Vehicle-to-X communication using millimeter waves (just in time for 5G)

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www.profheath.org
Fifth generation (5G) cellular communication

Multidimensional objectives*

- Peak data rate
- User exp. data rate
- Spectrum efficiency
- Mobility
- Connection density
- Latency

New industry verticals**

- Automotive
- e-Health
- Energy
- Media & Entertainment
- Factory of the Future

Higher rates

Lower latency

Trends in vehicle automation

INCREASING NUMBER OF SENSORS

CONNECTED CAR

SAFETY

AUTOMATED DRIVING

Higher automation levels

TRAFFIC EFFICIENCY

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

**MYTH 1**
Automated vehicles can be fully autonomous, no communication is required

**MYTH 2**
Infrastructure has no value for automated vehicles
Benefits of communication

- Expand the sensing range of the vehicle
- More informed safety decisions
- Allows interactions between vehicles with different automation levels
- Higher levels of traffic coordination like platooning
Benefits of infrastructure

Supports sensing of the environment, does not require all cars to have complete sensing equipment

Can be used for other functions, for example more precise navigation

Effective with non-connected cars, bicycles, and pedestrians

Helps coordinate traffic through intersections, eliminating lights
Key questions

What are the data rate requirements for sensors?

What are the capabilities of current automotive communication solutions?

Where is the communication theory and signal processing research?
State-of-the-art in vehicular sensing
### Current technologies for vehicular sensing

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Range (ideal)</th>
<th>Range (traffic)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radar</td>
<td>200 m</td>
<td>3-5 m</td>
</tr>
<tr>
<td>Camera</td>
<td>70 m</td>
<td>3-5 m</td>
</tr>
<tr>
<td>LIDAR</td>
<td>50 m</td>
<td>3-5 m</td>
</tr>
</tbody>
</table>

Powerful sensing technologies with limited range in traffic conditions.
## Sensor applications and data rates

<table>
<thead>
<tr>
<th>Sensor</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>

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.
- Supports very low data rates (27 Mbps max, much lower in practice)
- Non safety apps also possible

Based on IEEE 802.11p, IEEE 1609.x, SAE standards

DSRC is not designed for the exchange of high rate sensor data


4G cellular for V2X

- **V2V through D2D mode in LTE-A**
- **Cars communicate directly or through infrastructure**
- **Higher data rates than DSRC (up to 1Gbps)**

BS helps vehicles discover other nearby vehicles

Practical rates limited to several Mbps by inaccurate CSI

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*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>DSRC</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>100’s of Mb/s 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>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

Current connected vehicles are expected to drive 1.5GB monthly data in 2017**

Automated vehicles can generate up 1 TB per hour of driving

Handled with a combination of 4G and DSRC

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 for connected cars
Millimeter wave for automated cars

Exchanging raw sensor data is possible

Joint communication and radar is possible

V2V communication beams

Vehicle driving cloud

directional beamforming

V2I communication beam

Sensing technologies can be used to help establish mmWave links

Enables high data rate infotainment applications

MmWave is the only viable approach for high bandwidth connected vehicles*

Candidate millimeter wave spectrum for V2X

60 GHz band: currently used indoor such as WiGig

United States radio spectrum frequency allocation chart as of January 2016

- 63-64 GHz allocated for V2X in Europe
- 60 GHz unlicensed
- 20 GHz Automotive radar
- 5G licensed
- 5G mmWave: 28 and 39 GHz (USA) and 10 other bands
- Automotive radar: 24 GHz UWB, 76 GHz, and 79 GHz bands

5G licensed
Under FCC’s consideration
Existing bands
## Potential bandwidths and data rates at mmWave

<table>
<thead>
<tr>
<th></th>
<th>Total spectrum</th>
<th>Typical bandwidth</th>
<th>Peak rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEEE 802.11ad* in 60 GHz</td>
<td>7 GHz</td>
<td>2 GHz</td>
<td>6 Gbps</td>
</tr>
<tr>
<td>IEEE 802.11ay in 60 GHz</td>
<td>7 GHz</td>
<td>4 GHz</td>
<td>100 Gbps</td>
</tr>
<tr>
<td>28 GHz 5G</td>
<td>0.85 GHz</td>
<td>200 MHz</td>
<td>1.5 Gbps</td>
</tr>
<tr>
<td>39 GHz 5G</td>
<td>3 GHz</td>
<td>400 MHz</td>
<td>3 Gbps</td>
</tr>
<tr>
<td>E band 5G</td>
<td>10 GHz</td>
<td>2 GHz</td>
<td>24 Gbps</td>
</tr>
</tbody>
</table>

