V2X Communications for CCAM – Statuts and Future Trends and Challenges

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What is EURECOM?

- A consortium with a private status (EIG) that brings together:
  - 8 Universities: Politecnico di Torino ITALY, Aalto FINLAND, TUM GERMANY, NTNU NORWAY, Chalmers SWEDEN, CTU CZECH REPUBLIC, TU Wien, AUSTRIA
  - 6 International Companies: Orange, STMicroelectronics, SAP, BMW Group, Symantec, IABG Munich
  - The Government of Monaco

- A strong French-German relationship (Munich)
  - TUM, BMW, IABG, SAP, DLR, SIEMENS

- Three Departments:
  - Digital Security
  - Data Science.
  - Communication Systems
Related Books and References

http://www.amazon.co.uk/dp/1107046718


http://link.springer.com/book/10.1007/978-3-319-15497-8
Part I

INTRODUCTION TO C-ITS
V2X Communication – Back to the Future !!

- GM Futurama - 1939

https://www.youtube.com/watch?v=alu6DTbYnog (time code: 14:27)
From the early steps to current achievements

- Visionary aspect: GM Futurama in 1939 and 1964 !!

  - Deployment stopped due to expensive roadside infrastructure

- 1973-1979: Comprehensible Automobile Traffic Control (CACS) – Japan


- 1997: Cooperative autonomous driving demo: PATH, USA

- From the mid 1990:
  - Game Changer: 5.9 DSRC – 802.11p, later known as IEEE 802.11-2012 OCB / ITS G5
In 1994, the US Federal Communication Commission (FCC) allocated a 16 MHz band (unlicensed) at 902 MHz for ETC called Dedicated Short Range Communication (DSRC)

- In Europe, DSRC has been introduced solely for ETC at 5.8 GHz

In 1999, the FCC allocated a second DSRC frequency band at 5.9 GHz to be used specifically for inter-vehicular communication.

- **Primary Application:**
  - Saving lives by avoiding accident
  - Saving money by reducing traffic congestion

- **Secondary Application:**
  - Comfort (infotainment) application to ease the early deployment of this technology.

Since 2001 Japan has developed, implemented and deployed DSRC applications under the name ARIB STD T-75 & 88.

The European Commission allocated a 30 MHz frequency band at 5.9 GHz for safety applications in **August 2008**
Non-exhaustive Overview of Projects

- **C2C-CC** (2001)
- **SeVeCom** (2006-2008)
- **PreVent/WILL WARN** (2005-2008)
- **Coopers/CVI S/SAFESPOT** (2006-2010)
- **PreDrive** (2008-2010)
- **SIM-TD** (2008-2012)
- **Drive** (2011-2014)

- **Chauffeur I and II** (1996-2003)
- **FleetNet** (2000-2003)
- **NoW** (2004-2007)

- **FleetNet** (2000-2003)
- **NoW** (2004-2007)
- **PreDrive** (2008-2010)
- **SIM-TD** (2008-2012)
- **Drive** (2011-2014)

- **ASV II** (1996-2000)
- **ASV III** (2001-2005)
- **ASV VI** (2006-2010)

- **PATH** (1986)
- **IVI** (1998-2004)
- **VII / IntelliDrive** (2004-2009)

- **DSRC** (1999)
- **WAVE** (2004)
- **V2V Decision** (2013)

- **ITS Strategic Research Plan,** (2010-2014)

ETSI Technical Committee on ITS

Applications
- Road Safety
- Traffic Efficiency
- Value-Added Services

Facilities
- Application Support
- Information Support
- Session Support

Transport & Network
- ITS Transport
- Geo-Routing
- TCP/UDP
- Other Protocols
- Ipv6 + Mobility

Access Technologies
- ITS G5 A/B

Applications
- Active Road Safety
  - Cooperative awareness
  - Hazard warning
- Cooperative Traffic Efficiency
  - Adaptive speed management
  - Cooperative navigation

Technology
- DSRC
  - IEEE 802.11 for vehicular environment
  - a.k.a: 802.11p, ITS-G5

Source: C2C-CC
Objective: Highly Autonomous Driving

- Not such a new idea

- A very marketized idea

- …yet a very ambitious idea
Objective: Vulnerable Road Users

- V2X not only between Vehicles
- V2X connects to wearable devices
- V2X is part of the Internet-of-things (IoT)
Part II

