Radio Access for Future 5G Vehicular Networks

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Objective

To compare the performance of different technologies for radio access in actual and future vehicular networks
Outline

• **Context and Motivation**
  – Connected and autonomous vehicles
  – Cooperative awareness
  – Actual and future requirements

• **Enabling technologies**
  – IEEE 802.11p/ITS G5
  – LTE
  – LTE-V2X
  – Modifications to LTE-V2X toward 5G

• **Performance evaluation**
  – Resource allocation for cooperative awareness
  – Scenario and Output metrics
  – Results

• **Conclusion**
Context and Motivation
Where we are

Audi A8 Sedan first production **level 3 autonomous car** in 2018

Level 3 of autonomy: Driver shifts safety critical function to the vehicle under certain traffic or environmental conditions

**No connectivity on board**
Where we are going

• **Fully autonomous vehicles** (level 5)
  • A vehicle needs to see the surroundings and share information and intentions
  • Need convergence between connected and autonomous cars
Where we are going

- **Fully autonomous vehicles**
  - A vehicle needs to see the surroundings and share information and intentions
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- New **challenging applications** such as virtual traffic light or see through technology to:
  - Improve road **safety**
    - about 1.25 million people die each year as a result of road traffic crashes. Safety applications enabled by connected vehicles could eliminate or mitigate the severity of up to 80 percent of crashes. *Source: NHTSA*
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  • Improve road **safety**
    • about 1.25 million people die each year as a result of road traffic crashes. Safety applications enabled by connected vehicles could eliminate or mitigate the severity of up to 80 percent of crashes. [Source: NHTSA]
  • Improve **traffic management** and reduce pollution
    • Over 70% of transport greenhouse gas emissions, 39% of NOx and 13% of particulate matter
    • Annual delay per peak period: 47 hours
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  • Improve **traffic management** and reduce pollution
    • Over 70% of transport greenhouse gas emissions, 39% of NOx and 13% of particulate matter
    • Annual delay per peak period: 47 hours
  • Introduce **entertainment**
    • Internet access and Internet backbone
Awareness at the base of future apps

• Future applications made possible thanks to
  • Vehicle-to-everything (V2X) \[ \{ \text{Vehicle-to-vehicle (V2V)} \quad \text{communications} \] \[ \text{Vehicle-to-infrastructure (V2I)} \}

• Future (especially safety) applications are based on the awareness of the environment
Awareness at the base of future apps

- Future applications made possible thanks to
  - **Vehicle-to-everything (V2X)**
  - **Vehicle-to-vehicle (V2V)**
  - **Vehicle-to-infrastructure (V2I)**

- Future (especially safety) applications are based on the awareness of the environment

- **Focus on Cooperative Awareness service**
  - Enabled by the exchange of small packets (called beacons or CAMs) among vehicles
  - Beacons exchange provides a frequently updated awareness of the environment (neighborhood)
  - Allows coordinated operations
Requirements

**Actual requirements (before 5G)** – *ETSI, 3GPP, IEEE, NHTSA, ...*

- Periodic broadcast of beacon messages every 1-10 Hz
  - Beacons are typically small packets of ~100-500 bytes
- Latency lower than ~100 ms
- 90% of reception success within ~100-300m

**Future requirements (5G)** – *METIS, 5GAA, ...*

- Adaptive beaconing?
  - Beacon frequency adapted to the reliability of the app and to the channel load
- Latency lower than 5 ms (e.g., 1ms for platooning)
- 99% of reliability
- High data rate (e.g., exchange of video captured onboard for see through)
Enabling technologies
V2X Enabling Technologies

- **WAVE/IEEE 802.11p in USA and ETSI ITS G5 in EU**
- Widely tested and commercial devices available
- Fully distributed
- Reliability: random access is prone to collisions
- Unclear business model
- Not diffused