* IEEE 802.11ad is commercially available

**10x to 100x gains in bandwidth going to mmWave**
How will mmWave be realized?

5G mmWave cellular

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

Dedicated mmWave V2X

- Use new dedicated spectrum
- Requires special infrastructure

High data rates

Modification of IEEE 802.11ad

- Less efficient access
- Use of unlicensed band

5G is promising for mmWave connected cars

mmWave spectrum challenges for V2X

Ways to reduce license cost but allow carriers to share spectrum *

Regulations not harmonized

Cognitive radio for shared spectrum with satellite or radar**

New communication technology needed


Designing a mmWave V2X system
Overview of mmWave V2X channel

V2X channels
- Low antenna elevation
- Prone to blockage
- Tx & Rx moving
- Fast changing topology

MmWave channels
- Large penetration and diffraction loss
- Severe blockage
- Shrinking antenna aperture
- Directionality

MmWave V2X channels

Combined challenges from both sides

There are several measurements but still limited
Channel coherence time and directional reception

Mathematical expression relating coherence time and beamwidth

Optimum beamwidth is a tradeoff between pointing error and Doppler

Beams should be narrow but not too “pointy”

Long term beamforming can be used

Overheads of beam training are much less significant than expected

Even with poor accuracy of position information the beam alignment overhead is reduced

DSRC modules or automotive sensors can be used to reduce overhead

Reflection off building could be used in NLOS

Such paths via static objects can be learned beforehand

Infra collect database of multipath fingerprint (i.e. AoA/AoD) of paths indexed by location

Example of multipath fingerprint

<table>
<thead>
<tr>
<th>Location</th>
<th>Path</th>
<th>Rx Power</th>
<th>AoA</th>
<th>AoD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>#1</td>
<td>-59.81</td>
<td>84</td>
<td>87</td>
</tr>
<tr>
<td></td>
<td>#2</td>
<td>-67.66</td>
<td>80</td>
<td>61</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>#1</td>
<td>-60.9</td>
<td>82</td>
<td>87</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1. Rx request link via DSRC and inform its position
2. RSU responses with list of beam indices for training
3. Perform beam training

**Multiuser hybrid precoding: application to V2I**

Two-stage multi-user hybrid precoding algorithm

- SU analog beamforming design for max. desired power
- Multi-user interference management

Performance with quantized effective channels

L=3 paths, effective channels are quantized with B_{BB} bits

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Radar-aided millimeter wave V2X

Radar can be used to configure communication link more efficiently

mmWave BS supporting V2X+radar

Radar beam in another band

The dominant DoAs for the communication signal also appear at the radar echo in a different band

Algorithms for hybrid precoder & combiner design based on covariance information of the radar signal

Translating spatial correlation information

MmWave has higher spatial resolution (antennas) and temporal resolution (bandwidth)

SIMO operating at two bands

Construct an estimate of the high frequency spatial correlation matrix

\[ \hat{R}_H = f(R_L) \]

Compute low frequency spatial correlation matrix

\[ R_L = \mathbb{E} [h_L h_L^*] \]

True angle spread of high frequency

Joint mmWave comm. and radar using IEEE 802.11ad

Special structure of preamble enables good ranging performance

Existing WLAN RX algorithms for radar parameter estimation

fine range estimation achieves the desired accuracy of 0.01m

Joint system provides safety capabilities at lower cost

Prototyping mmWave for V2X

mmWave V2X and joint mmWave / radar prototype

- National Instruments PXI chassis interfaces with custom RF
- 2x2 MIMO prototype 60 GHz arrays
- Communication transmitter
- Radar receiver
- Automotive radar & DSRC
- Communication receiver
- Automotive radar & DSRC

Automotive radar test
- Target emulator
- Baseband and IF

mmWave 60 GHz phased array testbed
Research challenges for PHY design

- Effect of hardware impairments on mmWave V2X
- Fast beam alignment and tracking
- MIMO architectures for mmWave V2X: analog or hybrid?
- Diversity solutions against blockage
What are we doing at UT to address these challenges?
UT is well positioned to develop wireless networks for transportation systems.
Situation-aware vehicular engineering systems

UT-SAVES
An initiative in partnership with Toyota IDC, Huawei, & National Instruments*

* Looking for more partners!
Conclusion
Vision of cellular infrastructure supporting transportation

Combination of sensing, learning and communication

Sensing at the infrastructure

mmWave sensing-BS

mmWave relay

Multiband-connectivity supporting V2X

Vehicles exchanging sensor data

radar beam

mutiband BS

WHAT STARTS HERE CHANGES THE WORLD
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