Heterogeneous V2X Networks for Connected and Automated Vehicles

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Universidad Miguel Hernandez de Elche, Spain
President, IEEE Vehicular Technology Society
Current status

- First release of connected vehicles standards have been finalized worldwide
  - Based on IEEE 802.11p and operating in 5.9GHz (EU and US) band or in 760 MHz band (Japan)
  - ETSI ITS-G5 (EU), IEEE WAVE (US), ARIB T109 (Japan)

- Worldwide deployment plans
  - 1st Toyota cars with V2X since the end of 2015
  - GM selling Cadillac CTS units from 2017 with 802.11p V2V
  - Initial V2X deployment in Europe could begin in 2019 (C2C-CC)
Current status

- Day one applications: limited set only for information purposes

<table>
<thead>
<tr>
<th>#</th>
<th>Day 1 Services</th>
<th>Bundle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Emergency electronic brake light</td>
<td>V2V</td>
</tr>
<tr>
<td>2</td>
<td>Emergency vehicle approaching</td>
<td>V2V</td>
</tr>
<tr>
<td>3</td>
<td>Slow or stationary vehicle(s)</td>
<td>V2V</td>
</tr>
<tr>
<td>4</td>
<td>Traffic jam ahead warning</td>
<td>V2V</td>
</tr>
<tr>
<td>5</td>
<td>Hazardous location notification</td>
<td>V2I</td>
</tr>
<tr>
<td>6</td>
<td>Road works warning</td>
<td>V2I</td>
</tr>
<tr>
<td>7</td>
<td>Weather conditions</td>
<td>V2I</td>
</tr>
<tr>
<td>8</td>
<td>In-vehicle signage</td>
<td>V2I</td>
</tr>
<tr>
<td>9</td>
<td>In-vehicle speed limits</td>
<td>V2I</td>
</tr>
<tr>
<td>10</td>
<td>Probe vehicle data</td>
<td>V2I</td>
</tr>
<tr>
<td>11</td>
<td>Shockwave damping</td>
<td>V2I</td>
</tr>
<tr>
<td>12</td>
<td>GLOSA / Time To Green (TTG)</td>
<td>V2I</td>
</tr>
<tr>
<td>13</td>
<td>Signal violation/Intersection safety</td>
<td>V2I</td>
</tr>
<tr>
<td>14</td>
<td>Traffic signal priority request by designated vehicles</td>
<td>V2I</td>
</tr>
</tbody>
</table>
Should autonomous vehicles be connected?
Should autonomous vehicles be connected?

- V2X: part of a vehicle Active Safety Driver Assistance System

Source: RENESAS Electronics America Inc.
Should autonomous vehicles be connected?

- Cooperative driving
  - V2X facilitates communicating planned maneuvers
    - Reduces misunderstandings about intended maneuvers: communicating intentions directly rather than having to infer them indirectly from observed actions
Should autonomous vehicles be connected?

- Cooperative perception
  - V2X provides additional sources of information beyond those that can be sensed directly by onboard sensors
    - Beyond sensor line of sight

Should autonomous vehicles be connected?

• Cooperative perception
  – V2X provides additional sources of information beyond those that can be sensed directly by onboard sensors
    ▪ Beyond sensor line of sight
    ▪ Internal vehicle characteristics
    ▪ Locations & speeds of other vehicles
  – V2X improves quality of information and reduces uncertainties
    ▪ Higher accuracy and lower noise from sensors on other vehicles
    ▪ Faster detection of changes in conditions

Challenges in connected automated driving
Challenges in connected automated driving

• Cooperative perception
  – How much information should be exchanged?
    ▪ See-through use case:
      – 5G-PPP “5G automotive vision”: 10Mbps throughput
    ▪ Google self-driving cars generate 750Mb of data per second
Challenges in connected automated driving

• Cooperative perception
  – How much information should be exchanged?
    ▪ See-through use case:
      – 5G-PPP “5G automotive vision”: 10Mbps throughput
    ▪ Alternatives to exchanging raw sensor data
      – Position and size of objects (Cooperative Observation Service)
      – Occupancy grids

  – Uncertainty of remote information: delay, errors and security
Challenges in connected automated driving

• Cooperative driving

  – Increased road capacity: higher communications load

  – Challenge: coexistence of machines & humans in scenarios where cars will have different comms & sensing capabilities

    ▪ “A Preliminary Analysis of Real-World Crashes Involving Self-Driving Vehicles”, UMTRI, Oct. 2015

      – “the current best estimate is that self-driving vehicles have a higher crash rate per million miles traveled than conventional vehicles”

      – “self-driving vehicles were not at fault in any crashes they were involved in”
Challenges in connected automated driving

- Will we be ready to (successfully) handle all use cases running simultaneously?
Challenges in connected automated driving