5G
- Still to be clearly defined
- Very high performance

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- **LTE-V2X, defined in the Release 14 of 3GPP**
  - Exploitation of existing infrastructure/system
  - Standardized in June 2017
  - Sketches the road to 5G vehicular networks
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- **LTE, Releases 8 and 9**
  - For V2I and I2V communications
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- **5G**
  - Integration of flexible and reconfigurable interfaces
  - Still to be clearly defined (among the candidate access technologies, OFDMA, SC-FDMA, NOMA)

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LTE PHY and MAC

Release 8 and 9 (LTE-V2I): OFDM at PHY, OFDMA in the downlink and SC-FDMA at MAC
**LTE PHY and MAC**

**Release 14:** OFDM at PHY, SC-FDMA at MAC, based on device-to-device (D2D) communication introduced in Release 12 and improved to work in high mobility scenarios.

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**LTE-V2V (Release 14)**

- 12 subcarriers (12 x 15 kHz)
- Resource Block (RB)
- OFDM symbols
- 4 DMRS
- Tx-Rx switch and timing adjustment
- 2 RBs

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**Graphical Representation:**

- Time slot (0.5 ms)
- Subframe (1 ms)
- Frame (10 ms)
LTE and beyond for cooperative awareness

Comparison of:

- **LTE-V2I (Release 8)**
  - Each vehicle sends beacons in uplink; the network retransmits a copy to all the vehicles in the awareness range (bottleneck in the downlink)

- **LTE-V2I with eMBMS (Release 9)**
  - Each vehicle sends beacons in uplink; the network retransmits to all the vehicles in the cell (bottleneck in the uplink, lower tx power)

- **LTE-V2V (Release 14)**
  - Direct V2V communication (limit given by the number of subframe per beacon period)

- **LTE-V2V with short subframe (5G feature)**
  - Duration of a subframe halved (double the max number of communicating vehicles)

- **LTE-V2V with Full Duplex (FD) (5G feature)**
  - FD allows to transmit and receive at the same time on the same subframe (resources increases)
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Performance evaluation
Scenario

- **Highway road**
  - Covered by a single cell of radius $r_c$
  - Poisson distribution of vehicles with density $\rho$
  - Each vehicle tx a beacon of $B$ byte every $f_B$ Hz

- **Application: Cooperative Awareness**

- **Analytical model**
Output metrics and evaluation

- **Success probability** of the allocation, \( P_s \)

- **Efficiency**
  \[
  \eta = \frac{P_s \cdot N_U}{N_R}
  \]
  - average number of users in the cell
  - number of resources (maximum dedicated resource blocks per frame)
Output metrics and evaluation

- **Success probability** of the allocation, $P_s$
  - LTE-V2I unicast
    - Probability that resources are enough to allocate all the copies of the beacons to be forwarded in downlink
    
    $P_{S-V2I-u} = 1 - F_P \left( \left[ \sqrt{\frac{r_c}{r_{aw}}} \right] n_{DL-V2I}, \rho, 2r_c \right)$

  - LTE-V2I with eMBMS
    - Probability that resources are enough to allocate the beacons to be collected from all vehicles in uplink
    
    $P_{S-V2I-b} = 1 - F_P (n_{UL-V2I}, \rho, 2r_c)$

  - LTE-V2V
    - Probability that the allocation succeeds without any blocked vehicle
    
    $P_{S-V2V} = \left[ 1 - F_P \left( \left\lfloor \frac{n_{V2V}}{r_{reuse}} \right\rfloor, \rho, r_{reuse} \right) \right] \left\lfloor \frac{2r_c}{r_{reuse}} \right\rfloor$

  - LTE-V2V with short subframe

  - LTE-V2V with Full Duplex (FD)

- **Efficiency**

  $\eta = \frac{P_s \cdot N_U}{N_R}$

  - Average number of users in the cell
  - Number of resources (maximum dedicated resource blocks per frame)

