Cars communicating: Automotive Applications of 5G and Millimeter Wave

Professor Robert W. Heath Jr., PhD, PE

Wireless Networking and Communications Group
Department of Electrical and Computer Engineering
The University of Texas at Austin

Thanks to sponsors including the U.S. Department of Transportation through the Data-Supported Transportation Operations and Planning (D-STOP) Tier 1 University Transportation Center, the Texas Department of Transportation under Project 0-6877 entitled “Communications and Radar-Supported Transportation Operations and Planning (CAR-STOP)”, National Instruments, and Toyota IDC

www.profheath.org
The era of connected vehicles

- Vehicle to sensors
- Vehicle to road
- Vehicle to Internet
- Vehicle to pedestrian
- Vehicle to vehicle

Vehicle to X (V2X) connectivity

- Key element for the new generation Intelligent Transportation Systems
- Governments are pushing for the connected car revolution
  - NHTSA has announced intention to require DSRC in new cars by 2017

What is the difference?

CONNECTED

V2X communication capabilities

AUTOMATED

Some safety-critical control functions

without direct driver input

AUTONOMOUS

Self driving capabilities

without connectivity

M. Parent, "Automated Vehicles: Autonomous or Connected", IEEE 14th International Conference in Mobile Data Management (MDM), vol. I., no., pp.2-2, 3-6 June 2013
## Automated driving

<table>
<thead>
<tr>
<th>LEVEL 0</th>
<th>LEVEL 1</th>
<th>LEVEL 2</th>
<th>LEVEL 3</th>
<th>LEVEL 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>No automation</td>
<td>Function specific automation</td>
<td>Combined function automation</td>
<td>Limited Self-Driving Automation</td>
<td>Fully Self-Driving Automation</td>
</tr>
</tbody>
</table>

**LEVEL 0**
- No automation
- Full driver control at all times
- NHTSA, “Preliminary Statement of Policy Concerning Automated Vehicles”, 2013

**LEVEL 1**
- Function specific automation
- Driver can cede control over a primary function (e.g., ACC)
- Driver responsible for monitoring the roadway

**LEVEL 2**
- Combined function automation
- Driver can cede control on at least two primary functions
- Driver responsible for monitoring the roadway

**LEVEL 3**
- Limited Self-Driving Automation
- Driver can cede full control of all safety-critical functions
- Driver do not have to monitor the roadway at all times

**LEVEL 4**
- Fully Self-Driving Automation
- Driver provides destination
- Not available for control

**Limited/Full self driving cars**
To achieve higher automation levels, connectivity seems critical

- Vehicular communications to share sensing data and enhance sensing capability

New challenges for the underlying communication system

*5G-PPP White Paper on Automotive Vertical Sector, October 2015, https://5g-ppp.eu/white-papers/*
Connected, autonomous and automated

◆ Main conclusions
  ✦ Connected, automated and autonomous cars are not the same
  ✦ Connected cars may still be driven by humans
  ✦ Automated cars may have limited connectivity

◆ Claim: Automated cars should exploit connectivity
  ✦ Gives access to a richer set of sensor data
  ✦ Solves key challenges of automated driving in congested urban areas
  ✦ Motivates 5G and the application of millimeter wave
State-of-the-art in vehicular sensing
Automotive cameras

- Visual queues for the driver
  - Provides the driver with an additional view, i.e. “virtual mirrors”
- Sensing for driver assist
  - Lane departure, pedestrian detection, smart airbag, speed limit detection, etc.

