REAL-TIME TESTBED FOR SIMULTANEOUS POWERLINE AND WIRELESS SMART GRID COMMUNICATIONS

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ABSTRACT

Two-way communication is a key feature in a smart grid. It is enabled by either powerline communication (PLC) or wireless communication technologies. Utilizing both technologies can potentially enhance communication reliability, and many diversity combining schemes have been proposed. However, their assumptions may break under realistic conditions. In this paper, we propose a flexible real-time testbed to evaluate various diversity combining schemes over physical channels. The contributions of this paper are 1) a real-time testbed for simultaneous powerline and wireless communications, and (2) evaluation in the testbed of maximal ratio combining of the received powerline and wireless signals.

Index Terms— PLC, wireless, diversity, testbed, implementation

1. INTRODUCTION

People living in modern society count on electronic devices and appliances more than ever. Put differently, our society relies on electricity more than any other in human history. Power blackouts, thus, degrade the quality of lives and cause damage to businesses. Power outages were estimated to cost the U.S. more than $100B per year [1, 2]. Furthermore existing infrastructure is so aged that it will be challenging to meet growing power demand in the future. In 2015, 94 coal plants with an average age of 54 years were retired [3], which amounts to nearly 5% of total U.S. coal capacity.

Smart grid which has seen initial trials by some utilities [4,5] is anticipated to be a solution for managing the growing demand [6–8]. As an integration of communication and electricity distribution networks, information conveyed through the communication network is exploited to improve reliability and efficiency of the distribution system. Smart meters, thus, are expected to play a key role in smart grid communication [9]. They are capable of not only measuring power consumption at users' end but also exchanging information such as measured data, meter status, and control commands between smart meters and a data concentrator.

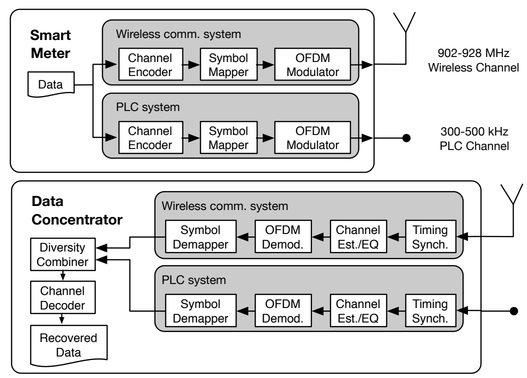

Fig. 1: Diagram of PLC/Wireless Diversity System

This two-way communication is being enabled by either powerline communication (PLC) or wireless communication technologies. Note that the powerline experiences more complicated noise and interference, which results in modeling and mitigation techniques that are different from those for the wireless channel [10, 11]. Smart meters are built to use one of the technologies or can switch between them, but do not make use of both simultaneously. Therefore there have been efforts to enhance communication reliability by utilizing two independent communication links available for the smart grid [12–15]. Fig. 1 illustrates an overall diagram of a PLC and wireless diversity system. Theoretical studies show that diversity schemes help the network to become more reliable; however, assumptions that the results are based on may break in an actual deployment. In order to verify functionality of those various schemes, they need to be implemented and tested under realistic conditions.

A flexible real-time testbed that we present in this paper is intended for such purposes. It provides simultaneous over-the-wire and over-the-air wireless smart grid communications. Moreover recovered soft bits are automatically aggregated into a diversity process where combining schemes under test will be operating. The contributions of this paper are: 1) we propose a flexible real-time testbed implementation for evaluation of various diversity combining schemes

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Table 1: Parameters for common baseband communication transceiver for simultaneous PLC and wireless transmission/reception

Parameter	Value
Sample rate	400 kHz
OFDM size	256
CP length	64
Packet duration	variable
Packet rate	10 packets/s
Number of data subcarriers	36
Data modulation	BPSK only

over simultaneous powerline and wireless communications and provide details of implementation as well as a code [16] and 2) we provide evaluation of maximal ratio combining implemented in the real time testbed.

2. SYSTEM OVERVIEW

The purpose of the real-time PLC/wireless diversity testbed is to provide an environment where various combining schemes can be tested under realistic conditions in real time. Smart grid wireless communication standards IEEE 802.11ah and IEEE 802.15.4g and powerline communication standards of G3, PRIME and IEEE P1901.2 use orthogonal frequency division multiplexing (OFDM). Even so, these standards do not share the same system parameter values. For the sake of simplicity, we use a common baseband transceiver for both wireless and powerline communications with the parameters in Table 1.