- Will we be ready to (successfully) handle all use cases running simultaneously?
  - 802.11p can face significant challenges

<table>
<thead>
<tr>
<th>Throughput Traffic Test Results Half-Rates on Channel 172 (Mbps) Without Channel Switch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rates</td>
</tr>
<tr>
<td>TCP</td>
</tr>
<tr>
<td>UDP</td>
</tr>
</tbody>
</table>

Source: Arada Systems LocoMate™ ASD data sheet
V2X communications for future connected & automated driving
V2X for future connected & automated driving

• Possible options
  – Optimize 802.11p (transmission parameters, advanced geo-networking, transport, etc.)
Optimize 802.11p

- Scalability is critical in vehicular networks
  - Congestion control protocols: mainly adjust transmission frequency and (sometimes) power of beacon messages

- 6Mbps (QPSK ½) has been generally used as the default data rate for beaconing in vehicular networks


- Fundamental trade-off
  - High data rates result in short packet durations, thus producing lower channel load levels and interferences for a given tx power
  - High data rates require higher tx power levels to maintain a communications range
Optimize 802.11p

• Simulation: vehicles configured with same data rate & tx power needed to achieve PDR=0.95 at Communications Range=100m

Higher data rates can reduce CBR around 20%

Reduction of CBR results in higher PDR at target distance with higher data rates

Urban street with 6 lanes, 50 veh/km/lane, 10Hz, WINNER+ B1 propagation model

Optimize 802.11p

- Vehicles running simultaneously multiple applications
Optimize 802.11p

• Vehicles running simultaneously multiple applications
  – Message Handler: SAE (Society of Automotive Engineers) J2735 DSRC Message Set Dictionary
    ▪ Considers: applications can require a different transmission frequency of beacon messages
    ▪ Ignores: each application could also require a different communication range
  – MERLIN- optiMum powER and message rate controL for multiple applications:
    ▪ Jointly considers the requirements from all the applications
    ▪ Optimization process to select the configuration of communication parameters that minimizes the channel load

M. Sepulcre, J. Gozalvez, “Power and Message Rate Control for Vehicular Networks in Multi-Application Scenarios”, under evaluation, IEEE Transactions on ITS.
Optimize 802.11p

- Vehicles running simultaneously multiple applications
  - PRESTO- PoweR and mESsage raTe cOntrol for multiple applications:
    - Computes for each application the configuration of communication parameters that satisfies its requirements
    - Combines the configurations and identifies a set of communication parameters that satisfies the requirements of all applications

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Optimize 802.11p

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Transmission power and packet transmission frequency per application

<table>
<thead>
<tr>
<th>Application 1 ((P_t=20,\text{dBm}, T_1=2,\text{Hz}))</th>
<th>20dBm</th>
<th>20dBm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application 2 ((P_t=10,\text{dBm}, T_2=3,\text{Hz}))</td>
<td>10dBm</td>
<td>10dBm</td>
</tr>
<tr>
<td>Application 3 ((P_t=6,\text{dBm}, T_3=5,\text{Hz}))</td>
<td>6dBm</td>
<td>6dBm</td>
</tr>
</tbody>
</table>

Packets transmitted per second

<table>
<thead>
<tr>
<th>Transmission power ((P_t))</th>
<th>20dBm</th>
<th>20dBm</th>
<th>10dBm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission frequency ((T))</td>
<td>2Hz</td>
<td>3Hz</td>
<td>5Hz</td>
</tr>
</tbody>
</table>

Combination process
Optimize 802.11p

- Vehicles running simultaneously multiple applications

Channel Busy Ratio (CBR): % of time that a vehicle senses the channel as busy

SAR: % of vehicles with satisfied application requirements

M. Sepulcre, J. Gozalvez, “Power and Message Rate Control for Vehicular Networks in Multi-Application Scenarios”, under evaluation, IEEE Transactions on ITS.
V2X for future connected & automated driving

- Possible options
  - Optimize 802.11p (transmission parameters, advanced geo-networking, transport, etc.)
  - Stop using IEEE 802.11p and use a new technology
Cellular V2X

• Cellular tech are being embedded into connected vehicles
  – Introduction of LTE modems in cars by most car manufacturers
    ▪ 60% cellular penetration in new light vehicles by 2021 (Strategy Analytics)
    ▪ 32% of new cellular accounts in the US in 1Q 2016 are for connected cars (Chetan Sharma Consulting)
  – Leverage on existing cellular infrastructure
    ▪ Trials completed in Finland and Netherlands using LTE to transmit C-ITS messages
Cellular V2X