OVERVIEW OF KEY ETSI STANDARDS
ETSI Communication Architecture

- Applications are standardized by ETSI TC WG1 & CEN
- Facilities is handled by ETSI TC WG1
- Network & Transport is done in ETSI TC WG3
- Access is specified by ETSI TC WG4
- Management & Cross-Layer is handled by ETSI WG 2
- Security is specified by ETSI TC WG5
ETSI ITS Access - ITS-G5 (EN 302 663, EN 302 571, TS 102 724)

- **EN 302 571**
  - Harmonized Standard for Radio-communications equipment operating in the 5 855 MHz to 5 925 MHz frequency band;

- **EN 302 663**
  - Access layer specification for Intelligent Transport Systems operating in the 5 GHz frequency band

- **TS 102 724**
  - Harmonized Channel Specifications for Intelligent Transport Systems operating in the 5 GHz frequency band

<table>
<thead>
<tr>
<th>Name</th>
<th>Center Frequency</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCH6</td>
<td>5920</td>
<td>ITS-G5D - Future ITS</td>
</tr>
<tr>
<td>SCH5</td>
<td>5910</td>
<td></td>
</tr>
<tr>
<td>SCH4</td>
<td>5860</td>
<td>ITS-G5B - Non-Safety related</td>
</tr>
<tr>
<td>SCH3</td>
<td>5870</td>
<td></td>
</tr>
<tr>
<td>SCH2</td>
<td>5880</td>
<td></td>
</tr>
<tr>
<td>SCH1</td>
<td>5890</td>
<td>ITS-G5A - Safety-Related</td>
</tr>
<tr>
<td>CCH</td>
<td>5900</td>
<td>Missing: ITS-G5C @ 5470 – 5710MHz - RLAN (EN 301 893)</td>
</tr>
</tbody>
</table>
**ETSI Harmonized Standard for Radio-communications in 5 GHZ (EN 302 571)**

- **European Norm –**
  - EU-level enforcement

<table>
<thead>
<tr>
<th>National transposition dates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date of adoption of this EN:</td>
</tr>
<tr>
<td>Date of latest announcement of this EN (doa):</td>
</tr>
<tr>
<td>Date of latest publication of new National Standard or endorsement of this EN (dope):</td>
</tr>
<tr>
<td>Date of withdrawal of any conflicting National Standard (dow):</td>
</tr>
</tbody>
</table>

- **EN 302 571 – Provides the Highest Level Specifications for accessing 5GHz bands**
  - **Technical Specifications:**
    - Spectrum Access Rights (Safety/non-safety)
    - Spectrum protection –
      - Maximum TX power
      - Out-of-Band emission
    - Coexistence between different technologies
    - Receiver Sensitivity
    - Distributed Congestion Control requirements
  - **Bound by Law**
    - IEEE 802.11-2016 is just an industry standard…
ETSII Profile Standard for ITS-G5 (EN 302 663)

- European Norm –
  - EU-level enforcement

- EN 302 663 - Access layer specification for Intelligent Transport Systems operating in the 5 GHz frequency band
  - Provides the access bands (ITS-G5A/B/C/D)
  - Provides the PHY/MAC specifications for ITS-G5 (so far)
  - Provides either specification or restrictions from EEE 802.11-2016
    - Example:
      - IEEE 820.11-2016 OCB only
      - PHY and MAC parameters

<table>
<thead>
<tr>
<th>Frequency range [MHz]</th>
<th>Usage</th>
<th>Regulation</th>
<th>Harmonized standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITS-G5D</td>
<td>5.905 to 5.925 Future ITS applications</td>
<td>ECC Decision ECC/DEC(02)01 [i.4]</td>
<td>EN 302 571 [1]</td>
</tr>
<tr>
<td>ITS-G5B</td>
<td>5.855 to 5.875 ITS non-safety applications</td>
<td>ECC Recommendation ECC/REC((08))01 [i.2]</td>
<td>EN 302 571 [1]</td>
</tr>
<tr>
<td>ITS-G5C</td>
<td>5.470 to 5.725 RLAN (BRAN, WLAN)</td>
<td>ERC Decision ERC/DEC(99)23 [i.3] and Commission Decisions 2005/513/EC [i.5] and 2007/90/EC [i.6]</td>
<td>EN 301 893 [i.14]</td>
</tr>
</tbody>
</table>
ETSI Facilities Layer – Main Topics

