Networking for Connected Vehicles: Prospects & Challenges

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Outline

Part I: Connected Vehicles: Use Cases from a Networking Perspective

Part II: Technology Options & Current Challenges
- A Happy Mess!
Connected Vehicles: v-2-v

- **Vehicle-to-Vehicle (V2V) Communications**
  - Allows nearby vehicles to exchange position data to warn drivers of potential collisions
  - Capable of warning drivers of potential hazards not visible to sensors (e.g. stopped vehicle blocked from view, or moving vehicle at a blind intersection)

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**Passive safety**
- ABS, ESC, BAS, AFS

**Active safety**
- Adaptive Cruise Control, Lane Keeping Support, Park Assist, Side Assist, Front Assist, Night Vision

**Cooperative safety**
- Universal Collision Avoidance Support, Traffic Signal Notification and Violation Warning, Pedestrian Collision Advisor, Vehicles/Road Condition Sensing and Alert

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**Electronics within vehicles**
- Vision and Radar

**Vehicle-to-vehicle (V2V) and Vehicle-to-infrastructure (V2I) Communications**
- Radar (< 200 m)
- Camera (< 80 m)
- Ultrasonic (< 4 m)

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**Radar**
- (< 200 m)

**Camera**
- (< 80 m)

**Ultrasonic**
- (< 4 m)
V2V-Based Cooperative Applications

- Address crashes/hazards that cannot be prevented by current in-vehicle camera and sensor-based technologies (“vehicle-resident” technologies)
  - Not restricted by line-of-sight limitations
- V2V communications (BSMs) contain additional information, such as path predictions and driver actions (braking, steering) not available from traditional sensors.
<table>
<thead>
<tr>
<th>Scenario and warning type</th>
<th>Scenario example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rear end collision scenarios</td>
<td><img src="image1" alt="Diagram" /></td>
</tr>
<tr>
<td>Forward collision warning</td>
<td>Approaching a vehicle that is decelerating or stopped.</td>
</tr>
<tr>
<td>Emergency electronic brake light warning</td>
<td>Approaching a vehicle braking hard or stopped in roadway but not visible due to obstructions.</td>
</tr>
<tr>
<td>Lane change scenarios</td>
<td><img src="image2" alt="Diagram" /></td>
</tr>
<tr>
<td>Blind spot warning</td>
<td>Beginning lane change that could encroach on the travel lane of another vehicle traveling in the same direction; can detect vehicles already in or soon to be in blind spot.</td>
</tr>
<tr>
<td>Do not pass warning</td>
<td>Encroaching onto the travel lane of another vehicle traveling in opposite direction.</td>
</tr>
<tr>
<td>Intersection scenario</td>
<td><img src="image3" alt="Diagram" /></td>
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<tr>
<td>Intersection warning</td>
<td>Encroaching onto the travel lane of another vehicle with whom driver is crossing paths at a blind intersection or an intersection without a traffic signal.</td>
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</tbody>
</table>
STOPPED VEHICLE WARNING

Stopped Vehicle Warning (SVW) message is sent in the direction of arriving traffic when the stopping vehicle’s brakes are applied and its speed drops 20 mph below the speed limit of the road or its speed drops below 5 mph. Sent every 100ms with range of 1000 ft.

5.9 GHz DSRC V-2-V APPLICATIONS

Cooperative Assistive Cruise Control (CACC)
- Platooning
Connected Vehicles: v-2-l

- **Vehicle-to-Infrastructure (V2I) Communications**
  - Inform drivers about weather, traffic, work zones etc.
  - Allows for coordinated signal timing and enhanced parking information systems to improve urban traffic flow
Note 1: The Intersection RSU retransmits the Emergency OBU warning to ALERT vehicles approaching on the side streets.
**5.9 GHz DSRC VEHICLE TO VEHICLE APPLICATION**

**IMMINENT COLLISION WARNING**

Note 1: The OBU in the vehicle recognizing the threat transmits a **WARNING and COLLISION PREPARATION MESSAGE** with the location address of the threat vehicle.