- Cellular V2X or LTE-V as part of 3GPP Release 14
  - C-V2X defines two transmission modes
    - Sidelink comms with in-and out-of cellular coverage (PC5 interface)
      - Mode 3: vehicles directly communicate, but selection & management of resources done by cellular infrastructure
      - Mode 4: vehicles autonomously select and manage the radio resources without any cellular infrastructure support
  - LTE-D (3GPP Release 12)
    - Enhancements to LTE Direct PHY/MAC
    - Reuses service & app layers defined by automotive community as well as security and transport layers
  - Network communications
    - LTE Broadcast (Release 9)
Cellular V2X

- LTE-V mode 4: alternative to 802.11p
  - Superior physical layer performance
Cellular V2X

- LTE-V mode 4: network perform. depends on distributed scheduling
  - Mode 4 organizes RBs into frequency sub-channels

![Diagram showing frequency and time subframes with SCI transmission, TB transmission, and subchannel allocation.](image)
Cellular V2X

- LTE-V mode 4: Sensing-based Semi-Persistent Scheduling
Cellular V2X

- LTE-V mode 4: Sensing-based Semi-Persistent Scheduling
Cellular V2X

- LTE-V mode 4: Sensing-based Semi-Persistent Scheduling
Cellular V2X

- LTE-V mode 4: Sensing-based Semi-Persistent Scheduling

Possible for each packet to be transmitted twice

- If 1\textsuperscript{st} copy is transmitted in sub-frame $SF \Rightarrow 2\textsuperscript{nd}$ copy transmitted in candidate resource selected randomly within time interval $[SF-15ms; SF+15ms]$
Cellular V2X

- LTE-V mode 4 vs 802.11p
  - Highway scenario with 6 lanes & 120 vehicles/km
  - Beacon packets every 100ms, 6Mbps data rate, 23dBm tx power

![Graph showing PDR vs Distance Tx-Rx (m) for 802.11p and LTE-V]
Cellular V2X

- LTE-V mode 4: there is room for improvement
  - Beacon packets every 100ms, 6Mbps data rate, 23dBm tx power

Percentage of TBs incorrectly received per type of transmission error as a function of the distance between transmitter and receiver

Cellular V2X

- Support of autonomous driving with LTE-V mode 4
  - Beacon packets transmitted every 100ms for connected vehicles

Highway with 6 lanes, 120 vehicles/km, 6Mbps bit rate, 23dBm tx power
Cellular V2X

- Support of autonomous driving with LTE-V mode 4
  - Beacon packets transmitted every 100ms for connected vehicles
  - Automated driving applications: packets every 20ms or 50ms

Highway with 6 lanes, 120 vehicles/km, 6Mbps bit rate, 23dBm tx power
Cellular V2X

- **Timeline**
  - C-V2X 3GPP Release 14 products ready by 2018-2019?
  - IEEE, ETSI and ISO: developed services and facilities on top PHY/MAC

- NHTSA: possible mandate of 802.11p V2V on all new light vehicles
- Average age of all light vehicles is 11.5 years on US roads and 9.73 years in the EU

Source: Huawei
V2X for future connected & automated driving

- Possible options
  - Optimize 802.11p (transmission parameters, advanced geo-networking, transport, etc.)
  - Stop using IEEE 802.11p and use a new technology
  - Use IEEE 802.11p and add new technologies
Heterogeneous V2X networks

Fundamental reason: a single technology cannot satisfy all needs

- Ready for deployment
- High capacity in dense scenarios and high bandwidth
- Reliability under dense scenarios & adverse propagation conditions
- Low latency even under dense communication conditions
- Ubiquitous connectivity
- Possibility for geo-broadcast support
- Integration of security/privacy
Heterogeneous V2X networks

Practical reasons: because they will be there anyway
Heterogeneous V2V
Heterogeneous V2V

- V2V communications face significant challenges
  - Network scalability
  - High reliability levels required by cooperative driving
  - High bandwidth for cooperative perception or sensing

- Possibility to apply heterogeneous networking to V2V
  - IEEE 802.11p
  - Cellular V2X
  - Visible Light Communications
  - Mm-Wave
  - TV white space
Heterogeneous V2V for Cooperative Driving
Heterogeneous V2V: cooperative driving

- Cooperative driving requires high reliability

“Volvo's Self-Driving Program Will Have Redundancy For Everything”
IEEE Spectrum, May 2016
Heterogeneous V2V: cooperative driving

Manhattan scenario. 20 packets per second
Heterogeneous V2V: cooperative driving

- Redundancy

Manhattan scenario. 20 packets per second
Heterogeneous V2V: cooperative driving

- Het. V2V for redundant tx: exploit different characteristics
  - Propagation

Manhattan scenario. 20 packets per second
Heterogeneous V2V: cooperative driving

- Het. V2V for redundant tx: exploit different characteristics
  - Congestion & packet collisions

Random: IEEE802.11p@5.9GHz, IEEE802.11p@760MHz or WiFi @2.4GHz
Heterogeneous V2V: cooperative driving