- **ETSI Basic Set of Applications** (TR 102 638, TS 102 637-1)
  - Users & Applications functional requirements
  - Common data dictionary (TS 102 894)

- **Local Dynamic Map (LDM)** (EN 302 895, TR 102 863)
  - Geographic data base of all ITS-related information (i.e. the brain)

- **Common Awareness Message (CAM)** (EN 302 637-2, TS 101 539-1)
  - Periodic broadcast message of a node’s status information, including position, heading, speed, and other traffic relevant information.
  - Some inputs are similar to Geonet header
    - Could lead to doubling information

- **Decentralised Environmental Notification Message (DENM)** (EN 302 637-3)
  - Event triggered broadcast message that includes a description of the triggering event and its duration
ETSI Facilities Layer – DAY ONE Applications

- **Road Hazard Signaling (TS 101 539-1)**
  - Emergency vehicle approaching, slow vehicle, stationary vehicle, emergency electronic brake lights, wrong way driving, adverse weather condition, hazardous location, traffic condition, road work, People on the road.

- **Intersection Collision Risk Warning Specification (TS 101 539-2)**
  - Traffic signal violation warning, monitoring of vehicle trajectories at road crossings (data from CAM).

- **Longitudinal Collision Risk Warning Specification (TS 101 539-3)**
  - **Forward collision:**
    - Dangerous lane change, emergency braking, road work, stationary vehicle, vehicle out of control.
  - **Frontal collision:**
    - Wrong way driving, dangerous overtaking, vehicle out of control.
  - Accounts for car types/abilities, speed, distance, weather, and driver intentions (e.g. overtake, turn...).

- **Electric Vehicle Charging Spot Notification Specification (TS 101 556-1)**
  - Automatic booking of charging spots for electric vehicles
ETSI Facilities Layer – DAY TWO Applications

- C-ACC Pre-standardization study (TR 103 299)
  - Early discussion of the definition, scenario and KPI of C-ACC
- Platooning pre-standardization study (TR 103 298)
  - Early discussion of the definition, scenario and KPI of Platooning
- Cooperative Vulnerable Road Users (VRU) (TR 103 300)
  - Early discussion of the definition, scenario and KPI of Vulnerable Road Users
- Multimedia Content Dissemination Basic Service specification (TS 103 152)
  - V2X exchange of multimedia information comprising video, audio, images and data.

- Collective Perception Service (TS 103 324)
  - Aims at sharing information about the current driving environment with other ITS-Ss.
- Facilities layer protocols and communication requirements for infrastructure services (TS 103 301)
  - In Vehicle Information (IVI)
  - Traffic Light Control
- Facility Position and Time (POTI) (TS 102 890-2)
  - Transmit time and raw position data between vehicle according to functional requirements
- Facilities Service Announcement (TS 102 890-1)
  - Service Announcement Message (SAM)
- Maneuver Coordination Service (TS 103 561)
  - Interaction protocol and corresponding messages to coordinate maneuvers between two or more vehicles
- Diagnose, Status and Logging Service (TS 103 693)
  - Information exchange between ITS-S related to maintenance of ITS-S
Part II

WIFI-BASED V2X COMMUNICATIONS
**Frequency Allocation**

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>5.7</th>
<th>5.75</th>
<th>5.8</th>
<th>5.85</th>
<th>5.9</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ISM</strong></td>
<td></td>
<td></td>
<td></td>
<td>5.725</td>
<td></td>
</tr>
<tr>
<td><strong>Allocated in 1999</strong></td>
<td></td>
<td></td>
<td></td>
<td>5.855</td>
<td>5.925</td>
</tr>
<tr>
<td><strong>Allocated in August 2008</strong></td>
<td></td>
<td></td>
<td></td>
<td>5.795</td>
<td>5.815</td>
</tr>
<tr>
<td><strong>Allocated in 2001</strong></td>
<td></td>
<td></td>
<td></td>
<td>5.77</td>
<td>5.85</td>
</tr>
</tbody>
</table>

- **DSRC** range: 0.902 to 0.928 GHz
- **WAVE** range: 5.725 to 5.905 GHz

Critical safety bands:
- **Japan**: 0.715 to 0.725 GHz
- **Allocated in 2001**
- **EU**: 5.77 to 5.85 GHz
- **Allocated in 2001**
Three Frequency Bands in 5 GHz Band