Note 2: Only the OBU in the threatening vehicle processes the message because only it matches the threat address.

Note 3: **COLLISION PREPARATION** includes seat belt tightening, side air bag deployment, side bumper expansion, etc.

In-Vehicle Displays and Annunciations
V2X: Vehicle-to-everything
(beyond v-2-v & v-2-I)

Vehicle-to-vehicle (V2V)
e.g. collision avoidance safety systems

Vehicle-to-infrastructure (V2I)
e.g. traffic signal timing/priority

Vehicle-to-network (V2N)
e.g. real-time traffic / routing, cloud services

Vehicle-to-pedestrian (V2P)
e.g. safety alerts to pedestrians, bicyclists
Advanced Driver Assistance Systems

- Collision warning and automatic braking
- Adaptive front headlights
- Lane departure warning
- Lane keeping assistance
- Blind spot
- Driver monitoring
- Speed alert
- Assisted parking
- Overtaking assistance
- Signal violation warning
- .... Cooperative systems
- V2V, V2I, V2X
Front Radar for adaptive cruise control and distance warning

Surround View displayed in infotainment system

Blind Spot Detection radar with visual warning

Front Camera with visual or haptic warning

Driver Monitoring with acoustic or haptic warning
HOW A SELF-DRIVING CAR WORKS

Signals from GPS (global positioning system) satellites are combined with readings from tachometers, altimeters and gyroscopes to provide more accurate positioning than is possible with GPS alone.

Lidar (light detection and ranging) sensors bounce pulses of light off the surroundings. These are analyzed to identify lane markings and the edges of roads.

Video cameras detect traffic lights, read road signs, keep track of the position of other vehicles and look out for pedestrians and obstacles on the road.

Radar sensors monitor the position of other vehicles nearby. Such sensors are already used.

The information from all of the sensors is analyzed by a central computer that manipulates the steering, accelerator and brakes. Its software must understand the rules of the road, both

Ultrasonic sensors may be used to measure the position of objects very close to the vehicle, such as curbs and other vehicles when parking.
Planning for CAV Convergence

- Connectivity enables V2X but also improved autonomy
- ITS planning should consider connected and autonomous markets
- Continue developing and testing V2X applications
- Be aware of technology evolution – momentum gaining for using both DSCR and 5G
Part II: Technology Options & Current Challenges
- A Happy Mess!
DSRC

Dedicated Short Range Communications: short to medium range communications service that supports both Public Safety and Private operations in roadside-2-vehicle and vehicle-2-vehicle environments. Attempts to providing reliable, low latency communication over relatively small communication zones (< 1 Km)

- FCC sets aside 75 MHz (5.850-5.925 GHz) in 1999 [licensed use, free]
- Since then: automakers + vendors have invested in V2X technology, but no real uptake by auto makers till recently (GM earliest to integrate DSRC in-vehicle, now Honda & VW, 2017)
  - Expectation: Public Safety should be a Federal Mandate!


aimed at mandating DSRC V2V technology on all light vehicles and standardizing the format of V2V transmissions

- No possibility of a Federal mandate currently → technology choices left to private sector & state/local agencies.
802.11 for Next Generation V2X Communication

- 802.11p - matured and robust for Dedicated Short Range Communications (DSRC) applications
  - short packets (BSMs), delivered over small ranges rapidly (100 ms) reliably

- Needs have escalated significantly beyond the original goals:
  - V2X applications: vehicle to anything on/ side of the road, beyond just v2v and v2I
  - Significant desire for increased rates for v2I, support for streaming type (continuous connectivity) applications

- 802.11 WLAN standards (on which .11p is based) have continue to evolved – to support much higher data rates, and now, lower latencies

→ Leverage the evolution of the 802.11 technologies to future proof 11p/DSRC for new application scenarios (v2X)
Direction for a long term roadmap (DSRC)

- 802.11 PHY has evolved after 802.11p amendments (.11n → 11ac → 11ax) with proven technologies, e.g. advanced coding, varying symbol/GI durations, higher data rates, longer range and better high Doppler performance.

