at risk in a given area. Although the concept of an area is relevant for both definitions of impact and exposure used in here, the definitions of exposure and impact are fundamentally different because a given hazard may not necessarily affect all elements at risk within the service area.

Typically, I_H is determined based on statistical analysis of past events similar to the one under study. Hence, I_H represents some expected outcome yielded by a combination of information from systems with varying characteristics. Thus, the impact measures the effects of a given hazard with a known H_i in an average condition. Since the system under study may or may not be planned to have this same average condition, an adjusting concept, called system combined vulnerabilities and defined next, needs to be included in the analysis in order to consider particular features of the system.

4) System Combined Vulnerabilities (V)*:* It is an indication of how much more or less susceptible the system under study is to receive the same impact than a reference standard system when both are subject to a hazard of a same given intensity.

In the past the concept of vulnerability has been the focus of controversy and varying definitions [26], [27]. Herein, V refers to some characteristics of the system under study that makes it more or less prone to being subject to an (average) expected impact from a hazard with a well identified intensity. The choice for how many of these characteristics are considered and how much detail is included in their description depends on the planning process accuracy goals and time constraints. In many practical cases the decision of how to consider V depends on a lead planner's executive decision as part of the planning scenario selection process.

From the definition, V is estimated with respect to a baseline case. This case represents a mean impact yielded by averaging observed past outcomes from different locations with the same value for H_i. Then V is the ratio between the value associated with the characteristic under study for the system under evaluation, and the value of the same characteristic for the baseline case. For example, if the analysis is evaluating power supply for a neighborhood with overhead distribution lines and the historical data is based on areas with an average of x times more wooden poles than concrete poles, then V may equal y/x where y is the planned ratio of wooden poles to concrete poles in the service area under evaluation.

5) Hazard Adjusted Impact (I_{adj})*:* It is the product of the hazard impact and the system combined vulnerability, or the maximum possible impact; whichever of the two is less.

In any critical event there is a limit to the worst effects that the system can receive. In terms of impact, this limit is given for example by the cost of loosing all the loads during phases I and/or II of the critical event, or by the cost of having a totally unused system capacity during Phase III. Yet, since V could be larger than one, then it may happen that the product of I_H and V exceeds the worst possible impact. This is a practical impossibility that leads to the need of defining I_{adj} as

$$I_{\mathrm{adj}} = \min[I_H V, M_I] \tag{2}$$

where the product $I_H V$ is the directly calculated impact, and M_I is the worst possible impact, e.g., a monetary measurement of an outage during phase I or II affecting all loads.

6) Risk (R)*:* It is the expected impact over an indicated period of time that a system at a given location, and with a given construction and configuration characteristics will suffer when subject to a hazard of a given intensity. Hence, risk is mathematically defined here as

$$R = P_H \left(\sum_{p=1}^{3} I_{\mathrm{adj,p}} \right) \tag{3}$$

where the index p indicates the critical event phase. Hence, the definition of risk considers a ternary approach in line with previous works such as [18], [24], [28] in which vulnerability is combined with the classical definition of risk involving hazard likelihood and impact [13] in order to reflect the fact that the analyzed system may differ from the baseline design.

IV. Technology Planning Framework

The lifetime cost, C_L, includes the expected cost from having the system operating in a zone subject to some hazard—i.e., the risk R from (3)—the system capital and installation cost C_{CI}, the operational cost C_O, and the down time cost when outages occur during normal operation, C_D. Hence, C_L is

$$C_L = R + C_{\mathrm{CI}} + C_O + C_D \tag{4}$$

which is used to compare system configurations among and within the three TOs in order to select the one with the lowest value for C_L. In (4) all costs are, actually, referred to some present value at the time when the technology is planned and selected, and they include some estimated financial cost. Analysis of financial and depreciation costs is not within the scope of this work so they will not be further discussed here.

The focus in (4) is on calculating R because $C_{\mathrm{CI}}, C_{\ D}$, and O_C can be obtained from vendors and other sources that are not necessary to discuss here. As it was alluded before, R may change depending on how H_i and the hazard return period are considered. When the historical data imply that a hazard of a given expected intensity may occur a given number of times during the system lifetime, R can be calculated as the product of R calculated for a single occurrence of such event by the number of times the event is expected to happen during the system lifetime. In other cases, it might be desirable to consider different intensities of the critical event, each of which have an associated expected return period. Hence, R can be obtained as the sum of the individual risks obtained for each considered H_i. Another scenario could yield R by considering the worst situation in terms of H_i and/or expected return time. The decision of which of these scenarios to choose—one or more if it is desirable to compare R for different cases—depends on a number of factors including the service area power infrastructure owner practices, strategies, and goals. Since analysis of these factors is out of the scope of this paper and the presented planning framework is not limited by which approach to choose, the discussion will be based on considering a single hazard of an expected intensity so P_H in (3) is known. For example, in case of hurricanes, P_H can be calculated based on public historical statistical data [29] and the fact that P_H follows a Poison distribution [30], [31].

A. Phase I: During the Critical Event

Phase I duration is represented by $\Delta t_{\ 1}$, which is often determined from historical statistical data. Since the proposed framework is not limited to a given hazard and the focus here is not on detailing how to determine $\Delta t_{\ 1}$ and other parameters associated to each hazard, but rather utilizing them, further discussion of these parameters will be limited to particular examples to clarify some concept. In order to have a uniform basis for discussion, most of these examples consider that the hazard is a hurricane for which Δt_1 can be considered to be equal to T_{TS}.

Since it is assumed that P_H is already known, risk calculation involves determining $I_{\mathrm{adj},1}$, which is the sum of two components, each with its respective values for vulnerability and impact: damaged hardware vulnerability and impact V_{1D} and I_{H1D}, respectively, and outage vulnerability and impact V_{1O} and I_{H1O}, respectively. The damaged hardware impact is

$$I_{H1D} = E_{\mathrm{DI}} C_{\mathrm{CI}} \tag{5}$$

where E_{DI} is the expected portion of damaged local power supply infrastructure depending on H_i. The outage impact is

$$I_{H1O} = E_{\mathrm{pu},1} O_{C/t} \Delta t_1 L \tag{6}$$

where $O_{C/t}$ is the cost of one outage per unit time and load, L is the total load existing before the critical event, and $E_{\mathrm{pu},1}$ is the expected portion of L that losses service if a given hazard with well specified H_i occurs. Load and $O_{C/t}$ can be specified based on two criteria: if the service area is a building, they are expressed in kW, but if the service area is a neighborhood they can be measured based on the number of customers.

The value for $E_{\mathrm{pu},1}$ depends on H_i, and its calculation depends on the choice for the TO under consideration, and on the system architecture design and configuration. Eventually, I_{H1O} is influenced by whether or not the substation (for TO A) or the power plant (for TOs B and C) survives the event. So

$$E_{\mathrm{pu},1} = P_S(1 - A_S) + (1 - P_S) = 1 - P_S A_S \tag{7}$$

where P_S is the local power supply infrastructure probability of survival—i.e., the probability as a function of H_i that the plant or substation and the local power distribution network are not destroyed obtained from historical statistical data—and A_S is the system availability. From a reliability perspective, the system is configured as a series combination of the substation or power plant and the distribution network. Thus

$$A_S = A_{\mathrm{ST/PP}}(1 - O_I) \tag{8}$$

where $A_{\mathrm{ST/PP}}$ is the availability of the substation or power plant while operating subject to the critical event and O_I is the expected portion of outages, by now, in the distribution network. In principle, when the service area is a building it can be considered that $O_I = 0$. When the service area is a residential neighborhood, O_I can be estimated based on statistical data from past events. But, in the particular case of TO A, O_I also factors in the critical event effect on the PESI, i.e., the grid. Thus, O_I should be considered in (8) regardless of the service area characteristics. As it is explained next, O_I is also considered—although implicitly—regardless of the service area characteristic as part of the power plant availability calculation for TO B through the grid's power supply availability.

Since substations do not usually have redundant configurations, for TO A the availability of the substation equals the product of the substation components availability. For TO B the power plant availability is obtained from [15]

$$A_{\mathrm{PP}} = \left(1 - \frac{(\lambda_{\mathrm{GS}} + \rho_{\mathrm{GS}}\mu_{\mathrm{MP}})\,\lambda_{\mathrm{MP}}}{\mu_{\mathrm{MP}}(\mu_{\mathrm{MP}} + \mu_{\mathrm{GS}})}\right) A_T A_I \tag{9}$$

where A_T is the transfer-switch availability, A_I is the power electronics interfaces availability that depends on the design of the individual interfaces and the power plant configuration—e.g., redundancy strategy—λ_{GS} is the failure rate of the series combination of the generator set and diesel circuit, μ_{GS} is the genset and fuel repair rate, ρ_{GS} is the genset failure-to-start probability, λ_{MP} is the mains power failure rate, and μ_{MP} is the mains power repair rate. These two last values are considered with the grid operating under the effects of the hazard of a given intensity, and can be estimated based on statistical data from past events, such as the curves indicated in Fig. 7. Since, usually, genset autonomy is much longer than Δt_1, access roads reliability characteristics are not a factor for Phase I. If batteries are used, their contribution to power plant availability can be considered with the approach discussed in [32]. However, if other backup technologies that do not include locally stored energy, such as natural gas generators, are used, then, the availability of these other infrastructures needs to be considered as discussed next with the TO C.

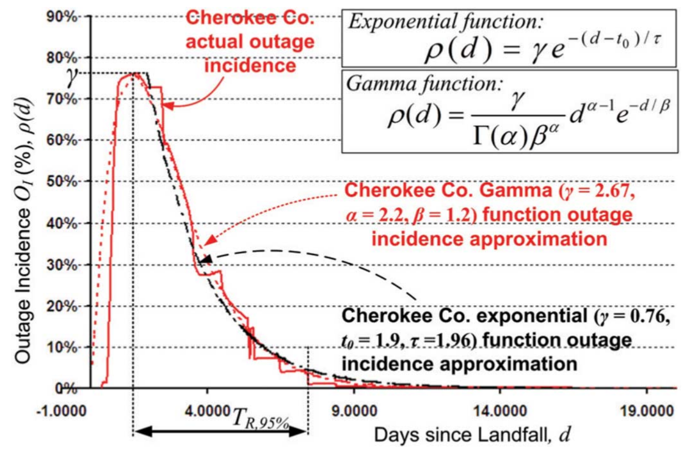

Fig. 7. Outage profile for Cherokee County after Hurricane Ike. and two possible curve approximations. $T_{R,95\%}$ and γ, are also are indicated.

Micro-grids do not necessarily rely on locally stored energy to achieve higher availability. Instead, high availability is achieved with a diverse power supply. Hence, PESI behavior is more relevant than for TO B systems. Thus, similarly to TO A systems, but contrary to TO B systems, critical event effects on the region surrounding the service area may be as relevant as the effects on the service area itself. Since local power sources in TO C are assumed to be in hot-standby, A_{PP} can be estimated using availability success diagrams, such as the one exemplified in Fig. 8 for a micro-grid primarily powered by natural gas microturbines, and complemented by the grid as a secondary supply to provide diversity. Then

$$\begin{aligned} A_{\mathrm{PP}} &= 1 - Q_{\mathrm{MTS}} Q_{\mathrm{EG}} \\ &= 1 - (1 - A_{\mathrm{NGs}} A_{\mathrm{MT}} A_{\mathrm{MTi}}) \\ &\quad \times (1 - A_{\mathrm{EG}} A_{\mathrm{EGi}}) \end{aligned} \tag{10}$$

where A indicates availability, Q indicates unavailability, and the subindices *MTS*, *EG*, *NGs*, *MT*, *MTi*, and *EGi* refer to the microturbine system, electric grid, natural gas supply, microturbine, microturbine interfaces, and electric grid interfaces. The availability of the power electronic interfaces, A_{MTi} and A_{EGi}, and the microturbines, A_{MT}, depend on how they are configured. For example, if there are $n+1$ microturbines in a redundant configuration ($m = 1$ in Fig. 8), then

$$A_{\mathrm{MT}} = (n+1) a_{\mathrm{MT}}^{n} (1 - a_{\mathrm{MT}}) + a_{\mathrm{MT}}^{n+1} \tag{11}$$

where a_{MT} is the availability of each microturbine unit. Once A_{MTi}, A_{EGi}, and A_{MT} are known, A_{NGs} and A_{EG} can be estimated from past events statistical data. For hurricanes, A_{EG} can be known based on the expected percentage of outages in a given area for a given LTCII. For example, A_{EG} for a micro-grid in

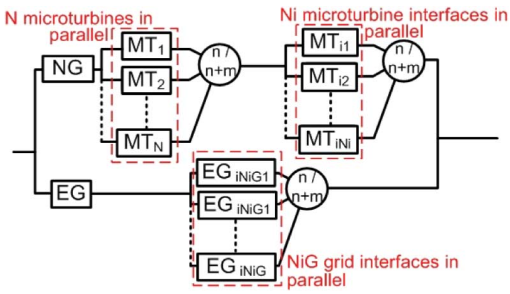

Fig. 8. Reliability success diagram of a micro-grid powered primarily by microturbines and secondarily by the electric grid.

Fig. 9. Gilchrist, TX, after Hurricane Ike.

Fig. 10. Galveston, TX, after Hurricane Ike.

Cherokee County in Texas for an LTCII of 0.55 can be estimated based on Hurricane Ike data (Fig. 7) at $1-\gamma=0.24$, where γ is the peak value for O_I. Natural gas supply availability, $A_{\rm NGs}$, is less dependent on the LTCII and from [33] it can be estimated at almost 5-nines. Hence, even when the grid is severely affected, from (7) and considering a building service area or a buried distribution network, $E_{\rm pu,1}$ is close to 0 because P_S in such area is almost 1, O_I is close to zero, and (10) indicates that $A_{\rm PP}$ is close to 1. Thus, unless micro-grids are severely damaged, a good choice of power supply technologies yields a very low impact in Phase I. This study is also useful in order to select the suitable local DG sources in micro-grids; e.g., during earthquakes both $A_{\rm NGs}$ and $A_{\rm EG}$ may be close to 0, leading to $A_{\rm PP}$ being near 0, too, which implies that some other power supply option needs to be selected. Since PV modules and small wind generators with enough locally stored energy do not need any PESI, they are usually excellent choices if there is enough space for the required capacity.

During Phase I, both V_{1D} and V_{1O} can be related with fragility characteristics. For this reason, it is important to distinguish whether the service area is confined to some building, as it occurs in a hospital or telephony central office (CO), or to some open area which includes a few blocks of a residential neighborhood. For a building, if the hazard is a hurricane, V_{1D} decreases as the facility is built higher to avoid storm surge or flood waters, but if the hazard is an earthquake, higher constructions and more batteries lead to higher values for V_{1D}. Soil characteristics at the building planned location also affect V_{1D} both for hurricanes and earthquakes. For a residential neighborhood service area and in case of a hurricane, outage chances are typically higher in zones where more trees or other constructions, such as billboards may affect the distribution network [5]. Thus, this vulnerability may be related to the number of line spans that have vegetation or billboards within a minimum distance. Similarly, another vulnerability can be considered based on the ratio of overhead distribution lines length with respect to buried distribution lines length.

Vulnerabilities also vary depending on particular characteristics of each TO. If the hazard under consideration is a hurricane, important vulnerabilities in TO A are the substation construction characteristics and the length of the service area feeder. Other characteristics that are important for TO B in addition to those for TO A are the height of the diesel fuel tank access points. In TO C vulnerabilities depend on the choice of local power generators. For PV modules and small wind generators vulnerabilities can be estimated for different LTCII values based on manufacturers and scientific studies on structures resistance and anchoring. In case of sources requiring natural gas, such as fuel cells with reformers and microturbines, V equals 1 for hurricanes but it may increase depending on the portion of the pipeline length running on the shore.

The relationship between P_H, and both I_{H1D} and I_{H1O} during Phase I can be examined with Hurricane Ike as a case study. As mentioned, service area exposure is considered only as part of P_H. Thus, for the same H_i a more exposed site has likely a higher P_H value. Conversely, for the same P_H, less exposed sites likely have lower LTCII. For example, consider two sites in Texas where the expected hazard is what was observed with Hurricane Ike—since the reference event is the same, P_H is the same in both sites: Gilchrist (Fig. 9) with an LTCII of 76 and where all infrastructure disappeared, and downtown Galveston (Fig. 10) with an LTCII of 3.22, and where the impact was less severe because the seawall made downtown Galveston to be less exposed than Gilchrist. Yet, $I_{\rm adj}$ for Galveston still equaled M_I because of Galveston's electric supply intrinsic vulnerabilities originated in the fact that it is on an island powered from the mainland. Away from the coast, likely values for LTCII for the same P_H typically decrease rapidly. With Hurricane Ike, the LTCII in Cherokee County was 0.55. Yet, although damage in such inland areas is significantly less severe (Fig. 2), impact on TO A systems may still be extreme because of the grid's weaknesses, such as predominant aerial wired infrastructure, centralized generation and control, and lack of redundancy in subtransmission feeders.

For many hazards, sensitivity to H_i varies depending on the TO. The previous discussion indicates that for hurricanes, full grid outages are observed for a wide range of LTCIIs, which suggests that TO A systems tend to have high risk values. In TO B systems, LTCII variations play a more influential role on $E_{\rm pu,1}$ through the estimated value for P_S, because locally stored diesel

Fig. 11. Near Point a La Hache, LA, after Hurricane Katrina.

Fig. 12. AT&T's Sherwood CO after Hurricane Ike.

energy makes the situation within the service area to be more important than that of the surrounding PESIs—i.e., mains grid and fuel delivery roads. For example, it can be predicted that P_S for an expected LTCII such as those observed in Gilchrist after Hurricane Ike, or near Point a La Hache, Louisiana after Hurricane Katrina (LTCII = 81) and shown in Figs. 9 and 11, respectively, to be so low that $E_{\mathrm{pu},1}$ equals nearly 1. On the contrary, relatively low LTCII such as that found in Cherokee County after Hurricane Ike likely lead to values of $E_{\mathrm{pu},1}$ close to $1 - A_{\mathrm{PP}}$ because P_S is approximately 1. Intermediate values for LTCII, such as 20 found where AT&T's Sherwood CO is located (about 3 miles SE from of the site in Fig. 10) likely imply P_S values between 0 and 1. Although I_{H1O} for this LTCII may not represent a complete outage, particular vulnerabilities such as a building almost at ground level (Fig. 12), makes V_{1D} to drive $I_{\mathrm{adj},1}$ for such LTCII to M_I, as it occurred with Hurricane Ike.

B. Phase II: Extreme Event Immediate Aftermath

Phase II duration is indicated by Δt_2. Calculation of Δt_2 needs to consider both the case in which the local power supply infrastructure survives (with a probability P_S of such event to happen) and the case in which it does not (with a probability $1 - P_S$). If for a given hazard and H_i value the expected repair time for the destroyed system is Δt_{2S}, and the expected restoration time for all relevant PESIs is Δt_{2i}, then

$$\Delta t_2 = P_S \Delta t_{2i} + (1 - P_S)\mathrm{Max}(\Delta t_{2i}, \Delta t_{2S}). \tag{12}$$

Δt_{2S} has two components: $\Delta t_{2\mathrm{PP/ST}}$ related to the power plant or substation repair time, and Δt_{2D}, related with the service area distribution repair time. Since the service area distribution network has a limited extension, in almost all applications $\Delta t_{2D} \ll \Delta t_{2\mathrm{PP/ST}}$. If $P_{\mathrm{DPP/ST}}$ is the probability that the power plant or substation is destroyed then

Fig. 13. AT&T's Lake CO in New Orleans and its surroundings.

$$\Delta t_{2S} = P_{D,\mathrm{PP/ST}} \Delta t_{2\mathrm{PP/ST}} + (1 - P_{D,\mathrm{PP/ST}})\Delta t_{2D}. \tag{13}$$

If it is assumed that adequate circuit protections are used, damage to the power plant or substation is independent to damage to the service area distribution, and probability for those events only depends on the hazard characteristics and on the attributes of each of those system parts. Thus, if P_{Ds} is the probability that the system does not survive and $P_{D,D}$ is the probability that the service area distribution is destroyed, then

$$P_{\mathrm{Ds}} = 1 - P_S = P_{D,\mathrm{PP/ST}} + P_{D,D} - P_{D,\mathrm{PP/ST}} P_{D,D}. \tag{14}$$

Another difference between phases I and II is that $E_{\mathrm{pu},2}$ is typically a function of time. If the power plant or the substation is destroyed, then $E_{\mathrm{pu},2}$ is 1 until those components have been repaired. Then, for the rest of Δt_2, $E_{\mathrm{pu},2}$ is the system unavailability Q_S which equals $1 - A_S$ given by (8). Otherwise, $E_{\mathrm{pu},2}$ equals $1 - A_S$ from (8) for the entire Δt_2, as shown in (15) at the bottom of the page. In some cases—e.g., TO A systems or TO B and C systems when the service area is a neighborhood—$E_{\mathrm{pu},2}$ also depends on time because O_I is a function of time as suggested by Fig. 7. Once $E_{\mathrm{pu},2}$ is known, I_{H2} is calculated from

$$I_{H2} = O_{C/t} L \int_0^{\Delta t_2} E_{\mathrm{pu},2}(t) dt. \tag{16}$$

It can be expected that in Phase II failure and repair rates and, thus, availabilities, such as A_{PP}, change according to the new operational conditions. For simplicity, failure and repair rates affecting $A_{\mathrm{PP/ST}}$ may be considered constant during Phase II. Yet, this framework does not limit this assumption, so a more detailed evaluation may consider them a function of time.

While in (6) Δt_1 depends on the hazard type and its intensity, as shown by its equivalence to T_{TS} in (1), it may seem that Δt_2 could also depend on the service operator management and

$$E_{\mathrm{pu},2}(t) = \begin{cases} P_{D,\mathrm{PP/ST}} + (1 - P_{D,\mathrm{PP/ST}})Q_S, & \text{for } 0 \le t \le P_{D,\mathrm{PP/ST}} \Delta t_{2,\mathrm{PP/ST}} \\ Q_S, & \text{for } P_{D,\mathrm{PP/ST}} \Delta t_{2,\mathrm{PP/ST}} \le t \le \Delta t_2. \end{cases} \tag{15}$$

maintenance procedures and strategies, and on external factors affecting repairs and service restoration speed. For example, the restoration time of the grid feeding the service area for TO A or B systems depends on the restoration process of the utility owning the local grid, e.g., the number of crews involved in restoring the grid service. Another example of these external factors is manufacturing lead times for replacement parts. However, since Δt_2 is obtained from a mean value representing a baseline case yielded by past events data, particular characteristics affecting Δt_2 for a given site are considered as part of Phase II vulnerabilities. As a result, repairs and logistic operations necessary to restore service and/or keep loads powered influence $I_{\mathrm{adj},2}$ through V but not I_{H2}.

In Phase I, V was mostly related with infrastructure weaknesses affecting both the service area and the PESIs. In Phase II, V also relates to logistical needs associated with the repair process and the service continuity strategies. For example, since TO B systems rely on diesel backup generators to power the load after a hurricane, then V depends on the service area access roads characteristics, and on a number of logistical aspects affecting fuel delivery, including refueling operation effectiveness and timing, diesel availability and contracting strategies, and number of sites owned by the same service operator that can compete for the same resources than the studied service area. For TO C, use of DG technologies, such as PV modules, that do not have logistical needs contribute to make V smaller. However, in many cases these DG technologies are not enough to power large loads. On the other hand, availability of other DG technologies depends on technical and logistical characteristics of infrastructures out of the service area. Thus, a good strategy for TO C is to choose a diverse pool of DG technologies that for a given hazard may reduce V by balancing logistical and external repairs influences with technical limitations. In any case, parameters for this phase are heavily influenced by the critical event effects both inside and outside the service area under study. Since logistical organization and operations are so important in this phase, decisions taken during pre-Phase I preparedness activities—in case the hazard allows for preparation, as it occurs with hurricanes—influence the outcome of this second phase. Thus, effects of pre-Phase I preparations, and logistical planning and actions are implicitly included in this Phase II.

C. *Phase III: Extreme Event Long-Term Aftermath*

Once infrastructures are repaired and service is restored there is still an often overlooked but potentially significant impact: capital costs of unused infrastructure caused by lower demand than the existing pre-Phase I. This is a typical situation for very intense hazards, such as in the area around Lake CO in New Orleans (Fig. 13), where the number of electric users three years after Hurricane Katrina was 50% of those existing before the storm. This demand shortage creates a financial cost associated with underutilized infrastructure due to differences between system capacity—planned, engineered, purchased, and installed before the critical event—and the post-event demand. The problem of unused capacity is aggravated by difficulties in estimating demand evolution after a critical event, which may lead during Phase II to repair the system to demand levels existing before the critical event. Hence, unused capacity costs have to be considered as part of C_L for of the system being planned. Thus, Phase III duration Δt_3 starts when Phase II ends, and lasts as long as there is idle capacity being depreciated. In Phase III, impact can be calculated with

$$I_{H3} = C_{I/t} \int_0^{\Delta t_3} U_{\mathrm{pu},3}(t)dt \tag{17}$$

where $C_{I/t}$ is the cost of the idle capacity per unit time and $U_{\mathrm{pu},3}\ (t)$ is the expected unused portion of the system capacity. The cost $C_{I//t}$ can be calculated by dividing the sum of the system's capital and installed costs by the system's design lifetime. Since it is expected that the load does not instantaneously recover its original level, $U_{\mathrm{pu},3}$ is a function of time. For most critical events with a low to moderate intensity, both $U_{\mathrm{pu},3}$ and Δt_3 are relatively simple to model because service areas are repopulated to the original load levels relatively quickly once the evacuation orders are lifted and the restoration process is completed. Even more, for low hazard intensities, $\Delta t_3 = 0$. Yet, for locations where hazards are intense, $U_{\mathrm{pu},3}$ and Δt_3 are difficult to determine because of the little existent consistent restoration data. For example, although there is some information about New Orleans and the Mississippi River delta repopulation after Hurricane Katrina [34], data is still insufficient. In these cases, the combined experience of service area operator's personnel and local officials may provide enough information to estimate these two parameters during the planning process. For extreme cases when the load never recovers its original level, an upper bound on Δt_3 can be set equal to the equipment total capital depreciation time. For example, for TO B, Δt_3 can be made to last at most ten years because this is the typical life of most commonly used lead-acid batteries. In practice, when the load never recovers Δt_3 spans from the time when the disaster is expected to happen to the time when the idle capacity has fully depreciated.

During Phase III, V relates to inflexibility or un-scalability, because underused infrastructure costs are more severe if the system under study cannot be modified in order to adapt to a reduced and uncertain demand. Although it may initially seem that systems with design based on the TO A may be less vulnerable in Phase III because it does not include a local power plant, their vulnerability may, actually be higher, because substations do not have modular components (e.g., transformers) and design. Designs based on TO B and C may, actually, be less vulnerable to this effect if power plants with modular-scalable and flexible designs are used because components associated with excess capacity can be relocated to other sites without affecting system functionalities.

D. *Significance of Estimation Errors in Risk Calculation*

In order to evaluate the effect of the parameter estimation errors, let's consider the relative error sensitivity

$$S_r = \left| \frac{x}{F(x)} \frac{dF(x)}{dx} \right| \tag{18}$$

where $F(x)$ is a function whose value depends on x, and dF is the error observed in $F(x)$ yielded by a small error dx in estimating x. Error estimation significance for R can be evaluated by calculating S_r with $F(x) = C_L$ and $x = R$. From (4) and (18),

$$S_r = \frac{1}{1 + (C_{\rm CI} + C_O + C_D)/R} = \frac{1}{1 + C_S/R}. \quad (19)$$

Thus, TOs in which C_S—sum of $C_{\rm CI}$, C_D, and C_O—is low with respect to R, as it typically happen with TO A when the load is not critical, are more susceptible to errors in R than those TOs, such as TO C, in which R is reduced through a higher $C_{\rm CI}$. Yet, since the ratio of C_S to R depends on many variables a definite answer depends on a case-by-case evaluation.

Calculation of S_r of R with respect to P_H, V, or I_H yields each the same result: $S_r = 1$. Hence, high (low) relative errors in the estimation of any of these 3 parameters lead to a high (low) relative error in R. There are extensive studies on disasters evaluating relative errors in estimating P_H [30] and since analyzing meteorological or geophysics values is not the focus of this paper, further discussion on errors in estimating P_H will not be discussed here. Nevertheless, in most cases P_H can be estimated with sufficient accuracy to avoid significant impacts on R. Vulnerability estimation errors are not discussed in detail here either because its evaluation is site and application specific. Indeed, since V is evaluated with respect to a baseline case, there are almost endless options to consider. Moreover, inclusion of V in the planning process is often dependent on the lead planner decision based on the desired analysis complexity level, so in those cases when V has a relative large error, part of the lead planner decision involves evaluating tradeoffs between acceptable error levels and planning process complexity.

Within the context of this work, it is more relevant to discuss errors in estimating parameters affecting I_H. The main parameters being estimated that affect the calculations of impacts are the durations of the phases (Δt_1 to Δt_3), infrastructure hardware-related parameters ($E_{\rm DI}$ and $U_{\rm pu,3}$ (t)), and load-related parameter (O_I affecting both $E_{\rm pu,1}$ and $E_{\rm pu,2}$). Errors in $E_{\rm DI}, U_{\rm pu,3}(t)$, and Δt_3 tend to affect more those TOs with higher $C_{\rm CI}$—i.e., TO C—whereas errors in $E_{\rm pu,1}$ and $E_{\rm pu,2}$, and in Δt_1 and Δt_2 tend to affect less reliable systems, such as TO A ones. Estimation errors for TO B systems represent cases somewhat in between TO A and TO C systems because TO B systems have higher $C_{\rm CI}$ and availability than TO A systems but lower $C_{\rm CI}$ and availability than TO C systems.

In Phase I, I_{H1D} and I_{H1O} are directly proportional to $E_{\rm DI}$, and Δt_1, respectively. Hence, S_r for I_{H1D} or I_{H1O} with respect to $E_{\rm DI}$ and Δt_1, respectively, is 1. The other parameter that affects I_{H1} is O_I through $E_{\rm pu,1}$, as indicated by (7) and (8). Except for TO C when the service area is a building, I_{H1O} depends implicitly or explicitly on $1 - O_I$. The resulting S_r increases from 0 when $O_I = 0$ to a positive value $\xi < 1$ when $O_I = 1$. Since $\xi < 1$, the relative error in I_{H1O} is less than that for O_I. Yet, since Δt_1 is almost always much shorter than Δt_2 or Δt_3, usually I_{H1O} does not have a significant weight over total risk calculation. Other estimated parameters in Phase I are those related with $A_{\rm ST/PP}$. Yet, these parameters can almost always be estimated with a negligible error because of industry's long experience in building databases for reliability studies. Survival probability P_S is another parameter often with a negligible error because for a given H_i and disaster complete destruction is relatively simple to model and anticipate, as Figs. 9 and 11 exemplify.

Estimation of most parameters in Phase II leads to similar observation than those in Phase I, except for the effects of that the time dependence of O_I has on Δt_2 and $E_{\rm pu,2}$. For simplicity, let's assume that electric service restoration follows an exponentially decaying form, as indicated in Fig. 7 through $\rho_e(t)$, with γ being the maximum value for O_I reached at the end of Phase I, and τ the time constant—obtained empirically based on the 95% restoration time, $T_{R,95\%}$ trough $\tau = T_{R,95\%}/3$. Since Δt_2 is related to τ—e.g., Δt_2 can be defined as equal to 5 τ or equal to $T_{R,95\%} = 3\tau$—then only τ needs to be estimated. For TO A it can be shown from (16) that if $\Delta t_2 = T_{\rm R,95\%}, I_{H2}$ is

$$I_{H2} = O_{C/t}L((1 - A_{\rm ST/PP})\Delta t_2 + 0.95 A_{\rm ST/PP}\gamma \Delta T_2/3) \quad (20)$$

then, the relative error in I_{H2} increases with increasing values of γ and Δt_2. Hence, special attention needs to be placed in studying these parameters in order to reduce errors in estimating I_{H2}. A similar relationship is observed for TO B or TO C when the service area is a neighborhood. However, when the service area is a building, $E_{\rm pu,2}$ for both TO B and C equals $(1 - A_S)$. Hence, S_r of I_{H2} with respect to Δt_2 is 1.

In Phase III, if load restoration is assumed to follow a bounded exponentially increasing curve (Fig. 6), then $U_{\rm pu,3}$ (t) has an exponentially decreasing form. The two parameters that need to be estimated are the initial idle capacity $U_{\rm pu,0}$ and Δt_3. Since Δt_3 is related to the time constant of $U_{\rm pu,3}$ (t), then S_r for I_{H3} with respect to either $U_{\rm pu,0}$ or Δt_3 equals 1 for all TOs, so relative significant errors in I_{H3} could be made when $U_{\rm pu,0}$ or Δt_3 are large. However, both $U_{\rm pu,0}$ and Δt_3 have deterministic upper boundaries—total system capacity for $U_{\rm pu,0}$ and equipment capital depreciation time for Δt_3. Hence, in their maximum values, when their effect on the error in calculating I_{H3} would be highest, there are no estimation errors.

In order to support this discussion, consider that in 2005, a few weeks after Hurricane Rita, a study is performed in order to evaluate power options for a data center to be located in Cherokee County, Texas, that will process banking data from 100 offices. The downtime cost for each bank is \$30 K/hour. For such a data center with a total power consumption of about 700 kW, $C_{\rm CI}$ for TO A is \$200K, for TO B is \$2.4M (includes 4 h of battery backup), and for TO C is \$2.8M (powered by natural gas microturbines and diesel reciprocating engines). For simplicity, C_O for all cases is \$613 K/year and total depreciation time is ten years. The potential hazard affecting the site is a strong category 2 hurricane striking the Texas northern Gulf Coast, which translates into an LTCII of 0.55. The return period for such hurricane is 19 years. Thus, P_H for a ten-year span is 0.31, and if the hurricane occurs it is more likely to happen at the 5.82 year mark. It is expected that such a hurricane will close 30% of the 100 banks for 30 days and another 20% of them will close permanently. Only for TO C it is possible to relocate half of the idle capacity. It is assumed that all vulnerabilities are 1 and that $P_S = 1$. Planners use data from the 2004 and 2005 hurricane seasons in order to characterize the hazard. From these data, it can be shown that γ follows a logistical regression curve

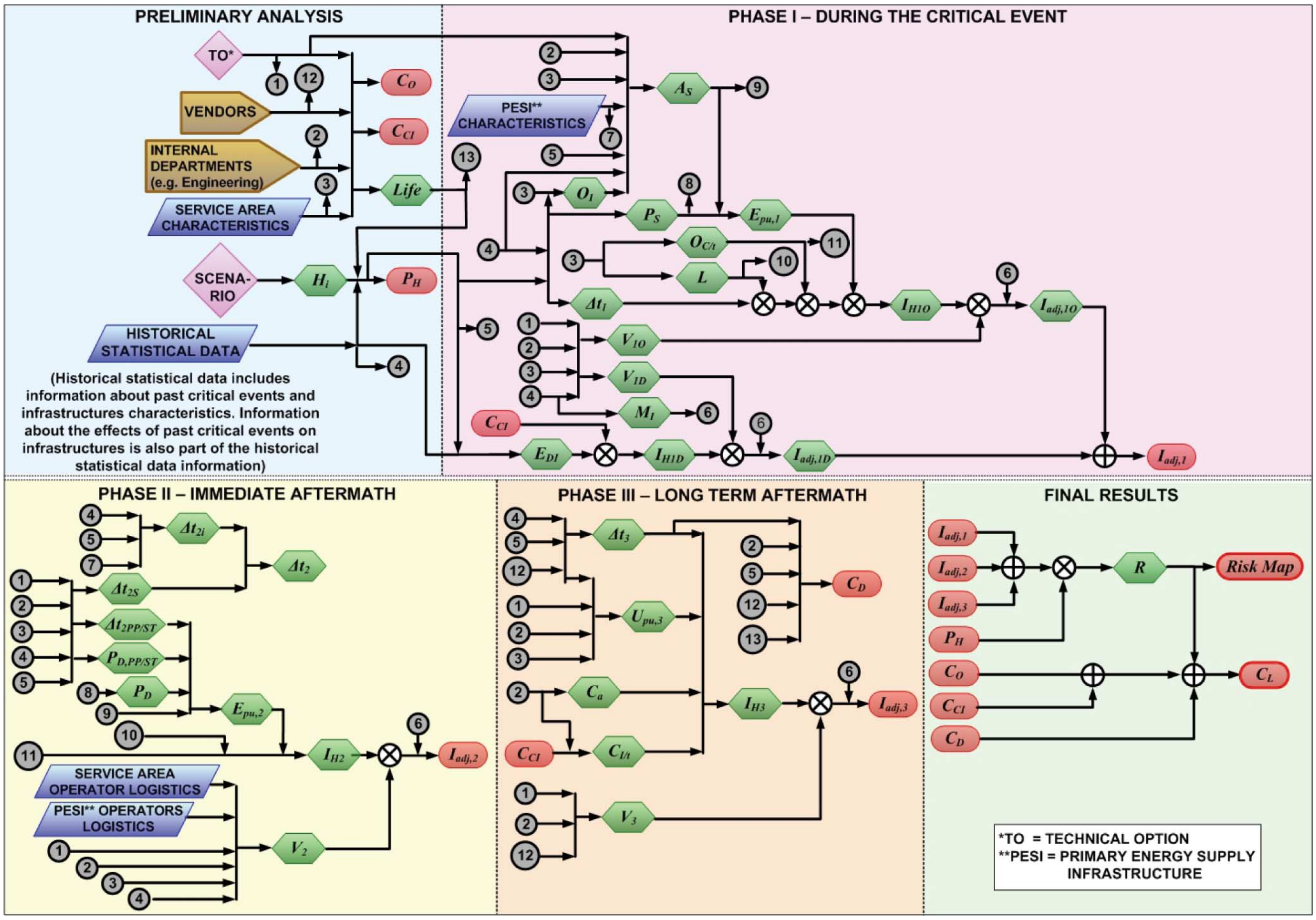

Fig. 14. Graphical flow chart representation of the described risk analysis-based planning framework process.