RLAN bands (U-NII2, WLAN, BRAN, HiperLAN2)

<table>
<thead>
<tr>
<th>RLAN Bands – ITS</th>
<th>ITS non safety</th>
<th>ITS Safety</th>
<th>F-ITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.50</td>
<td>5.855</td>
<td>5.905</td>
<td>5.925 GHz</td>
</tr>
<tr>
<td>5.7</td>
<td>5.875</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power: 1W EIRP</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ITS G5 C
Shared Spectrum
Dynamic Channel Selection & Power Control

EIRP : Effective Isotropic Radiated Power

Dedicated ITS bands

ITS non-safety

ITS safety

Future ITS

Bandwidth: 10Mhz

<table>
<thead>
<tr>
<th>SCH4</th>
<th>SCH3</th>
<th>SCH1</th>
<th>SCH2</th>
<th>CCH</th>
<th>SCH</th>
<th>SCH</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.855</td>
<td>5.865</td>
<td>5.875</td>
<td>5.885</td>
<td>5.895</td>
<td>5.905</td>
<td>5.915</td>
</tr>
</tbody>
</table>

SCH – ITS Service Channel
CCH – ITS Control Channel

Power: 2W CCH & SCH1; 200MW SCH2 & 3; 1mW SCH4

New since 2020: discussions on Coexistence between ITS-G5/C-V2X
New since 2020: Urban Rail (or: C-V2X exclusive..)

ITS G5 A
ITS Dedicated Spectrum
ITS G5 B
ITS Dedicated Spectrum
ITS G5 D
Future Usage
Forming a Wireless Network: Architecture

- **Basic Service Set (BSS)**
  - A station must join a BSS and an AP before being allowed to communicate

- **Communicating Outside of the Context of a BSS**
  - Vehicular-specific extension of the IEEE 802.11 not requiring a BSS to communicate
IEEE 802.11 Distributed Coordination Function (DCF)

- **Listen before Talk Principle**
  - If medium is free for a DIFS time, station sends data or control packet
  - Receivers acknowledge at once (after waiting for SIFS) if the packet was received correctly (CRC)
  - Automatic retransmission of data packets in case of transmission errors

- **Contention-based Access**
  - Contend for the channel access, back-off if you lose
EDCA Parameter Results – DSRC/ITS-G5 OCB

- The IEEE EDCA is modified to improve the prioritization of messages

- **IEEE 802.11e EDCA**

- **DSRC/ITS-G5 EDCA**

<table>
<thead>
<tr>
<th>Category</th>
<th>Slots</th>
<th>Wait</th>
<th>Assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voice</td>
<td>2 slots</td>
<td>0 ~ 7 slots</td>
<td>Assumptions: Default Parameters</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Backoff values shown are for initial CW equal to CWmin = 31</td>
</tr>
<tr>
<td>Video</td>
<td>2 slots</td>
<td>0 ~ 15 slots</td>
<td>Assumptions: Default Parameters</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Backoff values shown are for initial CW equal to CWmin = 31</td>
</tr>
<tr>
<td>Best Effort</td>
<td>3 slots</td>
<td>0 ~ 31 slots</td>
<td>Assumptions: Default Parameters</td>
</tr>
<tr>
<td>Background</td>
<td>7 slots</td>
<td>0 ~ 31 slots</td>
<td>Assumptions: Backoff values shown are for initial CW equal to CWmin = 31</td>
</tr>
<tr>
<td>Emergency DENM</td>
<td>2 slots</td>
<td>0 ~ 3 slots</td>
<td>Assumptions: Default Parameters</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Backoff values shown are for initial CW equal to CWmin = 31</td>
</tr>
<tr>
<td>High Priority DENM</td>
<td>3 slots</td>
<td>0 ~ 3 slots</td>
<td>Assumptions: Backoff values shown are for initial CW equal to CWmin = 15</td>
</tr>
<tr>
<td>CAM</td>
<td>6 slots</td>
<td>0 ~ 7 slots</td>
<td>Assumptions: Default Parameters</td>
</tr>
<tr>
<td>Other Traffic</td>
<td>9 slots</td>
<td>0 ~ 15 slots</td>
<td>Assumptions: Default Parameters</td>
</tr>
</tbody>
</table>

IEEE 802.11e EDCA and DSRC/ITS-G5 EDCA are used to improve the prioritization of messages in CCAM. The diagrams illustrate the different categories (Voice, Video, Best Effort, Background, Emergency DENM, High Priority DENM, CAM, Other Traffic) and their respective slots and wait times. Assumptions include default parameters and backoff values based on initial CW values.
DSRC/ITS-G5 Channel Characterization

- How does the channel characteristic at 5.9 GHz for 802.11p look like?