- Natural to adopt some recent 802.11 technologies for new V2X applications, e.g. for higher throughput applications, and/or better reliability/efficiency.

- Backward compatible with 802.11p.

- New design requirements from existing field trials may also be addressed.
FCC Pushing Spectrum Sharing for 5.9 GHz


→ reconcile use of 5.9 GHz band between DSRC and Wi-Fi
- “Detect and Vacate” - DSRC and Wi-Fi would share the spectrum, unlicensed devices would detect DSRC operations and vacate the spectrum.
- “Rechannelization” – Split the DSRC band into 2 contiguous blocks
  - Upper 30 MHz exclusively for safety-related communications; Lower 45 MHz for non-safety DSRC communications

➢ Concerns about ability to protect DSRC from interference!
Spectrum Sharing- 802.11 in 5.9 Ghz

- Wide bandwidth channels desired to support high throughput requirements
- At the same time, large number non-overlapping channels desired to support high QoS requirements
  - To avoid co-channel interference
- Current U-NII spectrum allows only
  - Six 80 MHz channels
  - Two 160 MHz channels
- Additional unlicensed use of 5.35-5.47 GHz and 5.85-5.925 GHz would potentially allow a total of
  - Nine 80 MHz channels (Three new)
  - Four 160 MHz channels (Two new)

Possibly shared between DSRC and WLAN
Cellular V2X (C-V2X): Building on LTE D-2-D

Part of Release 14 of the global 3GPP standard
C-V2X specification completed Jun. 2017

Builds upon existing LTE connectivity platform for automotive
LTE already delivering key services today, e.g. telematics, eCall, connected infotainment

**Enhances LTE Direct** for V2X direct communications
Improvements over 802.11p – up to a few additional seconds of alert latency and 2x range

Leverages existing LTE networks for V2X network communications
Using LTE Broadcast optimized for V2X to offer additional applications/services

Rich roadmap towards 5G with strong ecosystem support
Technology evolution to address expanding capabilities/use cases
Evolving LTE Direct device-to-device

Release 12
D2D platform for consumer and public safety use cases

Discovery of 1000s of devices/services in ~500m
Reliable one-to-many communications (in- and out-of-coverage)²

Release 13
Expanded D2D discovery and D2D communications

More flexible discovery such as restricted/private¹ and inter-frequency
Device-to-network relays²

Release 14 and beyond
Multi-hop communication and more use cases

Additional D2D communication capabilities, e.g. multi-hop for IoT
Enhancements for vehicle-to-everything (V2X)

¹ Important for e.g. Social Networking discovery use cases; ² Designed for Public Safety use cases
C-V2X: 2 complementary transmission modes

**Direct communications**
Building upon LTE Direct device-to-device design with enhancements for high speeds / high Doppler, high density, improved synchronization and low latency
- Proximal direct communications (100s of meters)
- Operates both in- and out-of-coverage
- Latency-sensitive use cases, e.g. V2V safety

**Network communications**
Using LTE Broadcast to broadcast messages from a V2X server to vehicles and beyond. Vehicles can send messages to server via unicast.
- Wide area networks communications
- Leverages existing LTE networks
- More latency tolerant use cases, e.g. V2N situational awareness
Overcoming the challenges of V2X

V2X Challenges | C-V2X Solutions
---|---
High relative speeds | Enhanced signal design
Leads to significant Doppler shift / frequency offset | E.g. increasing # of ref signal symbols to improve synchronization and channel estimation

High node densities | Enhanced transmission structure
Random resource allocation results in excessive resource collisions | Transmit control and data on the same sub-frame to reduce in-band emissions

Time synchronization | More efficient resource allocation
Lack of synchronization source when out-of-coverage | New methods using sensing and semi-persistent resource selection

Allow utilization of GPS timing | Enhancements to use satellite (e.g. GNSS) when out-of-coverage
C-V2X increases reaction time over 802.11p/DSRC

For improved safety use cases – especially at high-speeds, e.g. highway

Safer driving experience
Increased driver reaction time

Support for high speeds
Relative speeds up to 500km/h

Increased situational awareness
Gather data from further ahead

Based on link level curves and the 3GPP LOS path loss model @ 10% Packet Error – Actual performance varies significantly with vehicle density and environment
### 5G C-V2X vs DSRC?