TABLE I
LIFETIME COSTS AND ITS COMPONENTS IN MILLIONS OF DOLLARS

TO	Values	C_{CI}	C_O	C_D	R	C_L	Largest $I_{adj,i}$
A	Estimated	\$0.2	\$6.1	\$240.8	\$38	**\$285.1**	$I_{adj,2}$ = \$104.22
B	Estimated	\$2.4	\$6.1	\$2.4	\$0.69	**\$11.6**	$I_{adj,2}$ = \$1.93
C	Estimated	\$2.8	\$6.1	\$0.24	\$0.066	**\$9.2**	$I_{adj,3}$ = \$0.21
A	From Ike	\$0.2	\$6.1	\$226	\$38.07	**\$270.4**	$I_{adj,2}$ = \$102.24
B	From Ike	\$2.4	\$6.1	\$2.26	\$0.41	**\$11.2**	$I_{adj,2}$ = \$0.93
C	From Ike	\$2.8	\$6.1	\$0.23	\$0.11	**\$9.23**	$I_{adj,3}$ = \$0.35

with respect to Log(LTCII) in which there is a 75% chance that the actual value for γ falls within $\pm$10% of the value given by the regression curve, implying a correlation of almost 0.85. For $T_{R,95\%}$ the regression curve is a 6th degree polynomial with a similar correlation. The values estimated from these curves were $\gamma = 0.68$, and $T_{R,95\%} = 6.71$ days. An additional value of interest is A_S which equals 3-nines for TO A in normal operation, 0.996 for TO B during the expected hurricane and 5-nines in normal operation, and 6-nines for TO C [15]. Table I summarizes the results of the estimated calculations, and for comparison adds actual data from Hurricane Ike which affected the studied area three years after Rita causing at the data center site a $\gamma = 0.76$, and a $T_{R,95\%} = 5.89$. In both calculations TO C is the best choice with a minimal risk. Downtime cost leads to higher C_L for TO A. Outages in Phase II are the highest risk factor for TOs A and B. Errors between estimated and actual values for C_L are small enough to validate the proposed evaluation framework.

V. SUMMARY AND CONCLUSIONS

This paper presents a risk analysis-based framework—summarized in Fig. 14—to plan power procurement decisions for service areas that could be subject to a critical event. The planning process involves comparing three different TOs based on their lifetime cost obtained from adding the capital and installation cost, the operation cost, the downtime cost under normal conditions, and the risk associated with losses related with service outages, equipment damages, and unused hardware capacity that may result from a critical event. The three TOs are: direct power from the grid, grid supported by a backup power plant, and a micro-grid with local DG. For the last TO, the planning framework allows identifying the most suitable DG technologies to be used at the evaluated site.

The analysis divides the risk related with a given hazard in 3 phases: during the critical event, the immediate aftermath, and the long term aftermath. For each of these phases risk is calculated as the combined monetary effect of the hazard impact and the system vulnerability. Although hurricanes are the main hazard used to exemplify some of the concepts, the same framework can be used to a wide variety of critical events, both of nature and human origin. In practice, it is expected that the planning framework will be implemented with a computer. The systematic method represented in Fig. 14 and the use of a quantitative risk analysis approach (as opposed to a qualitative approach) facilitate computer implementation of the planning process and comparison of the relative value of each TO. It also allows for a simple mapping of risk levels that may affect a system when located at different sites. Although the described calculations rely primarily on using expected mean values from a random variable, the framework allows for more detailed evaluation using more elaborate distributions. Yet, in most practical problems, these more elaborate methods do not yield a significant difference over the expected mean value approach and likely demand more time. Future work will be dedicated to study historical statistical data from past hurricanes and earthquakes in order to support practical implementation of the planning framework.

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Telecom Power Planning for Natural Disasters: Technology Implications and Alternatives to U.S. Federal Communications Commission's "Katrina Order" in View of the Effects of 2008 Atlantic Hurricane Season

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Abstract — This work examines the potential value of the U.S. Federal Communications Commission "Katrina order" and discusses benefits and practicality of technology alternatives. The analysis is based on the effects of 2008 hurricanes Dolly, Gustav, and Ike through extensive supportive photographic evidence from on-site surveys. This information is compared with Hurricane Katrina's data. The analysis seems to indicate that the "Katrina Order" may not address some important issues, and that other technical approaches may provide a better solution.

I. INTRODUCTION

This paper discusses the implications of U.S. Federal Communications Commission (FCC) order 07-107 [1]. The analysis compares the conclusions reached by the FCC with those reached in [2], and evaluates the Order potential effectiveness by detailing some of the effects of 2008 hurricanes Dolly, Gustav, and Ike on telecom infrastructure through extensive photographic data obtained during on-site surveys performed few days after each storm passed.

After Hurricane Katrina caused an extensive outage in most communication networks in southeast Louisiana, and the coast of Mississippi, the FCC appointed a panel to study the causes of these extensive communication outages and to make recommendations in order to avoid the same situation to occur again in the future. The analysis of the FCC Katrina Panel was based, fundamentally, on a series of 5 meetings in order to "hear oral presentations" [3] by "interested parties" [3] and panel members—"called upon the experiences of its members, many of whom were directly involved in the recovery efforts following Katrina" [3]—and discussions both publicly and in three working groups. The panel issued its final report in June 2006 and identified "flooding, lack of power and/or fuel, and failure of redundant communication pathways for communications traffic" as the "three main problems that caused the majority of communications network interruptions" [3]. The panel's recommendations encompass four areas [3]:

- "Pre-positioning the communications industry and the government for disaster in order to achieve greater network reliability and resiliency.
- Improving recovery coordination to address existing shortcomings and to maximize the use of existing resources.
- Improving the operability and interoperability of public safety and 911 communications in times of crisis.
- Improving communication of emergency information to the public."

Approximately a year later the FCC issued its order FCC 07-107 [1] addressing the findings and recommendations of the FCC Katrina panel. In its key rule, in section § 12.2 Backup Power, the FCC mandated that "local exchange carriers (LECs), including incumbent LECS (ILECs) and competitive LECs (CLECs), and commercial mobile radio service (CMRS) providers must have an emergency backup power source for all assets that are normally powered from local AC commercial power, including those inside central offices, cell sites, remote switches and digital loop carrier system remote terminals. LECs and CMRS providers should maintain emergency back-up power for a minimum of 24 hours for assets inside central offices and eight hours for cell sites, remote switches and digital loop carrier system remote terminals that are normally powered from local AC commercial power. LECs that meet the definition of a Class B company as set forth in Section 32.11(b)(2) of the Commission's rules and non-nationwide CMRS providers with no more than 500,000 subscribers are exempt from this rule" [1]. Hence, this order specifying 24 or 8 hours of local back-up power applies not only to areas at risk of hurricanes (or other disasters, such as earthquakes) but it applies to the entire U.S. territory. Moreover, digital telephony providers, such as cable TV operators (CATV), are also included in the mandate if they have more than 500,000 subscribers.

Although the FCC acknowledged in the mandate that most of the service providers back-up capacity exceed FCC's requirements, the order was challenged by a group of wireless communication operators under the Cellular Telephone Industries Association, CTIA-The Wireless Association on the basis that the FCC was overstepping its power, and that additional back-up systems could create many practical issues, such as weight limitations in many cell site structures. In February of 2008 the U.S. Court of Appeals for the District of Columbia Circuit took some initial steps to hold the application of FCC's order and in July of the same year the

Court decided that it will not rule on the case until the Office of Management and Budget (OMB)—the OMB is an office within the U.S. executive branch that oversees the activities of federal agencies—decides on the matter. Finally, after the OMB disapproved Katrina's back-up power order at the end of 2008, the FCC decided to reformulate its approach in order to address the problems that originated with Katrina. Hence, it is important to study which aspects of the order are valuable enough so they are kept for further use, which aspects were not considered sufficiently, and which ones have been a distraction that have deviated the attention from understanding the fundamental problems and finding their long term critical solutions. This is the goal of this paper.

The analysis considers communication networks behavior during hurricanes Ike and Gustav, which also affected the area around New Orleans, but approximately three years after Katrina, in 2008. The next section describes some other lessons from Hurricane Katrina on the basis of another study [2] [4] which had a different approach than that of the FCC. Section III discusses these lessons in the context of last year's hurricanes and evaluates these lessons with the FCC Katrina mandate. Section IV includes a summary of the discussion as a conclusion for this paper.

II. Lessons from 2005 Hurricane Katrina

In addition to the FCC analysis, there was one other study that analyzed the effects of Hurricane Katrina on telecommunication networks and proposed some solutions [2] [4]. This study [4] was conducted independently of the FCC analysis [3]. In contrast to FCC panel analysis the work in [4] followed a traditional scientific approach in which the first step was to collect data on site through a damage assessment conducted few weeks after the storm. This data was combined with additional information from service providers and aerial pictures of the area in order to elucidate the causes for such extensive outage and propose solutions to overcome them in the future.

Although the study in [2] also identifies power issues as one of the main causes of the outage, it provides a more insightful and technical findings than the Katrina panel conclusions. During Katrina the storm surge destroyed nine of Bellsouth's central offices. Six other central offices lost service when the levees that protected New Orleans failed and the city flooded. Additionally, eighteen central offices lost service due to engine fuel starvation or other type of genset failures. Evidently, Hurricane Katrina affected Bellsouth's (now AT&T) centralized network elements more severely than other storms. Distributed network elements, such as cell sites and digital loop carrier (DLC) systems were certainly affected, but a small percentage of these distributed sites were damaged—most of outages at the many distributed elements were also caused by power issues. In part, these power issues at distributed network elements were caused by lack of a permanent power solution at the site which later led to more problems when many portable generators were deployed at each site. Another important issue was lack of consistent construction practices for base stations, with many sites having part of the infrastructure above the flood plane and below it.

The most significant finding of [4] was that the main issue that originated the extensive outages due to lack of power was that communication sites grid tie acted as a single point of failure for the system because back up power solutions could not ensure uninterrupted power indefinitely. Hence, the problem with communication sites power supply is lack of a diverse input. For this reason, additional back up or redundant power paths may not prevent loss of service due to lack of power at the sites. Hence, some of the alternatives proposed in [4] contradict the ones in the FCC mandate. Although increased used of permanent generators at cell sites is suggested, the analysis in [2] also proposes using natural gas supply for gensets (or, eventually, fuel cells) or increased use of local distributed generation sources.

Other observations and suggestions discussed in [2] in addition of increasing the use of natural gas and migrating from energy standby systems towards power distributed generation systems include:

- Implement coherent cell site construction practices locating all infrastructure above the flood plane.
- Use portable central offices instead of DLCs in order to restore service to damaged centralized network elements.
- Coordinate deployment of portable gensets to one per site instead of having multiple portable generators, one from each network operator, at the same cell site.
- Use wherever possible pole mounted systems over ground mounted systems.

Although air conditioning was not discussed as an important issue in [1] or [2] because cooling was not a contributing factor for the communication outages, air conditioner is another source of problems during critical events. As pointed out in [5], since air conditioners are usually connected to the ac mains with gensets as the only backup powering alternative, the air conditioner availability cannot be better than that of the grid-genset combination. Hence, air conditioners availability in normal conditions is less or equal than 4 nines [5], one order of magnitude less than the required one. The worst failure mode in terms of air conditioning system is an utility grid outage followed by a genset failure—a situation more probable to occur during critical events and that highlights fundamental availability issues in communication systems due to lack of diversity in the power supply. It is true that thermal inertia prevents immediate telecom equipment failure, but during critical events power outages usually last several days increasing the likelihood of a simultaneous genset failure. Even worse, during critical events it can be expected that a genset's down time will last longer than the 5 hours expected during normal conditions [5]. Within this time frame critical loads failure due to overheating is then very likely and even if failure does not occur, higher operating temperatures will eventually decrease components life.

III. Effects of the Hurricanes of the 2008 Season on Communication Networks

Three hurricanes—Dolly, Gustav, and Ike—made landfall on the U.S. Gulf Coast in 2008, the most significant cyclone action since the extremely active 2005 Hurricane Season when five hurricanes made landfall, including Katrina. Dolly made landfall in the south Texas coast on July 23. Except for some few towns and cities in the area, including South Padre Island, Harlingen, and Brownsville, the area affected by Dolly is not densely populated. Hence, although Dolly produced some significant flooding along the Rio Grande Valley where there exist levee issues as it occurs in New Orleans, communication outages were minimal, with less than 600 AT&T subscribers loosing service. Some more outages were reported in wireless communication networks, primarily caused by lack of power in cell sites. However, since roads were not significantly affected by the flooding and the storm surge was not very intense, portable generators and cell-on-wheels could be deployed quickly avoiding important outages.

Hurricane Gustav had some similarities with Katrina. It made landfall on September 1, just a three days after the third anniversary of Hurricane Katrina and just about 60 miles west of Katrina's point of contact with Louisiana's coast. In terms of wind speed, Gustav was somewhat less intense than Katrina, with maximum sustained winds of 90 kt. [6], about 10 to 20 kt. less than Katrina [7]. The most significant difference was in the storm surge. Gustav's storm surge was significant but less intense than that of Katrina and although some levees were just overtopped and a few breached, New Orleans did not flood. However, Gustav moved away from the coast much slower than Katrina originating some flooded areas and complicating restoration efforts due to persistent rain. Telephone outages were more significant than with Dolly, affecting close to 50,000 lines [8] in Louisiana with the peak occurring on September 4, 72 hours after Gustav made landfall. This delayed peak may point towards power related outages, when batteries at the sites were exhausted. Outages in distributed network elements in fixed telephony outside plant was not a extensive as with Katrina because many DLCs had been located on platforms and some were equipped with permanent natural gas gensets—as it happened with other hurricanes, including Katrina, natural gas outages were minimal after Gustav. Additional outages affected wireless cell sites, although their magnitude and extension was limited. Direct infrastructure damage was also limited.

The last of the three hurricanes was Ike. It made landfall in Galveston Island, in the northeast Texas coast on September 13^{th}. Ike was not an extremely intense hurricane in terms of wind strength but its storm surge was comparable to Katrina's reaching 20 ft at some points of the Bolivar Peninsula [9] versus maximum heights of 28 ft produced by Katrina in Mississippi [7]. Ike's very large size not only contributed in part to its significant storm surge but it also made its effect noticeable long before Ike made landfall. Its track parallel to the coast also led to large areas of the coast being affected, reaching practically all the northern Gulf coast but in particular Louisiana's and the northeastern Texas coast. Perhaps the most significant feature of Ike was not its effects on the coast, but the damage caused by very strong winds hundreds of miles inland, in the Ohio River Valley. In the same way that Katrina was compared with a classic military operation [10] similar to the effects of an overwhelming frontal attack, Ike could be compared with another military operation similar to pincer movement in which after flanking the main front the rear is attacked with the goal of breaking the logistical support for the front. In this sense, the extensive power outages caused in the Ohio River Valley, demanded resources, such as portable gensets and repair crews, that otherwise would have been deployed at the heart of the damaged area, near the coast.

Although the outages caused by Ike on communication networks were not as extensive as Katrina's they were nevertheless significant. The fixed telephony outages peaked at close to 340,000 [11]. AT&T lost service in 5 central offices with one of them, Sherwood (Fig. 1), been destroyed. Like Katrina, power issues were one of the most important outage causes, although with Ike, effects on distributed network elements were as significant on centralized elements. In addition to the discussed issues in the 5 central offices, AT&T also lost service in 551 remote terminals due to lack of power [11]. A few more DLCs were also destroyed (Figs. 2 and 3). Transmission links were also affected, particularly in the Bolivar Peninsula, which needed to be restored with microwave radios (Fig. 4). Although Verizon's central offices did not lost service, 321 remote terminals were affected, mostly from lack of power. Windstream lost service in 7 switching stations and 237 remote terminals due to lack of power [11]. More power originated outages were reported by Eastex, which lost service in 2 central offices due to failed gensets, and in 82 DLCs due to lack of power [11]. Time Warner Cable had almost three-quarters of its network affected by lack of power [11]. It is unknown the complete effect on Cameron Communication's network but the damage assessment conducted by the author of this paper identified some few of their sites, such as the one in Fig. 5, affected. Wireless communications networks were also affected, mostly at cell sites. Although some cell sites were destroyed (Fig. 6) most of the loss of service were caused by power outages. Like with Katrina, cells on light trucks (COLTs) and cell on wheels (COWs) were extensively used to restore service to damaged cell sites (Fig. 7).

IV. Potential Merits of FCC "Katrina Order" Based on the Effects of the Hurricanes of the 2008 Season

Although the FCC order was not effective during the 2008 Hurricane Season the question to address in this section is whether or not its mandate requiring a minimum stored energy in all U.S. communication sites of companies with more than half a million subscribers is valuable towards reducing or eliminating the number of communication outages during storms. The effects of Hurricane Ike on the Ohio River Valley indicate a positive aspect of the FCC mandate: it application in the entire U.S. territory and not just the coastal areas that are more expose to hurricanes. However, it is fair to acknowledge that a thorough and objective risk analysis [12] that would consider the cost of extending backup times in most of U.S. communication sites and the chances of suffering an extensive power outage would not yield the need for implementing such solution everywhere as the FCC mandated.

Another positive aspect of FCC's Katrina order is to include CATV operators, particularly because of the increased commercialization of data-based telephone systems operating over CATV infrastructure. However, there are two complicated issues to address in order to ensure a more reliable telephone service over CATV networks. One is that telephones for cable telephony need to be powered at the customer premises, which will not be typically possible after grid outages. Hence, CATV telephones will very likely loss service after a hurricane even when the CATV network is still operating. The other is difficulties to provide back-up power to pole mounted CATV infrastructure [13], which may lead to inadequate solutions, such as the one in Fig. 8.

The most controversial aspect of the FCC order is the requirement for a minimal backup time at all communication sites. For centralized network elements the 24 hours requirement do not seems to provide an improvement from the existing alternative because most of the communication companies comply and even further exceed this requirement at their central offices or other communication centers. This is a result of historical evolution of U.S. communication networks from the Bell System which had at least 48-hours of back-up power in all central offices [14]. Moreover, Bellsouth typically had at least 72-hours worth of diesel [15], which explains why most central offices that had outages due to power issues started to fail no sooner than 3-days after Katrina made landfall. The 8-hours of back-up in distributed elements is also common in fixed telephony's outside plant remote terminals, although not as common in cell sites [16]. However, 8 hours may not be enough to sustain operation during disasters [13].

Relying exclusively on locally stored energy for extended operation through back-up power supply, as implied in the FCC mandate, has several practical issues including the possibility of weakening the site structure, and limits in some local fire codes. Yet, the most important observation is that extended back-up operation time through locally stored energy does not address the fundamental issue which is the existence of a single point of failure at each communication site grid tie due to lack of power input diversity. Hence, genset failures, such as those mentioned during Ike or the one that seemed to have happened in Fig. 9, and/or air conditioner failures may still cause a significant outage in a central office regardless of how much diesel is stored at the site. Therefore, the FCC mandate focus on locally stored energy may have acted as a distraction towards finding a solution that addresses the true nature of the power issues in communication sites. This solution may include the possibility of using natural gas gensets where possible. This alternative showed its value in many AT&T outside plant remote terminals installed in and around New Orleans after Katrina. Another option could be using distributed generation systems although its application requires a case by case study considering a risk assessment and a study of the energy sources local vulnerability [12]. Still, there is possible to find sites with important potential for such solution, such as the Sabine Pass central office shown in Fig. 10.

The FCC mandate also leaves some infrastructure issues unconsidered which originated outages or logistical problems during Katrina and in the recent hurricanes of the 2008 season. One of those issues is the lack of consistency in distributed network elements—cell sites or outside plant remote terminals, such as DLCs—construction practices, particularly their construction below the expected flood plane, such as the cell site in Fig. 6 destroyed by Ike's storm surge. Another example is shown with the DLCs in Figs. 2 and 3. While the one in Fig. 11 that replaced Delacroix central office, destroyed by Katrina, survived both Gustav's and Ike's storm surge with damage in the fence only, or the one in Fig. 12 also undamaged, the ones in Figs. 2 and 3 were destroyed because although they were in a more vulnerable location they were placed on a platform at a much lower level than the other two. Some of the other infrastructure issues that were not addressed by the FCC mandate and that was commented in Section II of this paper have already been addressed by many of the communication companies. One example is the use of more propane-fed permanent gensets at base stations which reduces the number of sites with multiple deployments of portable gensets. Another example is the use of switches on wheels at Sherwood central office (Fig. 13) to restore service after Ike destroyed the existing equipment at the site. Thus, progress in order to achieve more resilient networks has been made even when some of these issues were not included in FCC's mandate. Yet, some more progress needs to be made in issues not considered by the FCC, particularly regarding hurricane resistant construction practices. Such practices may include analysis on one telephony infrastructure element not discussed in any previous work but not less important: service area interfaces (SAIs). Particularly after Ike, many of the SAIs, such as those in Figs. 14 and 15 were destroyed leading to more outages and complicated repairs.

V. Conclusions

This paper have discussed the value of the FCC order 07-107, the "Katrina order," towards improving communication networks availability after hurricanes, and, in particular, its power back-up mandate. This look is relevant even though the order was disapproved by the OMB because an analysis of the order may contribute to improve future reviews. The discussion in this paper compares the lessons and findings from the FCC with those yielded by a work based on a scientific approach and presented in INTELEC 2006. The study also considers the effects on communication networks of the three hurricanes that impacted the U.S. during the 2008 Hurricane Season: Dolly, Gustav, and Ike.

This paper identifies the country-wide application of the order as a positive aspect. Another positive aspect is the inclusion of CATV-based telephony networks, although important practical aspects, such as the need for power for digital telephones at the customer premises, are unaddressed in the order which may limit its effectiveness. However, the order seems to fail to identify the lack of power input diversity as the root issue behind outages originated due to lack of power. Hence, its goal of improving availability during disasters may not have been fully achievable. Another critical point of the order is that it did not addressed issues related with lack of common and coherent construction practices, particularly for distributed network elements. Thus, the OMB decision may open an opportunity to reach consensus on adequate practices needed to truly improve communication networks availability after disasters.

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Fig. 1. AT&T's Sherwood central office in Galveston Island, Texas.

Fig. 2. A DLC toppled and destroyed by Ike's storm surge.

Fig. 3. Destroyed DLC.

Fig. 4. South side (left) and North side (right) of an emergency microwave link in the Bolivar Peninsula.

Fig. 5. Cameron Communications site affected by Ike.

Fig. 6. Two views of the same cell site located on Texas Highway 124 destroyed by Hurricane Ike.

Fig. 7. A COLT (left) and a COW (right) used to restore service after Ike.

Fig. 8. A portable camping genset on top of a CATV pole-mounted UPS in the town of Plaquemine, Louisiana, after Hurricane Gustav.

Fig. 9. A large portable generator outside Goodwood central office in Baton Rouge, Louisiana, less than a week after Hurricane Gustav.

Fig. 10. Sabine Pass Central Office. The building in the center was the original central office building flooded by Hurricane Rita in 2005. This building was destroyed by Ike in 2008. The DLC on the right was used to initially restore service after Rita and was also destroyed by Ike. The remote switch operating when Ike made landfall is inside the shelter on the left. Ike's storm surge reached the level of the shelter platform.

Fig. 11. A damaged fence near the DLC that replaced Delacroix Central Office, destroyed by Hurricane Katrina in 2005.

Fig. 12. A DLC in Galveston Island. The Gulf of Mexico can be seen in the background on the right.

Fig. 13. Switches on wheels behind Sherwood central office.

Fig. 14. A destroyed SAI by Ike. Destroyed repeaters are mounted on the pole on the left.

Fig. 15. Two damaged SAIs in the Bolivar Peninsula.

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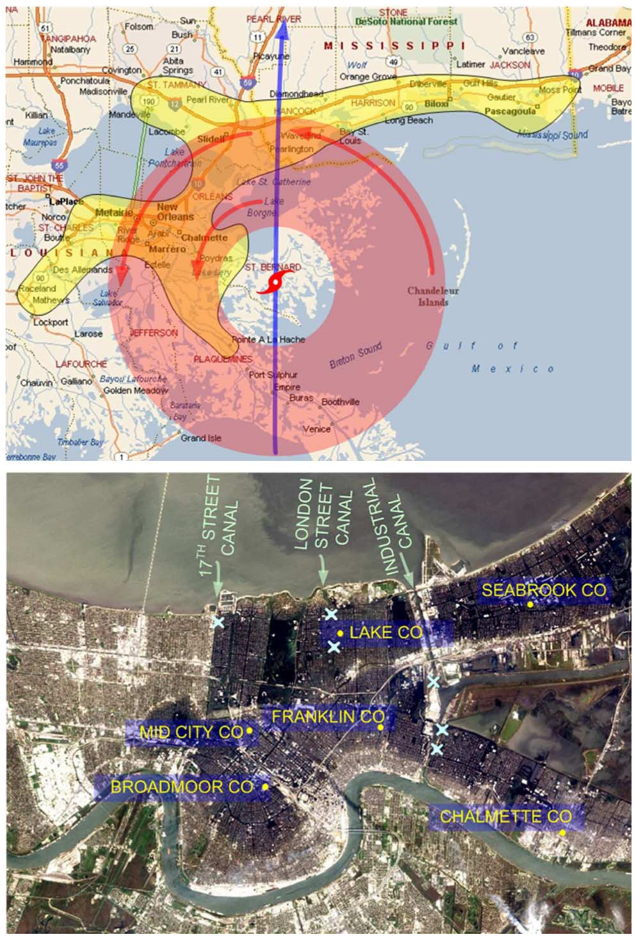

(Top) Hurricane Katrina at 6:45 AM local time on August 29, 2005. (Bottom) Satellite imagery of New Orleans showing the flooded areas in dark color and levee breaches shown in light blue crosses.

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Telecommunications Power Plant Damage Assessment for Hurricane Katrina–Site Survey and Follow-Up Results

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***Abstract*—This paper extends knowledge of disaster impact on the telecommunications power infrastructure by discussing the effects of Hurricane Katrina based on an on-site survey conducted in October 2005 and on public sources. It includes observations about power infrastructure damage in wire-line and wireless networks. In general, the impact on centralized network elements was more severe than on the distributed portion of the grids. The main cause of outage was lack of power due to fuel supply disruptions, flooding and security issues. This work also describes the means used to restore telecommunications services and proposes ways to improve logistics, such as coordinating portable generator set deployment among different network operators and reducing genset fuel consumption by installing permanent photovoltaic systems at sites where long electric outages are likely. One long term solution is to use of distributed generation. It also discusses the consequences on telecom power technology and practices since the storm.**

***Index Terms*—Damage assessment, hurricane, natural disaster, power systems, telecommunications power.**

I. Introduction

On August 29, 2005, Hurricane Katrina struck the United States Gulf Coast and delivered an extreme challenge to the combined telecommunications and power infrastructure. Devastating effects on both infrastructures hampered rescue efforts, stymied attempts to coordinate early responses, and made calls for aid impossible from the hardest hit areas. There is limited published research on disaster damage and restoration of telecommunications systems or on how their reliability under extreme conditions is related to power supply. The most comprehensive work was in the context of the 1995 Kobe earthquake [1] and other natural disasters in Japan [2]. High winds and hurricane studies have originated in the U.K. [3] and the U.S. [4]–[6]. The relevance of these studies to current network planning may be limited, since these past works are at least a decade old. Since then, the growth of cellular communications, broadband service, and other fundamental changes in services have influenced rapid change in the telecommunications infrastructure. A more recent effort towards disaster planning is led by the International Telecommunications Union (ITU) through the ITU-T (the ITU standardization sector) study group 2 [7]. Some of those related with the 2004 Indian Ocean tsunami [8]–[10] identify lack of power as one of the main post-disaster causes of outages, yet, there were no proposals related to telecom power management [11]. Another recent work focusing on disaster management is from Japan [12] but details about failures and restoration are few. Hurricane Katrina prompted several studies on the effect of natural disasters in the areas of communications [13], civil engineering [14], and medicine [15], among others. However, to this date, only the present study, originally presented in [16], has focused on the telecommunications power infrastructure.

This paper extends the knowledge of hurricane impact on the telecommunications power infrastructure. Information is presented both from a direct on-site survey conducted by two of the authors on October 17-23, 2005 in the area highlighted on the map shown in Fig. 1, and from other relevant sources. Satellite and aerial imagery taken shortly after the storm were used to determine the status of the affected area. Photographs and damage observations are from the site survey unless otherwise indicated. The analysis focuses primarily on technical and operational aspects and supports the conclusion that lack of power was a major cause of telecommunications outage. Power supply technology is identified as a critical need to enhance telecommunications system disaster survivability. Specific technologies and research needs for enhancing disaster resiliency in telecom power systems are identified. Some of the consequences of Hurricane Katrina on telecom power infrastructure planning and practices are also explained. In particular, this paper discusses orders issued by the Federal Communications Commission (FCC) affecting telecom power technology based on [13].

II. Hurricane Characteristics and Damaging Actions

Hurricanes are large, intense storms characterized by extreme low-pressure centers. They are categorized according to their maximum sustained wind speed using the 5-level Saffir-Simpson scale, with a category-one storm as the weakest.

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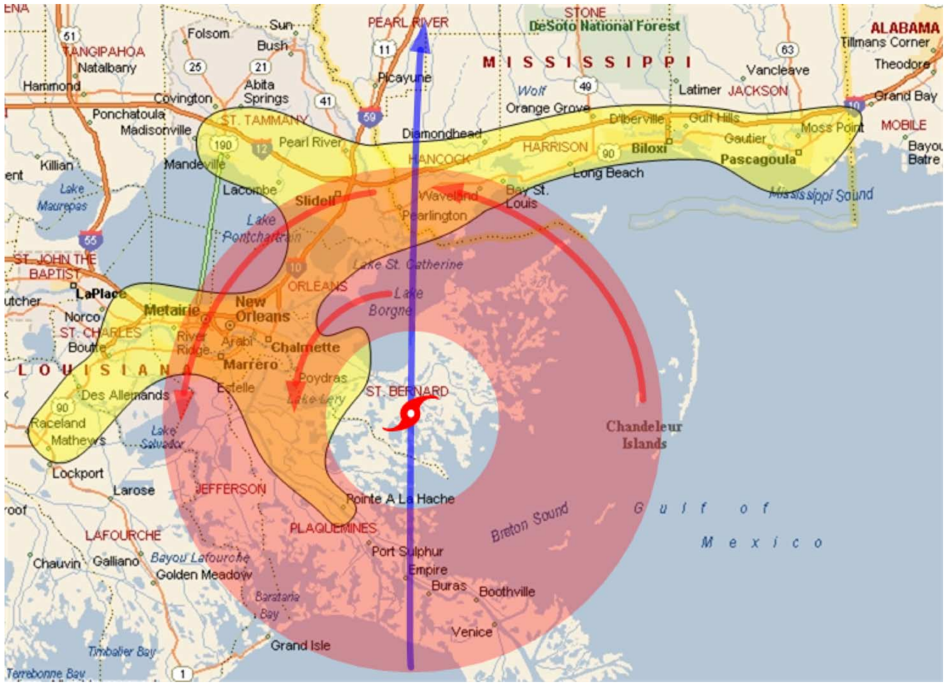

Fig. 1. Hurricane Katrina at 6:45 A.M. local time on August 29, 2005. The area of hurricane force winds is indicated with a red donut. The path is marked with a blue vertical arrow and the wind direction with counterclockwise red arrows. The site survey region is the lightly-shadowed area.

Fig. 2. Interior of a destroyed communications center. The power plant batteries (left and detail) and rectifier cabinets (right) are covered in mud.

In addition to wind, other important hurricane damage mechanisms include torrential rains, flooding, spun off tornados, and storm surges [17].

As discussed in [18]—Hurricane Katrina's official meteorological analysis—the storm made landfall on the U.S. coast near Buras, Louisiana, at 5 A.M. local time on August 29, 2005 with maximum sustained winds of 200 km/h, a category-three hurricane. Although winds were not as strong as some other hurricanes that have affected the U.S., Hurricane Katrina delivered an intense storm surge from Port Fourchon, Louisiana to Mobile, Alabama, with a maximum height of 9 m in coastal areas of Hancock County, Mississippi. The extreme strength of Hurricane Katrina is attested by central pressure of 920 mb at the storm peak, at the time, the third lowest pressure of any hurricane making landfall in the continental U.S. Although New Orleans experienced sustained surface winds below the category-three level, the storm surge converging on the city from the south along the Mississippi River, from the east along the Intracoastal Waterway, and from the north from Lake Pontchartrain, damaged the levees and flooded 80% of the city.

III. Telecommunication Systems Failure Analysis

A fault tree analysis (FTA), such as the one included in the Appendix , reveals the main failure causes for communication systems. When failures caused by Katrina are mapped, it can be observed that, in general, the analyzed systems had a similar geographical damage distribution. Failure due to direct infrastructure destruction by storm surge, such as the power plant shown in Fig. 2, and to a lesser degree by high winds, was found in Plaquemines Parish, the eastern half of St. Bernard Parish, and a strip 1-km wide along the Mississippi Gulf Coast between the Louisiana border and Biloxi Bay. Most telecom facilities in the region are concentrated in and around New Orleans, where fuel delivery disruption, flooding, and security issues caused extensive power-related outages.

Fig. 3 shows a scheme for a typical telecom power plant. In normal conditions, the rectifiers feed the load by converting incoming ac mains voltage into -48 V dc. When a blackout occurs, batteries power the load. If the site has a generator set (genset), the batteries discharge for a few minutes before the genset starts and begins providing power. Otherwise, as in small cell sites and digital loop carrier (DLC) cabinets, the batteries discharge until a portable genset is deployed to the site or until the load shuts off due to low input voltage. The FTA indicates

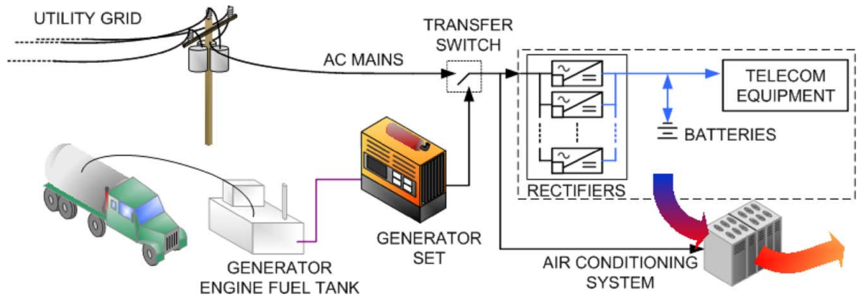

Fig. 3. Typical telecom power plant elements and architecture.

Fig. 4. Damage to the electric distribution grid near Pt. A La Hache, LA.

that ac power supply, made from the combination of the ac mains and the genset may become a vulnerable point during operation under critical condition because it is a common failure cause for all network nodes.