2.1. Hardware Architecture

The real-time testbed is built using products from National Instruments as shown in Fig. 2. The two chassis on the left and in the middle are for PLC and wireless communication, respectively. The two systems will be located in different places as they require different channels. Therefore the two communication systems will reside in different chassis. A PXI chassis has slots that can accommodate an x86 controller and various modules. As Fig. 2 depicts, a PXI-1045 chassis on the left has a PXI-8106 controller, a PXI-5421 signal generator and a PXI-5122 digitizer. This chassis functions as a baseband PLC system. Similarly a PXIe-1082 chassis contains a PXIe-8133 controller, a PXIe-7965R FPGA module and an NI-5791 RF adapter module. Since the RF adapter module has both a transmit and a receive port, a unidirectional single-input single-output (SISO) link can be established with a single adapter module. The transmit and receive antennas for the wireless system are currently spaced about 5 cm apart, and the transmit and receive ports in the PLC system are directly connected with a coaxial cable for testing purposes.

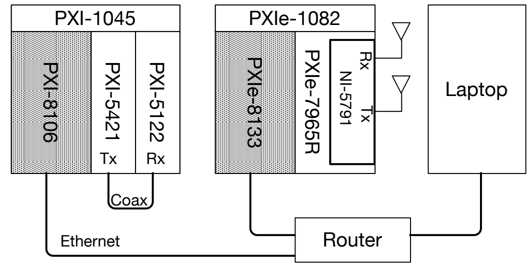
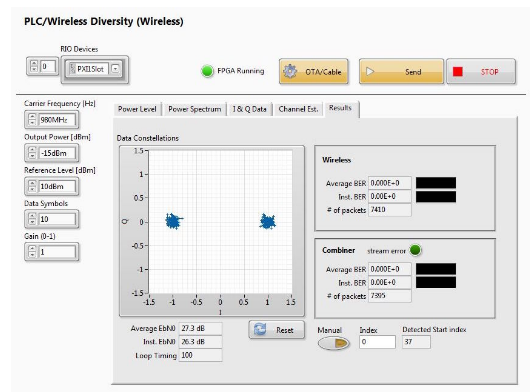
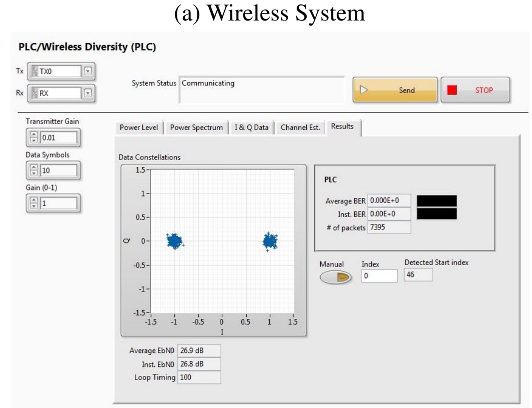


Fig. 2: Hardware Architecture



(a) Wireless System



(b) PLC System

Fig. 3: Front Panels

2.2. Software Architecture

Two controllers used in the testbed run a real-time operating system (RTOS), and each RTOS runs its main program. Fig. 3 shows front panels of the two systems. A controller dedicated to the PLC system runs one thread performing packet generation, bit recovery, and transmission and reception of signals with hardware. The transmitter output signal can optionally bypass the hardware and be directly sent to a receive process in case one wants to test the transceiver directly. The other controller for the wireless system also performs the same process with different hardware. These threads are configured to iterate the whole process at the same rate which determines

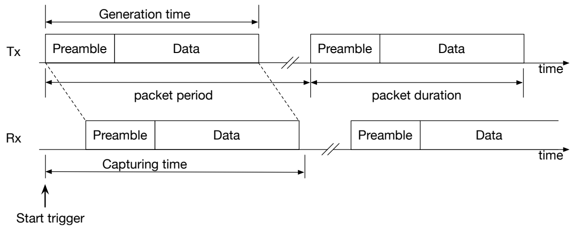


Fig. 4: Packet structure

a packet period. The wireless communication thread sends out start, idle and stop triggers to the PLC system. Note that any triggers or data transmission between the controllers happens over TCP/IP as an ethernet cable is the only connection between the systems.