<table>
<thead>
<tr>
<th>KEY ELEMENTS</th>
<th>DSRC/IEEE 802.11</th>
<th>Rel 14 C-V2X</th>
<th>5G C-V2X (Rel 15,16) (expected)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Out-of-network operation</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Support for V2V</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Support for safety-critical uses</td>
<td>✔</td>
<td>✔</td>
<td>❌*</td>
</tr>
<tr>
<td>Support for V2P</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Support for V2I</td>
<td>limited</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Support for multimedia services</td>
<td>❌</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Network coverage support</td>
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<td>✔</td>
</tr>
<tr>
<td>Global economies of scale</td>
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<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Regulatory/testing efforts</td>
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<td>limited</td>
<td>❌</td>
</tr>
<tr>
<td>Very high throughput</td>
<td>❌</td>
<td>❌</td>
<td>✔</td>
</tr>
<tr>
<td>Very high reliability</td>
<td>❌</td>
<td>❌</td>
<td>✔</td>
</tr>
</tbody>
</table>
LTE Rel.13,14 has V2X support
- PC5 and Uu interfaces
- Advanced Driving Assistance System (ADAS)
- V2X specification expected by early 2017

Enhancements for true V2V will not be seen until Rel 16 (5G), which is not expected until 2023

LTE Rel 13 (3/16) sufficient for some V2I use-cases, lacks low-latency & high-mobility support
- May not perform in high congestion
- Point to multipoint support eMBMS is static
- Unacceptable latency results when UEs on different MNO networks

2014 2016 2018 2020 2022
CONCLUDING REMARKS

Technology Options & Current Challenges - A Happy Mess!

• 802.11p (DSRC)
  ➢ Products ready - private manufacturers now beginning to integrate into vehicles.
  ➢ Testing at State/Local levels: e.g. Utah’s Salt Lake City Corridor
  ➢ GOOD FOR LIMITED ORIGINAL GOALS (reliable delivery of control info)

• Cellular-V2X (C-V2X):
  ➢ Not expected for several years
  ➢ More advanced PHY layer (coding etc.) under network control
  o supports diff. set of use cases - high throughput, lower latency (1 ms in 5G)
BACKUP
DSRC/WAVE Overview

- **WAVE: Wireless Access in Vehicular Environments**
  - IEEE 1609 (North America)
  - ETSI EN 302 (Europe)
  - Intended to provide automatic wireless communication services in transportation environments
  - Supports services to
    - Improve traveler safety
    - Reduce traffic congestion
    - Reduce fossil fuel consumption
DSRC/WAVE Overview

- IEEE1609 runs on top of 802.11p MAC and PHY layers
- Designed to operate outside of a BSS (Connectionless)
- Range of 1km with transmission rate of 3-27Mps and vehicle speeds of 260km/h
- Offers time division for coordinating CCH and SCH monitoring
- Offers control over priority, channel, transmit power, data rate
- Restricted channels for control and safety communications
WAVE/DSRC Protocol Stack

SAE J2735 Application primitive.

Management Plane

Data Plane

TCP/IP network stack.

WAVE upper MAC
WAVE lower MAC
WAVE PHY

802.11p Std.