As Fig. 4 exemplifies, damage to the electric grid was extensive and severe, especially in the areas affected by the storm surge. In affected areas of Mississippi, close to two-thirds of the transmission and distribution system was damaged in some way [19]. The electric grid in coastal Louisiana suffered similar damage. Even though only the eastern half of the state was affected, 678 850 customers were without power on September 3 [20]. In some areas, electric power outages lasted several weeks. Nearly 50% of New Orleans, 70% percent of St. Bernard Parish, and 75% of a 1-km strip along the Mississippi Coast were still without utility power at the time of the site survey (six weeks after the storm).

All telecommunications companies relied on stand-by diesel generators to power their facilities during the extended electrical outage that followed the storm. Caterpillar, Inc., a major manufacturer of portable and backup power systems, deployed over 230 MW to the Gulf region in the aftermath of Katrina [21]. Six months later, approximately 10%-20% of that capacity remained in the region. Extensive use of gensets creates a logistical challenge during long blackouts because they must be refueled regularly. Stand-by gensets have 85% availability when operated for more than 24 h [22]. As a result, communication network availability was reduced from approximately 99.99% before the storm to 85% a day later. Hence, gensets are not intended for long term operation [23].

An alternative solution of using extended battery back-up, suggested in [2], does not ensure power beyond several hours. Moreover, high-capacity battery installations are expensive, require reinforced structures, and pose a risk of fire due to high short-circuit currents. In addition, damaged battery replacement may be also an issue after a disaster because battery manufacturers do not carry extensive inventory, given the limited shelf life and storage challenges associated with lead acid cells. Furthermore, as Fig. 3 indicates, power back up for the air conditioner (a/c) is often provided only by the generator. Hence, even with extended battery back-up, without power from a genset, the entire site may fail after a few hours due to overheating [24]. There are alternatives that power a/c from the dc bus, but these options are either impractical [24], unsuitable during hurricanes, or increase dc power demands enough to limit backup time capability.

A summary of the effects of Hurricane Katrina on telecommunication networks is included in Table I. It indicates the most common failure causes with respect to the FTA in the Appendix , and the predominant severity and restoration strategy for such failure. The discussion can be divided among effects on the PSTN and on wireless networks.

A. *Effects on the PSTN*

This section will mostly focus on Hurricane Katrina's effects on the BellSouth (now AT&T) network, because, with a total of 4.9 million lines, it was the largest fixed telephony operator in the affected area. As a result of the storm, 2.475 million lines lost service due to damage to the outside plant (OSP) and outages in 33 central offices (COs) [25]. Nine COs were destroyed. Based on [26]–[28], Figs. 5 and 6 show outages cause and severity, respectively, in the areas where 29 of the 33 COs lost service. Hurricane Katrina affected approximately a third of the enhanced 911 (E-911) centers in Louisiana and Mississippi, both directly, when a public safety answering point or an E-911 center was destroyed, and indirectly, when E-911 calls could not be routed due to PSTN failure. All E-911 centers in Mississippi were restored by September 4th. However, five of Louisiana's E-911 centers were still out of service by September 25th.

The most severe effect on the PSTN was the storm surge destruction of 9 COs, depicted in red in Fig. 5. One of those,

TABLE I
SUMMARY OF MAIN FAILURE CAUSES AND RESTORATION STRATEGIES IN THE PSTN AND THE WIRELESS COMMUNICATION NETWORKS

Network	Network Element	Centralized (C) or distributed (D) element	Failure cause	Restoration Strategy	Predominant outage severity
PSTN	CO	C	Destruction	DLC homed by an undamaged CO	> 2 weeks
PSTN	CO	C	EFS(1) - logistics	Refuel	< 3 days
PSTN	CO	C	EFS(1) - flooding	Refuel gensets once flooded waters receded and conduct repairs	> 2 weeks
PSTN	OSP secondary distribution	D	Damage	Conduct repairs	> 2 weeks
PSTN	OSP Copper feeder cables	D	Damage	Conduct repairs / DLC and fiber optics replacement.	> 2 weeks
PSTN	Transmission trunks	C	Damage	Conduct repairs and re-direct traffic	3 days to 1 week
Wireless	MTSO (2)	C	Damage	Redirect traffic and re-home base stations	> 2 weeks
Wireless	Base station	D	Lack of power - missing genset	Deploy mobile gensets	< 3days
Wireless	Base station	D	EFS(1) - logistics	Refuel	< 3days
Wireless	Base station	D	EFS(1) - flooding	Refuel gensets once flooded waters receded	> 2 weeks
Wireless	Base stations	D	Flood damage	Deploy COWs	> 2 weeks
Wireless	Base stations	D	Wind damage	Deploy COWs	3 days to 1 week

(1) EFS = Engine fuel starvation
(2) MTSO = Mobile telephony switching office

Delacroix, is shown in Fig. 7. Another destroyed CO, Pass Christian, is shown in Fig. 8 with the DLC used to restore service. This restoration technology was used in destroyed COs. It provided limited services to priority lines with a DLC system linked to an undamaged CO through a fiber-optic cable. This implementation indicates that the outside plant was in adequate condition to support lines connected to the DLC, and that the damage was more severe in the central network elements than in the distribution. DLC cabinets fed by fiber-optic cables were also used to replace damaged copper feeder cables in six COs.

Using DLC systems as a replacement for COs and feeders is advantageous from an outside plant planning perspective because they can be deployed quickly and they provide more flexibility to adapt to uncertain demands. However, reliability is reduced when DLC systems replace a switch because DLCs, are usually designed with a lower target availability than major network components, such as a switch fabric [29]. Most of the DLC systems used to replace destroyed switches were hosted by a few central offices, which became points of failure for a large area. Thus, the PSTN may have become more vulnerable than before Hurricane Katrina hit. As it can be inferred from the FTA in the Appendix , the two main DLC failure causes are lack of power and direct damage. Power issues were originated in the need to deploy a portable genset, such as the one in Fig. 9 to each DLC. Hence, their use increases the logistical needs even after moderate storms. The solution implemented by AT&T since Katrina is to install natural gas powered gensets, such as the one in Fig. 10. Use of natural gas not only eliminates most logistical needs but it also reduces the risk of failure due to lack of power because during hurricanes utility gas outages are not as widespread as electric grid failures. For example, during Katrina, the city of Mobile lost most of its electrical supply but natural gas was not affected [30]. Even in New Orleans, a few businesses were operable throughout the storm and afterwards thanks to natural gas gensets [31]. Risk of direct damage by a hurricane is reduced if DLCs are mounted on platforms a few meters above ground. As Fig. 10 exemplifies with a photo of the DLC installed to replace the one in Fig. 9, this was the solution implemented by AT&T after Katrina. Elevated mounting reduces recovery time by avoiding flood damage.

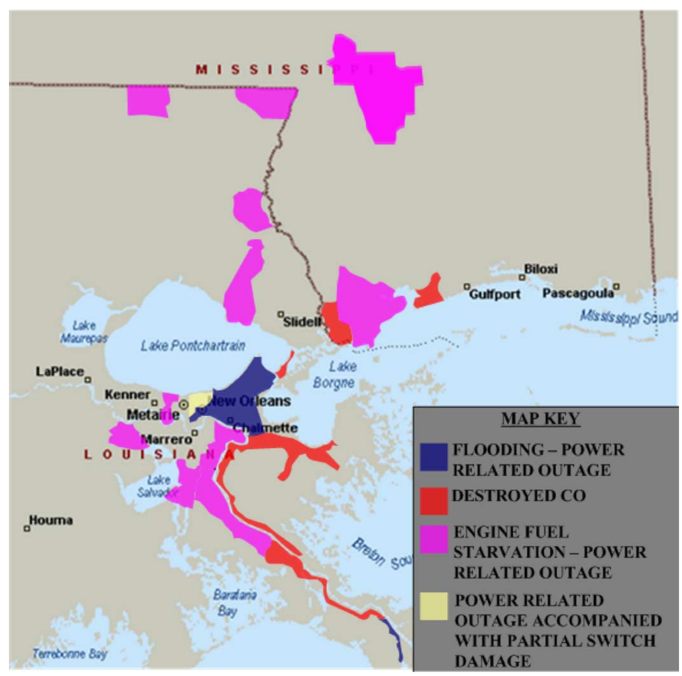

Fig. 5. Bellsouth failed central offices indicating the outage cause.

The resilience of raised equipment to hurricane damage was verified during the site survey with cable TV (CATV) uninterruptible power supplies (UPS). CATV networks can be used to transmit internet based telephony services (voice-over-IP). With multiple redundant paths and network elements, Internet architecture is relatively resilient to catastrophes. However, CATV outside plant seems to be vulnerable since power supplies are needed every few hundred meters. Although there were some serious losses, especially in the coastal areas of Mississippi, most pole-mounted UPSs, such as the one showed in Fig. 11, seemed undamaged while the one on the ground was destroyed. Still, pole-mounted UPS have power issues during hurricanes

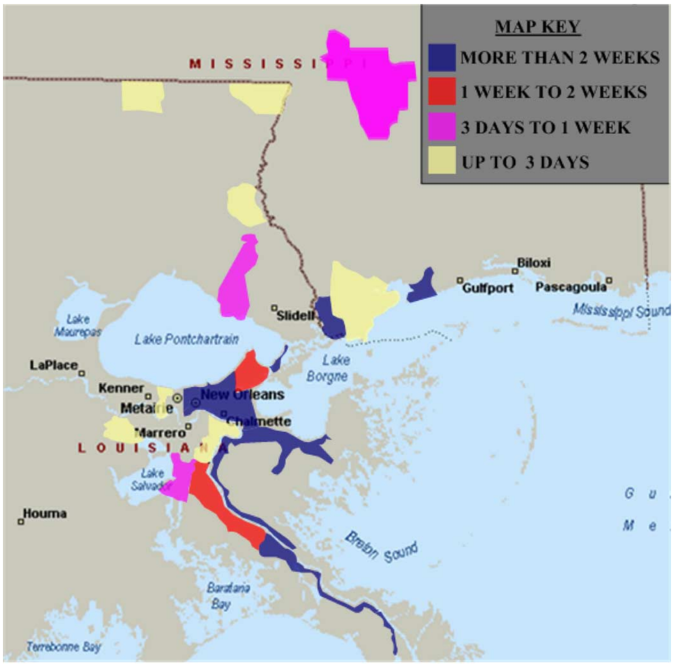

Fig. 6. Bellsouth failed central offices and severity of the outage.

Fig. 7. Delacroix central office.

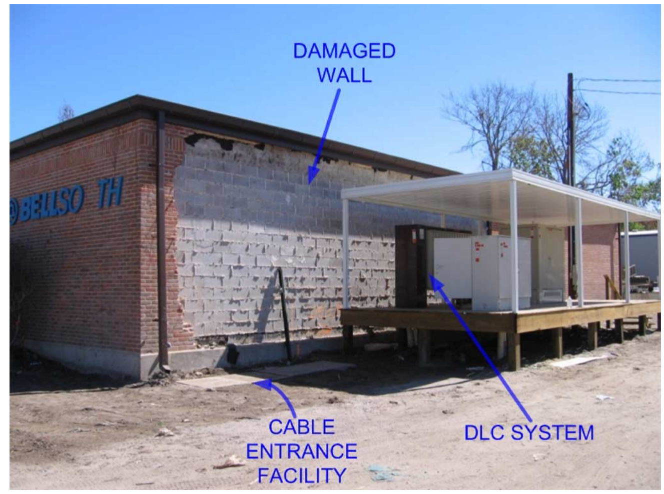

Fig. 8. Pass Christian CO showing the DLC system used to replace the destroyed switch.

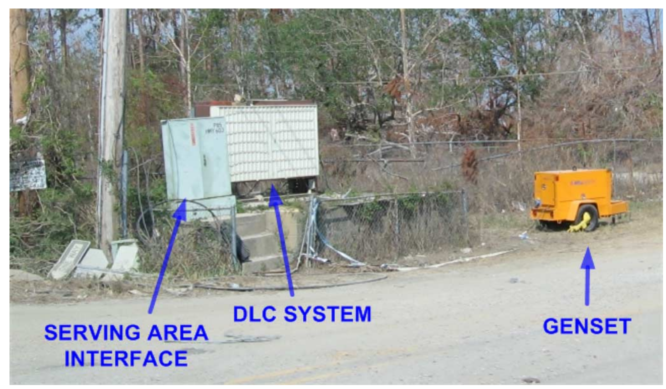

Fig. 9. DLC system providing telephony service to Bay St. Louis CO area subscribers fed with a portable generator deployed after the storm.

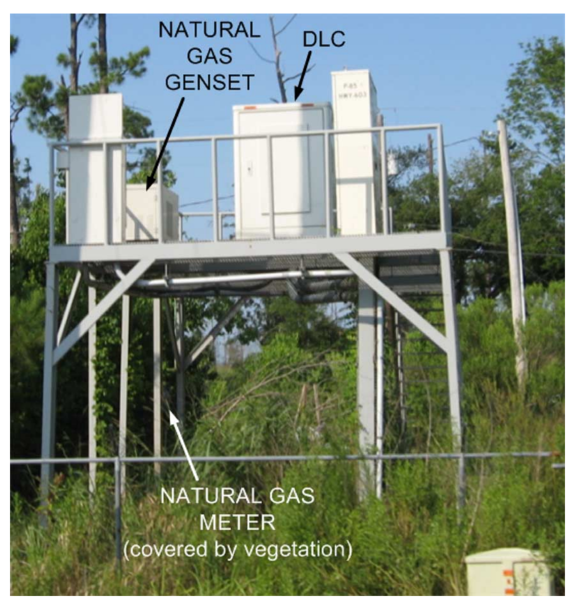

Fig. 10. New elevated DLC with a permanent natural gas genset, built a few meters away from the location of DLC in Fig. 9. Photo date: July 2008.

because they require a separate power source to maintain operation during extended outages.

A better option to replace destroyed central offices may have been to use switches placed inside containers or prefabricated buildings, and transported to the site on a truck. They have been suggested as a solution for natural disasters in [2] and [16] and this was the solution implemented by AT&T in 2008 to restore service in Galveston's Sherwood CO after Hurricane Ike. Although SOWs are more expensive than DLC enclosures, they are more reliable, provide better functionality for trunks, and reduce congestion nodes by allowing better traffic distribution. Disadvantages of SOWs include the need for periodic maintenance and floating the batteries during the year. The weight of batteries reduces the switch mobility.

As Fig. 5 indicates, the cause of the majority of CO outages was power-related. With the exception of Lake CO, whose oldest switch suffered damage [32], extensive damage was prevented because the majority of the equipment was located on high floors. The Appendix shows that power-related outages

Fig. 11. Undamaged CATV UPS mounted on the pole and a destroyed CATV UPS installed on the ground.

Fig. 12. New Orleans satellite picture showing the flooded areas in a darker color with the location of 6 COs that failed indicated with yellow dots. Levees breaches are marked with light-blue crosses. Background photo: NASA.

can originate in damage to the power plant, or ac mains supply and genset failures. Among the COs in the flooded area, only Mid City [26] lost service due to damage to its power plant because it was located in the basement. The other COs in the area lost power due to genset related failures. As Table I summarizes, there were two genset failure causes. The former cause was less severe and was caused by logistic issues when fuel was diverted by authorities or when civil unrest prevented the possibility of reaching the site with fuel. The latter, occurring in the six COs shown in Fig. 12, was more severe and was caused when long lasting floods prevented reaching the CO, or when direct floodwater contact damaged the gensets, the fuel tanks, or the power plants, but not the main communications equipment.

Natural gas powered gensets could also reduce the risk of failure due to engine fuel starvation in COs that do not receive any damage. Although natural gas service may be interrupted in coastal areas affected by a hurricane, service is maintained inland. Hence, having natural gas gensets inland may reduce the demand of diesel, freeing up fuel to be used in COs directly affected by the hurricane. This solution may not be suitable for other areas with limited natural gas supply, such as in Florida, or prone to earthquakes, such as Japan. Larger fuel tanks are another solution to ease logistics requirements and reduce the risk of outage due to engine fuel starvation. Larger tanks have the added advantage of higher access points, which makes them less likely to have fuel contaminated by floodwater.

Fuel consumption can be reduced by installing solar energy. In addition, solar power for COs can reduce utility expenses. A long-term solution may also involve more complex distributed generation systems such as fuel cells and microturbines to reduce dependence on the electric grid. As the FTA in the Appendix suggests, telecom systems lack a diverse power supply. Although the power plants have built in multiple redundant elements and availability is enhanced through standby local energy storage in batteries or genset fuel, telecom power supply is very vulnerable during long lasting critical conditions affecting significant areas of the electric grid. The reason for such vulnerability is that redundant components do not improve availability when the entire main power supply provided by the local electric utility company loose service for such a long time that exceed the energy stored locally. Use of distributed generation address this vulnerability through added diversity, by incorporating at least one new and independent power supply branch to the FTA included in the Appendix . Moreover, systems based on distributed generation systems may provide an integrated solution that also addresses the a/c power supply [24]. Studies of the use of distributed generation in telecom power systems is limited [33], [34] and experiences are few [35], mainly because of high cost and other operational limitations. Further analysis on these limitations and their implication from a telecom power perspective are out of the scope of this paper, but further insights can be found in [36]. Still, there is an opportunity for research in distributed generation based systems to make telecom power systems more resilient, ranging from power electronics interfaces and on-site distributed generation technologies design to operation, stability, and economic analysis.

Other failure causes included in the FTA occurred more sporadically than those discussed before. Only 5% of AT&T transmission network capacity was affected. It was restored by software that automatically reconfigured transmission links and by installing a new fiber optic cable. An important factor in avoiding even major disruptions was that Bellsouth tandem switch and AT&T main switch, both located in the Bellsouth New Orleans Main CO, were kept operational.

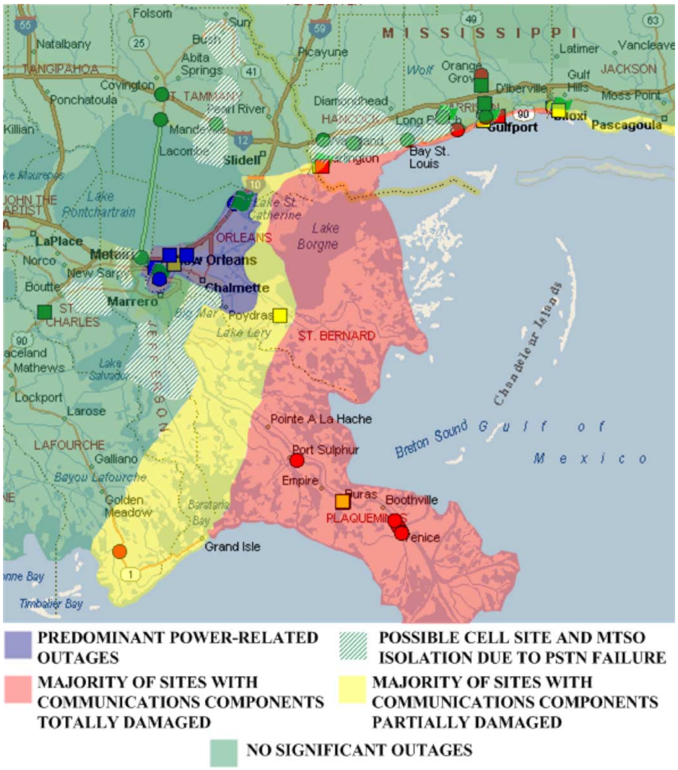

Fig. 13. Map prepared by the authors showing sampled cell site locations and predominant failure type zones.

B. Effects on Wireless Communications Networks

There were over 3000 cell sites in the area affected by Hurricane Katrina. Half were located in the hardest hit areas of the Mississippi coast, New Orleans and Plaquemines Parish. Due to the large number of affected sites, a sample of cell sites, shown in Fig. 13, was surveyed to map the effects on mobile communications networks. This map shows that the predominant failure cause geographic pattern is the same than the one in Fig. 5. Although the area where wireless network elements failed due to damage to all base stations at the cell site is large, it includes less than 1% of all cell sites in the affected region and no mobile telephony switching offices (MTSOs). Some of these sites had inadequate construction for a hurricane-prone zone, such as having the equipment on the ground in areas below the flood plane. The same construction issues explained why in some cell sites not all the base stations were damaged. In many of these sites, indicated in yellow in Fig. 13, there was a lack of uniformity in cell site construction practices, with only a part of the base stations above the flood plane. Fig. 14 shows one of many such sites. This site was located approximately 1.5 m below sea level with only the base station inside the south shelter above the flood plane. Nonuniform construction practice is still prevalent. Fig. 15, from the same site, shows that the north shelter is still below the flood plane. The adjacent fixed genset installed is also below the flood plane.

Wireless communications companies restored service to damaged based stations either by direct repair or by using a *cell-on-wheels* (COW) unit. A COW is a standard base station mounted inside a container. Fig. 16(a) shows a COW set up next to a portable transmission site, which was likely used to

Fig. 14. Cell site in New Orleans with two indoor and two outdoor base stations. The south shelter did not flood.

Fig. 15. Photo taken in July 2008 showing a part of the same cell site in Fig. 14 with some improvements but also some equipment around and inside the north shelter below the flood plane.

restore Sprint's coastal links that failed when Sprint's repeater in Biloxi and a switch in New Orleans [37] flooded. Damaged cell site links were often replaced by microwave connections.

Table I summarizes some other failure causes in wireless networks. One common failure cause indicated in the FTA included in the Appendix and not indicated in Table I was MTSO or base station isolation due to PSTN failure because the root causes for this undeveloped event were part of the effects on the PSTN section. Lack of power was an important cause of failure in wireless network sites. The blue area in Fig. 5, comprising the portion of New Orleans east of the 17th St. Canal and the neighboring northern portion of St. Bernard Parish, indicates zones where most cell sites were isolated by the flood such that they could not receive portable gensets or fuel. In some cases, the power plant may have suffered damage, but the rest of the base station was not affected. This area contained nearly 50% of all sites in the region affected by Hurricane Katrina.

The widespread solution for powering sites during long grid outages was gensets. Cell sites without permanent gensets were equipped with portable generators, such as those depicted in Fig. 16(b). In preparation for the storm, portable gensets were stored in safe places away from the storm but close enough for quick deployment. After the storm, genset transport was complicated because roads were damaged or filled with debris, bridges

(a) (b)

Fig. 16. Cell sites restoration technologies. (a) Left: Sprint-Nextel's COW (center of the image) and portable transmission site. (b) Right: Cell site in Irish Bayou, LA, with four gensets, only one of them permanent.

Fig. 17. I-10 bridge damage over Lake Pontchartrain.

were washed away (Fig. 17), or areas were closed during rescue activities. These logistic issues persisted during the refueling period that lasted several weeks in some areas. Since gensets were usually deployed hours after the site lost power, most cell sites with portable gensets likely lost service either because the batteries were fully discharged or because base stations automatically turned off due to high temperature caused by lack of a/c. Fig. 16(b) shows a common occurrence at many sites: each company deployed and refueled its own portable genset at each location. Logistical burdens may have been eased if cellular companies and tower owners had coordinated their efforts with one genset per location. Since Katrina, fixed generators have been deployed at many, but not all sites, and many of those new gensets have been equipped with propane tanks. An alternative solution would have been to have photovoltaic (PV) systems at cell sites. For some cell-sites, use of distributed generation [33], [34] could also provide a better solution during long blackouts while reducing operational cost. Since Katrina, solutions involving fuel cells as back-up power seem to have gained more acceptance [38], but high costs and limited hydrogen availability, especially after a disaster, are limiting the application of this alternative. Moreover, fuel cells are often connected to the dc bus, so the a/c input power lacks back up.

Table I indicates for the same failure cause, wireless networks restoration time was shorter than for the PSTN. Thanks to their modular architecture and the lack of fixed connection to subscribers wireless networks were almost fully operational a week after the storm along the Gulf Coast and partially operational in New Orleans and Plaquemines Parish. Wireless network recovery was aided, as Bellsouth prioritized restoring cell sites and remote MTSOs links connections [25]. Moreover, wireless networks shorter restoration time is also explained by the fact that centralized network elements, i.e., MTSOs, were less affected than centralized network elements in the PSTN. i.e., COs. The reason for this difference in how Katrina affected these networks is that MTSOs do not need to be close to demand centers because there are no distance technical limitations as occurs between COs and PSTN subscribers, so MTSOs can be located further inland in less vulnerable locations. For instance, Verizon's switches maintained full operation during the storm because they were located in Baton Rouge and Covington, LA, away from the coast and flood prone areas. In contrast, one of the two Cingular MTSOs in New Orleans flooded [39]. The T-Mobile MTSO maintained operation purely by chance, as the facility is located below sea level and 3 km west of the eastward breached 17th Street Canal levee.

IV. FCC Order 07-107 on Backup Power

As a result of [13], in June 2007 the FCC issued order 07-107 requesting virtually all telecommunications service providers with more than 500 000 subscribers to "maintain emergency back-up power for a minimum of 24 h for assets inside central offices and 8 h for cell sites, remote switches and digital loop carrier system remote terminals that are normally powered from local ac commercial power" [40]. Although this order may lead to marginal extended operation for cell sites and DLCs by forcing the installation of fixed gensets or fuel cells, it seems incomplete in addressing power issues. All COs that failed during Hurricane Katrina were already in compliance with this FCC order, so Hurricane Katrina effects would have been the same if FCC's order had been in place in August 2005.

For cell sites and DLCs, target time of 8 h seems inadequate for hurricane mitigation. In addition, many of the powering alternatives that have been discussed throughout this paper, including adding more batteries, installing fixed gensets (preferably fuel with natural gas), and using fuel cells, have important drawbacks. A broader solution is to diversify the power input through the use of local distributed generation resources [36]. Sites with self-sufficient local power sources presumably are exempt from the new FCC order. Even so, high cost and technological limitations may limit the application of distributed generation to a few selected critical sites. These initial installations may lead to further development of local power generation technologies.

Unfortunately, the order does not address other fundamental problems, such as suitable guidelines for cell site construction and restoration logistics. A more comprehensive approach that addresses all failure causes shown in the FTA is still necessary. At the time of writing, order 07-107 has been challenged in court. Among the arguments against the order are technical issues and whether or not the FCC has authority to mandate network technology and procedures. Some requirements within the order, such as reporting power backup assets, are in their initial stages of implementation.

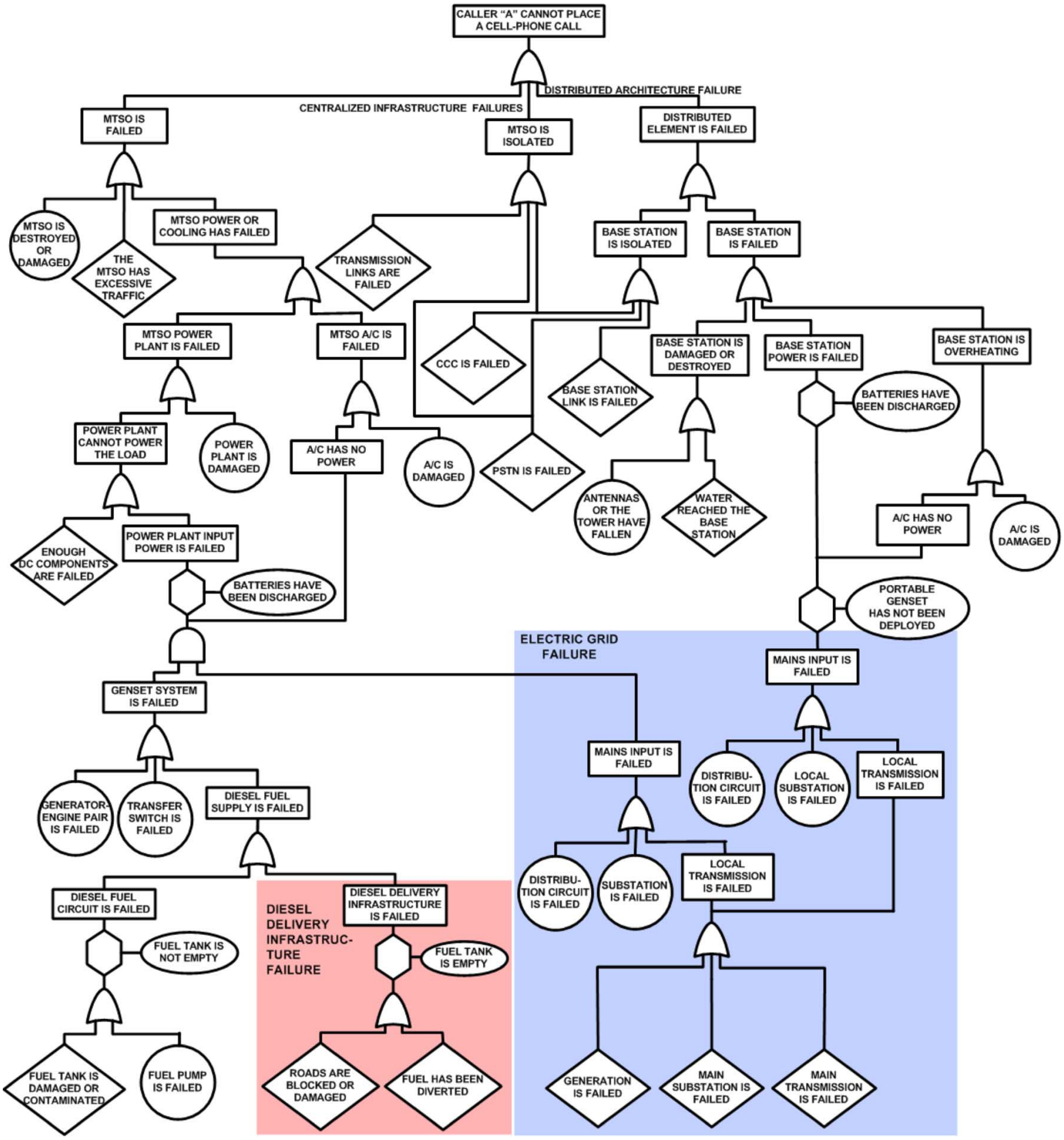

Fig. 18. Wireless network fault tree. External power supply branches are highlighted.

V. CONCLUSIONS

After Katrina, communication network failures were severe. The unusual strength of the storm surge was a significant problem. This particular characteristic was more favorable for mobile communications networks than for the PSTN. Failures in the PSTN were more severe to the centralized network elements which are difficult to restore, whereas failures in wireless networks mostly affected distributed elements, which are simpler to restore. Additional failures in mobile communication networks were caused by PSTN outages, which became a single point of failure for the entire system. One solution could be to increase mobile communication transmission capacities and provide architectures with more network diversity and more direct connections among different wireless communication networks. A short-term, relatively inexpensive way to implement this solution is to install new microwave links. On the PSTN side, damaged switches could be replaced by switches on wheels. Bellsouth used DLC systems both to replace destroyed COs and copper feeder facilities. Extensive use of DLC cabinets will likely increase logistical burdens in the future.

Lack of power at communication sites was the main cause of outages. The site survey revealed that all networks relied almost entirely on diesel gensets to provide extended backup power. However, generators have relatively low availability when they are required to operate for more than few hours. Genset reliability can be improved if logistics and fuel delivery are enhanced by diversifying fuel supply, by using natural gas or propane fuelled gensets, by installing larger fuel tanks at sites close to the coast, and by coordinating cell site genset distribution so that only one generator is needed for each site. An alternative is to seek more independence from the electric grid and more power diversity by installing distributed generation sources, including reciprocating engines, photovoltaic modules, microturbines, and fuel cells.

After Katrina, telecommunication service providers have been improving infrastructure resiliency to hurricanes. One example is placing DLCs on platforms, although many sites on the Gulf Coast are still below the flood plane. Another example is that more wireless base stations have been equipped with fixed gensets. A more active role can be played by electric utilities to improve grid reliability. Near-term changes may be motivated by a recent FCC order. However, its scope is limited because important failure causes, such as inconsistent cell site installation practices are not considered. Power-related outages are also addressed with a limited perspective because the order follows from a traditional concept that emphasizes relatively short-term standby energy at each site, a concept that Hurricane Katrina showed to be vulnerable. However, cost effective alternatives, such as the use of local power generation, require more development. A suitable solution may require deeper understanding how hurricanes affect telecom power infrastructure. Since infrastructure planning and investment cycles extend years into the future, carefully planned solutions are vital.

Appendix

Fig. 18 shows the fault tree analyzing the possible failure causes for a wireless caller not being able to place a call. The fault tree for the PSTN is similar. In the PSTN the MTSO is replaced by the CO. The PSTN do not require a cell site controller (CCC) to administrate the calls between the MTSO and the cell sites and in between cell sites. Instead central offices in the PSTN are interconnected with tandem switches. The CCC failure is considered separate from the MTSO failure because the CCC can be located in a different MTSO from the one that routes the base station calls. Evidently, PSTN failure is not a failure cause for the PSTN. When base stations are replaced by DLCs, there are only a few differences in the distributed infrastructure failure branch. One difference in this branch exists in the DLC isolation cause. DLCs are isolated from its home central office only when the fiber optic link is damaged. Another difference is that in the PSTN outside plant there are no antennas or towers that can fail. Instead, the corresponding failure cause in the PSTN is damage in the distribution cables. This failure cause may exist regardless of the presence of a DLC. If the DLC is not present, distribution cable failure is the only primary event in the distributed element failure. In Fig. 18, it is assumed that the base station has no permanent genset but it has an a/c although this is not true for all base stations. Small base stations usually located in outdoor enclosures as well as DLCs are typically cooled with dc-fed heat exchangers.

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Telecommunications Power Plant Damage Assessment Caused by Hurricane Katrina – Site Survey and Follow-Up Results

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Abstract **– This paper extends knowledge of disaster impact on the telecommunications power infrastructure. It presents results both from an on-site survey conducted in October 2005 in the area affected by Hurricane Katrina and from industry and government sources. The analysis includes observations about power infrastructure damage to wire-line networks, wireless networks, transmission links, cable TV grids, and TV and radio facilities along a wide section of the U.S. Gulf Coast. In general, the impact on centralized network elements was more severe than on the distributed portion of the grids. The main cause of outage was lack of power due to fuel supply disruptions, flooding and security issues. This work also describes the means used to restore telecommunications services and proposes ways to improve logistics, such as coordinating genset deployment between different network operators and reducing genset fuel consumption by installing permanent photovoltaic systems at certain sites where long electric outages are expected.**

I. INTRODUCTION

Hurricane Katrina has become the costliest and one of the five deadliest hurricanes to strike the United States. After crossing Florida and strengthening, it made landfall for the second time on the U.S. coast at 5 AM local time on August 29th, 2005. The entry point was near Buras, Louisiana (LA). At that time the storm had maximum sustained winds of 200 km/h, a strong Category 3 hurricane out of a possible maximum of 5 on the Saffir-Simpson Scale [1]. Even though winds had decreased from the storm's peak strength and were not as strong as some other hurricanes that have affected the U.S., Hurricane Katrina delivered an intense storm surge. A substantial surge affected the Gulf Coast from Port Fourchon, LA, to Mobile, Alabama, and reached a height of 9 m in the coastal areas of Hancock County, Mississippi. Hurricane Katrina's extreme strength is attested by her very low central pressure of 920 mb at the storm peak, which was at the time the third lowest pressure of any hurricane making landfall in the continental U.S. Although New Orleans experienced sustained surface winds below the Category 3 level, the storm surge converging onto the city from the south along the Mississippi River, from the west along the Intracoastal Waterway, and from the north from Lake Pontchartrain, damaged the levees and flooded 80% of the city.