More cameras will be mandated for safety or integrate for comfort
Automotive radar

- Long range radar (LRR) is used for adaptive cruise control (ACC)
- Medium range radar (MRR) supports CTA, LCA, stop & go and BSD
- Short range radar (SRR) is used for parking aid and precrash applications

Radar application table:

<table>
<thead>
<tr>
<th>Type</th>
<th>LRR</th>
<th>MRR</th>
<th>SRR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency band (GHz)</td>
<td>76-77</td>
<td>77-81</td>
<td>77-81</td>
</tr>
<tr>
<td>Bandwidth (GHz)</td>
<td>0.6</td>
<td>0.6</td>
<td>4</td>
</tr>
<tr>
<td>Range (m)</td>
<td>10-250</td>
<td>1-100</td>
<td>0.15-30</td>
</tr>
<tr>
<td>Distance accuracy</td>
<td>0.1</td>
<td>0.1</td>
<td>0.02</td>
</tr>
</tbody>
</table>


Radar application diagram:

- 79 GHz LRR
- 79 GHz SRR
- 77 GHz MRR

Applications:
- Stop&Go
- Pre-crash
- Blind Spot Detection (BSD)
- Cross Traffic Alert (CTA)
- Lane Change Assistance (LCA)

Radar application summary:

Radar systems are already deployed, but not a fool-proof technology.
Automotive LIDAR

- Radar using laser instead of radio waves
  - Narrow laser beam allows high resolution depth associated range maps
  - Already deployed in autonomous vehicles
- Extremely expensive: $8,000 ~ $80,000 per LIDAR
- Major LIDAR manufacturers: Velodyne, Valeo, Bosch, Google

*http://www.extremetech.com/extreme/147940-google-self-driving-cars-in-3-5-years-feds-not-so-fast
**http://articles.sae.org/13899/
Summarizing automotive sensors

<table>
<thead>
<tr>
<th></th>
<th>Purpose</th>
<th>Drawback</th>
<th>Data rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radar</td>
<td>Target detection, velocity estimation</td>
<td>Hard to distinguish targets</td>
<td>Less than 1 Mbps</td>
</tr>
<tr>
<td>Camera</td>
<td>Virtual mirrors for drivers</td>
<td>Need computer vision techniques</td>
<td>100-700 Mbps for raw images, 10-90 Mbps for compressed images</td>
</tr>
<tr>
<td>LIDAR</td>
<td>Target detection and recognition, velocity estimation</td>
<td>High cost</td>
<td>10-100 Mbps</td>
</tr>
</tbody>
</table>

- Is it possible to exchange raw sensor data between vehicles?

Automotive sensors generate a huge amount of data
State-of-the-art in connected cars
DSRC: current technology for vehicular communications

- Forward collision warning, do not pass warning, blind intersection warning, etc.
- Non-safety apps also possible – improve congestion, weather, toll collection
- Based on IEEE 802.11p, IEEE 1609.x, SAE standards
- Supports very low data rates (27 Mbps max, much lower in practice)

DSRC is not designed for the exchange of sensor data

---


4G cellular for V2X

- **V2V through D2D mode in LTE-A**
  - BS helps vehicles discover other nearby vehicles
  - **Cars communicate directly** without routing the traffic through the LTE network
- **Higher data rates than DSRC (up to 1Gbps), but**
  - Practical **rates limited to several Mbps** by inaccurate CSI

*3GPP. LTE Device to Device Proximity Services; User Equipment (UE) Radio Transmission and Reception. TR 36.877, 3rd Generation Partnership Project (3GPP), 2015.
**M. Rumney et al. LTE and the evolution to 4G wireless: Design and measurement challenges. John Wiley & Sons, 2013*
## DSRC versus LTE-A for V2X

<table>
<thead>
<tr>
<th>Features</th>
<th>802.11p</th>
<th>LTE-A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel width</td>
<td>10 MHz</td>
<td>Up to 100 MHz</td>
</tr>
<tr>
<td>Frequency Band</td>
<td>5.86–5.92 GHz</td>
<td>450 MHz–4.99 GHz</td>
</tr>
<tr>
<td>Bit Rate</td>
<td>3–27 Mb/s</td>
<td>Up to 1 Gb/s</td>
</tr>
<tr>
<td>Range</td>
<td>Up to 1 km</td>
<td>Up to 30 km</td>
</tr>
<tr>
<td>Capacity</td>
<td>Medium</td>
<td>Very High</td>
</tr>
<tr>
<td>Coverage</td>
<td>Intermittent</td>
<td>Ubiquitous</td>
</tr>
<tr>
<td>Mobility support</td>
<td>Medium</td>
<td>Very high</td>
</tr>
<tr>
<td>Market penetration</td>
<td>Low</td>
<td>Potentially high</td>
</tr>
</tbody>
</table>