In addition, there is one more thread in the wireless system controller that carries out diversity combining. Log-likelihood ratios (LLRs) obtained from the PLC and wireless communication threads are forwarded to this thread over first-in first-out memories (FIFO) and are processed in real time. A log-likelihood function for maximum ratio combining (MRC) can be expressed as

$$LL(x) = \log[(p(y_p|x) \times p(y_w|x)] = -\frac{|y_p - x|^2}{\sigma_p^2} - \frac{|y_w - x|^2}{\sigma_w^2} \quad (1)$$

where σ_p^2 and σ_w^2 are Gaussian noise variances of a powerline link and a wireless link, respectively as in [13].

2.3. Packet Structure

A packet consists of a variable number of OFDM symbols. The first two symbols are always a preamble which is used for channel estimation, noise estimation and timing synchronization. The following OFDM symbols contain transmitted data. Both OFDM symbols in the preamble have 236 subcarriers of a Zadoff-Chu sequence around the DC subcarrier. Other sequences or symbols can be employed and replace the Zadoff-Chu sequence, or different timing synchronization techniques can be used. When it comes to the data symbols, BPSK symbols made with a pseudo random bit sequence are mapped onto only 36 subcarriers on the positive frequency side, and the others are zeros. The requested number of OFDM symbols compose the data part. Thus the packet has a variable length and is transmitted every 100 ms as shown in Fig. 4. All these parameters such as the number of subcarriers, the number of OFDM symbols and the packet period can be easily modified to fit specific needs.

In the testbed, the receiver does not capture signals all the time, but starts simultaneously with the transmitter by the start trigger and stops upon receiving the requested number of samples. This synchronization is described in detail in Section 2.4. Since the receiver is started by the transmitter, but does not know a time of arrival of a transmitted packet, it captures a signal longer than a sum of the packet length and the delay as shown in Fig. 4.

2.4. Synchronization

The testbed implements both system synchronization and packet synchronization. The system synchronization refers to transmit/receive synchronization, sample timing synchronization, sample clock and local oscillator synchronization, and so forth. A packet synchronization pertains to ensuring that two systems transmit and receive packets at the same rate in order that the FIFOs through which LLRs are delivered do not overflow over time.

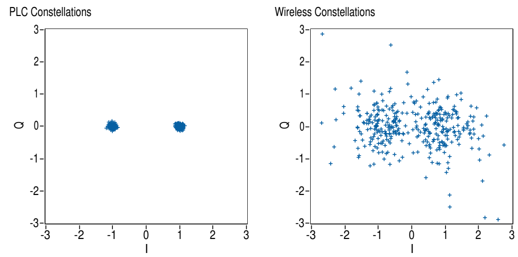
The transmitter and receiver are synchronized in a couple of ways. The PLC system synchronizes sample clocks of the transmitter and the receiver to a reference clock generated in a backplane of a PXI chassis to prevent two sample clocks from drifting away. The transmitter also sends out a start trigger to the receiver so that they can start simultaneously. The wireless system employs the identical synchronization technique. Plus, a single local oscillator located in the adapter module is used by both an upconverter and a downconverter resulting in a zero carrier frequency offset. These synchronization techniques do not need extra signal processing to compensate for impairments.

Sample timing synchronization is one of the most important and the earliest processes on the receiver side. To find a starting point of a packet, the first peak of cross correlation between a known preamble and a received preamble within a captured signal is detected and is chosen as a packet starting point. For this reason, a Zadoff-Chu sequence is used in generating a preamble. Sample timing synchronization would be lost when a signal power is too low. The testbed, therefore, provides an option to manually correct the timing. The timing offset remains almost the same as long as an antenna distance or a cable length does not change. Once a correct offset is obtained when the signal power is high enough, one can switch over to manual correction and use the obtained offset.

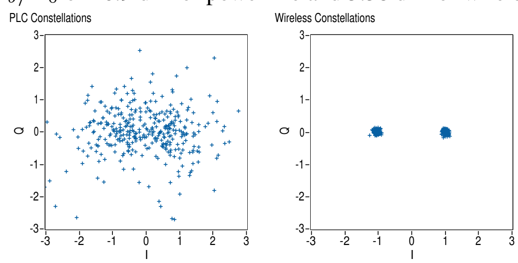
Two systems should start almost at the same time and transmit packets at a similar rate so that FIFO memories in the combining thread will not overflow. However, they operate independently without sharing any triggers or signals over a wire. The testbed, thus, takes advantage of the deterministic RTOS, and uses a timed-loop in both the PLC and the wireless threads. And the start signal is generated from the wireless system and is sent to the PLC system over TCP/IP.