Hurricane Katrina brought heavy damage to the U.S. Gulf Coast infrastructure. Direct damage and loss of electric supply caused complete communication failure which hampered rescue efforts, stymied attempts to coordinate early responses, and made calls for aid impossible from the hardest hit areas. There is limited research on disaster damage and restoration of telecommunications systems or on how their reliability under extreme conditions relates to power supply. The most comprehensive work is in the context of the 1995 Kobe earthquake [2] and other natural disasters in Japan [3]. More limited studies exist on strong wind storms and hurricanes in the UK [4] and the US [5,6]. This paper extends the knowledge of catastrophic disaster impact on the telecommunications power infrastructure. Information is presented both from a direct on-site survey conducted by two of the authors on October 17-23, 2005 in the area highlighted on the map shown in Fig. 1, and from other relevant sources. Satellite and aerial imagery taken shortly after the storm was also used to determine the status of the affected area. Photographs and damage observations are from the site survey unless otherwise indicated

II. DAMAGE TO TELECOM POWER SYSTEMS

In general, the networks and systems analyzed exhibited a similar geographical damage distribution. Failure due to direct infrastructure destruction by storm surge, such as the

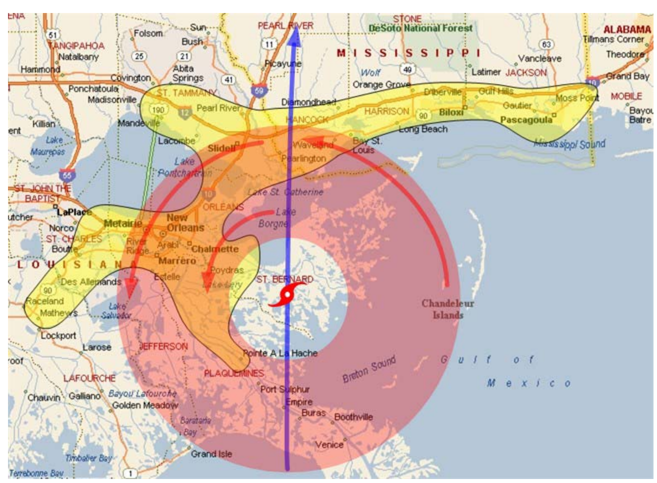

Fig. 1. Hurricane Katrina at 6:45 local time on Aug. 29 2005. The area of hurricane force winds is indicated with a red donut. The path is marked with a blue vertical arrow and the wind direction with counterclockwise red arrows. The site survey region is the lightly-shadowed area.

batteries shown in Fig. 2, and to a lesser degree by high winds, was found in Plaquemines Parish, the eastern half of St. Bernard Parish, and a strip 1 km wide along the Mississippi Gulf Coast between the Louisiana border and Biloxi Bay. However, most of the region's telecom facilities are concentrated in and around New Orleans, where fuel delivery disruption, flooding, and security issues caused power-related outages.

As Fig. 3 exemplifies, damage to the electric grid was extensive and severe. In Mississippi's affected area nearly two-thirds of the transmission and distribution system was damaged or destroyed [7]. Louisiana's electric grid suffered similar damage. Even though only the eastern half of the state was affected, 678,850 customers were without power on Sept 3rd [8]. In some areas, the electric power outages lasted several weeks. Nearly 50% of New Orleans, 70% percent of St. Bernard Parish, and 75% of a 1 km strip along the Mississippi Coast were still without mains power at the time of the site survey (6 weeks later).

All telecommunications companies relied on stand-by diesel generators to power their facilities during the extended electrical outage that followed the storm. Caterpillar Inc., a major manufacturer of portable and backup power systems, deployed over 230 MW to the gulf region in the aftermath of Katrina [9]. Six months later, approximately 10-20% of that capacity remained in the region. Stand-by generators have an 85% availability when operated for more than 24 hours [10] because they are not intended for long term operation [11]. As a result, communication network availability was reduced from approximately 99.99% before the storm to 85% a day later. An alternative solution of using extended battery back-up, suggested in [3], does not ensure power for long periods. Moreover, high capacity battery installations are expensive, require reinforced structures, and poise a risk of fire due to high short-circuit currents. Damaged battery replacement may be an issue after a disaster. As the site survey showed, damage to CO battery plants was extensive along the gulf coast. Battery manufacturers do not carry extensive inventory, given the limited shelf life and storage challenges associated with lead acid cells. Batteries, such as the ones in Fig. 2, are produced exclusively for telecom applications in limited numbers. Hence, the damaged strings could represent an appreciable percentage of annual telecom-type U.S. lead-acid battery production. Long lead times can be expected as the restoration process continues.

A. *Effects on the public switched telephony network (PSTN)*

This section will mostly focus on Hurricane Katrina's effects on BellSouth's network, because with a total of 4.9 million lines, it is the largest fixed telephony operator in the affected area. As a result of the storm, 2.475 million lines lost service due to damage to the outside plant and outages in 33 central offices (COs) [12]. Nine COs were destroyed. Figs. 4 and 5, prepared by the authors, show the areas where 29 of the 33 COs lost service with the causes and severity of the outage, respectively, based on [13] and information published on the Bellsouth Interconnection Services Internet page during the recovery period.

Fig. 2. Batteries damaged due to water immersion.

Hurricane Katrina severely impacted enhanced 911 (E-911) centers both directly, when a public safety answering point (PSAP) or an E-911 center was destroyed, and indirectly, when E-911 calls could not be routed due to PSTN failure. In Mississippi, service was affected in 43 out of 138 E-911 centers. All 43 centers, many of which required traffic re-routing, were back in service by September 4th. In Louisiana, 35 out of 91 E-911 centers failed [12]. However, due to the severity of the PSTN damage service restoration took much longer than in Mississippi. By September 25th, almost one month after Hurricane Katrina landfall, 5 of the E-911 centers in Louisiana were still out of service.

Fig. 4 depicts in red the area where 9 COs were destroyed by the storm surge. All but three, St. Bernard, Pass Christian and Pearlington, were built on pilings. Of the 6 others, including Delacroix (Fig. 6), Lake Catherine was completely obliterated. Only the pilings remained.

Fig. 7 shows Pass Christian CO along with the solution implemented by Bellsouth to replace most destroyed switches: provide limited services to priority lines with a digital loop carrier (DLC) system linked to an undamaged CO through a fiber-optic cable. This implementation indicates that the outside plant was in adequate condition to

Fig. 3. Typical damage to the electric distribution grid near Pt. A La Hache, LA.

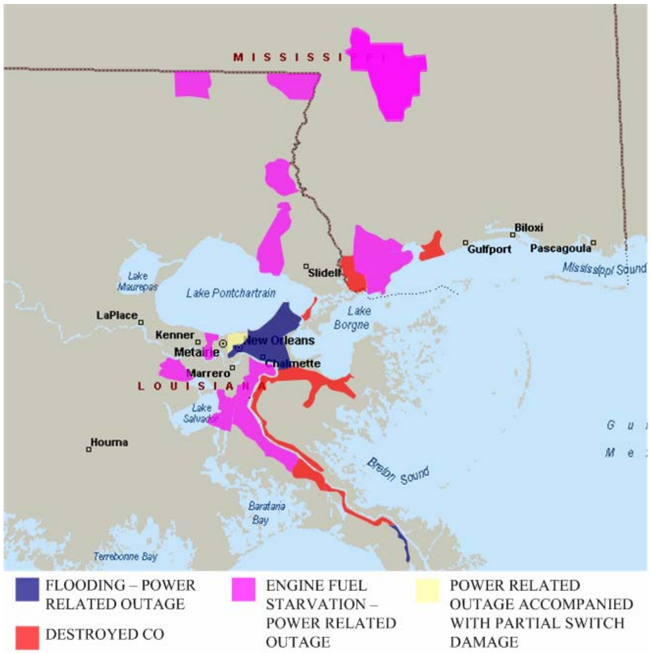

Fig. 4. BellSouth failed central offices indicating the outage cause.

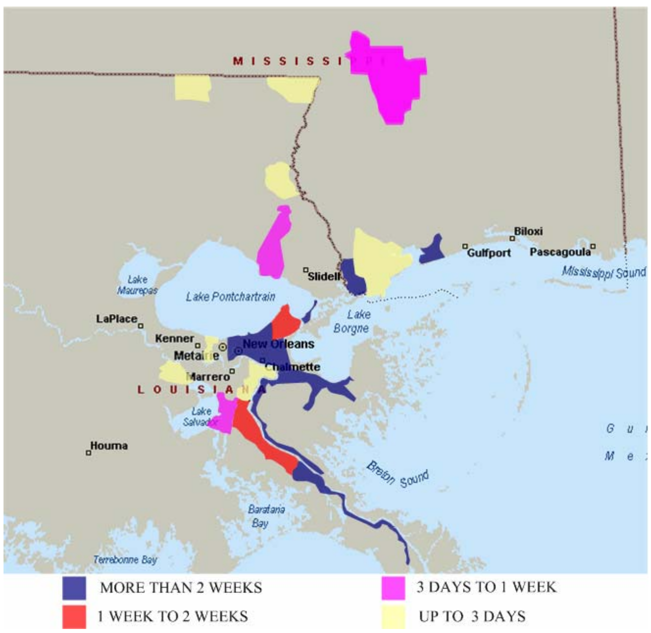

Fig. 5. BellSouth failed central offices and severity of the outage.

support the lines connected to the DLC, and that the damage was more severe in the central network elements than in the distribution. Using DLC systems to replace destroyed switches is advantageous from a planning perspective because they can be quickly deployed and they provide more flexibility to adapt to uncertain demands. DLC cabinets fed by fiber-optic cables were used to replace damaged copper feeder cables in six COs. Some DLC systems, such as the one in Fig. 8, were operating in the area before the storm, mainly in areas of the Mississippi Gulf Coast, to provide service to subscribers far away from the corresponding central office. Only a few of these were destroyed. The undamaged sites were equipped with portable generators, also shown in Fig. 8.

The most important disadvantage of using DLC cabinets so extensively is the logistical effort of deploying portable generators to each site to maintain service during long electric outages. Reliability will be negatively affected when DLC systems replace a switch; subscriber circuit elements, such as DLCs, are usually designed with a lower target reliability than main network components, such as a switch fabric [14]. Most of the DLC systems used to replace destroyed switches were hosted by a few central offices, which became points of failure for a large area. Thus, the PSTN is now more vulnerable than before Hurricane Katrina hit.

A better option to replace destroyed central offices may have been to use switches placed inside containers or prefabricated buildings, with all the ancillary elements, and transported to the site on a truck. These rapidly deployable switches, often called *switch on wheels* (SOW) had previously been used in countries such as Argentina and Nigeria [15] during the initial set-up of new networks. Although SOWs are more expensive than DLC enclosures, they are more reliable, provide better functionality for trunks, and reduce congestion nodes by allowing better traffic distribution. SOW disadvantages include need for periodic maintenance and floating the batteries during the year.

As Fig. 4 indicates, the cause of the majority of central office outages was power-related. In New Orleans, flooding caused six CO failures, indicated in Fig. 9. In some of these sites, direct flood water contact damaged the gensets, the fuel tanks, or the power plants, but not the main communications equipment. In the other cases, high water levels or civil unrest prevented the possibility of reaching the site with fuel, as in Chalmette (Fig. 10). With the exception of Lake CO, whose oldest switch suffered damage [16], extensive damage at these sites was prevented because the majority of the equipment was located on high floors. Lake CO suffered the highest floodwaters of all the central offices with power-related outages. In this location, floodwaters reached more than 3 meters. Besides being in one of the lowest points in the city, the building is located 300 m from the London St. Canal levee, which breached 800 m southwest of the central office. Mid City was the other CO with equipment damage, in this case affecting the power plant located in the basement. Some

Fig. 6. Delacroix Central Office.

Fig. 7. Pass Christian CO showing the DLC system used to replace the destroyed switch.

of these central offices also had damage to copper feeders, probably when pumps that inject air into the cables failed to operate, either because of power failure or direct water contact at the cable entrance. Two other central offices that had direct flood-induced power failure were Michoud and Venice. The latter is Louisiana's southernmost central office, located near the mouth of the Mississippi River and about 15 km west of the landfall point.

All the remaining failed central offices had outages due to genset engine fuel starvation [13]. Two primary reasons for this failure were disrupted local diesel supply and obstructed roads. In these locations flooding did not persist and played no significant role in the outage. In the case of Bay St. Louis, the destroyed bridge on Route-90, flooding of a section of Highway 603, and catastrophic damage west of Bay St. Louis, in Waveland, likely delayed any effort to refuel the genset. A minor deviation in Hurricane Katrina's path may have been the only reason why Aurora and Schrewsbury, two central offices located below sea level and next to canals, avoided flooding. These two COs now host some of the DLC systems that replaced destroyed CO, and other remote switches, and constitute vulnerable spots in the PSTN.

Natural gas could have provided a means to alleviate genset engine fuel demand in some of these sites. In many disasters, utility gas outages are not usually as widespread as electric grid failures. For example, during Katrina, the city of Mobile lost most of its electrical supply but natural gas was not affected. Even though natural gas service is often

Fig. 8. DLC system providing telephony service to Bay St. Louis CO area subscribers fed with a portable generator deployed after the storm.

Fig. 9. New Orleans satellite picture showing the flooded areas in a darker color with the location of 6 central offices that failed indicated with yellow dots. Levees breaches are marked with red dots. Photo: NASA

interrupted in the coastal areas affected by a hurricane, the service is maintained inland. Hence, having natural gas or dual natural gas and diesel gensets may alleviate diesel delivery needs inland, freeing up fuel to be used in central offices directly affected by the hurricane. Larger fuel tanks are another solution to ease logistics requirements and reduce the risk of outage due to engine fuel starvation. Observations at other hurricane-prone areas in the Gulf Coast, as in Tampa, Florida, revealed that the fuel tanks of the COs in Louisiana and Mississippi are smaller for COs of similar capacities. Larger tanks have the added advantage of higher access points, which makes them less likely to have fuel contaminated by flood water.

Fuel consumption can be dramatically reduced by installing solar energy panels. In addition, solar power in COs used throughout the year can reduce expenses owed to the electric utility company. A long-term solution may also involve more complex distributed generation systems to reduce the dependency on the electric grid [17].

The remarkable efforts of Bellsouth's employees certainly played an important role in avoiding outages in other central offices in the region [12]. An important example is found in New Orleans Main CO located in downtown New Orleans, halfway between the Convention Center and the Louisiana

Fig. 10. Chalmette's CO electric drop being repaired. Photo taken on October 18th, 2006.

Superdome. This CO houses several class 5 switches, a tandem switch, an AT&T long-distance switch, and many important transmission terminals. Operations in this site were severely affected by violence and looting which forced its evacuation for several hours until the FBI and the Louisiana State Police occupied the building. Armed and escorted caravans, carrying fuel for the generator and water for the chillers, followed the building securing operation. Good fortune also played a favorable role, since flooding reached within a few meters of the CO front door.

Bellsouth employees also saved COs along the Mississippi Coast by keeping gensets running. In Gulfport, the wall of the room that houses the generator broke due to hurricane damage; a provisional repair was improvised with plastic tarps, plywood and cardboard to keep the switch operating [12]. Biloxi CO, located 300 m from the coast, maintained operation, thanks to its location on slightly elevated terrain that protected the building from the storm surge.

B. Effects on high-capacity transmission networks

Equipment damage, not power outages, was the most important cause of transmission network failures. Sprint was the long distance carrier that suffered the most severe damage in its network, including the total loss of two key facilities: a POP in Biloxi and a switch in New Orleans. When these two facilities flooded, all the sites between them along the coast were cut off, affecting not only the transmission network but also the links between mobile communications cells sites. Neither did loss of electric power play a role in the single outage reported by AT&T, a flooded regeneration hut near New Orleans. This outage reduced AT&T transmission network capacity by 5%. It was restored by redirecting traffic using software that automatically reconfigured transmission equipment and by installing a new fiber optic cable. An important factor in avoiding major disruptions to the AT&T's network was keeping operational their main switch in New Orleans, located in Bellsouth's Main CO. MCI also reported light damage to its network with loss of capacity due to some "water issues" in regeneration sites and a severed fiber optic cable east of New Orleans, probably running along I-10's bridge over Lake Pontchartrain.

Level3 Communications may have been one of the few transmission networks that had interruptions due to power-related causes. During a site survey, we identified a regeneration site on Route 90, south of Pearlington, MS, which on September 2nd, 2005, did not have generators while the electric power in the area was still out.

C. Effects on Wireless Communications Networks

There were over 3000 cell sites in the area affected by Hurricane Katrina. Half are located in the hardest hit areas of the Mississippi coast, New Orleans and the Plaquemines. Due to the large number of affected sites, a small sample of cell sites, shown in Fig. 11, was surveyed to map Katrina's effects on mobile communications networks. When this map is compared with the one in Fig. 4, it shows that failure causes follow the same geographical pattern.

PSTN outages affected not only local calls using fixed lines but also extended into wireless service. One failure cause of many cell sites was isolation from their host mobile telephony switching office (MTSO) when their link through the PSTN was interrupted due to a CO outage. Unfortunately, identifying which cells failed for this reason requires highly detailed proprietary information about the network architecture, which is not typically provided by the service providers. Hence, it was only possible to mark the area where this failure may have happened.

As Fig. 11 indicates, destruction of cell sites due to storm surge, flood and strong winds is found in the Plaquemines, the eastern half of St. Bernard Parish and a 1 km wide strip of the Mississippi Gulf Coast between the border of Louisiana and Mississippi, and Biloxi Bay. Even though this is a large area, it includes less than 1% of all cell sites in the affected region. Some of these sites had inadequate construction for a hurricane-prone zone, such as having the equipment on the ground in areas below sea level.

The yellow areas in Fig. 11 mark zones where the majority of the cell sites may have been only partially damaged rather than destroyed. At least one of the base stations in each of these locations survived. As in the previous area, less than 1 % of the total cell sites affected by Hurricane Katrina are located in this region. The fact that only a portion of a cell site may have been damaged at a particular cell site is explained by a lack of uniformity in cell site construction practices, such as having base stations installed at different heights with respect to the flood plane. Fig. 12 shows one of many such sites. In this case, the cell site was located approximately 1.5 m below sea level with all the base stations but the one inside the south shelter installed on the ground. When the site flooded, the water reached the top of the fence indicated on Fig. 12, avoiding damage to only the base station inside the south shelter.

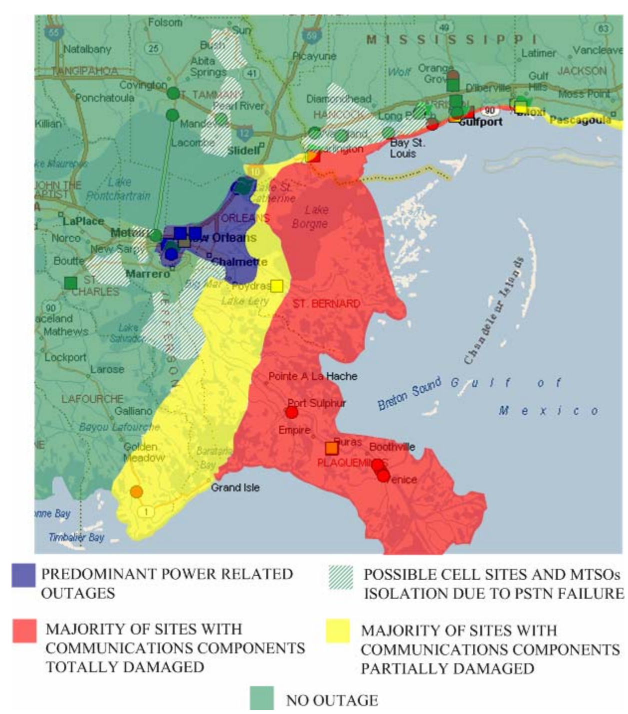

Fig. 11. Map prepared by the authors showing sampled cell site locations and predominant failure type zones.

Fig. 12. Cell site in New Orleans with 2 indoor and 2 outdoor base stations. The south shelter is on the front of the picture.

Wireless communications companies restored service in damaged cells either by direct repair or by using a *cell-on-wheels* (COW). A COW is a standard base station mounted inside a container that is placed on a trailer or directly inside the back of a truck. Fig. 13 shows a COW setup next to a portable transmission site, which was likely used to restore Sprint's coastal links. Damaged cell site links were often replaced by microwave connections. One alternative is to use satellite links. However, there were few COWs and regular base stations using satellite links, likely because establishing them is not a standard feature of most base stations software.

The widespread solution for powering cells during long-lasting power outages was to use generator sets. Cell sites without permanent gensets were equipped with portable generators, such as those depicted in Figs. 14 and 15. In preparation for the storm, portable gensets were stored in safe places away from the storm but close enough to their assigned sites so that they could be deployed quickly. After the storm, taking the genset to the site was usually complicated because roads were damaged or filled with debris, and bridges were washed away. Security checkpoints and areas closed during rescue activities added more complication to the portable power distribution. The same logistic issues persisted during the refueling period that lasted several weeks in some areas. Several portable gensets were refueled daily by a single person who drove hundreds of miles each day. As with COs, an alternative solution to ease the logistic burden of deploying and refueling gensets would have been to have photovoltaic (PV) systems in cell sites.

Figs. 14 and 15 show a common occurrence in many visited cell sites; each company deployed and refueled its own portable genset to each location. Thus, a significant number of cell sites received multiple gensets. Logistical burdens may have been eased if cellular companies and tower owners had coordinated their efforts so that only one genset was used at each site to power all the base stations.

Cellular telephony companies made extensive use of COWs and portable diesel fueled gensets in Hurricane Katrina's aftermath. Cingular deployed approximately 500 portable gensets and 30 COWs [18]. Verizon, Sprint-Nextel, Cellular South and T-Mobile also used hundreds of gensets and dozens of COWs. Because of all the mobile company efforts during the restoration process, a week after Katrina hit the coast, the cellular telephony networks were almost fully operational in the Gulf Coast and partially operational in New Orleans and the Plaquemines. The mobile communications networks proved to be more flexible and resilient to natural catastrophes than the PSTN, thanks to their modular architecture and the lack of fixed connection to the subscribers. Wire-line networks were more complicated to restore than wireless networks due to the PSTN fixed outside plant and especially inflexible CO main distribution frame. Wireless network recovery was also relatively fast, as Bellsouth prioritized restoring cell sites and remote MTSOs links over other connections.

Another advantage of cellular telephony networks over fixed telephony networks is their switch location; MTSOs do not need to be close to the demand centers and, thus, can be located further inland in less vulnerable locations. For instance, Verizon's switches maintained full operation during the storm because they were located further inland, in Baton Rouge, LA, and Covington, LA. Luck, bad for one of the two Cingular MSC in New Orleans that got flooded, played the opposite role in keeping the T-Mobile switch in New Orleans operational. T-Mobile MSC is located below sea level and 3 km west of the 17th Street Canal. If the 17th Street Canal levees had breached to the west instead of to the east, T-Mobile's MTSO would have likely been flooded and destroyed. The T-Mobile switch location may also have contributed in securing supplies and fuel airlifted to the building because it became the main staging and evacuation area west of the city.

The blue area in Fig. 11 that comprises the portion of New Orleans east of the 17th St. Canal and the neighboring northern portion of St. Bernard Parish indicates the zones where most of the cell sites were isolated by the flood such

Fig. 13. Sprint-Nextel's COW (middle of the image) and portable transmission site.

Fig. 14. Cell site in Biloxi, MS where 4 portable gensets, indicated with arrows, were deployed. Another stationary generator not shown in the picture was also installed at the site.

Fig. 15. Cell site in the Irish Bayou, LA with 4 gensets.

that they could not receive portable generators or existing gensets could not be refueled. In some cases, the power plant may have also suffered damage, but the rest of the base station was not affected. This area had nearly contained 50 % of all the sites in the region affected by Hurricane Katrina.

D. Effects on cable TV (CATV), broadcasting TV and radio

Even though radio and TV transmissions allow for one-way communications only, they are valuable during disasters because they provide rescue and relief-related information: battery-operated radios are a main item in a storm kit. However, most radio and TV transmissions ceased to work well after Hurricane Katrina. Radio and TV studios and transmitters experienced similar damage as the cell sites. Most of the transmitters close to the Mississippi Coast and in the southwestern half of the Plaquemines and St. Bernard Parish were destroyed. Fig. 16 shows one of such sites located in Delacroix, LA. The storm surge destroyed the transmitter although the antenna remained standing. The genset was also damaged even though it was located on a high platform. Some antenna towers, including WLOX-TV in Biloxi, MS, were toppled. Power-related outages also occurred in these systems. The transmitter for WWL radio located in Estelle, south of Marrero, LA, stopped transmitting when the genset failed and provided only half of its rated power. In many cases, the solution to a failed transmitter was to use alternative sites.

A CATV outside plant seems to be more vulnerable due to the need of having power supplies every few meters. Yet, during the site survey, we did not observe more significant damage than in the PSTN outside plant. Although there were some serious losses, especially in the coastal areas of Mississippi, most of pole-mounted UPSs, such as the one showed in Fig.17, seemed to have been untouched. These UPSs were able to operate until the batteries were exhausted. After that, service was only recovered when the electric grid was restored. During the on-site survey, we also noticed that pedestal-mounted UPSs seemed to have received more damage than pole-mounted units. Pedestal UPSs are located at ground level, which implies a vulnerable configuration. Fig. 17 also shows a pedestal-mounted UPS that was clearly destroyed while the pole-mounted one seems intact.

III. Conclusions

There are many reasons that explain why communications networks failed in such a severe way due to Hurricane Katrina. One was not Katrina's wind speeds, but the unusual strength of the storm surge made evident by its height and extension inland. This particular characteristic may have influenced the more centralized rather than distributed effect, which was more favorable for mobile communications networks than for the PSTN.

The PSTN became a single point of failure for the entire system because it acted in many areas as the single transmission backbone for most of the networks. One solution could be to increase mobile communication transmission capacities and provide architectures with more network diversity and more direct connections among different wireless communication networks. A short-term, relatively inexpensive way to implement this solution is to install new microwave links. On the PSTN side, destroyed switches could be replaced by switches on wheels. Bellsouth, instead, used DLC systems both to replace destroyed COs and copper feeders facilities. Extensive use of DLC cabinets

Fig. 16. KQLD-FM Radio transmitter and tower in Delacroix, LA. A genset is on top of the damaged structure on the left.

Fig. 17. An undamaged CATV UPS mounted on the pole and a destroyed CATV UPS installed on the ground.

will surely increase logistical burdens in the future.

Another vulnerable common point of failure is the connection between electrical and telecommunications networks. Lack of power in communication sites was the main cause of outages. The site survey revealed that all networks relied almost entirely on diesel gensets to provide extended backup power. However, generators have a relatively low availability when they are required to operate for more than few hours. Genset reliability can be improved if logistics and fuel delivery are enhanced by diversifying fuel supply, using gas gensets inland, installing larger fuel tanks in sites close to the coast, and by coordinating cell site genset distribution so that only one generator is deployed in each site. A better solution is to seek more independence from the electric grid by installing a permanent solar-assisted power plant to ease genset fuel demand after disasters and reduce operational cost yearlong. Using distributed generation resources, such as reciprocating engines, microturbines and fuel cells, may also serve as a long-term solution.

Power-related outages could also be reduced by revising and improving restoration plans based on several different disaster scenarios. The plan needs to consider three equally important factors: resource availability after the storm, resource deployment, and response timing. The telecom industry should develop a common infrastructure design and construction guideline for coastal areas with high risk of hurricanes, as it is done in earthquake-prone regions.

Employees' remarkable efforts amid extremely difficult conditions was the single most important factor that prevented further damage. Flexibility to adapt to the new conditions and implement alternative on-the-spot solutions to clear outages showed extraordinary experience levels. Finally, good fortune played a favorable role in some sites where flooding was avoided by a few meters.

IV. ACNOWLEDGMENTS

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Background maps are from Microsoft MapPoint 2004.

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Telecom Power Planning for Natural and Man-Made Disasters

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***Abstract*- This paper discusses a planning framework to reduce telecommunication network power supply vulnerability during natural and man-made disasters. The analysis proposes a three-part structure for a plan. The first part is an assessment of risk. Risk assessment involves identifying potential disasters at each site as well as evaluating the probability of occurrence and its impact. Impact evaluation focuses on electric grid, roads, and natural gas distribution infrastructure. The second part is an evaluation of resources and logistics. Use of alternative technologies to diversify energy supply, such as distributed generation power units, is discussed. The last part of the plan is its execution. The importance of record keeping and control of the plan outcome during this phase is emphasized, as well as conducting periodic drills to test and improve the plan.**

I. Introduction

Good communications are essential during rescue and recovery operations after a disaster because, as the International Telecommunications Union recognizes, “when disaster strikes, telecommunications save lives” [1]. In the wake of recent disasters, including Hurricane Katrina [2], the October 2006 Hawaii earthquake [3], and the December 2004 Indian Ocean Tsunami [4], telecommunication networks failed for lack of power. Although there are some studies on the effects of natural disasters on communication networks [2] – [13], limited work has been published on power planning for disasters, such as in [14] and [15]. The available analysis tends to provide general recommendations without focusing on telecom power supply issues. The previous work often addresses restoration activities rather than on long-term activities to mitigate effects on network resiliency in disasters.

Damage assessment of the power infrastructure after Hurricane Katrina [16] yielded many significant issues that need to be addressed as part of any plan to mitigate negative effects of disasters on telecommunication networks. Since the main cause of outage was the lack of power, a disaster preparedness plan needs to focus on the power supply. In particular, the plan needs to address the fact that there exists a single point of failure for the entire system at the connection point of the telecom power plant and the ac mains [2]. This issue is not easy to address as operations during and after a disaster are constrained by infrastructure damage that may make sites unreachable. Hence, the challenge is to devise a plan that reduces power supply vulnerability to disasters and, at the same time, takes into consideration operational and economical constraints, during and after disasters.

This paper proposes a methodology to develop a plan for reducing telecommunications power supply vulnerability in case of disasters. The discussion includes strategic aspects that need to be carried out long before a disaster, such as technology procurement plans, and short-term actions that could be implemented during the restoration phase, such as methods to reduce power consumption. The analysis includes, first, a description of key characteristics of certain disasters, and discusses how these characteristics could be considered during the risk assessment stage. The results are combined with an evaluation of technical and human resources and logistical needs to develop a plan to secure the power supply. Based on different types of risk, the analysis proposes technical alternatives that can be used to reduce network power supply vulnerability to disasters. Finally, the paper analyses power operation options during disasters and restoration.

II. Risk Assessment

A. Disaster characteristics

Whether natural or man made, disasters present some characteristics and effects that influence a preparedness and restoration plan. Hence, the first part of a plan is to identify and understand these characteristics and risks posed at each site.

Fig. 1 shows the distribution of disasters around the world [17]. Earthquakes and tropical cyclones are the two most significant natural disasters, particularly because many highly populated areas are susceptible to them. From a telecom power perspective, there are significant differences. Earthquakes damage equipment and infrastructure through vibration, while tropical cyclones generate damage from storm surges, very intense winds. While earthquakes can trigger tsunamis and hurricanes often lead to flooding, flooding damage is often decoupled, and therefore is treated here as a separate disaster.

Winter storms may also affect telecommunication network operations. Prolonged heavy snowfall, as in blizzards or mountain storms, often leads to problems. Ice storms, such as the 1998 event in Quebec [18], can cause widespread damage. Ironically, large wild fires may create effects similar to those of snow storms, as roads may be interrupted and electric transmission lines may be damaged. Volcanic eruptions may have a significant impact not only locally, but also regionally, and in extreme cases even globally. In addition to blocked roads, ashes and toxic fumes may affect a relatively large area around the volcano, such as the 1991 eruptions of mounts Pinatubo and Hudson. Eruptions on islands, such as the 1995 eruption on Montserrat Island, tend to generate logistical issues as regions may become isolated.

Thunderstorms are not usually intense enough or large enough to produce significant damage to a telecom network. However, as Fig. 2 [19] shows, sometimes weather conditions are favorable for widespread storms accompanied by tornados and hail. Such outbreaks can deliver significant damage to the electric grid, which, in turn may affect telecommunication networks.

Most natural disasters tend to affect telecom power supply indirectly by destroying the necessary infrastructure for the power plant to operate, such as roads and the electric grid. Geomagnetic storms [20] and lightning during thunderstorms have, instead, a direct action. These events generate power surges that flow through electric lines and may reach telecom sites through the power supply input. The impact in these cases might be severe, as a strong surge may damage all the rectifiers, leaving the affected site powered only from batteries. Although surge arresters are usually located at the point of entrance of the electric supply, arrester failures due to a defective ground connection or incorrect dimensioning are common. Site location and feeder design may affect the impact of surges. Geomagnetic-induced surges occur at relatively high latitudes, while lightning primarily affects overhead lines.

Natural disasters limit telecom site power supplies in two ways. First, electric supply is often interrupted, and, second, public infrastructure needed to reach the site to deliver or refuel gensets may be damaged. However, not all natural disasters affect these services equally. As Figs. 3 to 5 show, natural disasters act differently on the infrastructure. Although the distribution of natural disaster effects varies for different world regions, the figures serve as a tool to identify different effects of natural disasters on infrastructure. For example, tropical cyclones tend to produce severe and extensive damage to the electric grid and roads, but only moderate and more localized damage to the natural gas infrastructure [2]. Although

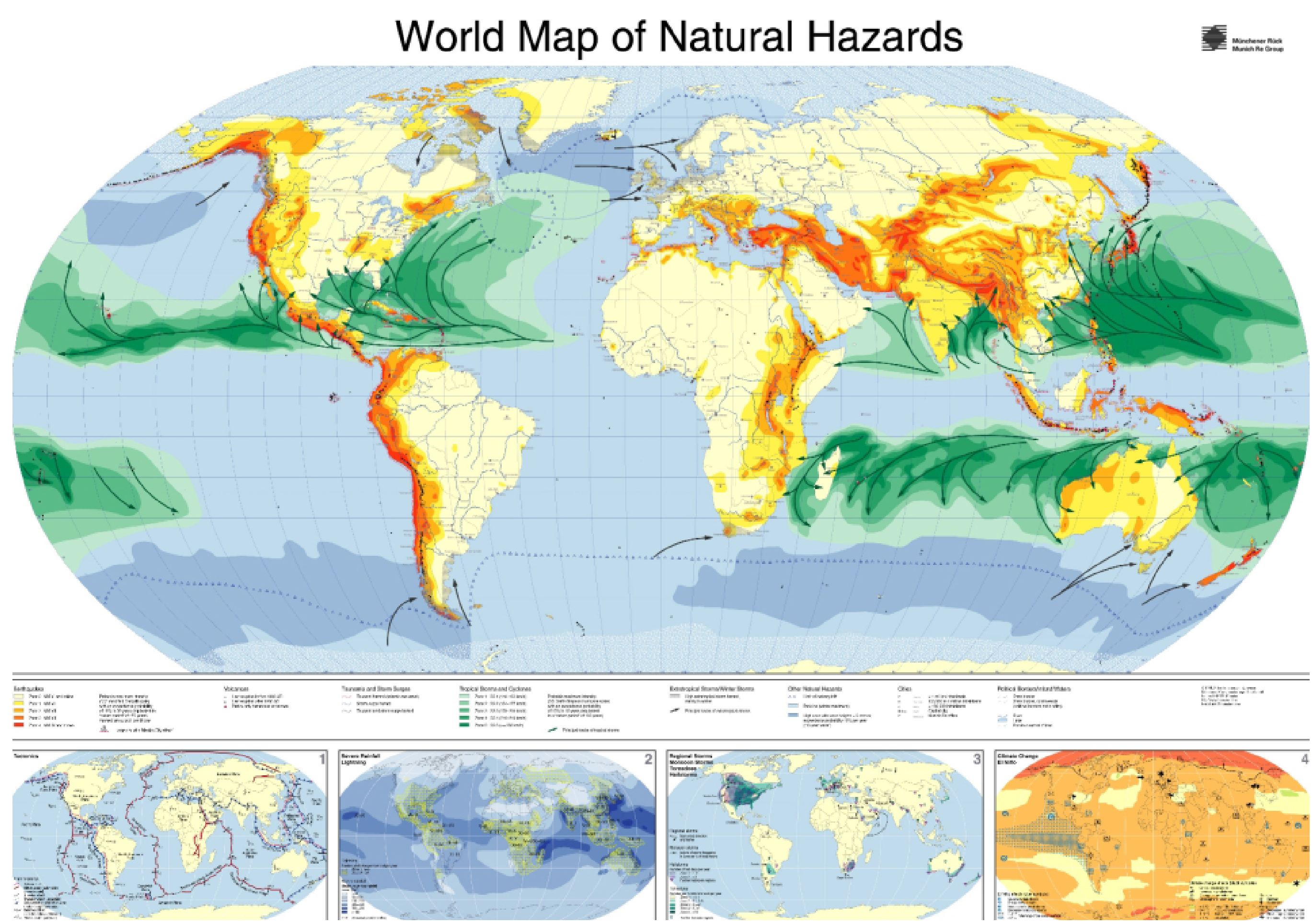


Fig. 1. Munich Re Group’s World Map of Natural Hazards, reproduced from [17]. The main map indicates the risk of suffering the effect of tropical cyclones, earthquakes, extra tropical storms, volcanic eruptions, and tsunamis. Bottom map #2 illustrates the risk for severe rainfall and lightning. Bottom map #3 displays the risk for regional storms, monsoon storms, tornados, and hailstorms

earthquakes have similar effects on the electric grid and roads, the effect on natural gas distribution lines is much more severe and widespread than with tropical cyclones. Usually, more severe damage leads to longer restoration times and more widespread effects create logistical problems. Hence, an essential part of the risk assessment step is to identify the potential effects of those disasters posing a risk to every site. The output of the process might be in the forms of qualitative figures, such as Figs. 3 to 5, or, even better, in the form of tables that include probability values of events.