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## Settings

<table>
<thead>
<tr>
<th>Parameter (Symbol)</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Common</strong></td>
<td></td>
</tr>
<tr>
<td>Number of RBs dedicated to the service per frame ($N_R$)</td>
<td>408</td>
</tr>
<tr>
<td>Beacon frequency ($f_B$)</td>
<td>10 Hz</td>
</tr>
<tr>
<td>Beacon size ($B$)</td>
<td>100</td>
</tr>
<tr>
<td>Equivalent radiated power</td>
<td>Vehciles: 23 dBm</td>
</tr>
<tr>
<td></td>
<td>e-NodeB: 33 dBm</td>
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<tr>
<td>Antenna gain at the receiver</td>
<td>3 dB</td>
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<tr>
<td>Path loss at 1 m at 5.9 GHz</td>
<td>47.86 dB</td>
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<tr>
<td>Loss exponent</td>
<td>2.75</td>
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<tr>
<td>Noise power over an RB</td>
<td>Vehciles: -110 dBm</td>
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<tr>
<td></td>
<td>e-NodeB: -115 dBm</td>
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<tr>
<td>Cell range ($r_c$)</td>
<td>500 m</td>
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<td><strong>V2I unicast</strong></td>
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<tr>
<td>MCS (downlink)</td>
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</tr>
<tr>
<td>Modulation</td>
<td>16-QAM</td>
</tr>
<tr>
<td>Coding rate</td>
<td>0.56</td>
</tr>
<tr>
<td>Maximum beacons per beacon period in downlink ($n_{DL-V2I}$)</td>
<td>340</td>
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<tr>
<td><strong>V2I broadcast</strong></td>
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<tr>
<td>MCS (downlink)</td>
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<tr>
<td>Modulation</td>
<td>16-QAM</td>
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<tr>
<td>Coding rate</td>
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<tr>
<td>Maximum beacons per beacon period in uplink ($n_{UL-V2I}$)</td>
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<tr>
<td><strong>V2V with half duration subframe</strong></td>
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<td>MCS (downlink)</td>
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<tr>
<td>Modulation</td>
<td>16-QAM</td>
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<tr>
<td>Coding rate</td>
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<tr>
<td>Maximum beacons per beacon period in uplink ($n_{V2-Vshf}$)</td>
<td>200</td>
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<tr>
<td>Reuse distance</td>
<td>246 m</td>
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<tr>
<td><strong>V2V with FD radios</strong></td>
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<tr>
<td>Self interference cancellation (FD)</td>
<td>-110 dB</td>
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<tr>
<td>MCS (downlink)</td>
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<tr>
<td>Modulation</td>
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<tr>
<td>Coding distance</td>
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<tr>
<td>Maximum beacons per beacon period in uplink ($n_{V2V-FD}$)</td>
<td>250</td>
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<tr>
<td>Reuse range</td>
<td>287 m</td>
</tr>
</tbody>
</table>

*Details in the paper*...
Results: success probability
Results: success probability

Example: with 3+3 lanes:
- $\rho=0.2$ corresponds to $\sim33$ vehicles/lane/km (high density)
- $\rho=0.05$ corresponds to $\sim8$ vehicles/lane/km (fluent traffic)
Results: efficiency

\[ \eta = \frac{P_S \cdot N_U}{N_R} \]
Results: efficiency

Example: with 3+3 lanes:
- $\rho=0.2$ corresponds to ~33 vehicles/lane/km (high density)
- $\rho=0.05$ corresponds to ~8 vehicles/lane/km (fluent traffic)

$$\eta = \frac{P_S \cdot N_U}{N_R}$$
Conclusion

• LTE-V2X opened the road to 5G vehicular networks
• In 2019/2020 V2X connectivity mandatory on board in EU and USA
  – Should we wait for 5G or cover the gap with IEEE 802.11p and LTE-V2X?
  – Which technology will be on board in the short term? IEEE 802.11p or LTE-V2X?
• Simulations in realistic scenarios with LTEV2Vsim (Available at: http://www.wcsg.ieiit.cnr.it/products/LTEV2Vsim.html) in:

Thank you for the attention!

Q&A