UDP
TCP
IP
LLC
WSMP

1609.X

WME
U_MLME
L_MLME
PLME

WAVE = Wireless Access in Vehicular Environments
DSRC/WAVE Overview

- DSRC: Dedicated Short Range Communications
  - 5.850 - 5.925 GHz band allocated in NA for vehicular communications
  - 7 Channels = 6 Service (SCH) + 1 Control (CCH), each 10 MHz

172 – Public Safety V2V (collision avoidance) uses
174, 176, 180, 182: for private use
184 – High Power Public Safety and Non-public safety (v2I)
178 - control channel for link between the Roadside Unit (RSU) and OnBoard Unit (OBU)
DSRC/WAVE Overview

- CH 174-176 and 180-182 can be combined to make 20MHz channels (SCH)

- CCH (control channel): short control messages/service announcements [broadcast] 10x/sec – info about vehicle state

- SCH (service channel): data channel (can be aggregated to 20 MHz) bidirectional, TCP/IP traffic
DSRC/WAVE Overview

- Each unit has 2 radios: one permanently listening to CCH, and the other on SCH as needed
- All devices synchronized with a network clock
- Services available on SCH advertised with service advertisement on CCH.
  - WSA (Wave Service Announcements)
  - WSMP (Short Message Protocol) for high-priority traffic
WAVE Protocol Stack

Each link:

- WAVE mode (default)
  - Use broadcast for instant message exchange.

V2I: WAVE BSS

- A car can join a WAVE BSS passively by only receiving an AP advertisement.
- Neither association nor authentication.

V2V Networking

- WSMP: WAVE Short Message Protocol Layer
  - No layer 3 control over broadcast packets
  - No routing provided

Compared to WLAN, WAVE system has low overhead operation that is specially adapted for vehicular environments.

BSS = Basic Service Set
Basic Safety Message

Each class of device must be capable of transmitting a valid, signed Basic Safety Message (BSM) and receiving BSMs.

• The “Here I Am” message is the BSM (subset) of SAE J2735 conveyed in the 5.9GHz DSRC medium according to IEEE 802.11p and 1609.2 - 1609.4.
• The primary information conveyed in the message is the location of a vehicle at a particular time.
• Other data items are included as well.
• The message is properly signed so that receivers can check authenticity.
Vehicular Mesh Routing

- Prior Work: uses airplug middleware to transmit WAVE packets over 802.11a (instead of 802.11p)
  1. Packets are routed opportunistically as per the WAVE standard from one vehicle to another till it reaches an RSU (connected to the internet).
  2. Delays are characterized vs. increasing number of vehicles in the network [see graph]

Challenges/Issues:
  1. 802.11p accounts for mobility, thus results could have been refined if 802.11p PHY/MAC were used.
  2. Vehicular (and not infrastructure) multi-hopping
  3. Opportunistic communication leaves room for exploring routing algorithms in WAVE scenarios.
5G will bring new capabilities for the connected vehicle

New OFDM-based 5G air interface scalable to an extreme variation of requirements

5G

Extreme throughput
Up to multi-Gpbs with more uniformity—wider bandwidths, advanced antenna techniques

1ms end-to-end latency
Through a faster, more flexible frame structure; also new uplink RSMA non-orthogonal access

Edgeless connectivity
New ways of connect, e.g. multi-hop to extend coverage, plus natively incorporate D2D

High availability
Multi-connectivity to provide multiple links for failure tolerance and mobility

High reliability
Ultra-reliable transmissions that can be time multiplexed with nominal traffic through puncturing
5G will build upon and enhance C-V2X

New 5G platform will augment / complement C-V2X—no ‘rip and replace’

- Multi-mode vehicle with simultaneous connectivity across 4G LTE, C-V2X and 5G
- 4G LTE
  - Continue to evolve and provide ubiquitous coverage as 5G is rolled out
- C-V2X
  - C-V2X direct and network communications
- 5G
  - Bring new capabilities for C-V2X network communications and augment C-V2X direct communications over time
5G standardization progressing for 2020 launch

5G study items

R15 5G WI's

R16 5G WI's

R17+ 5G evolution

First 5G launch\(^1\)

5G phase 2

Continued LTE evolution in parallel with 5G


Learn more at: www.qualcomm.com/5G

Note: Estimated commercial dates; 1 Forward compatibility with R16 and beyond