Man-made disasters are another hazard that needs to be identified. Like natural disasters, man-made disasters may affect telecommunications network operations by interrupting the electric power supply or damaging other necessary infrastructure such as roads or natural gas supply. Although some natural disasters, such as floods and fires, can be man made, in this work we consider direct or indirect attacks to the infrastructure during some conflict. For example, destruction of electric transmission lines, such as Peruvian Shining Path attacks during the 1990s, can be considered a direct attack, whereas severe central office damage during the September 11, 2001 events can be considered an indirect attack.

One other factor that may influence some planning choices is whether or not a disaster can be anticipated, and if so, how far in advance. Accurate forecasts provide about three days notice prior to major storms. Tropical cyclones are most intense during a specific time of the year.

B. Risk assessment for disasters

The next step in the planning process for each site is to quantify the risk of being affected by a given natural disaster. The risk can be defined as

$$R = p.i \qquad (1)$$

where p is the probability of a given disaster and i is the impact, measured in terms of cost. Depending on the plan, different hazards can be combined in a single risk figure, or if prioritization is desired, each hazard's risk can be used to define a list of resource priority assignments.

Risk quantification is important because it provides an objective parameter on which to base the analysis and plan. For example, a meteorite impact is a possible natural disaster, but is not considered in this work because of the extremely low probability of a large impact. However, it is important to recognize that an objective approach may lead to controversy involving the role of telecommunication networks in society, especially during disasters.

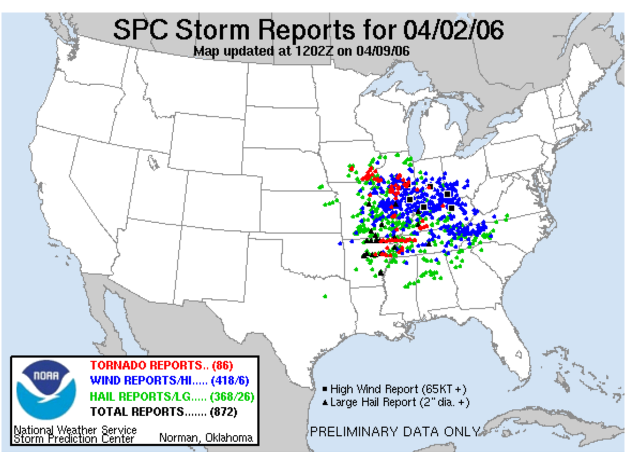


Fig. 2. Significant storm event reports in the USA [19].

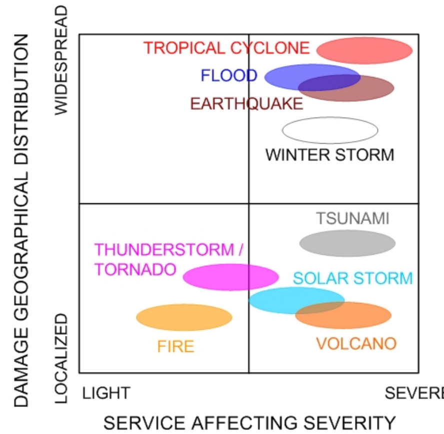


Fig. 3. Natural disaster impact on the electric grid.

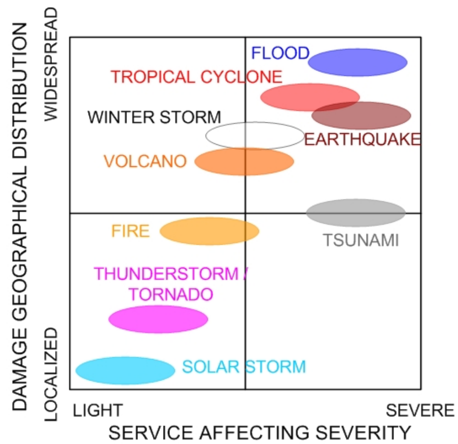


Fig. 4. Natural disasters effect on transportation infrastructure and liquid fuel delivery.

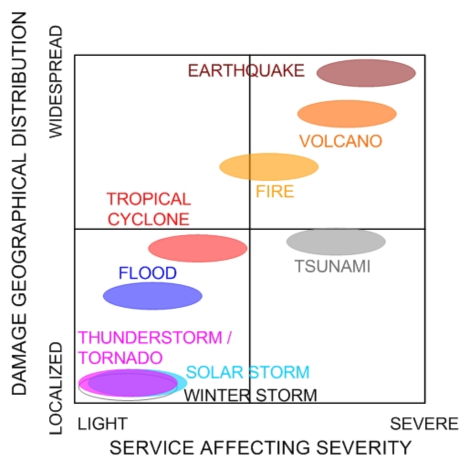


Fig. 5 Natural disasters effect on natural gas distribution.

Conventional telecommunications practice considers power plants as ancillary network elements because they generate no direct revenue. This presents a paradox: telecom power systems do not yield revenue, but without power, no revenue is generated. During natural disasters, this telecommunication power paradigm is challenged because the focus is on saving lives, not on revenue. But networks are planned to make a profit. Thus, disaster planning based only on objective risk values may lead to failure in meeting the primary objective during natural disasters: assist in saving lives by keeping the network operating. Plan effectiveness can be improved if this dilemma is addressed, i.e. actions that improve system availability during natural disasters without affecting the financial bottom line are highly beneficial.

III. Resources and Logistics Evaluation

Once risk assessment is complete, the next step in the planning process is to evaluate technical and human resources, as well as logistics within the context of the results obtained from the risk assessment study. Technical resource evaluation should not only assess present equipment capabilities and limitations, but should also identify potential technologies to be integrated into the network. Thus, the plan should be prepared by a joint effort of operational units and technical planning departments.

One of the critical issues that the plan needs to address is how to reduce power supply vulnerability to electric grid events such as outages and surges. The traditional solution employs batteries and gensets, but has limitations when outages last several hours. One issue is that gensets are not intended for long-term operation: a study by the nuclear power industry showed that diesel gensets have 85% availability when they operate more than 24 hours [21]. Another problem, as several analyses [7], [12], [14], [18], [22] indicate, is that engine-generator sets make diesel delivery an important logistical issue.

Some previous studies have suggested alternatives to reduce power supply vulnerability. One proposal is to increase battery back up time [14]. This solution is rarely feasible beyond twenty-four hours. An important drawback building structures may not accommodate larger batteries. Another option is to use fuel cells to extend the back-up time to 10 or more hours [23] – [25]. This remains an expensive option, especially if hydrogen delivery logistical burdens are avoided by installing an on-site reforming unit [26].

Other studies suggest the use of distributed generation units as a way to improve energy supply reliability [2], [27] by achieving control independence from the electric grid. In these systems, survivability to disasters is increased by eliminating the single point of failure in the ac tie through source diversification. These systems also address the tradeoff between improving system availability during disasters without negatively affecting profits. This is because distributed generation units placed permanently at each site can reduce operational costs owed to the electric utility company by utilizing the ac supply more economically.

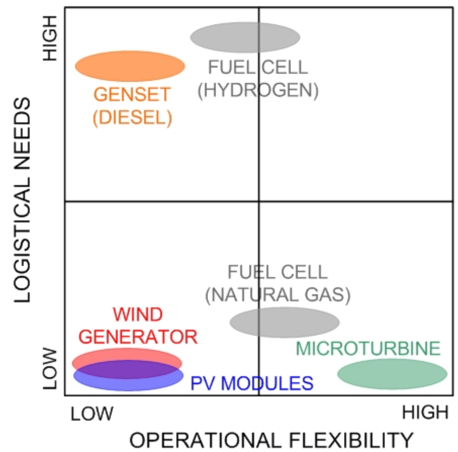


Fig. 6.Characteristics of distributed generation units .

In the plan, selection of the most suitable distributed generation unit for each site can be performed by considering Figs. 3 to 5 in conjunction with Table I and Fig. 6. In the analysis, three primary factors are considered: electric power outage probable duration based on the event severity indicated in Fig. 3, the number of similar affected sites indicated by how widespread the effects of the disaster are on the electric grid, and post-disaster fuel supply limitations as indicated by Figs. 4 and 5. As part of the plan, these factors are evaluated considering the logistical need and operational flexibility from Fig. 6 and the required fuel from Table I. For example, if the site under analysis is a cell site in a hurricane-prone zone, it is expected that grid power outages will last a long time and that large groups of cell sites will be affected. From Fig. 4 it is clear that generating units fueled by hydrogen or diesel are not good options due to the significant damage expected to the transportation infrastructure. Fig. 5 suggests that natural gas fueled units are preferred choices, e.g. natural gas powered gensets, fuel cells with onsite reformers, and microturbines. Table I illustrates that traditional gensets are not the preferred choice owing to low availability during long outages. The final decision can be taken based on Fig. 6. From this figure, microturbines offer an interesting choice because of their higher flexibility and lower logistical needs compared to fuel cells.

The methodology described for distributed generation units can be also applied to decide how to allocate portable genset units after a disaster. This decision can be taken by considering the value of R at a given site under study and use Figs. 3, 4, and 6 to estimate the logistical needs and expected availability. It is important to notice that different types of telecommunication sites involve different logistical needs. In particular, networks with a large number of digital loop carrier systems or cell sites create significant logistical burdens not only during the deployment phase but also during the restoration period due to daily refueling needs. Another problem with relying on gensets to power small sites in areas at

TABLE I

ALTERNATIVE POWER SUPPLY UNITS: SOURCE OF ENERGY AND AVAILABILITY

Power supply units	Fuel / source of energy	Availability *a*
Genset (operation time< 2 hours) Fail to start probability: 0.0241	Diesel / Natural gas	0.9939
Genset (operation time > 24 hours) Fail to start probability: 0.0241	Diesel / Natural gas	0.85
PV generation system*	Solar energy	0.996
PEM Fuel Cell	Hydrogen / Natural Gas	0.967742
Microturbine	Natural Gas / Propane / liquid fuels	0.993789
Wind turbine*	Wind	0.9595

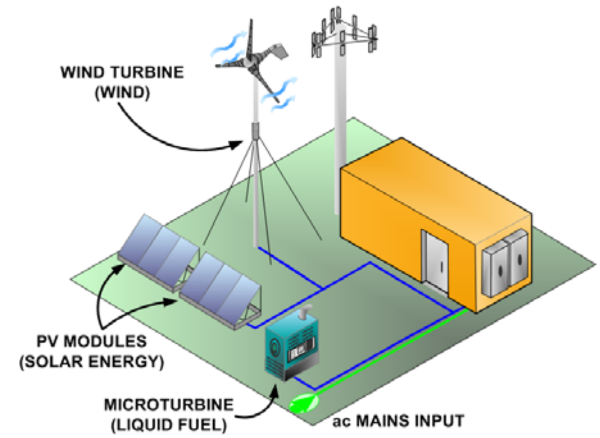
* Operational availability, measured when the energy source is present

risk of storms or floods is that usually portable gensets can only be safely deployed several hours after the disaster ends. This is usually beyond the available battery back up time. Hence, if portable gensets are used to power sites after storms or other relatively long duration disasters, it is helpful to deploy them prior to the event. Otherwise, communication services may not be available at the most critical time: the initial part of rescue and recovery operations.

Fig. 6 shows that photovoltaic (PV) modules and wind turbines are the two most advantageous of types of distributed generation units in terms of logistical needs because if they survive the disaster they are not subject to fuel delivery limitations. However, the stochastic nature of these units generally requires their combination with some other distributed generation unit. During disasters, PV modules or wind turbines offer advantages even if the units are not designed to provide the entire power needed by the load, as they can reduce fuel requirements. Figs. 4 and 5 indicate that this application of renewable energy units is advantageous in earthquake-prone regions where all types of fuel supplies are likely to be constrained severely. Like other distributed generation units, renewable energy units might be designed to improve operational economics. Some examples of renewable energy units used to reduce vulnerability to natural disasters are shown in Figs. 7 and 8. Fig. 7 illustrates a cell site designed to survive tropical cyclones, where a PV module and a wind generator have been added to a microturbine. In Fig. 8, PV modules and wind turbines have been added to support operations of a standard central office power plant during a disaster, while reducing operational costs year round.

An effective plan requires that the evaluation of resources to be conducted in the entire network area, including regions where there is no significant risk of a disaster. The objective is to avoid allocating resources that are essential in a disaster area to areas where there is no significant risk of such disaster.

As a result of the resource evaluation step, planners should have a more complete picture of existing hardware and human resources. They would be in a position to identify technical needs that can be included in procurement plans. Planners should also be capable of deciding the most convenient way to



-**Fig. 7**. Cell site with a disaster hardened power supply configuration.

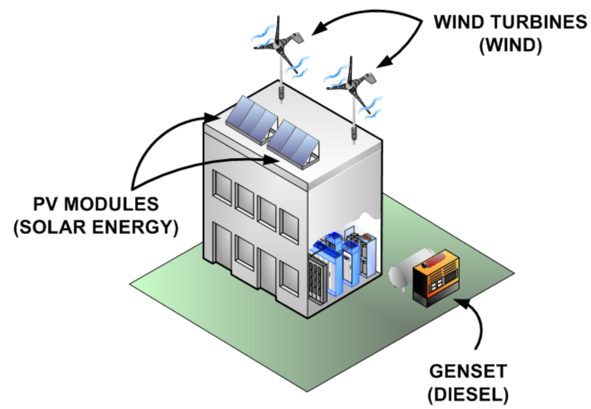


Fig. 8. Central office with PV modules and wind turbines to support operations during disasters and reduce costs year round.

allocate resources in preparation for a disaster. In this part of the plan, it is essential that network operators coordinate their plan with local law enforcement authorities to minimize access restrictions into the potential affected area. The plan should include an evaluation of the area to identify *a priori* potential staging areas and multiple routes to reach each site. Resource evaluation, and especially human resource assessments, are important to develop a realistic resource deployment schedule for different severities of the disaster under study.

IV. PLAN EXECUTION

Execution is the product of the plan and not part of the plan itself. However, there are several issues occurring during plan execution that should be considered during planning activities. One issue is to find strategies that reduce power consumption during persistent ac mains outages. From the planning perspective, the objective of reducing power consumption also reduces site logistical needs. One effective way to reduce power consumption is to increase the air conditioning reference temperature range under disaster conditions [28]. Power consumption can also be reduced if the system is configured to operate in simplex mode instead of relying on a duplicated power supply. However, simplex operation involves a higher risk for telecom outage because the load loses one of its two duplicate circuits. If the site is unreachable, reconfiguration into simplex mode may not possible because the operation sometimes requires physical removal of one power supply card from each pair in the system. One extreme measure is to turn off less critical circuits. This operation tends to be more complicated in switching centers than in cell sites as the risk of total system outage due to an error is much higher in the former than in the latter.

Record keeping associated with the plan application outcome is another very important activity that is performed during the execution phase but that needs to explicitly be considered and specified in the planning phase. The plan outcome records should be combined with plan performance control activities to yield improvements or changes. Since plan improvement from lessons learned during the execution phase is so important, it is essential that the plan be tested before any actual disaster happens. Thus, the plan should include a drill schedule with indications of specific areas of the plan under test.

The most complicated part of planning drills is to reproduce the conditions under test as realistically as possible without compromising system operations. Sometimes this is difficult. For example, testing gensets for few hours may not be acceptable because genset availability decreases significantly after 24 hours of operation. It is possible to test gensets during very long running times of over 24 hours, as batteries can maintain the load if a failure occurs during the test. Other tests, such as operation in simplex mode, are not convenient on live systems. However, these tests can be included as part of employee training programs that are coordinated with equipment manufacturers. A training schedule should be part of the plan.

V. Conclusions

Analysis of previous disasters shows that the most important cause for widespread telecommunication network outages is lack of power. However, specific published work on telecom power planning for disasters is rare. This paper discusses a planning framework to reduce telecommunication network power supply vulnerability during natural and man-made disasters. It proposes to divide the plan into three parts: risk assessment, resource and logistics evaluation, and execution.

Risk assessment involves identifying potential disasters at each site, with the probability of occurrence and a measure of impact. The impact evaluation should focus on severity and geographical distribution of damage to power delivery infrastructure, including the utility grid, roads, and natural gas lines. The discussion points out that direct application of an objective risk measurement could lead to failure to meet essential operations during the initial rescue period. It is acknowledged that an effective plan should address the trade off between achieving high network availability during a disaster and maintaining cost low.

Resource and logistics evaluation involves not only an assessment of the existing technology used in the network but also of human resources. In this part of the plan, resources and logistics are examined in the context of results obtained from the risk assessment. Resource evaluation may identify technology procurement needs to reduce power supply vulnerability during natural disasters. This paper emphasizes the use of distributed generation units as a way to improve power supply availability during disasters without compromising profit.

In the execution part, the paper highlights the importance of including within the plan ways of recording and analyzing the results of implementing the plan. Issues related to testing the plan through drills were discussed.

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By the time of the publication of this paper, Alexis Kwasinski is expected to be a faculty member at the University of Texas at Austin.

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Analysis of Vulnerabilities of Telecommunication Systems to Natural Disasters

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***Abstract*—This papers discusses vulnerability aspects of telecommunication systems to natural disasters. The discussion focuses on power supply and other ancillary infrastructure issues, such as air conditioners, because this is the source of most outages on communication systems during such critical events. The discussion points out that the conventional approach of studying communication network availability by considering each site an autonomous entity may have hidden important vulnerabilities that become evident during disasters. In the alternative view provided here, communication systems are viewed as a system within a larger system-of-systems that includes other fundamental infrastructures necessary for their correct interdependent operation in all conditions. The analysis is based on reliability analysis tools and supported by empirical observations from damage assessments of past hurricanes.**

Keywords-Communication networks, disaster response, power grid, power supply, natural disasters, system-of-systems, systems reliability, transportation systems.

I. INTRODUCTION

This paper discusses vulnerabilities in communication systems including interdependencies with other infrastructures. Communication networks have been identified by the US Department of Homeland Security as one of its critical infrastructures within the National Infrastructure Protection Plan [1]. The reason is that communication networks support many essential society functions, including E-911 emergency call services, financial services, and health services. Due to its critical nature, communication networks are typically required to have a very high availability, in the order of at least 5-nines [2]. Although telecommunication networks normally exceed this requirement in normal operation thanks to the inclusion of redundancy and the use of other reliability techniques tending to the elimination of single point of failures, service outages during natural disasters, such as hurricanes, are relatively common [3]. Thus, natural disasters seem to emphasize intrinsic vulnerabilities that are not usually detected during operation under conventional conditions.

Most recent studies of communication systems in recent past disasters [4] [5] have agreed in identifying issues related with power supply as one of the main outage causes of communication systems during natural disasters. Hurricane Katrina is one notable example that identifies power issues as one of the main causes of outages, and although the US government study conducted by the Federal Communications Commission (FCC) [6] also agreed on this conclusion, it did not provided insights of the fundamental causes of the problem as other works [7] [8] did. In these other works power issues were explored within a broader view in which communications systems are not isolated but they are rather part of a larger system-of-systems in which interdependencies with other infrastructures play an important role in communication networks reliability behavior. This may be the reason why the now suspended FCC order on backup power [9] derived from [6] still relied on the traditional approach of using locally stored energy in order to address power issues in telecommunication sites during disasters whereas other works [10] suggested other options. Since it is likely that a revised order may be issued by the FCC, it is relevant to identify communication systems fundamental vulnerabilities so they can be addressed in an effective way. This is the ultimate goal of this work by focusing on power and infrastructure issues exposed during natural disasters, and, in particular, hurricanes.

II. DISCUSSION

Figure 1 shows a typical telecommunications power supply system for a central office (CO). In normal operation the load is powered from the ac grid through rectifiers. In case of a relatively short power outage in the ac mains, the load is supported by batteries. For long ac mains outages, the load is typically maintained operating powered by a diesel generator. Although a diesel generator is present in most centralized communication centers, such as COs and data centers, many distributed network elements, such as wireless networks cell sites, or wire-line networks digital loop carrier (DLC) remote terminals (RTs), lack a permanent genset. Hence, almost all of these sites require the deployment of a portable genset in order to prevent a loss of service during long ac mains outages, as it occurs during disasters (Fig. 2.a). One alternative to the deployment of portable gensets—already implemented in a very small portion of DLCs in the US Gulf Coast with a high

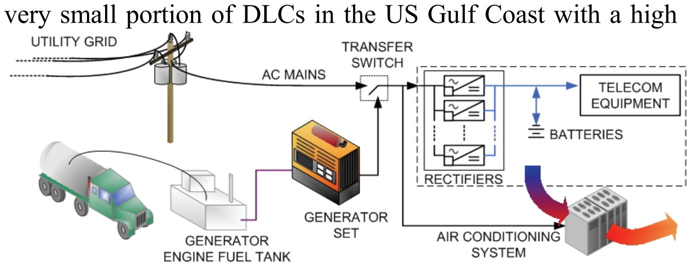

Fig. 1. Typical telecom power plant elements and architecture.

probability of being affected by hurricanes—is to install permanent natural gas gensets (Fig. 2.b), or hydrogen fuel cells.

A better understanding of telecom power supply vulnerabilities can be gained from a theoretical characterization. Usually, telecommunications power plant availability behavior can be represented with the help of the reliability success diagram in Fig. 3. For such model and if batteries are by now ignored—i.e, the power plant is composed of the ac mains tie, the genset, and the rectifier system, which is formed by all the rectifier modules—availability can be calculated from the corresponding Markov diagram in Fig. 3. This model is an extended form of the diagram shown in [11] by adding the rectifier system portion of the plant. Each state is represented by a 3-digit binary number in which the first digit represents the state of the rectifier system formed by all rectifiers, the second digit represents the state of the ac mains, and the third digit represents the state of the genset. A "one" represents a failed state and a "zero" represents a working condition. For example, state S_3 is represented by the binary number 011, which implies that only the rectifiers have not failed, whereas both the ac mains and the genset have failed. Hence, the power plant availability is, then, given by [11]

$$A_{PP} = \left(1 - \frac{(\lambda_{GS} + \rho_{GS}\mu_{MP})\lambda_{MP}}{\mu_{MP}(\mu_{MP} + \mu_{GS})}\right) A_{TS} A_{RS} \qquad (1)$$

where A_{RS} is the rectifier system availability that depends on the design of the individual interfaces and the power plant configuration—e.g. redundancy strategy—λ_{GS} is the failure rate of the series combination of the generator set and diesel circuit, μ_{GS} is the genset and fuel repair rate, ρ_{GS} is the genset failure-to-start probability, λ_{MP} is the mains power failure rate, and μ_{MP} is the mains power repair rate. The availability A_{RS} can be calculated considering that rectifiers are typically configured in an n+1 redundant configuration. However, even if the power plant fails the load will still be powered by the batteries until the power plant is repaired or the batteries are discharged. In this latter case, service will be lost. In order to calculate the probability of a power related communication load outage, the Markov graph in Fig. 4 is useful. The failure and repair rate, λ_{RS} and μ_{RS}, for the n+1 redundant arrangement of rectifiers are

$$\lambda_{RS} = \frac{n\lambda_R^2(n+1)}{(n+1)\lambda_R + \mu_R} \quad \text{and} \quad \mu_{RS} = \frac{2\lambda_r^2\mu_r^{n}\,{}^{n-1}C_{n+1}}{\sum_{i=0}^{n-1} {}^{i}C_{n+1}\mu_r^{i}\lambda_r^{n+1-i}} \qquad (2)$$

where λ_r and μ_r are the failure and repair rates of each rectifier, respectively.

Based on Fig. 4, a vector $\mathbf{P}(t)$ can be defined to represent the probability of being at any given state at time t. It can be obtained by solving the differential equation

Fig.2. **(a) Left:** DLC powered by a natural gas dc genset.. **(b) Right:** DLC powered by a 10 kW portable genset after Hurricane Gustav.

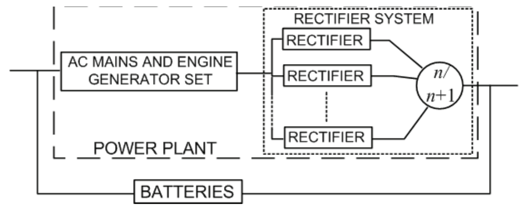

Fig.3. Reliability success diagram for a telecom site power supply chain.

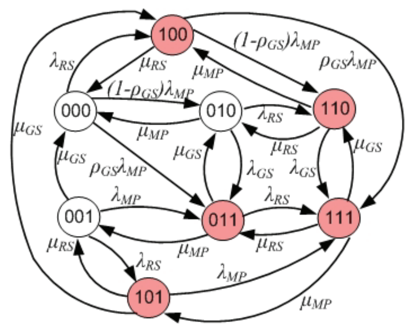

Fig. 4. Markov diagram for the power plant portion of the system in Fig. 2.

$$\dot{\mathbf{P}}(t) = \mathbf{A}^T\mathbf{P}(t) \qquad (3)$$

where $\mathbf{A}$ is indicated in (4) and $P_i(t)$ is the coordinate i of the vector $\mathbf{P}(t)$. The probability $P_i(t)$ coincides with the probability P_{Sk} of being at the state $k = i$-1 at time t. In Fig. 4, all shaded states represent a power plant failure state and belong to the set $\mathcal{F}$, whereas states S_0, S_1, and S_2 belong to the set $\mathcal{W}$ of the "working" states. The probability of power plant failure is then,

$$P_{PPf}(t) = \sum_{S_i \in \mathcal{F}} P_{S_i}(t) = 1 - \sum_{S_i \in \mathcal{W}} P_{S_i}(t) \qquad (5)$$

It can be shown [12] [13] that the probability density function $f_{PPf}(t)$ associated with the probability of leaving the set $\mathcal{F}$ after being in the set from $t = 0$ and entering $\mathcal{W}$ at time $t + dt$ is

$$f_{PPf}(t) = -a_{\mathcal{F}} e^{a_{\mathcal{F}} t} \qquad (6)$$

where $a_{\mathcal{F}}$ represent all the transitions from $\mathcal{F}$ to $\mathcal{W}$. That is,

$$a_{\mathcal{F}} = -(3\mu_{RS} + \mu_{MP} + \mu_{GS}) \qquad (7)$$

Thus, the probability of leaving the set $\mathcal{F}$ after being in the set

$$\mathbf{A} = \begin{pmatrix} -(\lambda_{MP}+\lambda_{RS}) & 0 & (1-\rho_{GS})\lambda_{MP} & \rho_{GS}\lambda_{MP} & \lambda_{RS} & 0 & 0 & 0 \\ \mu_{GS} & -(\mu_{GS}+\lambda_{MP}+\lambda_{RS}) & 0 & \lambda_{MP} & 0 & \lambda_{RS} & 0 & 0 \\ \mu_{MP} & 0 & -(\lambda_{GS}+\mu_{MP}+\lambda_{RS}) & \lambda_{GS} & 0 & 0 & \lambda_{RS} & 0 \\ 0 & \mu_{MP} & \mu_{GS} & -(\mu_{GS}+\mu_{MP}+\lambda_{RS}) & 0 & 0 & 0 & \lambda_{RS} \\ \mu_{RS} & 0 & 0 & 0 & -(\lambda_{MP}+\mu_{RS}) & 0 & (1-\rho_{GS})\lambda_{MP} & \rho_{GS}\lambda_{MP} \\ 0 & \mu_{RS} & 0 & 0 & \mu_{GS} & -(\mu_{GS}+\lambda_{MP}+\mu_{RS}) & 0 & \lambda_{MP} \\ 0 & 0 & \mu_{RS} & 0 & \mu_{MP} & 0 & -(\lambda_{GS}+\mu_{MP}+\mu_{RS}) & \lambda_{GS} \\ 0 & 0 & 0 & \mu_{RS} & 0 & \mu_{MP} & \mu_{GS} & -(\mu_{GS}+\mu_{MP}+\mu_{RS}) \end{pmatrix} \qquad (4)$$

from $t = 0$ and entering $\mathcal{W}$ at a time longer than the battery backup time T_{BAT}—i.e. the probability of discharging the batteries—in such condition is

$$P_{BD}(t > T_{BAT}) = 1 - \int_{\tau=0}^{\tau=T_{BAT}} f_{PPf}(\tau)d\tau = \\ = 1 - \int_{\tau=0}^{\tau=T_{BAT}} -a_{\mathcal{F}} e^{a_{\mathcal{F}}\tau} d\tau = e^{a_{\mathcal{F}} T_{BAT}} \quad (8)$$

The outage probability P_O is, then, the probability that the system failed at $t = 0$ and the batteries were discharged. If it is assumed that the system has been turned into operation at some time $T_{inic} \rightarrow -\infty$ then P_O is approximately the unavailability U_a of the 3-state system represented in Fig. 4, i.e., $P_{PPf}(t \rightarrow \infty)$ Hence,

$$P_O = U_a e^{a_{\mathcal{F}} T_{BAT}} \quad (9)$$

where T_{BAT} is the battery backup time. In some cases, such as in DLCs and cell sites, battery backup time selection is a critical planning decision because without a permanent genset many of these sites depend on the batteries to maintain operation until a portable genset is deployed to the site. The expected outage time can be found to equal

$$T_{Out/Bat} = \frac{e^{a_{\mathcal{F}} T_{BAT}}}{a_{\mathcal{F}}} \quad (10)$$

With the help of the values in Table 1, the previous equations allow to calculate the basic availability parameters of a power plant with different configurations. These values, summarized in Fig. 5, are calculated in normal operating conditions and, in the case when a genset is used, it is assumed that its fuel supply is unlimited. These values show that even in normal operating conditions, the grid's relatively low availability creates a floor for the maximum availability that can be observed at the rectifier system output. With a genset this value is approximately 4-nines and without a genset is 3-nines. Hence, batteries are a critical need in order to reach an availability of 5-nines. In the case when a genset is used, around 3 hours of battery backup are needed and when no genset is used at least 8 hours of battery backup are needed. If an outage occurs, in theory it can be expected that the power outage will last over 9 minutes in the former case and 2.4 minutes in the latter. The reason why the latter is shorter than the former is that extended battery backup time yields lower chances of experiencing outages exceeding the battery backup time. However, in practice, longer and equal outage durations can be expected because once power is restored it usually takes several minutes to restore system operation. This extra time is spent in activities such as re-starting the software controllers

TABLE 1. TELECOM POWER PLANT COMPONENT AVAILABILITY DATA IN NORMAL CONDITIONS [14].

Item	MUT[a] (hours)	MDT[b] (hours)	Availability *A*
Rectifier	500 000	166.6	0.999 667
Genset (ρ_{GS}=0.0241)	823	5	0.993 9
Transfer switch	102 041	5.74	0.999 94
Power grid tie	2440	2.08	0.999 150

a MUT: Mean up-time which equals the inverse of λ
b MDT: Mean down-time which equals the inverse of μ

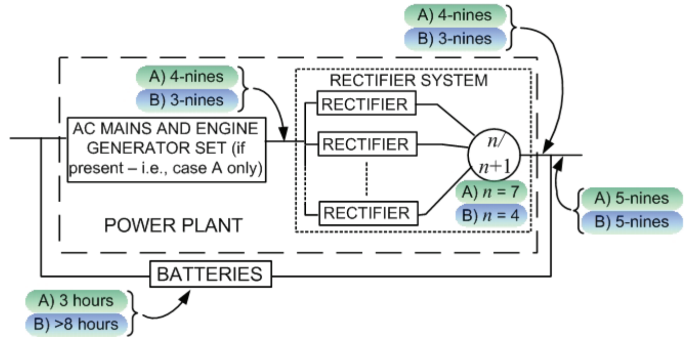

Fig.5. Availability and parameters for two cases corresponding to Fig. 3. Case A: CO with a permanent genset. Case B: DLC without genset.

and reloading databases. Thanks to their n+1 redundant configuration, rectifiers availability does not have a significant impact on overall system availability.

Although the previous conventional analysis is insightful and indicates that power supply availability is improved with respect to that of the mains power by implementing diverse techniques, such as connecting rectifiers in an n+1 redundant configuration or by relying on extended backup battery time, it still does not indicate fundamental reliability issues in telecom power systems. A deeper understanding of communication networks power supply availability during natural disasters can be gained from the fault tree included in Fig. 14 in the Appendix. This figure indicates important interdependencies between a communication system and other systems including the power grid, roads to deliver fuel to gensets or to deploy portable gensets, and natural gas distribution systems in case natural gas gensets are used. Thus, all these systems constitute a system-of-systems that needs to be considered as a single entity when analyzing vulnerabilities in order to eliminate single point of failures.

A clear vulnerability indicated from the fault tree analysis is the single point of failure existing at the power grid tie point with the communication networks. As the tree in the Appendix indicates, there is typically only one power grid providing electricity to the entire communication network so the entire failure of this single grid, as it typically happens during disasters, such as hurricanes, has a significant negative effect in any communication system. Failure of the transportation system—roads—may also have an important effect. However, since not all roads are equally severely affected, some communication sites may still maintain operation by receiving supplies through roads. The fault tree also indicates by showing a path of possible failure mode from the output of the event *CO power or cooling has failed* into its distributed elements in the outside plant, that access roads into the COs, are more critical than those reaching the distributed elements. Hence, damaged or blocked roads that allow access to COs are more important than those reaching DLCs. Fuel delivery issues into COs wsa the main failure mode during Hurricane Katrina, when most communication outages were caused by engine fuel starvation of the CO gensets [7]. Hence, even though the solution mandated by the FCC in its "Katrina Order" [9] of extending backup times at all communication sites—8 hours in distributed network elements and 24 hours in centralized network elements—may improve availability during disasters it did not address the fundamental issues of the existence of lack of diversity in the communication system power supply.

One solution to the problem of a single-point of failure at the grid tie is, from a power perspective, to provide diverse local power sources, such as fuel cells, microturbines, photovoltaic modules, small wind generators, or reciprocating engines. But many of these sources require infrastructures to be energized. So careful planning that considers the different effects (Figs. 4 to 6) of disasters on these critical infrastructures—also called lifelines—is required in this option. Hence, use of hybrid power plants with diverse local distributed generators are a suitable solution only if network planners select each site power supply technologies based on an assessment of the hazards potentially affecting the site. Other approaches to improve communication networks availability, even without eliminating the single-point of failure at the grid tie, deals with information architectures. Typically, data networks, such as the Internet, are more distributed than voice networks because more functions are placed in the endpoints. Hence, although some centralization exists at the backbone, dominant hierarchical architectures with important centralized network elements, are less prevalent in data networks than in telephony networks. Thus, increased penetration of digital telephony, such as voice-over-IP systems, may improve communication network availability during disasters. Yet, without addressing the single-point of failure at the grid tie, such as using diverse distributed generation, potential for power related outages still persists, particularly closer to the end user, where there are fewer diverse resources. Nevertheless, providing diverse power supply in distributed network elements both in data or voice networks is a challenging problem that was discussed in [3] and it is exemplified here with the ad-hoc power solution used in a CATV amplifier—likely supporting voice-over-IP telephony—shown in Fig. 9. Digitalization of communication networks has also increased the need for powering equipment at the customer premises. Whereas a few years ago most people relied on their wired telephones for communication that did not need local power at the phone's site, cell-phones, IP telephones, and other end user devices that are displacing conventional telephones require at least periodic charging. Although lack of power in the end-user devices is not a problem when the disaster is acting because they have batteries, lack of recharging options in the immediate aftermath of a disaster is increasingly creating significant issues, as exemplified in [15] with the 2008 Sichuan province earthquake in China. Powering distributed network elements and equipment located at customer premises is certainly an important topic of immediate future research.

Another vulnerability indicated through the fault tree is observed in the air conditioners (A/C). As shown both in Figs. 1 and 14 (in the Appendix), conventional telecom power plants design does not allow the A/C to receive energy from the batteries. Hence, a failure in both the power grid and the genset will likely lead to a site failure due to over-temperature even before the time T_{BAT} passes. This is an important failure mode not considered in the conventional calculation described above, but it is a relatively common one, particularly in those wireless communications base stations that are not equipped with permanent gensets, such as the one shown in Fig. 10. Preliminary information seems to suggest that this was the failure mode for an important switch during the recent earthquake in Haiti. Some emergency solutions commonly

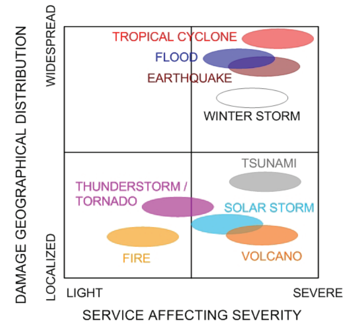

Fig. 6. Natural disaster impact on the electric grid [10].