3. INITIAL RESULTS

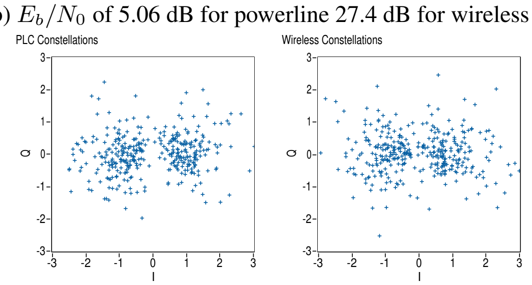
A combining scheme used to gather initial results is the MRC scheme that combines LLRs from both links. As the log-likelihood function described in [13] indicates, the LLR computed with the MRC scheme is nothing but a sum of LLRs



(a) E_b/N_0 of 26.9 dB for powerline and 5.38 dB for wireless link



(b) E_b/N_0 of 5.06 dB for powerline 27.4 dB for wireless link



(c) E_b/N_0 of 6.98 dB for powerline and 7.15 dB for wireless link

Fig. 5: Receive constellations for operating conditions given in Table 2

from both links.

In this testbed, all noise variances and E_b/N_0 are estimated as in [17] and averaged in real-time at the receiver with the preamble in every packet, which means the estimates are not as accurate as desktop simulation.

In this section, we consider two different test cases. In the first case, one of the two links has a much lower E_b/N_0 than the other, and in the second case, both the two links has a low E_b/N_0. A link with a low E_b/N_0 refers to a link with a non-zero BER.

3.1. One link with a low E_b/N_0

Since a purpose of diversity is to improve reliability of the communication system, the first test case is that one link is reliable, but the other is not due to a low E_b/N_0. Fig. 5 shows snapshots of the constellation diagrams of a received packet with an average estimated E_b/N_0 over time. In Fig. 5a, the PLC link achieves E_b/N_0 of 26.9 dB whereas the wireless link E_b/N_0 of 5.38 dB. Fig. 5b, on the contrary, depicts constellations of the PLC link with E_b/N_0 of 5.06 dB and the

Table 2: Combiner Performance

(a) Wireless link with a low E_b/N_0

	PLC	Wireless	Combiner
E_b/N_0	26.9 dB	5.38 dB	N/A
BER	0	2.65×10^{-2}	0

(b) PLC link with a low E_b/N_0

	PLC	Wireless	Combiner
E_b/N_0	5.06 dB	27.4 dB	N/A
BER	3.33×10^{-2}	0	0

(c) Both links with a low E_b/N_0

	PLC	Wireless	Combiner
E_b/N_0	6.98 dB	7.15 dB	N/A
BER	3.61×10^{-3}	4.12×10^{-3}	1.77×10^{-3}

wireless link with E_b/N_0 of 27.4 dB. Average BERs of each case are calculated with over 20,000 packets and are listed in Table 2. We can see in Fig. 5 that BPSK symbols are clearly separated when the estimated E_b/N_0 is high, which results in zero BERs as shown in Table 2a and 2b. In such cases, the combiner always can yield zero BER implying that the MRC scheme can recover the transmitted information when one of the channels undergoes deep fading while the other does not.

3.2. Two links with low E_b/N_0

Now we assume that the both channels are in deep fading and that their E_b/N_0 are not high enough to achieve zero BERs. Constellation diagram snapshots of the case are displayed in Fig. 5c, and their average estimated E_b/N_0 are 6.98 dB and 7.15 dB in the PLC and wireless links, respectively. Corresponding BERs are computed with more than 40,000 packets and are shown in Table 2c. It can be seen that the MRC scheme, as expected, can reduce a BER by combining LLRs from two systems.

4. CONCLUSION

In this paper, we proposed implementation of a flexible real-time testbed for evaluation of various PLC and wireless combining schemes. The testbed consists of powerline and wireless OFDM communication systems which are ready to emulate a smart grid communication network. Two systems have similar transceiver processing such as packet generation and recovery, channel coding and decoding, time and frequency synchronization and channel estimation and equalization. We also demonstrated the testbed in two different scenarios by employing a simple MRC scheme. The constellation diagrams and resulting BERs show that the MRC can improve communication reliability when one or both links are in deep fading.

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