- Het. V2V for redundant tx
  - ‘Diversity’ in medium access: LTE-V for Cellular V2X

![Graph showing PDR vs Distance Tx-Rx (m)]
Heterogeneous V2V: cooperative driving

- Het. V2V for redundant tx
  - ‘Diversity’ in medium access: LTE-V for Cellular V2X
Heterogeneous V2V: cooperative driving

- Het. V2V for redundant tx
  - 'Diversity' in medium access: LTE-V for Cellular V2X
    - 'Uncorrelated interference patterns'

![Graph showing PDR vs Distance Tx-Rx (m) for different transmission scenarios]
Heterogeneous V2V for Cooperative Sensing
Heterogeneous V2V: cooperative sensing

- Cooperative perception or sensing: exchange of sensor data
  - Requires higher bandwidth than provided by 802.11p
  - Scenario: vehicles equipped with different technologies

<table>
<thead>
<tr>
<th></th>
<th>802.11p 760MHz</th>
<th>802.11p 5.9GHz</th>
<th>WiFi 2.4GHz</th>
<th>WiFi 5.6GHz</th>
<th>TVWS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>10MHz</td>
<td>10MHz</td>
<td>20MHz</td>
<td>20MHz</td>
<td>6MHz</td>
</tr>
<tr>
<td>Power</td>
<td>20dBm 100mW</td>
<td>23dBm 200mW</td>
<td>20dBm 100mW</td>
<td>17dBm 50mW</td>
<td>20dBm 100mW</td>
</tr>
<tr>
<td>Data rate</td>
<td>18Mbps</td>
<td>27Mbps</td>
<td>54Mbps</td>
<td>54Mbps</td>
<td>7.2Mbps</td>
</tr>
<tr>
<td>MCS</td>
<td>16QAM 3/4</td>
<td>64QAM 3/4</td>
<td>64QAM 3/4</td>
<td>64-QAM 3/4</td>
<td>64-QAM 3/4</td>
</tr>
<tr>
<td>Freq.</td>
<td>0.76GHz</td>
<td>5.9GHz</td>
<td>2.4GHz</td>
<td>5.6GHz</td>
<td>0.46GHz</td>
</tr>
</tbody>
</table>
Heterogeneous V2V: cooperative sensing

- Cooperative perception or sensing: exchange of sensor data
  - Requires higher bandwidth than provided by 802.11p
  - Scenario: vehicles equipped with different technologies
    - Can transmit using one, but can receive on all

Which technology should each vehicle use to transmit?
Heterogeneous V2V: cooperative sensing

- CARHet: Heterogeneous V2V alg. for cooperative perception
  - Local decisions at each vehicle
    - Identifies comms. technologies that satisfy application requirements
    - Selects the one that minimizes the maximum channel load experienced by any neighbor
  - Proposal to extend the Collective Observation Service
    - Vehicles periodically share information about their communications context conditions
  - Risk of instability (constant changes of selected technologies)
Heterogeneous V2V: cooperative sensing

- **CARHet**: Heterogeneous V2V alg. for cooperative perception
  - Highway with traffic density of 20 veh/km/lane (80 veh/km)
  - Application requirements: 1Mbps, 40m

**CBR (Channel Busy Ratio): metric for channel load**
Heterogeneous V2V: cooperative sensing

- CARHet: Heterogeneous V2V alg. for cooperative perception
  - Highway with traffic density of 20 veh/km/lane (80 veh/km)
  - Application requirements: 1Mbps, 40m
Heterogeneous V2V: cooperative sensing

- Tx. of raw sensor data (autonomous driving): high bandwidth
  - mmWave technologies above 30GHz
  - Challenge 1: mmWave beam alignment & tracking in high mobility
    - Brute force: test all possible transmit and receive beams sequentially
      - high overhead
  - Use 802.11p data for mmWave communication link configuration
    - Obtain relative position of neighboring vehicles

Heterogeneous V2V: cooperative sensing

- Tx. of raw sensor data (autonomous driving): high bandwidth
  - mmWave technologies above 30GHz
  - Challenge 2: scheduling of transmissions

A needs to schedule a message to its mmWave neighbors
Heterogeneous V2V: cooperative sensing

- Tx. of raw sensor data (autonomous driving): high bandwidth
  - mmWave technologies above 30GHz
  - Challenge 2: scheduling of transmissions

A needs to schedule a message to its mmWave neighbors

H needs to schedule a message to its mmWave neighbors

Beacon interval < 1024ms

F cannot communicate with A and H at the same time

E does not participate in H scheduling
Heterogeneous V2V: cooperative sensing

- Tx. of raw sensor data (autonomous driving): high bandwidth
  - mmWave technologies above 30GHz
  - Challenge 2: scheduling of transmissions

Use 802.11p to support scheduling: low frequency control plane with omnidirectional transmissions
Thank you for your attention!

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