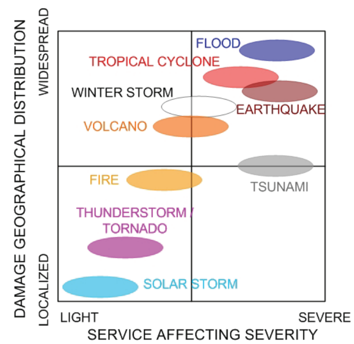

Fig. 7. Natural disasters effect on transportation infrastructure and liquid fuel delivery [10].

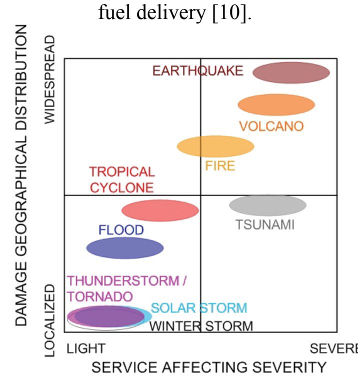

Fig. 8 Natural disasters effect on natural gas distribution [10].

implemented in telecom sites in order to reduce the heat load and diminish power consumption are, for example, turning off some base station sectors, prioritize circuit utilization, and operate in simplex power mode instead of conventional duplex operation.

Another vulnerability to natural disasters is observed in communication networks infrastructure construction practices. A common issue is inconsistent construction practices which are many times verified in wireless cell sites in hurricane prone areas by observing at the same site some base stations above the flood plane and other base stations below it [7]. In some other cases, the base station is located safely on a platform but critical power infrastructure is located on the ground (Fig 11). Similar issues are observed in DLCs or service area interfaces (Fig. 12) located many times at ground level and, thus, at risk of flood or storm surge waters. Yet, important efforts have been taken by network operators in order to place DLC RTs on elevated platforms. However, extension of this solution to all sites that may be affected by flood or storm surge waters is economically unfeasible so many times the decision of whether or not to elevate a DLC cabinet on a platform is dependent on a risk assessment evaluation. Inconsistent construction practices

Fig. 9 Genset on top of a pole-mounted CATV UPS after Gustav

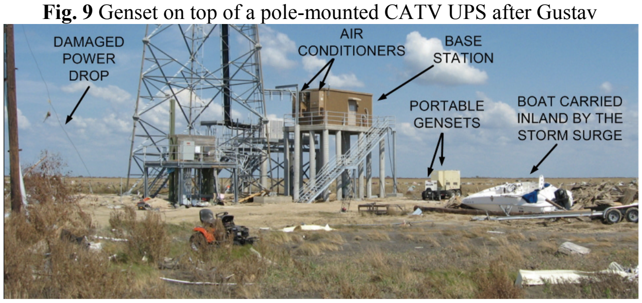

Fig. 10. Cell site without permanent genset affected by Hurricane Ike The base station was not damaged but service was lost due to lack of power

is a critical problem particularly for wire-line telephony COs because, contrary to wireless communications switching centers, the existence of a fixed connection between the subscribers and the CO limits choices on where to locate the CO building. In some cases the only option is to locate the CO at a place that may be affected by hurricanes storm surges. The solution is once again to construct the CO building above ground, such as the building in Fig. 13.

CONCLUSIONS

This paper discusses vulnerabilities of communication systems during natural disasters. The initial discussion utilizes a conventional approach to study communication networks availability, which concludes that there exist a single-point of failure at the grid tie that is manifested during natural disasters, particularly those affecting large areas and many lifelines. With the help of a fault tree, it is concluded that a correct approach leads to the need of considering a system-of-systems in which the communication network is one of the constituents systems. An alternative to eliminate the single-point of failure at the grid tie is a diverse power supply through distributed generators. Yet, these generators also rely on lifelines, thus supporting the concept of communication networks as part of a system-of-systems. Specific vulnerabilities are commented in the last part of the discussion including A/C power architecture and inadequate construction practices. The analysis is supported with photographic evidence from damage assessments conducted after some recent hurricanes.

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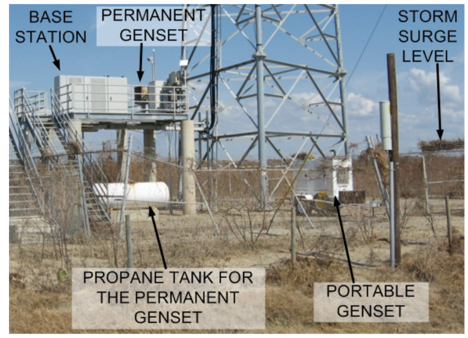

Fig. 11. A cell site affected by Hurricane Ike that required a portable genset because its permanent one likely failed due to damage received by its propane tank located at ground level.

Fig. 12. A destroyed service area interface by Ike. Destroyed repeaters are mounted on the pole on the left.

Fig. 13. South Padre Island CO. Although it is located close to the shore, it did not loose service after Hurricane Dolly.

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APPENDIX – FAULT TREE

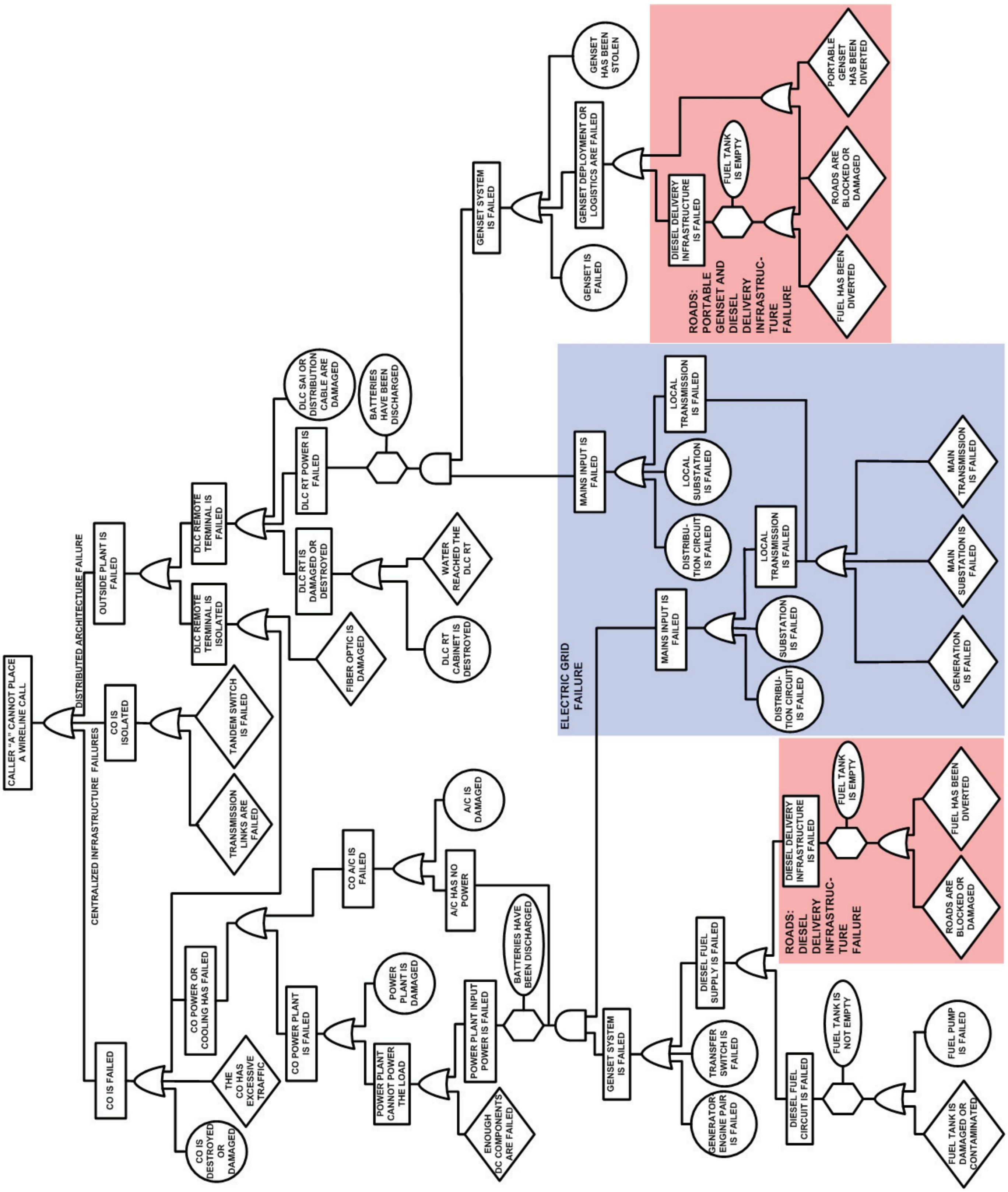

Fig. 14. Fault tree for a wire line communications network.

Examination of power supply options for communication sites operating in grid-islanded environments

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Abstract – **This paper discusses technological alternatives to operate communication sites without a grid connection. Two cases are the focus of this discussion: systems that are normally operating connected to the grid and they need to operate in islanded mode due to an involuntary event, such as a natural disasters, and systems where islanded operation is a desired choice, usually, for economic reasons. For the former, the performance of NTT-Facilities micro-grid in the city of Sendai after the March 11, 2011 earthquake is commented and lessons are drawn. For the latter case a new concept of data networking using distributed modular data centers is presented. The paper also discussed the availability model of these systems with particular focus on lifelines and sources modeling, including availability models for fuel delivery and for combination of renewable energy sources and batteries.**

I. INTRODUCTION

This paper explores technological options to power communication sites when they are operating isolated from a main grid. Such operational mode may be originated in:

1) a necessity, as it happens with transmission repeaters because the communication site has to be located in a place of difficult access or on an island, or
2) involuntary outcome caused by an external action, as it happens during natural disasters when grid power outages are common and extensive, or
3) a desired design or planning choice, as it happens in a herein presented data management and storage alternative in order to be able to achieve cost and energy savings and advantages with respect to conventional data center designs.

The first case typically involves the use of diesel generators. Since examples of this case can be found since the origins of telecommunication networks their operation is extensively known and understood. Hence, this paper will focus primarily on the next two cases: an involuntary outcome caused by an external action and a desired design or planning choice.

The second case of islanded operation is typically found after natural disasters or intentional attacks that result in extensive power outages affecting a given communications site under evaluation, such as a large data center or a PSTN central office. In this case, the main grid is the primary power source for the communications site during normal operating conditions. When an emergency that cause loss of grid power happens, a secondary power source—typically diesel generators—takes over the grid functions and provides power to the load. Even if a diesel generator is not present at the site, batteries are almost always provided in order to maintain the site operational. That is, power plants at these sites are planned to be stand-by energy systems.

The third case of islanded operation is presented in a newly proposed data center architecture oriented towards multiple distributed small modular data centers primarily powered by local sources. Although the grid can still be used, it is a secondary input considered only for economic purposes and not essential for the operation of the system or individual site. That is, each site is a micro-grid in itself.

In Section II, this paper describes these two cases and specific applications in which they apply. Then, in Section III the power availability models for these cases are presented. Additional considerations, such as comments about power electronic interfaces and their control are made in Section IV. Finally, this paper summarizes the main points by concluding in Section V

II. DESCRIPTION OF ISLANDED OPERATIONAL MODE

A. *Involuntary islanding*

Involuntary islanding occurs when a power outage affects a circuit feeding a site that is normally powered by a power grid. The solution for short outages is to power the site with batteries. For longer outages, communications sites are powered by diesel generators and in some cases natural gas generators. The interest in this paper is with long outages lasting several hours—e.g. a day or more—which typically occurs during extreme events, such as natural disasters.

A notable example of this case is NTT-Facilities micro-grid that was operating backing up the main grid operated by Tohoku Electric Power Company when a M_w 9.0 struck off the coast of the Tohoku Region in Japan on March 11, 2011.

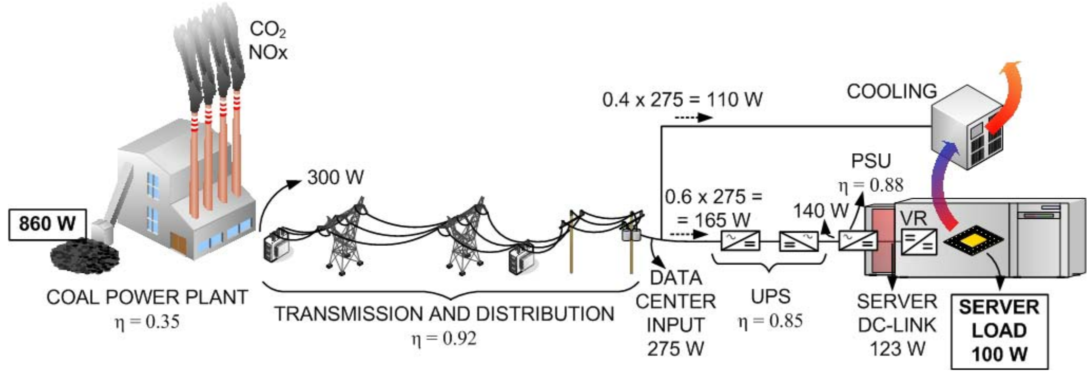

Fig. 1. Power path and power flow values for a server at a data center with a conventional configuration.

At the time of the earthquake the micro-grid loads distributed in a dc circuit and three ac circuits (A, B1 and B3). The onsite available generation included two 350 kW natural gas generators and 50 kW in photovoltaic (PV) arrays. A string of batteries we also present at the site. The earthquake happened at at 14:47 on March 11. As explained in [1], when the earthquake happened, the main electric grid serving the city of Sendai connected to the microgrid lost service as result of strong shaking affecting power generation plants and damaging components in substations and transmission lines. When this event happened, the electric grid was being used to power the micro-grid loads and its natural gas generators were in hot stand by. However, when the main grid lost service, the two 350 kW natural gas generators failed to start and power the loads, seemingly because the natural gas compressors were powered from the ac grid. At this time, all distribution circuits at the site except B3 which was the one designed with the lowest intended power quality level remained operating powered by the batteries while circuit B3 lost service. At 2:06 on March 12, the remaining ac circuits were manually disconnected in order to preserve energy stored in the batteries for the dc circuit—intended to have the highest quality level of all distribution circuits in the microgrid. At approximately noon on March 12, the natural gas generators were brought back into service—apparently by using inverters to power the natural gas compressors. Two hours later is was possible to power all circuits by these generators. Natural gas service was maintained at the site thanks to the hardened design of the natural gas pipeline serving the microgrid and the differentiated natural gas storage [2] (although most natural gas facilities for the city of Sendai were destroyed by the tsunami, the micro-grid has a natural gas connection to a site with storage located inland and that was not significantly damaged). Once the natural gas generators were brought back into service and all ac and dc circuits were powered by these generators, the micro-grid continued operating in island mode until 8:16 on March 14 when the local electric utility company restored its service. During this entire period, the 50 kW PV array contributed to power the load during day time when the weather was in a good enough condition.

Some important lessons from this event is that batteries are always important because they represent an energy asset that fails in rare occasions. Photovoltaic power was also an important power generation asset that can support the load during extreme events but on a limited basis. One of its main drawback is large footprint that leads to limited capacity. However, PV panels are rarely affected in these situations because they do not require lifelines in order to operate. Another lesson from this micro-grid's performance is that it is recommended to have all generators components with backup power and not exclusively powered by a main grid.

B. Planned islanding

As it was mentioned, one application in which islanding operation from a grid may be desired is in a presented architecture for data networks in which instead of relying on large multi-MW data centers, the data network is based on small distributed modular data centers that are placed at a location where power is generated at a low cost. The goal of this new data center architecture is to address increasing information and communications technology (ICT) sites energy-related cost by taking advantage of reduced costs of communications equipment and optical communications infrastructure. As Fig. 1 represents, the origin of this increased cost of energy is systemic and caused, among other things, by cooling inefficiencies in large data centers and higher costs associated to conventional grids centralized infrastructure (e.g. the cost of a new transmission line is in the order of a few million dollars per mile). Fig. 1 also indicates that in a conventional approach, 860 W of equivalent coal power are needed to obtain 100 W of power at the end load of an ICT site. That is, about 760 W are lost per 100 W of load mostly due to thermal inefficiencies both on the generation side and on the cooling infrastructure for the load.

In the data management architecture presented in this paper large data centers are replaced by small modular distributed data "centers" (MDDC) placed in large outdoor cabinets or small modular shelters. The smaller size of these sites allows for a more efficient cooling and, even, more cost effective use of new cooling approaches based on fluid flows. Even without extremely advanced cooling techniques, modular data centers power usage effectiveness (PUE) could be about 1.25 versus a PUE of about 1.9 in conventional data centers, where the PUE is from

$$PUE = \frac{\text{Total data center power consumption}}{\text{IT equipment power consumption}} \quad (1)$$

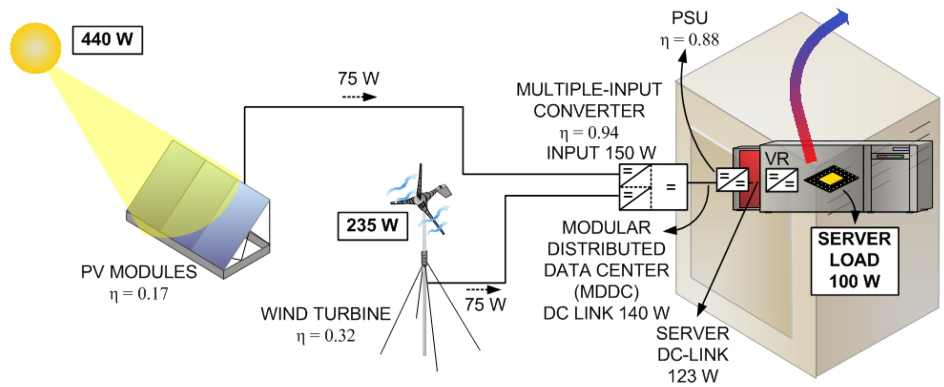

Fig. 2. Power path and power flow values for a server at a MDDC.

But more importantly, as Fig. 2 shows, the concept involves a paradigm change: these distributed data centers are primarily powered by local energy sources, particularly but not limited to renewables. That is, each of them forms a microgrid or local power system that may or may not be connected to a local grid. These MDDCs are expected to be geographically dispersed in a large area or among different regions of a country (Fig. 3) or the world. Hence, (if) when power is not enough at a given site, another site in the "cloud" with enough power and idle data capacity takes over the tasks of the site with insufficient power. Interconnection among these sites is made primarily through fiber optics cables, which have a cost at worst of a few tens of thousand dollars, i.e., 100 times less than a transmission line. That is, photons transmitted through fiber optic cables are used as a "proxy" for electrons that, otherwise, would be circulating though transmission lines. In this way, data and power portions of the ICT systems become integrated into a single operational entity. These sites may have local energy storage to provide more operational flexibility both for power generation and for data storage used as part of site hand-over processes. However, as Fig. 4 represents, the local power sources are the primary source of power. Also notice in Fig. 2 that energy is used more effectively, requiring 635 W of equivalent wind and solar power to feed a 100 W load. However, contrary to the case in Fig. 1, most of the power difference between the load and the equivalent sources is not lost power but energy that is not harvested in the local generation units. This approach also enables a more intense penetration of renewables which in large data centers are mostly constrained by limited space and siting constraints. Still, it is fair to point out that the difference between potential power available from renewable energy sources (635 W in Fig. 2) and effective output power from these sources (150 W), although they do not represent power lost mainly in ohmic losses, they result in relatively large footprints—i.e., space "inefficiencies." Another potential limitation of this approach for data computing and storage is that latency among different MDDCs may prevent using this concept in applications, such as real time video processing and viewing, in which latency must be minimal. Nevertheless, due to the local focus of the power approach, this concept of distributed data centers is a tool for economic development in the areas where the MDDCs are dispersed.

III. Availability Models

One of the important aspects of doing an unbiased technological assessment of islanding operation characteristics is to use a quantitative approach. In particular, during islanding operation it is necessary to quantify availability not only of the communications site power plant, but also of the lifelines because even with a perfectly available power plant, if its lifelines fail, the communication site will not be powered Hence, due to its importance, this paper initially summarizes the models used to calculate availability in grid-islanded systems. These models necessary to assess power availability that are summarized here were originally presented in [3] and [4] and also commented in [1]. These works are used next as the basis for the analysis. Hence, some portions of them are included next for convenience.

A. Calculation of System Availability

In a broad sense, the availability of a system or a repairable component is defined as

$$A = \frac{\mu}{\mu + \lambda} = \frac{T_U}{T_U + T_D} \qquad (2)$$

where μ and λ are the failure and repair rates, respectively, and T_U and T_D are the mean up time and mean down time, respectively. Mean time between failures is, then, $T_U + T_D$. Unavailability is the complement to 1 of the availability. Using a minimal cut set (mcs) approach [5] the unavailability of a system with reliable components can be approximated as

$$U_{SYS} \cong \sum_{j=1}^{M_C} \prod_{l=1}^{c_j} u_{l,j} \qquad (3)$$

where M_C is the total number of mcs, c_j is the number of (failed) components in the mcs j, and $u_{l,j}$ is the individual unavailability of each of the c_j components in mcs K_j. In the analysis $u_{l,j}$ is the ratio of a component failure rate $\lambda_{l,j}$ to the sum of its failure rate $\lambda_{l,j}$ and repair rate $\mu_{l,j}$. A mcs is a group of failed components such that when all of those components are in a failed state, the system is also in a failed state—characterized here by the impossibility of feeding completely the load—but if any single one of those components is repaired, then the system is back again into an operational state. Each mcs can be associated with a failed operational

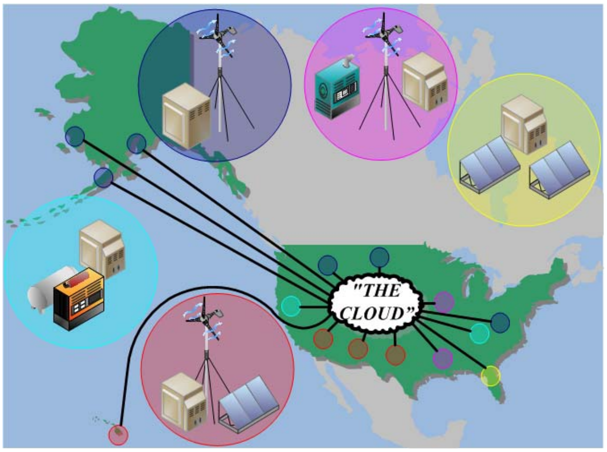

Fig. 3. System configuration for a network of MDDCs.

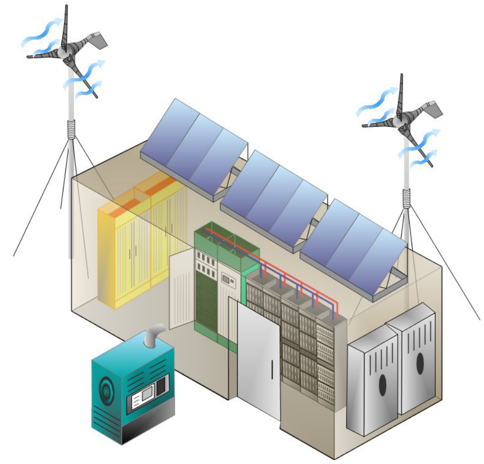

Fig. 4. Representation of a possible configuration for an MDDC.

state of the system under analysis called minimal cut states. In a Markov process representation, transitions involving repair rates out of minimal cut states end in states representing a working condition for the system. Such working condition does not necessarily imply that all components are operational. However, it does represent the condition in which the load is powered.

In order to calculate (3) for a communications site power supply, it is necessary to know the unavailability of all of its components and to identify the minimal cut sets. Since the focus here is on operation isolated from a main grid, it is of particular importance to consider the contribution of the various energy storage subsystems—e.g., batteries, diesel in storage tank, etc.—and, if present, local power generation sources. to the availability calculation. Two types of sources can be identified: those that do not have lifelines, such as renewable energy sources, and those that require lifelines. Hence, the discussion summarizes next how to perform such calculation based on the approach detailed in [3] and [4]. Another important contributing factor related with the calculation of (3) is the availability of the power architecture and the power electronic interfaces circuit topology. Such calculation has been presented in [6].

B. Sources without lifelines—renewable energy sources.

In [7] it was identified that renewable energy sources are a good solution to power communication sites particularly during extreme events, such as natural disasters, because they do not have lifelines. The focus here is on the most commonly used power generation units based on renewable energy: PV modules and wind generators. Although these systems do not require lifelines their output is at least partially stochastic—e.g. in PV modules it is possible to know for sure that no power is generated at night and to calculate how much power they can generate during day with an ideal sunny day; the problem is not knowing for sure when the weather of a given day will be perfectly sunny. This partially stochastic nature makes their operation complicated unless batteries are added that allow compensating both when there is excess or insufficient power being generated by the renewable energy-based sources. Thus, for the renewable energy sources model, it is assumed that batteries or other form of energy storage is used in conjunction with the renewable energy sources.

Consider initially only a PV array. In the availability model the power output from the PV array and the load are sampled at regular intervals. In each of these intervals the difference between the power produced by the PV array and the load is the power balance P_B given by

$$P_B = P_{PV} - L \tag{4}$$

where P_{PV} is the power generated by the PV array and L is the load of the communications site under analysis. When $P_{PV} > L$ then the extra generated PV power is used to charge the batteries used in conjunction with the PV array. If the batteries are already charged then, the power electronic interface used to control the operation of the PV modules at their maximum power point (MPPT) is disables and the controller is used to move the PV modules operating point to one in which $P_{PV} = L$. If $P_{PV} <$ L then the batteries provide the power difference between L and P_{PV} until they are discharged. If $P_{PV} < L$ and the batteries have not enough capacity to provide the difference in power between P_{PV} and L, then it is considered that the system formed by the PV array and the batteries is in a failed state.

In a practical non-ideal setting, many times PV arrays cannot provide all their theoretical power because of aging and other factors, such as dust, reduce the output power. These real effects can be considered in (4) based on

$$P_{PV,d} = (1-\delta) P_{PV,i} \tag{5}$$

where $P_{PV,i}$ is the ideal PV array power output and δ is a performance degradation factor. Reliability characteristics of PV modules can also be considered in a somewhat similar way, by considering that a PV array expected power output equals the PV array availability, a_{PV}, multiplied by $P_{PV,d}$

$$P_{PV} = a_{PV} P_{PV,d} \tag{6}$$

Some typical values for the performance degradation factor δ are between 0.002 and 0.007 per year [8], whereas a typical availability value for PV arrays is 0.996 [9]. Wind power generation can be considered in the same than PV power generation. In terms of performance degradation, the factor δ

may take various values depending on the process affecting the wind turbine performance. For example, the value of δ for ice accumulation may vary between 0.14 and 0.2 [10]. In areas with high concentration of dust and no rain δ may reach values up to 0.55 over a 9-month period [11]. A typical value for wind turbine availability is about 0.96 [12]. It is important to point out that the data used for this availability value is for large wind turbines that may or may not be used in some of the applications described here. For smaller wind turbines, availability tends to be better due to the lack of a gearbox.

The availability model for the combination of a renewable energy source and batteries connected to its output that is used here is based on a Markov chain approach presented in detail in [4] and summarized in [1] and [3] within the context of operation during natural disasters. The graphic representation of this Markov chain model of the PV array / battery system (PVABS) is shown in Fig. 5. As shown in Fig. 5, each state represents an energy level for the storage system, so each state transition, characterized by a probability p_i or p_{-i}, represents a charge or discharge process. State *#1* is the state corresponding to having the batteries completely discharged—here completely discharged refers to end of operational capacity as defined by the system user—and State *#N* is the state when batteries are fully charged. If it is assumed that the batteries have linear charge and discharge processes, the energy difference between any two adjacent states is Δ so the power involved in such process is Δ divided by the time step T_s between two consecutive steps in the Markov chain. Hence, p_{-i} represents the probability of a transition among states with an energy efflux of $i\Delta$ in T_s, and p_i represents the probability of a transition among states with an energy influx of $i\Delta$ in T_s. The probabilities p_i can be known based on statistical data from the communications site location. Once they are known, it is possible to define a transition probability matrix P that defines the Markov chain model [3]. A detailed definition of P can be find in [4]. Then, the limiting probabilities vector, π, can be found from

$$\pi = \pi P \tag{7}$$

where each of the components in π represents the long term steady state probabilities that the energy storage system is at a certain energy state. The unavailability of the PVABS, is, then

$$u_{PVABS} = \sum_{i \in \{1, N-1\}} \left(p_{-i} \sum_{j \le i} \pi_j \right) \tag{8}$$

Failure and repair rates can be calculated with the approach given in [3] when the Markov chain in Fig. 5 is considered to be the embedded Markov chain for a 2-state Markov process.

The batteries capacity is then given by

$$C_{PVABS} = (N-1)\Delta \tag{9}$$

Thus, C_{PVABS} can be changed by changing Δ, which, in turn, changes P and, hence, u_{PVABS}. It can be found that considerable energy storage needs to be added to renewable sources in order to achieve high availability levels. Another issue found with renewable sources is that they also require large footprints with respect to the area occupied by the load. For example, consider the case presented in [1] of a 4.1 kW load—which could have corresponded to the load in the dc circuit of the Sendai micro-grid—and a 50 kW PV array in order to make it match the capacity at the micro-grid in Sendai. Considering solar data in Austin, Texas, because this is the data available to the author at the time of writing this paper, such PV array would generate an average power of close to 12 kW during daytime, i.e. 7:00 am to 7:00 pm. (12 hours of daytime is considered because that is the approximate length of daytime on March 11, 10 days before an equinox when daytime duration is exactly 12 hours). With such configuration, if 5-nines availability is desired, the micro-grid requires a total capacity for the batteries equivalent to powering the load for 1.2 days or about 118 kWh (Fig. 6). However, if a PV array is intended to be used to power all the load at a given site of, for example, 1 MW, then a PV array of 12.25 MW (occupying an area of at least about 61,000 m^2) and 28.8 MWh of battery energy storage would be needed. If it is desired to reduce the footprint of such PV array, Fig. 6 shows that a reduction of 25 % of the PV array capacity would reduce the availability of the system from 5-nines to about 2-nines. As explained in [3], wind combined with PV can reduce battery capacity requirements.

One way of reducing the necessary battery capacity is through source diversification. As another example, consider now the case discussed in [3] of an MDDC totaling a 100 kW load. In order to provide some generation overhead consider first that only a PV array of 1.225 MW is used—which gives an average power generation of 293.63 kW (variance = 68.2) during daytime, i.e. 7:00 am to 7:00 pm. By following the described approach the PV curve in Fig. 7 can be found. Suppose that a 5-nine availability is sought for the sources, which is a typical minimum availability value for communication sites. Then, Fig. 7 indicates that 1.15-day capacity of energy storage is needed which translates into a battery capacity of 2.7 MWh obtained for a time step T_S of 1 hour, and with Δ/T_S and N equal to 10 kW and 277, respectively. When 225 kW of wind power generators are added, yielding 110.82 kW of average generated wind power—so each wind or PV generators can sustain the load alone—the necessary energy storage to achieve an availability of 5-nines decreases significantly to about 0.5 days worth of load power, or 1.2 MWh.

C. *Sources that have lifelines—continuous fuel supply*

This case corresponds to power sources that receive fuel continuously and that such fuel is not stored locally. One example of this case is a generator driven by a microturbine or an internal combustion engine fueled by natural gas provided by a local distribution company. Thus, the two natural gas generators in NTT-Facilities micro-grid in Sendai fall into this case.

Two operational modes influence the calculation of the unavailability. If the local generator is the primary power source and is operating continuously powering the load, as it could be the case of an MDDC, then the unavailability of the local power generation unit system, u_{PGS} is

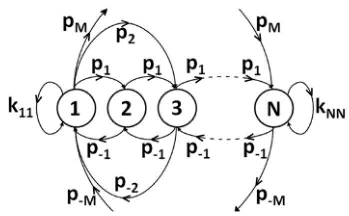

Fig. 5. Markov chain diagram for availability model of a PVABS [4].

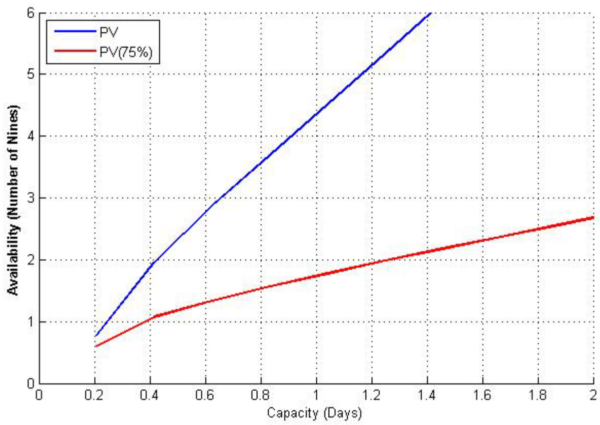

Fig. 6. Availability as a function of battery capacity for an example of a PVABS [1].

$$u_{PGS} = 1 - (a_{GenU} a_f) \tag{10}$$

where a_{GenU} is the availability of the generation unit and a_f is the availability of its fuel source, which is usually natural gas. Both of them can be calculated with (2). The values for T_U and T_D can be obtained from the fuel suppliers or from other sources [13]. In case of operation during extreme events, such value for the mean-up time and mean-down time can be adjusted in order to consider the special conditions found during these extreme events, such as natural disasters. The other possible operational mode is the one observed in the micro-grid in Sendai, where the local main grid was the primary power source and the generators were in standby mode. In this case, the unavailability of the combined system made of the local grid and the generators is given by [14]

$$u_{SB} = \frac{\lambda_{MG}(\lambda_{PGS} + \rho_{GenU}\mu_{MG})}{\mu_{MG}(\mu_{MG} + \mu_{PGS})} \tag{11}$$

where λ_{PGU} and μ_{PGU} are the failure and repair rates of the series combination—from an availability analysis perspective—of the generator unit and its natural gas supply, respectively, λ_{MG} and μ_{MG} are the failure and repair rates for the main grid, respectively, and ρ_{GenU} is the failure to start probability for the generator. Thus, λ_{PGU} and μ_{PGU} are those related with the unavailability calculated in (10). In case of the study of operation under natural disasters, all these values, are evaluated under the anticipated extreme event conditions.

D. Sources that have lifelines—discontinuous fuel supply

This case represents sources, such as diesel engine generators, in which fuel is delivered periodically according to a probability density function $f_d(t_d)$ and, then, stored in a

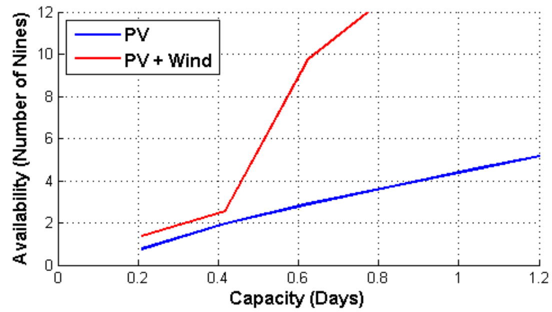

Fig. 7. Availability vs. battery capacity for PV and PV combined with wind generation [3]

tank with a capacity that provides an autonomy of T_{TC}. Then the probability of emptying the fuel tank P_E because the fuel delivery time t_d exceeds T_{TC} is

$$P_E = 1 - P_{E*} = P\{t_d > T_{TC}\} = 1 - \int_{t_d=0}^{t_d=T_{TC}} f_d(t_d)\,dt_d \tag{12}$$

A key aspect of this model is the fuel delivery probability density function $f_d(t_d)$. There are many possible ways of defining this function. An exponential form, typically seen for other applications in reliability studies is not realistic in this application because it makes more probable to have a fuel delivery at the beginning of a fuel delivery cycle, i.e., immediately after the site has been refueled, than at the end. A uniform distribution is not a significant improvement in terms of achieving a realistic representation. Instead, a triangular-shaped function detailed in [3] and used here is a more realistic option because the probability of observing a fuel delivery from the beginning to of the fuel delivery cycle until some initial time , T_i, when the fuel can be delivered is zero, but then the probability density increases linearly until reaching a maximum at a fuel due delivery time , T_D, and, finally, it decreases linearly until the probability density reaches zero again at a time, T_M that is the maximum time when the fuel can be delivered.