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delay spread</td>
<td>~ 0.8 µs</td>
</tr>
<tr>
<td>Coherence Bandwidth</td>
<td>~ 1.25 MHz</td>
</tr>
<tr>
<td>Coherence Time</td>
<td>~ 1.02 ms</td>
</tr>
<tr>
<td>Doppler spread</td>
<td>~ 2 kHz</td>
</tr>
</tbody>
</table>


- What does it tell us?
  - We have a time- and frequency-selective channel
  - We have a doppler spread which needs to be considered

- Actions:
  - We have to use narrow-band communication to mitigate frequency-selective channel
  - We have to make sure that successive OFDM symbols are sufficiently separated in time to avoid ISI
  - We have to make sure that the 52 OFDM sub-carriers are have an inter-carrier distance of at least 2 kHz to avoid ICI
Mitigating Inter-Symbol Interference

- OFDM introduces a guard period after each OFDM symbol to protect symbols from ISI

DSRC/ITS-G5 PHY Countermeasures

- **Mitigating Inter-Carrier Interference**
  - 802.11p OFDM uses a carrier spacing of 156.25 kHz
  - The Doppler Spread of 2 kHz is “easily” covered by this spacing.

- **Mitigating Time-selectivity (or narrowband fast fading)**
  - Problem: the channel estimation at the beginning of a packet may be invalid at the end of the packet
    - This results in an increased Bit error rate and decreased Packet reception rate
  
    Several solutions:
  - Increase data-rate to reduce transmission time below channel coherence time
  - Estimate the channel several times during the transmission
  - Use modulation schemes which overcome the channel fading, e.g. differential BPSK
Key PHY characteristics
- 5.9 GHz frequency domain
- Based on IEEE 802.11a (OFDM PHY)
- 10 MHz channel bandwidth
- Rates: 3, 4.5, 6, 9, 12, 18, 24, 27 Mbps
- Symbol time: 8µs (1.6µs guard interval + 6.4µs data symbol)

Key MAC characteristics
- EDCA QoS Provisioning
- Multi-channel Operation (1 CCH, several SCHs) (not discussed here..)
- Congestion Control (adaptive TX power, TX rate, multi-channel)

Classic 802.11 WLAN

<table>
<thead>
<tr>
<th>Synchronizing</th>
<th>DSRC/ITS-G5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scanning</td>
<td>OPTIONAL HIGHER LAYER</td>
</tr>
<tr>
<td>Authentication</td>
<td>NO Scanning</td>
</tr>
<tr>
<td>Association</td>
<td>HIGHER LAYER</td>
</tr>
<tr>
<td>Communication</td>
<td>IMPLICIT Association</td>
</tr>
</tbody>
</table>

Concept of Basic Service Sets (BSS)

"Communication outside of the context of the BSS"
Part III

CELLULAR-BASED V2X COMMUNICATIONS
Progress and Releases

- 3GPP technologies are evolving through ‘Generations’
- Progresses are measured by milestones known as ‘release’
LTE Proximity Service (ProSe)

- Evolution of Proximity Services

Convergence of Actors:
- Pedestrians
- Cars, Buses, Trains
- Any-'Wheelers'
- Your coffee machine!!

- Evolution of Proximity Technology

Convergence of Technologies:
- LTE-D2D
- WiFi-Direct
- ITS-G5
- Bluetooth
- Zigbee

Focus for Proximity Services
- Personal Area
- Local Area
- Wide Area

PAN: Bluetooth, Zigbee

Wireless LAN: IEEE 802.11, Hyperlan, WiFi-Direct

Cellular Systems: GSM, UMTS, LTE
LTE Proximity Service (ProSe) - Motivations

- **General advantages**
  - improve spectrum utilization
  - improve overall throughput and performance
  - improve energy consumption
  - enable new peer-to-peer and location-based applications and services

- **Advantages related to public safety**
  - fallback public safety networks that must function when cellular networks are not available or fail
  - closing the evolution gap of safety networks to LTE

- **Challenges and risks**
  - Business opportunity related to the long-standing cellular architecture
**LTE Proximity Services (ProSe)**