- LTE-A is interesting because of its wide expected coverage*
- Gbps data rates are not supported

Massive data rates from sensors vs DSRC/4G

Each sensor generates data

Lots of sensors in a vehicle

Massive amount of data per vehicle

- Connected vehicle is expected to drive 1.5GB monthly mobile data in 2017
  - May be handled with a combination of conventional cellular and DSRC
- Autonomous vehicles can generate up 1 TB per hour of driving
  - 4G and DSRC can not support these data rates

New communication solution is needed for connected cars

**Cisco, “The Internet of Cars: A Catalyst to Unlock Societal Benefits of Transportation,” Mar. 2013
Millimeter wave and 5G for connected cars
Millimeter wave for connected cars

MmWave is the only viable approach for high bandwidth connected vehicles.
How will mmWave be realized?

Use new dedicated spectrum

Dedicated mmWave V2X

Requires special infrastructure

5G mmWave cellular

Uses cellular infrastructure
Access is highly coordinated
Leverages (coming) mmWave spectrum

High data rates

Modification of IEEE 802.11ad

Less efficient access
Use of unlicensed band

5G is promising for mmWave connected cars

Challenges for mmWave in V2X

Lack of propagation channel models

High penetration rate needed for most gains

Communication overhead

High penetration rate needed for most gains

Typical antenna height: 1.5 m

Implications of using mmWave in automotive

- Increased sensing capability in the car
- Joint automotive radar and communication is possible
- New kinds of infrastructure to be deployed near roads
- Sensing technologies can be used to help establishing communications
MmWave V2X at UT

Some examples of current research work
Using position information to reduce beam alignment overhead in mmWave V2X

- Each vehicle decides candidate beams from other vehicles’ position and size info

DSRC modules or automotive sensors can be used to reduce overhead

Adding radar to the infrastructure

- A BS with a radar can capture information of the scattering environment
- Used to design multiuser beamforming, support remote car traffic control

Sensing at the infrastructure can help in establishing the communication links
Predicting blockage from out-of-band sensing

- Radar can detect potential obstacles and their associated mobility
- Machine learning can classify particular radar responses as blockages

Sensing & learning are symbiotic technologies

Joint radar and communications based on 802.11ad

- IEEE 802.11ad mmWave waveform works well for radar
  - Special structure of preamble enables good ranging performance
  - Leverages existing WLAN receiver algorithms for radar parameter estimation
- Target vehicle information from 11ad radar can be directly used for communication

Joint system provides safety capabilities at lower cost

Conclusions

**Why mmWave V2X?**
- Provides the only high data rate solution for sensor exchange
- Already used in other automotive technologies

**Why 5G?**
- Already exploring a mmWave waveform
- Will operate in dedicated spectrum with heavy management
- Will support lower frequencies as a backup

**MmWave V2X** MmWave introduce new challenges
- Lack of propagation channel models
- New signal processing techniques need to be developed
- Infrastructure and penetration rate
MmWave

20 GHz

<1 GHz

CmWave

6 GHz

Unlicensed

Even more spectrum

900 MHz

5.2 GHz

2.4 GHz

37/42 GHz

39 GHz

60 GHz

E-band

100 GHz

x100 GHz
Antenna diversity to overcome blockage in V2I

- A BS with a radar is assumed at the infrastructure side
  - Antennas are assumed to be placed at the virtual scattering points in the car
  - Radar info is used to design a multi-beam pattern to track several antennas
- High mobility is considered and the positions of the antennas are predicted

Sensing at the infrastructure can help to manage blockage