Assuming a triangular fuel delivery probability density function [3] and many refueling cycles, the unavailability of the fuel supply can be calculated considering there are $r = P_{E*}/P_E$ fuel delivery cycles in which the truck arrived before T_{TC} and, hence, does not fails, for every fuel delivery cycle in which the generator stops operating after running for T_{TC} hours because the tank was emptied. If it is also assumed that T_{TC} is selected within the interval $[T_D,T_M]$, the average time when the generator is refueled before T_{TC} is given by a time T_{Uf} equal to [3]

$$T_{Uf} = T_{TC} + r\,\frac{(T_M - T_D)\int_{T_i}^{T_D} t(t-T_i)dt + (T_D - T_i)\int_{T_D}^{T_{TC}} t(T_M - t)dt}{(T_M - T_D)\int_{T_i}^{T_D} (t-T_i)dt + (T_D - T_i)\int_{T_D}^{T_{TC}} (T_M - t)dt} \tag{13}$$

whereas the average time that the generator will remain down when it is not refueled before T_{TC} passes is [3]

$$T_{Df} = \frac{T_M - T_{TC}}{3} \tag{14}$$

Then the fuel supply unavailability is, then

$$u_f = \frac{T_{Df}}{T_{Uf} + T_{Df}} \tag{15}$$

The unavailability of the combined system made of the generator and its fuel supply is, then

$$u_{PGS} = 1 - (1 - u_f)(1 - u_{GenU}) \tag{16}$$

where u_{GenU} is the unavailability of the generator.

This fuel unavailability evaluation approach can be used not only when the local generator is the main power supply when the grid is absent and when it is not (as in the MDDC application), but it can also be used when the local generator is operating as a back up for the main grid, as it usually occurs in most communication sites. This common calculation approach can be applied because when the local generator is used as a back up for the grid, it is assumed that when the grid fails the fuel tank is full and that the power grid outage is long enough so there will be many refueling cycles involved until the grid service is restored. That is, it is the expected case of a grid isolated operation due to a involuntary situation, such as a natural disaster. Notice also that in the backup case, the availability model is the one presented in [14], which implies that the local generator cannot fail when the grid is operating. The model in [14] also provides a common unavailability for the combination of grid and the generator even when it is expected that the communication sites operates isolated from the grid for a long time because it takes into account the failure to start probability of the generation units. Since the model in [14] is used in (11), it can be used again with the new values resulting from (16).

E. *Effect on availability of batteries added to the main bus of the system*

One of the observations that can be made from the performance of the NTT Facilities micro-grid in Sendai after the earthquake of March 11, 2011, is that added batteries seem to be an important way of preventing micro-grid failure. This failure may be caused by a malfunction of the local generators or it may serve as a decouple mechanism for lifeline dependence [15]. It is important to highlight that in the case of a system with a PVABS these added batteries are summed to those considered directly associated to the renewable energy sources. When batteries are added to the main bus of communications site power system, its unavailability U_L as seen by the load can be calculated from [3]

$$U_L = U_{NB} e^{-\left[\sum_{\mu_i \in M_{mcs}} (\mu_{MCS,i} T_{BAT})\right]} \tag{17}$$

where U_{NB} is the unavailability of the distributed generation system without the batteries added to the main bus and calculated using (3), T_{BAT} is the autonomy of the added batteries at the given load, and $\mu_{MCS,i}$ is all the transition rates from minimal cut states M_{mcs} into operational states. Notice in (17) that U_{NB} considers the effect of lifelines and local sources performance into system availability through the inclusion of sources and lifelines unavailabilities in the calculations of some of the minimal cut sets probabilities. Numerical examples showing the effect of these added batteries are also shown in [3].

IV. Additional Considerations

Although the focus of this paper is on systems operating in an isolated fashion with respect to a main grid, in the case that islanded operation is chosen due to a desired design choice—e.g., as in the MDDCs,--it is possible in some cases to prefer to have the option of still count with a grid connection as a secondary power source. Such connection may be used in order to optimize economical operation of the site. Then, the question becomes how to interconnect the grid and the micro-grid at the communications site. For a communications and data networking sites it is reasonable to assume that the micro-grid has a dc power distribution architecture. This option is even true when the site is a MDDC in which for historical reasons it could be expected an ac power distribution scheme. There are several reasons for a dc choice—likely at 380 Vdc. One is that dc is a natural choice when integrating local sources and energy storage. Another reason is that the load is inherently dc. Moreover, as it was shown in [16], efficiency gains can be achieved for air conditioners in dc power architectures over ac systems. Thus, with a dc power distribution system at the site, the most likely choice for an interface is a controllable rectifier/inverter. Since this interface is added for economical reasons, it is expected that it is able to inject power into the grid so excess power generated locally can be provided into the grid for an economic benefit. Hence, the next question to answer is how to control the power injected into the grid. Consider that the inverter operates at unity power factor because it is not common to observe utilities providing economical benefits for reactive power injection. Also, assume that the inverter is controlled in order to present a resistive impedance R_{inv} to the grid. For simplicity, consider a single-phase inverter. Still, the same analysis can be used for a three-phase inverter considering its single-phase equivalent circuit. Since the grid's voltage at the grid-tie point, V_G, is fixed due to the main grid stiffness, then the power P_{inv} of the inverter can be regulated by controlling the inverter internal output voltage amplitude V_i through the modulation index as indicated by

$$P_{inv} = \frac{V_G}{R_{inv}}(V_i - V_G) \tag{18}$$

If due to its output filter and controller the inverter presents, instead, a reactive impedance X_{inv} to the grid, then (18) becomes

$$P_{inv} = \frac{V_G}{X_{inv}}\sqrt{\left(V_i^2 - V_G^2\right)} \tag{19}$$

Another question is about the power electronic interfaces for the sources. One important observation that can be made from the availability analysis is the importance of having diverse power sources. As discussed in [1] a suitable approach for integrating diverse power sources is with multiple-input converters, such as those in [17], or the one in Fig. 2. Such converters should also be able to integrate batteries or other energy storage devices, which implies the need for bidirectional power flow. Hence, it is desirable that multiple-input converters allow for such bi-directional power flow. A discussion about this feature is found in [1], with an example of such a circuit in [18].

Another important observation is that the MDDC concept integrates data and power use not only at a system level by interconnecting sites purely optically instead of electrically, but also within each MDDC. This internal integration is observed through the energy storage needs. Short time energy storage is needed in the MDDC in order to provide time for the data processes to be interrupted and commutated to another site when the local power supply is reduced. Hence, local energy storage needs to be coordinate with data storage size and speed. This coordination involves short times but frequent use of the local energy storage. Optimization of this coordinated operation is still under analysis.

V. CONCLUSIONS

This paper has explored powering alternative for communication sites when there is no grid connection. Two main cases were presented for the analysis: a forced operation in islanded mode caused by an extensive power grid outage and a preferred operation separately from the grid due to a design choice. As a test study for the forced islanded operation this paper has described the performance of NTT-Facilities micro-grid in Sendai during the March 2011 earthquake. Importance of diverse power sources and local energy storage was identified through this experience. As a case of chosen islanded operation, this paper presents a new approach for data networking that is based on the use of modular distributed data centers that may not need a grid connection because they are powered by local power sources. Optical connection serves to manage the operation of the system as a whole by shifting data processing and storage capabilities where it is more convenient based on the local power generation mix and local weather and electric prices conditions.

In its second part this paper discusses availability models for sources and lifelines because they heavily influence the operation of micro-grids when no main grid is present. Three main models are commented: renewable energy sources combined with batteries, sources that require continuous fuel supply, and sources with discontinuous fuel supply that is stored locally after it is regularly delivered. The models suggest that it is important to have diverse power sources. Quantifiable effect of availability by energy storage is also discussed in this paper.

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Availability Evaluation of Micro-Grids for Resistant Power Supply During Natural Disasters

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***Abstract*—This paper discusses how micro-grids availability during natural disasters and in their aftermath can be assessed. The analysis focuses on two critical groups of components that allow micro-grids to improve power supply availability: distributed generators and local energy storage. For distributed generators and, due to their importance during natural disasters, this paper presents a novel focus by exploring the importance of lifelines for system availability. Renewable energy sources are identified as valuable distributed generation assets during disasters because they do not require lifelines; yet, their variable generation nature leads to the need for significant local energy storage. Additional local energy storage may be desirable as a backup solution to address potential failures that would blackout the load because they reduce the impact of lifeline performance during disasters on micro-grid availability. Analysis of micro-grids availability is performed based on Markov state space models and calculated using minimal cut sets approximations. This calculation method has the advantage of being very simple, not requiring extensive knowledge in the subject or computational needs. Results are verified with numerical experiments using Monte Carlo simulations.**

***Index Terms*—Availability model, distributed generation, energy storage, lifelines, Markov chain, microgrids, minimal cut sets, natural disasters, reliability, renewable energy sources.**

NOTATION

F	Set of failed micro-grid states.
W	Set of working micro-grid states.
K_j	jth minimum cut set (mcs).
$\mathrm{P}(K_j)$	mcs K_j probability of occurrence.
M_C	Total number of mcs.
c_j	Number of (failed) components in the minimum cut set j.
$u_{l,j}$	Individual unavailability of each of the c_j components in mcs K_j.
T_i	Initial time when fuel delivery may occur.
T_D	Fuel delivery due time.
T_M	Maximum amount of time a fuel delivery may occur.
u_f	Unavailability of the fuel supply system.
P_{OD}	Probability of exceeding the fuel delivery due time.
$P_{OD,\mathrm{ref}}$	Reference probability of not meeting a fuel demand reference time.
T_{TC}	Tank autonomy for the specified load.
P_E	Probability of emptying the fuel tank.
MDT_f	Mean down time of the fuel supply.
MUT_f	Mean up time of the fuel supply.
Δ	Unit energy step difference between two of the battery charge states.
P	One step transition probability matrix for the Markov chain model of the renewable source and battery system.
M	Transition rate matrix for the continuous time Markov process associated to the Markov chain represented by P.
π	Limiting distribution of the Markov chain model.
T_s	Time step length for the Markov chain.
L_{day}	Load during the day.
L_{night}	Load during the night.
P_{PV}	Power generated by the PV array at a given time.
C_{RW}	Capacity of a battery connected to a renewable source.
$\pi_{RW,W}(t)$	Probability that the renewable energy sources are in the state W at time t.
$\pi_{RW,F}(t)$	Probability that the renewable energy sources are in the state F at time t.
λ_{RW}	Failure rate of the renewable energy sources.
μ_{RW}	Repair rate of the renewable energy sources.

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$f_{MG\mu}(t)$	Micro-grid's failure probability density function.
U_{MG}	Micro-grid unavailability without distribution-level batteries.
$P_{MGf}(t)$	Micro-grid failure probability at time t.
μ_{FW}	Sum of all the transition rates from F to W.

I. Introduction

THIS paper explores the possibility of using micro-grids as a way to improve power supply availability during natural disasters. Due to their impact on micro-grids operations during disasters and their aftermath, the analysis presents a novel approach that focuses on evaluating lifeline performance and their quantifiable impact on micro-grids availability. The presented methodology also considers the effect of added local energy storage because of their importance for reducing the effect of lifeline dependencies—a critical factor affecting micro-grids during disasters—and variability of renewable energy sources. As it is anticipated that most micro-grid owners and operators may not likely be experts in power systems or count with extensive computational capabilities, a simple availability calculation approach is presented and discussed.

A. Motivation and Problem Formulation

Recent natural disasters have created growing concerns about power supply availability and raised doubts about the capability of conventional power grids to sustain operation so vital society services—e.g., food refrigeration cycles, water provision, health care, communications, financial services, oil refining, and others—are not interrupted during disasters and in their aftermath. The experience through these disasters is that due to bulk power grids large geographical layout, combined with their centralized generation and control architectures, conventional power grids are fragile systems in which damage to less than 1% of their components can lead to extensive high-incidence outages [1] so it could be expected that large areas may experience high power grid outage probability. Thus, within the context discussed here, the grid may likely be unavailable at the critical load mains tie and its neighboring area from a few weeks to several weeks. Evidently, such performance may not be observed for all disasters or in all areas, but there is still evidence of such performance observed in various recent disasters, such as hurricanes Katrina [2] and Ike, the 2008 Sichuan earthquake in China [3], and the 2011 earthquake and tsunami in Japan (Fig. 1).

However, despite the large extension of power outages that may be observed after some natural disasters, such as hurricanes, earthquakes and tsunamis, damage assessments indicate that areas with intense infrastructure and dwellings damage is generally a much smaller area than that observed with high-incidence power grid outages. Moreover, damage distribution is very inhomogeneous and with abrupt variations in the damage severity—i.e., as Fig. 2 shows, it is very common to find a zone with extreme damage surrounded just a few meters away by areas with little damage. This characteristic is even observed in less extreme cases, such as after Hurricane Ike when damage to the only line serving the Bolivar Peninsula (Fig. 3) led to several weeks of lack of power in towns with extreme damage (Gilchrist), moderate damage (Port Bolivar), and little damage (High Island). From an user perspective these are two important observations that support the use of micro-grids to power electric loads during disasters because the fundamental problem for electricity consumers is the lack of powering alternatives—i.e., lack of diversity—to continuously power their loads other than conventional grids or stand-by power systems—commonly, diesel gensets. Still, these stand-by systems have also reliability issues, such as a relatively high failure to start probability for gensets that limits stand-by power plants availability to about 0.9999 or 4-nines [4].

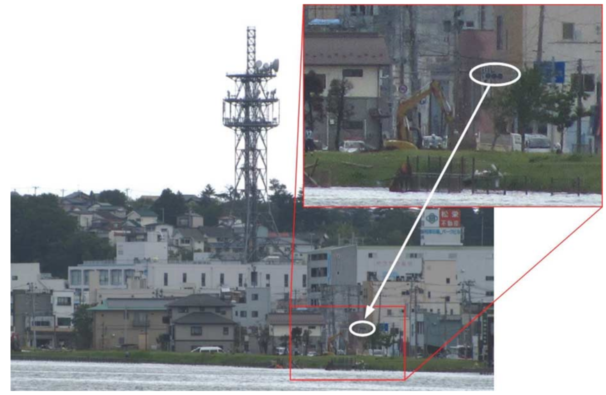

Fig. 1. Ishinomaki, Japan. The ovals highlight evidence of persisting power outages around NTT central office (the building with the large communications tower) more than 3 months after the earthquake and tsunami struck this area on March 11, 2011 (photo taken on June, 15, 2011).

Fig. 2. Onagawa, Japan. While all buildings and infrastructure in the foreground were demolished by the tsunami, there is little damage in the background area higher on the hills where the tsunami did not reach.

Here, micro-grids are considered to be locally confined and independently controlled electric power grids in which a distribution architecture integrates distributed energy resources (DERs)—i.e., local distributed generators and energy storage devices—and loads [5], [6]. Hence, when micro-grids interact with a bulk grid with an interface that provides both communications and control for a coordinated operation, they could become building blocks of an advanced smart grid [7], [8]. A key fundamental difference with respect to conventional grids is that micro-grids add active network components at the distribution level, which provide more operational flexibility and reduce conventional power grids vulnerabilities caused

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Fig. 3. Broken and tilted poles caused by Hurricane Ike in the only line serving the Bolivar Peninsula area.

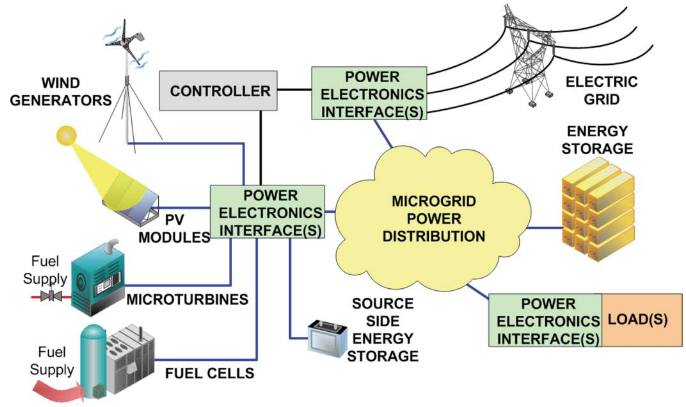

Fig. 4. General representation of a micro-grid.

by centralized generation and control architectures and long distances between power sources and loads [9]. With this approach, micro-grids contribute to locally achieve one of smart grids goals of being "*resilient to attack and natural disasters with rapid restoration capabilities*" [10]. However, potential high cost of distributed generation (DG) and local energy storage—the active network elements that are key to realize enhanced local power supply availability through micro-grids—create cost concerns that in the short term may limit application of this solution to cases in which risk assessments may include downtime cost as part of their calculations. One such risk assessment framework was presented in [11], in which the downtime cost is an important factor that contributes to make micro-grids competitive with respect to other conventional approaches. Hence, the analysis considers this more demanding case of critical loads, such as in military bases, data centers, or hospitals, where very high power availability is required because downtime costs tend to be high. Nevertheless, the analysis can also be extended to conventional loads, as indicated as part of the discussion.

One of the aforementioned observations—uneven damage distribution—provides an answer for a common concern when using micro-grids for powering a local area during disasters: micro-grid power sources can themselves be damaged, too. Yet, if the sources are located in an adequate site, chances of them being damaged are very low. Validity of this concept was recently demonstrated during the earthquake and tsunami of March 2011 in Japan, where a micro-grid in Sendai [12] was able to maintain operation powering its local loads [1]. The relevance of micro-grids in this context may be further reinforced as significant reduction of generation capacity due to safety concerns directly derived from the Fukushima #1 nuclear power plant incident leads to a long period of potential lower power quality in Japan with rotating blackouts.

Although inhomogeneous damage distribution may answer concerns about direct damage to the micro-grid, there is one potential source of problems that has been little explored: many micro-grids generation technologies, such as engine generators or microturbines, depend on other infrastructures called lifelines, such as roads or natural gas distribution networks, in order to receive fuel supply for these sources to keep them operating. These lifelines may be affected by the disasters like conventional grids are [4]. A close analysis of potential hazards at the micro-grid site may allow addressing this problem by choosing local generation sources for which their lifelines may not be severely affected by the considered hazard—e.g., natural gas supply is less vulnerable to hurricanes than to earthquakes. But, in some situations, it may not be possible to select such choice. In such situations, energy storage may be necessary in order to reduce lifeline dependencies [13]. Another option is to rely on renewable energy sources, such as solar radiation or wind that do not depend on a lifeline to reach the local micro-grid generators. However, large footprints may limit the application of these renewable energy-based power sources in sites with reduced space or relatively high power demand. Moreover, variable output also restricts the application of renewable energy sources. Like in the case of lifeline dependencies, energy storage may address this latter issue found with renewable energy sources. However, added energy storage needs due to lifeline dependencies or renewable energy sources variable output increase micro-grid capital cost with respect to the micro-grid design intended for operation during normal conditions because well designed micro-grids may not have significant requirements in terms of energy storage in order to reach high availabilities [14]. But adequate sizing of the added energy storage leads to one additional practical issue: micro-grid operators are expected to be private individuals that may not have extensive knowledge of power systems reliability theory or have extensive computational assets. Hence, quantitative assessment of lifelines and energy storage impact on micro-grids availability need to rely on a simple calculation method.

B. Previous Work and Proposed Approach

Fig. 4 shows a simplified schematic of a typical micro-grid considered for the analysis, which could have an ac, dc, or hybrid distribution system. Notice in Fig. 4 that all loads and DERs are on the micro-grid side of the power electronic interface separating the grid from the micro-grid. This interface acts as a boundary that provides electrical confinement to the micro-grid and enables implementing the availability analysis techniques used in this work. It also allows such a micro-grid to meet interconnection standards [15] and operate in an island mode enhancing local power supply availability during natural disasters when grid outages are expected to happen [16]–[19].

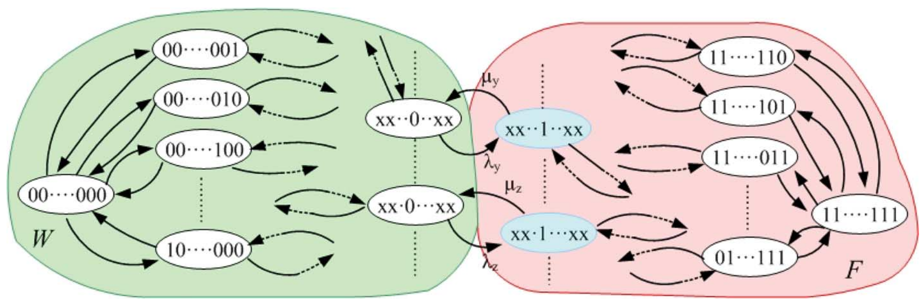

Fig. 5. General Markov representation of a micro-grid availability behavior with the minimal cut states indicated with a shaded interior.

During natural disasters, micro-grids are expected to operate in island mode. Hence, power supply availability is predominately influenced by micro-grids DERs performance [20]–[22]. Hence, the discussion is oriented towards DER and, in particular, effect on availability from local energy storage and lifelines. Thanks to micro-grids confined electric domain, their availability can be studied with somewhat simpler approaches that those used to assess conventional power distribution reliability [23]. One example of such alternative approaches using minimal cut sets (mcs) theory. An mcs can be related to a group of failed components such that when all of those components are in a failed state, the system is also in a failed state—characterized here by the impossibility of completely feeding the load—but if any single one of those components is repaired, then the system is back again into an operational state. Such approach can be found in [22] and [24] but their focus is not on lifelines or energy storage as we present here. A relevant result in [24] is to identify the importance of having diverse power sources—while redundancy refers to having more of the same components than the minimum required, diversity implies having different entities serving the same goal. In the past there has also been a number of works studying micro-grids availability including [25]–[36]. Yet, although lifeline performance—e.g., roads to deliver fuel—is a critical aspect of micro-grid availability the only basic diesel fuel delivery availability model have only been recently suggested in [13] and only for stand-by operation and not for continuous operation as needed in micro-grids. Instead, past analyses have been oriented to other micro-grid portions, such as power distribution [31], or renewable sources energy profile characterization in an average sense [36], or local DG units [31]–[33] (still, without considering their fuel supply) That is, past work explores DG generators reliability performance without considering that, in turn, these sources cannot operate if they are not fueled, and that such fuel supply is dependent on lifeline performance.

In this paper, Section II presents a simple approach to calculate micro-grids availability using mcs with special focus on modeling lifelines performance and the effect of energy storage—both aspects not previously explored in the literature—because of their importance for micro-grid performance during disasters. Case studies are presented in Section III and calculations performed with the presented mcs approach are compared with Monte Carlo simulations used as an experimental validation mean. Finally, this paper concludes with a summary of its main findings in Section IV.

II. Micro-Grid Availability Calculation Methodology

A. System Availability Calculation Approach

Consider the general Markov representation in Fig. 5 for a micro-grid like the one in Fig. 4. In Fig. 5, each state is represented by a binary number in which each digit represents the operating state of a micro-grid component. A “1” indicates a failed state and a “0” indicates an operating state. Although this model may initially seem complicated because even for micro-grids there are a large number of states, an mcs approach allows to greatly simplifying the analysis. For system components that are reliable enough, each mcs can be associated with a shadowed state in Fig. 5—called minimal cut state [37]—at the boundary between the set F of failed micro-grid states and the set W of working micro-grid states. The micro-grid unavailability U_{MG} can be calculated with [37]

$$U_{MG} = \mathrm{P}\left(\bigcup_{j=1}^{M_C} K_j\right) \cong \sum_{j=1}^{M_C} \mathrm{P}(K_j) = \sum_{j=1}^{M_C} \prod_{l=1}^{c_j} u_{l,j} \quad (1)$$

where K_j represents the mcs, $\mathrm{P}(K_j)$ is the mcs probability, M_C is the total number of mcs, c_j is the number of (failed) components in the mcs K_j, and $u_{l,j}$ is the individual unavailability of each of the c_j components in mcs K_j. In the analysis, $u_{l,j}$ is the ratio of the component failure rate $\lambda_{l,j}$ to the sum of its failure rate $\lambda_{l,j}$ and repair rate $\mu_{l,j}$. Failure and repair rates are practically calculated by taking the inverse of the mean up time (MUT) and mean down time (MDT), respectively. The error in the approximation in (1) can be evaluated considering that [37]

$$\sum_{i=1}^{M_C} \mathrm{P}(K_i) - \sum_{i=2}^{M_C} \sum_{j=1}^{i-1} \mathrm{P}\left(K_i \bigcap K_j\right) \leq U_{MG} \leq \sum_{i=1}^{M_C} \mathrm{P}(K_i). \quad (2)$$

Although an mcs approach is simpler than Markov-based methods, in some systems it may be tedious to identify all the mcs. This task can be simplified and automated by recognizing that given systems structures (from an availability perspective) give rise to specific mcs. Consider the following most common availability relationship of system's elements under the assumption of reliable components [the error bound implied in this assumption can be assessed by (2)]:

a) Series configuration: Consider Fig. 6 where all components in the micro-grid need to be operational in order to power the load. This configuration, then, constitutes from an availability perspective a series connected group of components—in an electrical circuit, this functional reliability relationship in series may or may not correspond to their electric topological layout; e.g., essential electrical components that in a circuit are connected in parallel may be represented as a series connection from an availability perspective. Thus, each mcs is associated with the failure of a given system component while all other components are considered to be operational. Hence, the probability of each mcs of occurring equals the unavailability of the failed component associated with such mcs, so the system unavailability under the assumption of reliable components is approximately equal to the sum of their unavailabilities. The transition rate from the minimal cut states into W is the sum of the repair rates of the components in the series configuration.

b) Parallel configuration: Consider Fig. 7 with a parallel combination of two paths, each path with a series combination of components. For the micro-grid to power the load it is necessary that all components in at least one of the two paths are operational. Each mcs is, then, formed by one component from each path—e.g., one mcs in Fig. 7 is formed by the natural gas supply in the top path and the DG unit #2 in the bottom path—so the number of mcs yielded by this configuration equals the product of the number of components in one path by the number of components in the other path. The probability of each mcs is the product of unavailabilities of each of the components in the mcs. That is, the probability of each mcs equals the product of unavailabilities of a component in each path. This general description of a parallel configuration of two paths can be directly reduced to a simple parallel configuration by considering only one component in each path, which results in only one mcs with probability equal to the product of unavailabilities of all the components in the parallel configuration. The sum of the transition rates from all minimal cut states to W equals the sum of the repair rate of each component multiplied by the number of components in the other parallel path.

c) $n+1$ redundant configuration: In this case, a total of ${}_{n+1}C_2$ mcs are formed representing all possible groupings of two of the $n+1$ components in the redundant arrangement. Since it is assumed that all components in the redundant arrangement are equal, the probability of each mcs is the square of the unavailability of each component. The number ${}_{n+1}C_2$ equals [38]

$$ {}_{n+1}C_2 = \frac{n+1!}{2!(n-1)!}. \quad (3)$$

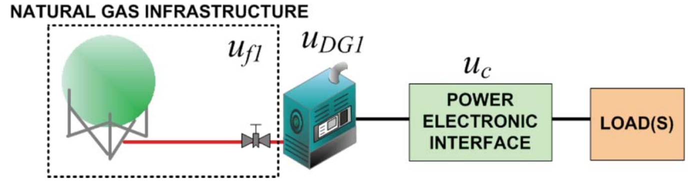

Fig. 6. Scheme for a micro-grid with one power supply path to the load.

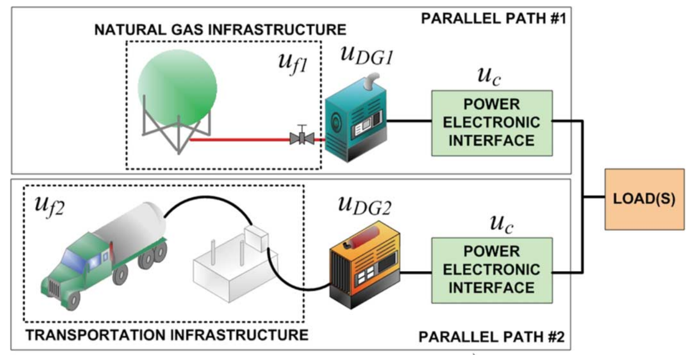

Fig. 7. Scheme of a micro-grid in which the load can be powered from two power paths.

These three general cases typically represent the most common arrangements that can be found in practical micro-grids. Hence, a combination of them can yield all necessary mcs of a micro-grid without significant complexities. From [24], it is also possible to identify failure and repair rates for each type of configuration. Once mcs are identified, the next step is to calculate the unavailability of each component. For most components, such as power electronic interfaces, distribution cables and local DG sources, there exists industry information with failure rates, such as [39]. As it was explained above regarding inhomogeneous damage distribution during disasters, if the micro-grid is located in a site where observed damage is not extreme, then these values for these particular micro-grid components should not change during disasters. Repair rates can be evaluated for these components based on known or assumed maintenance, logistical and repair processes. However, these common approaches may not be applied to renewable sources because of their variable stochastic nature. Neither can these common approaches be used to sources that has a discontinuous fuel delivery model—e.g., diesel carried to the micro-grid site through trucks—or to added energy storage. The discussion that follows next aims at addressing these other challenges.

B. General Analysis Assumptions

In addition to particular assumptions considered in the analysis and discussed at the point where they are relevant, the proposed methodology considers some general assumptions worth emphasizing here. As mentioned, one of the general assumptions is that, based on damage assessment experiences (e.g., Figs. 1–3) and collected extensive outage data, the conventional power grid around the micro-grid may likely fail for several weeks as a result of a natural disaster even when the damage in such area is light. The micro-grid is assumed to be located in one of such areas with light damage but extensive power outages. The use of the term availability is chosen in this work in order to emphasize the fact that the studied entities can be repaired when they fail so it is possible to distinguish its use from the term reliability which applies to non-repairable components [37]. Hence, in such use of the term availability, it is being relaxed the implicit assumption that availability—or more strictly steady-state or asymptotic availability—may only apply to processes in a long-run sense, and it is used, instead, in a more general sense as it may be associated to the use of availability for repairable components or entities that operate in standby regimes [37]. Another general assumption is that, for simplicity and in order to relate the discussion with the typical load profile found in a critical load represented by a digital communications facility, such as that in Fig. 1, the load is assumed to be constant and known. Such load can also be associated with the expected (average) value of a variable load. However, this assumption is not a requirement for the proposed model that can also consider instantaneously uncertain loads. Yet another general assumption considered in the analysis is that, since stability study is out of the scope of this work, the micro-grid under evaluation has already been designed and engineered ensuring adequate stability. Finally, lifelines failure and repair rates are considered to take typical values found during disaster conditions or in their aftermath. These values vary depending the intensity of the disaster.

C. Model for Continuous Delivery of Fuel Supply

In most micro-grid applications, this model applies to natural gas for microturbines, internal combustion engines, or fuel cells with local reformers. Hence, a natural gas distribution system is the lifeline for these sources. Information about MUT and MDT for natural gas supply can be obtained from their suppliers or from studies [40] and be adjusted to natural disasters conditions without difficulty.

D. Model for Discontinuous Delivery of Fuel Supply

Let us consider the case of a local source, such as a diesel generator, that requires periodic delivery of fuel which is stored on-site in a tank. For simplicity consider that the micro-grid load is known and constant so the tank capacity provides a known autonomy of T_{TC}. Such load may be, typically represented, by a modern digital communications center, already identified as a critical site during disasters [41]. For variables loads with a given uncertainty, the expected (average) value of such load can be considered for the calculations because for operation in an aftermath of a natural disaster, load changes occur at a time scale much shorter—e.g., in the order of minutes—than the necessary local energy storage, in this case represented by T_{TC}—in the order of hours or days. In this case, the roads network is the lifeline for the micro-grid so the time, t_d, at which the fuel is delivered to the micro-grid site is a random variable that depends on a fuel delivery probability density distribution function $f_d\,(t_d)$. Although $f_d\,(t_d)$ can take many forms, some of those, like an exponential distribution applied in [24], are not realistic. Some of the issues found with the exponential distribution includes the fact that its maximum is found at its initial time T_i instead at the defined delivery time T_D, and then it decreases continuously within a semi-infinite time interval $[T_i, \infty)$—i.e., there are non-zero chances of receiving the fuel delivery in a time instant infinitely away in the future. Instead, a triangular form proposed here is a realistic representation that at the same time does not cause excessive calculations complexities. In order to represent a realistic fuel delivery process, it is assumed that there is a fuel contract that establishes a due delivery time indicated by T_D, when it is more likely to have the fuel delivered. Fuel can be delivered from some initial time T_i and it is certain that fuel cannot be delivered before T_i. Then, the probability of having the fuel delivered increases linearly until T_D when it reaches its maximum. Still, fuel delivery may be overdue and occur until a maximum possible time T_M. After T_M passes, fuel delivery can no longer occur or is no longer accepted. For simplicity, the decreasing fuel delivery probability between T_D and T_M is assumed to decrease linearly. This triangular distribution is, then

$$f_d(t_d) = \begin{cases} 0, & 0 \le t_d < T_i \\ \frac{2(t_d - T_i)}{(T_M - T_i)(T_D - T_i)}, & T_i \le t_d \le T_D \\ \frac{-2(t_d - T_M)}{(T_M - T_i)(T_M - T_D)}, & T_D \le t_d \le T_M. \end{cases} \quad (4)$$

In order to represent the overdue delivery process T_M is considered to be given by

$$T_M = \frac{T_D - T_i P_{OD}}{1 - P_{OD}} \quad (5)$$

where P_{OD} is the probability of exceeding the fuel delivery due time. That is, P_{OD} represents the chances of having an overdue fuel delivery so the difference between T_D and T_M accounts for a potential delay—i.e., loss of performance—of the transportation infrastructure. There are several studies in the literature and, in particular, in logistics and transportation sciences dedicated to evaluate P_{OD} [42]–[46]. In normal conditions, P_{OD} may take values at most in the single digit percentage points or lower. However, during disasters, data from typical transportation delays observed after disasters make P_{OD} to take values from 0.2 to 0.6 and higher, depending on the disaster intensity. A simple and reasonable approach from [13] considers that P_{OD} varies linearly from being 1 when the time interval ΔT_D between T_D and T_i—i.e., ΔT_D is T_D–T_i—is 0 to being 0 when ΔT_D equals a time interval, $\Delta T_{D,0}$, that is long enough to ensure that fuel delivery will be for sure delivered on time—i.e., $P_{OD} = 0$ when $\Delta T_D = \Delta T_{D,0}$. Hence

$$P_{OD} = 1 - \frac{\Delta T_D}{\Delta T_{D,0}} \quad \text{for } 0 \le \Delta T_D \le \Delta T_{D,0} \quad (6)$$

and

$$\Delta T_{D,0} = \frac{\Delta T_{D,\mathrm{ref}}}{1 - P_{OD,\mathrm{ref}}} \quad (7)$$

where $P_{OD,\mathrm{ref}}$ is the probability of exceeding T_D corresponding to a known interval $\Delta T_{D,\mathrm{ref}}$. For example, consider that $T_D =$ 72 h, $T_i = 48$ h, and that $P_{OD} = 0.3$ when $\Delta T_D = 24$ h. Then, $T_M = 82.28$ h so $\Delta T_{D,0} = 82.28 - 72 + 24 = 34.28$.

Now, assume for simplicity that the inter-arrival time between each truck can be assumed to be independent and identically distributed. It is also assumed that the truck instantaneously replenishes the fuel tank and leaves and the next truck arrives at the location after a random time with identical probability density function than the previous truck. Since refueling occurs instantaneously, the generator's engine fuel supply from the diesel tank at the engine's fuel intake will essentially determine the unavailability of the fuel supply system. That is, when the diesel tank is empty the fuel supply system is at a failed state. Since it is assumed that the load is constant and known (or for a variable load represented by its expected value over T_{TC}), the tank autonomy T_{TC} provides an indication of the probability of emptying the fuel tank P_E when the fuel delivery time exceeds T_{TC}

$$P_E = P\{t_d > T_{TC}\} = 1 - P_{E^*} = 1 - \int_{t_d=0}^{t_d=T_{TC}} f_d(t_d)\, dt_d. \quad (8)$$

Evidently, choosing T_{TC} long enough so it exceeds T_M would ensure that $P_E = 0$, but the problem at hand here is that when the micro-grid is planned, T_{TC} may likely be estimated for normal operating conditions when both P_{OD} and T_M are much lower values than what it can be obtained when they are calculated based on natural disaster conditions. Hence, T_{TC} calculated under normal conditions may likely be less than T_M calculated during natural disasters conditions, as it is evaluated in this work.

In order to find the fuel supply unavailability indicated by this process, consider that based on the relaxed assumption about the definition of availability in Section II-B that a very large number of refueling cycles have passed because the grid power outage lasts at least a few times longer than T_{TC}. It can be expected that in $100P_E$ percent of these cycles the fuel delivery truck arrived after T_{TC} with an expected fuel supply down time of MDT_f. Conversely, it can be expected that in $100P_{E^*}$ percent of the cycles the fuel truck arrived before T_{TC} so the generator did not fail due to fuel starvation. It can be noted that there are $r = P_{E^*}/P_E$ fuel delivery cycles in which the truck arrived before T_{TC} for every fuel delivery cycle in which the generator stops operating after running for T_{TC} hours because the tank was emptied. Hence, in an average sense and over a very large number of cycles it can be expected that r refueling cycles lasting in average T_{E^*} are immediately followed by one refueling cycle in which the generator fails during a time T_E after running for T_{TC} hours because it is out of fuel. That is, according to this described process and assuming that T_{TC} is selected within the interval $[T_D, T_M]$, the MDT_f for a generator fuel supply model equals

$$\mathrm{MDT}_f = T_E = \frac{T_M - T_{TC}}{3} \quad (9)$$

whereas the MUT_f is

$$\mathrm{MUT}_f = rT_{E^*} + T_{TC} \quad (10)$$

where for $f_d(t_d)$ given by (4) T_{E^*} is shown in (11) at the bottom of the page. The choice for T_{TC} selected within the interval $[T_D, T_M]$ considers that for the aforementioned reasons—that T_{TC} is estimated for normal conditions whereas T_M is now calculated during extreme events—the option $T_{TC} > T_M$ may be an unrealistic and trivial scenario, and that a micro-grid planer would rarely choose a tank autonomy shorter than the fuel delivery due time.

Based on this analysis the unavailability of the fuel supply system is, then

$$u_f = \frac{\mathrm{MDT}_f}{\mathrm{MUT}_f + \mathrm{MDT}_f} \quad (12)$$

with failure and repair rates, λ_f and μ_f equal to the inverse of MUT_f and MDT_f, respectively. For example, in the case of $T_D = T_{TC} = 72$ h, $T_i = 48$ h, $T_M = 82.28$ h, MUT_f equals 221.3 h, MDT_f equals 3.4 h, and the fuel supply availability $a_f = 1 - u_f$ is 0.985.

E. Model for Renewable Energy Sources

As it was mentioned, renewable energy sources may be suitable to sustain micro-grid operation during natural disasters because they do not require lifelines. However, their variable output nature complicates their application. In order to address their variable output nature—part stochastic and part deterministic—of renewable energy sources, it is assumed here that energy storage is added on the renewable energy-based distributed generators side of the micro-grid. With this added energy storage these variable renewable energy sources can be considered to be more dispatchable and have a given availability determined by the capacity of the added energy storage and the solar or wind energy profiles. Thus, a Markov chain model indicated in Fig. 8 is used to model energy states in the energy storage system associated to a given renewable energy source. As shown in Fig. 8, each state represents an energy level for the storage system, so each state transition, characterized by a probability p_i or p_{-i}, represents a charge or discharge process. For example, State #1 symbolizes the energy level of storage when it is fully discharged, and State #*N* symbolizes the energy

$$T_{E^*} = \frac{(T_M - T_D)\int_{T_i}^{T_D} t(t - T_i)\, dt + (T_D - T_i)\int_{T_D}^{T_{TC}} t(T_M - t)\, dt}{(T_M - T_D)\int_{T_i}^{T_D} (t - T_i)\, dt + (T_D - T_i)\int_{T_D}^{T_{TC}} (T_M - t)\, dt} \quad (11)$$

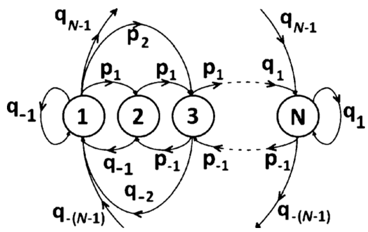

Fig. 8. Markov chain diagram.

level when it is fully charged. If it is assumed that the energy storage devices have linear charge and discharge processes, the energy difference between any two adjacent states is Δ so the power involved in such process is Δ divided by the time step T_s between two consecutive steps in the Markov chain. Hence, p_{-i} generally represents the probability of a transition among states with an energy efflux of $i\Delta$ in T_s, and p_i represents the probability of a transition among states with an energy influx of $i\Delta$ in T_s, with i taking values from 1 to $N-1$. Then, the one-step transition probability matrix, P, is

$$P = \begin{bmatrix} q_{-1} & p_1 & p_2 & p_3 & \cdots & & & \\ q_{-1} & 0 & p_1 & p_2 & \cdots & & & \\ q_{-2} & p_{-1} & 0 & p_1 & \cdots & & & \\ q_{-3} & p_{-2} & p_{-1} & 0 & \cdots & & & \\ \vdots & \vdots & \vdots & \vdots & \ddots & & & \\ & & & & & 0 & p_1 & q_2 \\ & & & & & p_{-1} & 0 & q_1 \\ & & & & & p_{-2} & p_{-1} & q_1 \end{bmatrix}_{N\times N} \quad (13)$$

where

$$q_{-1} = 1 - \sum_{i\in S} p_i \quad (14)$$

$$q_1 = 1 - \sum_{i\in S} p_{-i} \quad (15)$$

$$q_{-k} = 1 - \left(\sum_{i=1}^{k-1} p_{-i} + \sum_{i\in S} p_i\right) \quad (16)$$

$$q_k = 1 - \left(\sum_{i=1}^{k-1} p_i + \sum_{i\in S} p_{-i}\right). \quad (17)$$

The transition probabilities terms indicated by the terms q_k correspond to the particular cases when there is an overflow or a demand of energy greater beyond the battery capacity range. Like for the other terms, a negative subscript corresponds to a battery discharge process and a positive subscript indicates a battery charge process.

Consider first the case in which the renewable energy sources are made of a PV array. Since each state in Fig. 8 represent the energy level of the energy storage devices—e.g., batteries—transition among states will depend on the power difference between generated and consumed power at the micro-grid. For simplicity, the load is assumed to be constant and known or to be represented by the expected (average) value of a variable load. However, this assumption is not a requirement for the proposed model that can also consider instantaneously uncertain loads. In order to obtain the values for the probabilities p_i and p_{-i} of each Markov chain transition, it is first necessary to realize that the power balance P_B is

$$P_B = (P_{PV} - L_{\text{day}} - L_{\text{night}}) = P_{PV} - 2L \quad (18)$$

where L is the load, which is considered for simplicity of the discussion the same both during the day, L_{day}, and night, L_{night} (different values for L_{day} and L_{night} could also have been considered as part of the calculations) and P_{PV} is the power generated by the PV array. Then, a histogram of actual PV generated power at the micro-grid site during a 12-h period is used to characterize PV generation at the site through a probability density function. This distribution is used as an input for a Monte Carlo process in order to generate random PV generated power P_{PV} at each Markov chain time step. The application of a Monte Carlo approach provides the necessary uniform discretization process for the generated PV power. Since the load is known and the PV generated power is now known, the power balance for each Monte Carlo run and the number of occurrences for each power balance value are also known, which, in turn, is used in order to estimate the state transition probabilities p_i and p_{-i}. Since the PV generated power histogram considers data for a 12-h period when the load is $L_{\text{day}} = L$, the power balance (18) adds an equal load L in order to consider that the output of the PV array and energy storage needs to sustain the load during the entire 24-h period, which implies that the night load is effectively shifted to daytime as a battery charging load for the PV array.

Once the one-step transition probability matrix, P, is known, the limiting probabilities vector, π, can be found from [47]

$$\pi = \pi\, P \quad (19)$$

where each of the components in π represents the long term steady state probabilities that the energy storage system is at a certain energy state—e.g., π_1 represents the probability that energy storage is at State #1. Finally, system unavailability u_{RW} can be calculated considering that the load is not fully powered when energy storage is at state i and the load requires an energy of $i\Delta$ or more for one time step T_s of the Markov chain. Considering all possible transitions from all possible states for the considered time step, the unavailability is

$$u_{RW} = \sum_{i\in\{1,N-1\}} \left(p_{-i} \sum_{j\leq i} \pi_j\right). \quad (20)$$

Energy storage capacity, C_{RW}, affects unavailability by realizing that

$$C_{RW} = (N-1)\Delta \quad (21)$$

so C_{RW} can be changed by modifying Δ, which, in turn, changes P and, hence, u_{RW}.

This same analysis can be extended to the case of a hybrid micro-grid with PV and wind energy power generators so their diverse source of energy could reduce the required energy storage capacity. In this case, if it is assumed that each of the renewable sources could power the load alone when their source of energy is present, then the power balance equation is

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

$$P_B = (P_{PV} + P_W - L_{\text{day}}) + (P_W - L_{\text{night}}) = P_{PV} + 2(P_W - L). \quad (22)$$

As an example, consider a micro-grid with a 100-kW load. In order to provide some generation overhead consider that only a PV array of 1.225 MW is used—which gives an average power generation of 293.63 kW ($\text{variance} = 68.2$) during daytime, i.e., 7:00 am to 7:00 pm. By following the described approach, the PV curve in Fig. 9 can be found. Suppose that the load is a critical one—e.g., a communications site—so a 5-nine availability is sought for the sources. Then, Fig. 9 indicates that 1.15-day capacity of energy storage is needed which translates into a battery capacity of 2.7 MWh obtained for a time step T_S of 1 h, and with Δ/T_S and N equal to 10 kW and 277, respectively. When 225 kW of wind power generators are added, yielding 110.82 kW of average generated wind power—so each wind or PV generators can sustain the load alone—the necessary energy storage to achieve an availability of 5-nines decreases significantly. Both solar and wind data for this example were obtained from actual measurements performed in Austin during the same time periods, and, hence, they naturally and implicitly consider profile correlation existing between these two renewable energy sources. As Fig. 9 represents, with this diverse pool of sources energy storage requirements dropped to about 0.5 days worth of load power, or 1.2 MWh. If only a 2-nine target availability is sought, 960 kWh—equivalent to 0.4 days—of energy storage are needed when only the PV array is considered, and 720 kWh—equivalent to 0.3 days—are needed for the combined PV and wind case.

The failure and repair rates for these sources can be obtained by considering that the Markov chain in Fig. 8 is the embedded Markov chain for a 2-state Markov process in which a state S_0 represents the renewable energy power source failure condition—inability to power the load fully which corresponds to the condition described by (20)—and the other state S_1 represent the opposite situation. The equivalent Markov process is described, then by

$$\dot{\pi}^T_{RW}(t) = \pi^T_{RW}(t)M = \left(\pi_{RW,W}(t) \quad \pi_{RW,F}(t)\right)\begin{pmatrix} -\lambda_{RW} & \lambda_{RW} \\ \mu_{RW} & -\mu_{RW}\end{pmatrix} \quad (23)$$

where the superscript index "T" represents a transpose operation, $\pi_{RW,W}(t)$ is the probability of having the system operating in state S_1 at time t, $\pi_{RW,F}(t)$ is the same probability for S_0, M is the transition rate matrix for the 2-state equivalent Markov process with failure rate λ_{RW} and repair rate μ_{RW}. The Markov chain and Markov process are related by [47]

$$M = \gamma(P - I) \quad (24)$$

where I is the identity matrix and γ is obtained from [47]

$$\gamma = \frac{1}{T_S}\frac{p_{11}}{1 - p_{11}} \quad (25)$$

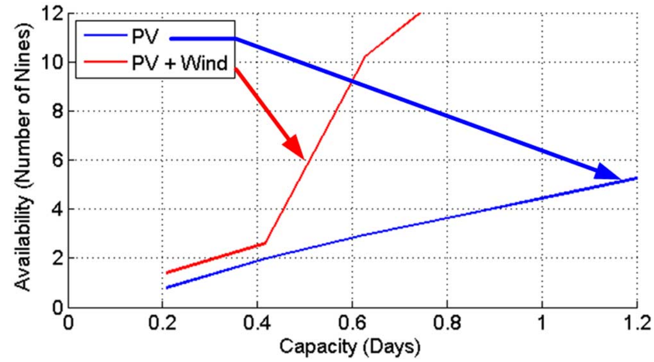

Fig. 9. Availability versus energy storage capacity.

where p_{11} is the term in row #1 and column #1 of P, i.e., it equals q_{-1}. Hence, for the 100-kW load powered by PV and energy storage combination and a target availability of 5-nines, $\lambda_{RW} = 5.252\ 10^{-6}$ and $\mu_{RW} = 0.5252$, whereas for the case with added wind generators $\lambda_{RW} = 8.189\ 10^{-6}$ and $\mu_{RW} = 0.8189$. When the target availability is 2-nines, $\lambda_{RW} = 5.2\ 10^{-3}$ and $\mu_{RW} = 0.512$ when only the PV array is present, $\lambda_{RW} = 7.3\ 10^{-3}$ and $\mu_{RW} = 0.7219$ when PV is combined with wind energy.

F. Model for Power Distribution Level Energy Storage

In addition to source-level energy storage—e.g., in stored diesel for an internal combustion engine generator or in batteries for a PV system—it may be desired to add additional energy storage at the micro-grid distribution level—e.g., at the main bus—in order to further increase availability. For example, in the recent earthquake that affected Japan, local energy storage was a key aspect of keeping the micro-grid in Sendai [1] operating. Consider now Fig. 5. From [37] and [48], the probability density function $f_{MG\mu}(t)$ associated with the probability of leaving the set F at time $t + dt$ after being in F from $t = 0$ is

$$f_{MG\mu}(t) = \mu_{FW}e^{-\mu_{FW}t} \quad (26)$$

where μ_{FW} is the sum of all the transition rates from F to W. Since each of the minimal cut states at the boundary between F and W can be associated to an mcs, μ_{FW} can be calculated once the mcs are known. Then, the probability of discharging the batteries while the system is in F since $t = 0$ is the probability of leaving F at a time longer than the battery backup time T_{BAT}. Hence

$$P_{BD} = P\{t > T_{BAT}\} = 1 - \int_{\tau=0}^{\tau=T_{BAT}} f_{MG\mu}(\tau)d\tau = e^{-\mu_{FW}T_{BAT}}. \quad (27)$$

The micro-grid failure probability $P_{MGf}(t)$ is, then, the probability that the system failed at $t = 0$ and the batteries discharged. If it is assumed that the micro-grid had been turned into operation a very long time in the past, then $P_{MGf}(t)$ equals the unavailability of the micro-grid U_{MG} without distribution-level batteries, which is obtained from (1). Thus, the micro-grid unavailability with added batteries at the distribution level is

$$U_{MG,T} = U_{MG} e^{-\mu_{FW} T_{BAT}}. \tag{28}$$

III. Case Studies

Several case studies were considered in order to evaluate the previous discussion. These cases are:

- Case 1: Load fed through converters by a microturbine fueled by natural gas (represented in Fig. 6).
- Case 2: Same as Case 1 but with two microturbines in parallel so each of them can power the load alone.
- Case 3: Load fed through converters by an engine generator fueled by diesel delivered by truck and stored in a local tank.
- Case 4: Same as Case 3 but with two engine generators in parallel so each of them can power the load alone.
- Case 5: Two power paths to the load; one is as indicated by Case 1 and the other by Case 3. Each path can power the load alone (represented in Fig. 7).
- Case 6: Combined PV and energy storage powering the load through a converter.
- Case 7: Same as Case 6 but combining PV and wind.
- Case 8: Same as Case 5 but with the diesel generator path replaced by the path indicated in Case 6.
- Case 9: Same as Case 5 but with the diesel generator path replaced by the path indicated in Case 7.

These cases assume that the potential hazard at the micro-grid site is a hurricane so natural gas supply availability is still high [4]. However, transportation infrastructure has a poor performance so the value for P_{OD} is relatively high, indicating high chances of delays. Component parameters are shown in Table I—unless clarified otherwise those are the same values used throughout this paper—and results of the calculations in Table II. Two options are considered for the renewable energy sources in cases 6 to 9: subcase "a" considers that there is sufficient energy storage to yield an availability of 5-nines at the output of the renewable energy source and sub-case "b" considers that their output availability is 2-nines. Parameter values for the PV or PV + wind combined with energy storage are those discussed in Section II-E. In a practical setting, the outcome of the analysis of power output availability for renewable sources combined with energy storage could be presented in tables or simple to read graphs, such as that in Fig. 9. All converters are assumed to be in an $n + 1$ redundant configuration with $n = 6$. Comparison between unavailabilities calculated with mcs and with Monte Carlo yield almost identical results. However, the mcs approach is extremely simple to calculate. In these particular examples presented here, calculations involving mcs did not require the use of computers and only a simple calculator was used. Such simplicity leads to two benefits: for the expert operator of a micro-grid, simple calculations reduce the chances of involuntary calculation mistakes, but for the more common case of a micro-grid operator that is not an expert in power systems—e.g., an infrastructure manager in a hospital or a data center manager—the proposed approach provides a way to assess micro-grid availability in order, for example, to perform quantifiable risk assessments. Still, one potential weakness of the proposed method is that it may lead to some errors because, as (1) indicates, the calculation involves approximations. Nevertheless, the proposed method allows quantifying the boundary of such error with (2). For example, consider here Case 3 which is the one more prone to error due to the relatively low availability of the diesel delivery process. The exact unavailability of this case based on the availability of the three components in the series arrangement—the diesel supply, the diesel generator, and the converters—is 0.02101 whereas the unavailability obtained by the mcs approach obtained by summing the unavailabilities of the diesel supply, the diesel generator, and the converters is 0.021103. The error, as indicated by the second term of the left side of the inequality in (2), is calculated by summing the three terms that represent the product of the unavailabilities of two of the three components (components in the series arrangement) considered in this case. Such calculation yields that the error is $9.156\ 10^{-5}$. When this error is subtracted from the mcs obtained unavailability of 0.021103, the result is 0.02101 which coincides with the exact unavailability value.

Another important advantage of the proposed approach is that it provides valuable planning insights about the micro-grid. High diesel fuel supply unavailability yields no significant availability improvement when paralleling generators (cases 3 versus 4) because diesel fuel supply is the determining component for availability calculation. However, such improvement is evident with microturbines (cases 1 versus 2) because the limiting component is the microturbine. Yet, in order to reach 6-nines availability the cases with microturbine require significant more energy storage than those with diesel generators. This observation seems to be counterintuitive based on the base unavailability of these cases. The explanation is found when the MDT for the micro-grid in each case is calculated. While

TABLE I
Reliability Values Used in the Case Studies

Item and origin of the value	μ (1/hours)	Unavailability u
Diesel generator [24]	0.2	0.0061
Microturbine [24]	0.02	0.006
Natural gas supply [24]	0.02	$2.5\ 10^{-5}$
Diesel fuel supply [current paper]	0.294	0.015
Converter [24]	0.003	$3.33\ 10^{-4}$
$n + 1$ arrangement of 7 converters	0.012	$3\ 10^{-6}$

TABLE II
Case Studies Evaluation Results

Case #	U_{MG} (mcs-based)	U_{MG} (Monte Carlo-based)	μ_{FW}	T_{BAT} for $U_{MG,T}$=1 10^{-6}
1	0.006028	0.0060836	0.052	167.4 hrs
2	0.000064	0.000068	0.072	57.76 hrs
3	0.0211	0.02103	0.506	19.67 hrs
4	0.01504	0.014986	0.706	13.62 hrs
5	0.000127	0.000124	1.674	2.89 hrs
6.a	0.000013	0.0000146	0.538	4.28 hrs
6.b	0.010003	0.0100265	0.524	17.57 hrs
7.a	0.000013	0.0000141	0.8309	3.09 hrs
7.b	0.010003	0.0100051	1.5408	5.97 hrs
8.a	$0.78\ 10^{-7}$	0.0000001	1.718	N/A
8.b	0.0000603	0.0000598	1.676	2.44 hrs
9.a	$0.78\ 10^{-7}$	0.0000002	2.6	N/A
9.b	0.0000603	0.0000597	2.3	1.78 hrs

the micro-grid in Case 1 has an MDT of 48.3 h (repair rate of micro-grid $\mu_{MG} = 0.0207$), the micro-grid in Case 3 has an MDT of 4.29 ($\mu_{MG} = 0.233$) because diesel generators tend to be simpler to repair than microturbines. That is, a micro-grid with microturbines need more stored energy because although it is more unlikely to fail, when it fails—and that is when the added energy storage is needed—it is likely to stay in the failed state longer. Although renewable energy sources do not have lifelines, they require significant energy storage in order to reach desired levels of availability. This issue combined with their large required footprint limits their application. In all cases, diverse power sources contribute to improve availability and reduce the need for local energy storage. Hence, Case 5 seems to be the most suitable choice in this case. Moreover it is the most cost effective of all. Another potential alternative to Case 5 is Case 2 with the microturbines replaced by natural gas internal combustion engines. However, this last option may be unsuitable in case of earthquakes when the unavailability of natural gas supply is worse than with hurricanes. Still, if precautions are taken so adequate availability for natural gas is ensured, this last option is also adequate for earthquakes, as practically demonstrated by the aforementioned micro-grid in Sendai, whose power sources were 2 natural gas generators and at least 20 minutes worth of batteries.

IV. Conclusion

This paper evaluates micro-grids availability oriented towards operation during natural disasters and their aftermath. A key contribution of this paper is to focus on representing the effect of two critical aspects affecting micro-grid availability during natural disasters and in their aftermath: lifelines performance and local energy storage contribution. Such representation is done by presenting and discussing their availability models. The selected calculated approach is based on minimal cut sets theory. It is shown that this approach involves extremely simple calculations that do not require computers or extensive theoretical knowledge on the matter in order to assess micro-grid availability. Moreover, if desired, the proposed approach allows quantifying the error involved in the availability calculations.

Theoretical calculations confirmed with Monte Carlo simulations seem to show that in the context of natural disasters micro-grids may achieve availabilities much higher than conventional grids, making micro-grids a prime option for developing advanced smart grids. Still, local energy storage and diverse energy sources are required in order to achieve high availabilities. Although renewable energy sources have been identified as a suitable choice to power micro-grid during natural disasters because they do not require lifelines, large footprints, high cost, and the need for significant added energy storage limit their application.

Future research will involve studying alternative fuel delivery probability distribution functions and modeling the availability of both fixed and portable standby diesel generators.

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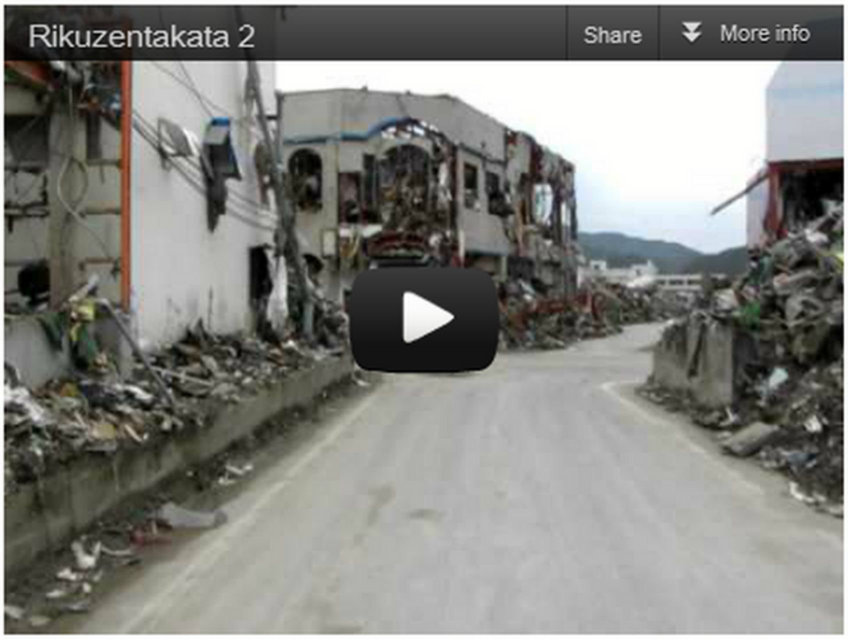
ENERGY / THE SMARTER GRID

FEATURE

Disaster Forensics

What can electrical engineers learn from the world's worst natural disasters?

By ALEXIS KWASINSKI / DECEMBER 2011



Video: Alexis Kwasinski

This tsunami-wrecked street was once the heart of downtown in Rikuzentaka, Japan.

It's my job to drive straight into the heart of disaster zones.

On 11 March, a 9.0-magnitude earthquake triggered a monstrous tsunami that smashed into Japan's northeast coast, killing more than 15 000 people in minutes and reducing entire towns to rubble. In the days that followed, more than 80 000 Japanese citizens fled their homes after the tsunami started a meltdown at three of the reactors at the Fukushima Dai-ichi nuclear power station. Those citizens left their whole lives behind, and most are still living as refugees. But in early April, I drove into the wreckage of Japan's coastal towns to see what lessons I could learn in the ruins.

As an electrical engineer with a keen interest in what I call "disaster forensics," I travel to the worst natural disaster sites around the world to assess the damage inflicted on communication networks and electric power grids. I've surveyed the aftermath of three major Gulf Coast hurricanes, including Katrina, and I've stood in the rubble caused by earthquakes in Chile, New Zealand, and Japan. As I've collected field data, I've begun to challenge the common belief that humans can't compete with nature's fury and that most of our creations will fail in a hurricane's winds or a tsunami's waves. That fatalism doesn't sit well with me. I think that studying the world's worst natural disasters can lead to better designs and critical infrastructures that can better withstand the brunt of a storm or the upheaval of an earthquake.

Of all the assessments I've performed, my April 2011 trip to Japan was undoubtedly the most challenging—and the most heart wrenching. At that time, the damaged nuclear reactors at Fukushima Dai-ichi had not been fully stabilized, and the extent of the area contaminated by radiation fallout was not clear. I drove a circuitous route on the west side of Japan's main island because the Sendai Airport had just started limited operations, the "bullet" train wasn't yet back in service, and the highway from Tokyo ran within the U.S. State Department's recommended evacuation zone. I carried all the food I would need for my five days on the road and water for my entire 10-day trip, because I'd heard stories of contaminated tap water and shortages of bottled water. I also carried a dosimeter to measure radiation levels everywhere I went and quickly left areas that set off the dosimeter.

Photo: Alexis Kwasinski

The 11 March tsunami in Japan destroyed a base station and cell tow er near Rikuzentakata.

When I started my assessment, I was surprised to find that ground-shaking damage was relatively minor for a 9.0-magnitude earthquake. But the tsunami damage was shocking. As I stood next to a damaged cell tower on a hill about 20 meters above sea level near the town of Ryoishi, I could only imagine the horror of the people who ran from the tsunami and found no safety even on that high hill. In the towns of Otsuchi, Rikuzentakata, and Onagawa I walked through eerie silences and gazed at the piles of debris that towered over my head. In Otsuchi, I stood in front of a destroyed firehouse and thought of the firefighters who died after closing the seawall gates in a desperate attempt to stop the onrushing water.

Photo: Alexis Kwasinski

The telecommunications central office in Rikuzentakata w as one of the few buildings still standing after the tsunami.

Amid this destruction, I looked carefully at the structures that survived. I found that the central office buildings belonging to Japan's biggest telecom company, NTT, were often still standing, although they had been submerged by the tsunami and had been hit by floating debris. In Onagawa the remains of a home ended up perched on top of a two-story NTT building. These buildings housed the switches that routed telecom data, and in Japan they were designed to withstand the most powerful earthquakes. The buildings also had some precautions against tsunamis—such as watertight seals around the doors on the ground floor—but these safety measures were insufficient protection, because no one anticipated a tsunami of such extraordinary height. On 11 March, water poured into the windows on the upper floors of the buildings and soaked the equipment inside.

In Japan, I saw the inherent fragility of the power grid. There were extensive outages not only in the heavily tsunami-damaged coastal areas but also in the lightly affected inland regions. I also came up against some frustrating facts of life regarding residential solar power. Japan has a relatively high number of homes equipped with photovoltaic (PV) solar panels, and many inland homes equipped with these PV panels could theoretically have remained powered during the day. Unfortunately, residential PV-grid interconnection standards prevent PV panels from providing power during a grid outage [PDF], so these homes got no benefit from the panels on their own rooftops.

This may seem like a wasted opportunity—and maybe it is—but utilities say that homeowners shouldn't be allowed to

Photo: Alexis Kwasinski

After the tsunami, NTT's central office building in Onagawa had the remains of a house on its roof.

disconnect from the grid and power their households with solar panels during an outage due to safety issues. Utilities worry that if the disconnection from the grid is incomplete, a lineman could go out to work on damaged power lines thinking they're safe when in fact they have power running through them from a solar panel somewhere. This argument is controversial, because technical solutions exist to ensure a proper disconnection and thus solve any safety problems. Unfortunately, these solutions require technology that isn't in common use right now and therefore might incur higher costs. Almost all conventional "off-the-shelf" inverter controllers, which are used to manage the electricity from residential solar panels, prevent their operation unless the main power grid is present and live.

Photo: Alexis Kwasinski

This religious center in Kamaishi, which was used as an emergency shelter after the tsunami, couldn't draw power from its solar panels or wind generator, which were left undamaged.

Nevertheless, there are some ways to "go local" with energy production under the current rules. In the Japanese city of Sendai, a small local power grid, called a microgrid, showed its potential during the blackout. Powered by natural-gas engine generators and solar panels, the microgrid was able to keep the lights on at Tohoku Fukushi University and a neighboring hospital throughout the blackout. While under normal circumstances the Sendai microgrid is connected to the city's macrogrid, its ability to isolate itself and keep generating power is valuable to customers who need a highly reliable source of electricity.

I got my start in disaster forensics in October 2005, when I took part in a National Science Foundation study on the damage caused by Hurricane Katrina. That enormous and devastating hurricane barreled into the Gulf Coast in late August of 2005. The furious winds and extensive flooding caused damage amounting to US $108 billion, more than any other hurricane in U.S. history. I had the assignment of collecting field data to determine why and how the storm had wreaked such havoc on critical communication and electric power infrastructures.

I drove south from Champaign, Ill., where I was completing my Ph.D. in electrical engineering, and headed for the most heavily damaged areas of southern Louisiana. On the east side of the Mississippi River Delta, I turned onto a narrow highway that runs through endless marshlands and found my way to the tiny towns of Yscloskey, Delacroix, and Point à la Hache. The debris-filled streets were silent—the people who lived there, mostly fishermen and workers in the offshore oil industry, hadn't been able to return. Katrina had pushed huge swells of ocean water up coastal rivers and canals, and that storm surge submerged this low-lying delta area and destroyed most of the homes. Smashed cars and boats poked out of the canals, mixed with uprooted trees and clumps of seaweed.

Photo: Alexis Kwasinski

Hurricane Katrina didn't leave much of Delacroix, La., intact.

When I began studying the power grid, I was surprised to find that very light damage—in some places, less than 1 percent of components—had still resulted in total blackouts for large geographic areas. For example, in some places a single toppled utility pole or a broken switch at a substation had brought down a wide swath of the network.

Problems in the grid rippled outward to the telecom system: Katrina left many cellular towers intact, but the power problems quickly took a toll. During the blackout, intact cell towers switched to backup battery and diesel generator power. But within a day or two, the cell towers began blinking out of service: Their batteries were depleted, their generators were out of fuel, and workers couldn't travel through the disaster zone to reach them. When workers finally did arrive at the failed cell towers, they deployed multiple portable generators at each site to power the telecom base stations at the towers. However, that only created a more complicated problem: Workers then faced the daunting logistics of refueling hundreds or even thousands of generators for several weeks. One solution I can see to this problem in some sites would be to rely on alternative local sources of energy, such as solar panels or small wind generators, in order to reduce the load on the portable generators. Small permanent generators connected to city gas lines could provide an even better solution for these sites.

Photo: Alexis Kwasinski

Multiple portable generators pow ered various base stations sharing a cell tow er in Louisiana after Katrina. Each generator needed to be refueled about every 24 to 48 hours.

Katrina also destroyed the telecom central office buildings housing equipment that routed landline and wireless communications through nearby towns. As telecom companies tried to restore service, they faced a grim question unique to the world's worst disaster zones: How much service needed to be restored? Most of the demand for telecom service in the storm-tossed areas of the Gulf Coast had disappeared because the residents had fled their ravaged homes—or they had no homes to return to. So BellSouth, the primary operating company in southern Louisiana, decided not to rebuild many central offices in damaged areas and instead deployed small digital loop carrier (DLC) system cabinets. These cabinets transmit phone calls and Internet data to distant central offices through fiber-optic cables, which have greater capacity than conventional copper lines. When placed on high platforms to avoid future floods, these cabinets can form part of a resilient telecom system.

Photo: Alexis Kwasinski

The central office building in Yscloskey, La., w as destroyed by Katrina and w asn't rebuilt.

Photo: Alexis Kwasinski

A DLC cabinet system [left], seen here after Hurricane Gustav in 2008, replaced the Yscloskey central office building. The seaw eed draping the fence w as carried there by the hurricane's storm surge.

However, as I saw three years later, when I surveyed the wreckage that Hurricane Ike caused in Texas, DLC cabinets have problems of their own.

Hurricane Ike, which struck the Gulf shores in September 2008, hit with great fury and caused a total of $30 billion of damage in Texas, Louisiana, and beyond, making it the third-costliest hurricane in U.S. history (after only Katrina and 1992's Andrew). I'll never forget the coastal town of Gilchrist, Texas, where one lonely home remained standing. Power outages extended from the battered coastline more than 100 miles inland and caused widespread telecom outages (the storm's remnants went on to cause problems all the way up to Canada). In Texas, DLC cabinets that routed landline communication data were largely responsible for the telecom problems.

DLC cabinets have the same problem as cell towers—in a blackout, their batteries give out within a few hours. (Telecom central offices typically have permanent generators that can keep power flowing for at least 72 hours, which is a reasonable cushion.) In order to restore service, power companies distributed hundreds of portable generators to DLC cabinets throughout east Texas; this gesture created the extra logistical burden of keeping them fueled. Since the spread of broadband communication systems is increasing the use of similar curbside cabinets, it's a safe bet that this problem will become more common in future disasters.

Downtown Houston power outages were not as severe as in neighboring areas, thanks to the partially buried power grid. Buried power lines are expensive enough to limit their use, but they could be a solution for relatively small but particularly vulnerable areas, such as the Bolivar Peninsula and Galveston Island in Texas. Burying the single transmission line that serves the peninsula would have prevented multiple failures due to broken and fallen poles. Doing so would also have reduced blackouts during the critical evacuation period—the line failed several hours before the hurricane made landfall—when power was needed for traffic lights and gas stations.

I was also struck by the scattershot, uneven nature of the severe damage. Just a few miles from Gilchrist, the town of

Photo: Alexis Kwasinski

Gilchrist, Texas, was knocked flat by Hurricane Ike.

Photo: Alexis Kwasinski

Poles snapped by Ike brought down the only power line serving the Bolivar Peninsula.

High Island made it through the storm with only light damage. This fact suggests that engineers face an important challenge: to build an overall infrastructure that is resilient and flexible, so that when serious problems arise in one small area, the rest of the network doesn't go down.

As I've worked in this field of disaster forensics, I've come to think of disasters as undesirable stress experiments that allow us to evaluate the performance of critical infrastructures. The lessons we learn may allow us to save lives and reduce the economic impact of future disasters. A category 5 hurricane is statistically overdue in Florida, and major earthquakes have long been expected near Tokyo and on the United States' Pacific Northwest coast, where a tsunami is also likely.

It's not just communications and power engineers who can learn from my recent tours of the world's worst catastrophes. For example, the successful construction practices observed in NTT's central office buildings in Japan could be replicated along the Pacific Northwest coast to reinforce existing emergency facilities and school classrooms. Japan's tsunami evacuation structures for coastal communities with distant high-ground areas could be duplicated in the United States. Perhaps the main lesson that I took from my travels is that it's simply not true that little can be done to prevent disasters. But it's up to the communities at risk, from government officials to individual citizens, to demand the investments that will prepare their towns and cities for the worst. If these communities don't learn from those who have suffered before, history will tragically repeat itself.

About the Author

Alexis Kwasinski is an assistant professor of electrical engineering at the University of Texas at Austin. He's working with the IEEE Power Electronics Society's technical committee on communications energy systems on a new technical thrust to study the impact of disasters on infrastructure. He's also involved with the IEEE Future Directions Committee's new online community dedicated to discussing disaster mitigation and relief.

Photo: Alexis Kwasinski

The tsunami evacuation structure seen in the background saved lives in Minami Sanriku, Japan. Such buildings could also save lives along the U.S. Pacific Northw est coast.