- LTE ProSe enables establishment of communication paths between two or more ProSe-enabled UEs.
  - Radical architecture change for D2D
  - Since LTE Rel.12

- LTE ProSe enables communication functions
  - One-to-One – Direct UE to UE Communication
  - One-to-Many – Communication to a ProSe group

- LTE ProSe Functions:
  - Discovery
    - Mode A – ‘I am here’
    - Mode B – ‘how is there?’
  - Direct Communication
    - Mode 1 – Coordinated by eNB
    - Mode 2 – Ad-Hoc mode

Restricted to Public Safety & V2X (rel.14)
LTE Vehicular-to-Everything (V2X)

- 2007: 3G
- 2008: 4G LTE rel.8
- 2009: 4G LTE rel.9
- 2010: 4G LTE-A rel.10
- 2011: 4G LTE-A rel.11
- 2012: 4G LTE-A rel.12
- 2013: 4G LTE-A Pro rel.13
- 2014: 4G LTE-A Pro rel.14
- 2015: 4G LTE rel.15
- 2016: 5G LTE rel.15
- 2017: 5G LTE rel.16
- 2018: Sept. 2018
- 2019: V2X Phase 1
- 2019: V2X Phase 2
- 2019: V2X Phase 3
- 2019: eV2X Phase 3

4G - 12 years development
LTE V2X Extended Architecture

- New Architecture Elements:
  - V2X Control Function – similar to Prose Function
  - PC5 interface – as D2D Prose
  - V3 interface – as PC3, but with V2X-related messages
**LTE-V2X – ‘Slidelink’ (SL) Channels**

- **Slide link channels**
  - Reduced set
    - No discovery
    - Only one-to-many

- **Slidelink Pool**
  - Modified PSCCH on same Subframe as PSSCH
    - Reduced delay

Source: Dr. Gallo, EURECOM
LTE-V2X – Distributed Scheduler

- **LTE V2X mode 3 (eNB)**
  - Dynamic or SPS scheduling allowed
  - can be different period/MCS for flexibility

- **LTE V2X mode 4 (Ad-Hoc)**
  - resource location and MCS selected autonomously
  - resources are reserved in advance (“SPS”)
  - control-data in the same subframe (Reduced latency)

- **LTE V2X mode 4 Resource Allocation**
  - 1s monitoring windows
  - Selection of the 20% RB with lowest RSSI
  - Exclude any reserved resources
Cellular LTE-V2X – Standardization Status

- **3GPP specification freeze in July 2017**
- **In January 2017, the CAR 2 CAR initiated a WI on LTE-V2X**
- **Objectives:**
  - Introduce new concepts behind LTE-V2X
  - Define common scenarios and parameters
  - Identify required architecture extension
  - Gather open challenges
- **In October 2017, Cellular Stakeholders proposed multiple WI to ETSI ITS for LTE-V2X**
  - C-V2X is expected to be integrated in ETSI ITS in 2018
  - **Access Technology** -
    - LTE-V2X mode 3-4 rel.14 on PC5 for V2V
    - LTE-V2X on Uu for V2I/V2N communication
**LTE-V2X vs. ITS-G5 – Comparison**

### Link-level vs. Packet-level Comparisons

- **Source:** J. Kenney et al., ITS-World Congress 2016


**Disclaimer:** Not meant to advocate one technology over another, but rather to emphasize the complexity of their comparison and true performance.
**LTE-V2X vs. ITS-G5 – Comparison**

- **Need to compare an apple with an apple**
  - ITS-G5 is not only IEEE 802.11p (a.k.a old technology)
    - Improved channel tracking has been developed (e.g. NXP)

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**Source:** A. Turley, K. Moeman, A. Filippi, V. Martinez, C-ITS: Three observations on LTE-V2X and ETSI ITS-G5—A comparison, NXP White Paper

**Source:** A Bazzi, et al., Co-channel Coexistence: Let ITS-G5 and Sidelink C-V2X Make Peace, 2020
Time for a Break…

Meet again in 15 minutes
Part IV

COEXISTENCE AND REGULATIONS
Coexistence with ITS-G5 – Spectrum issue..

- EU imposes a Technology Neutrality approach to ITS-G5 spectrum
  - Both ITS-G5 and LTE-V2X can use ITS-G5-A spectrum if safety-related
  - Also increasing interest from WiFi (IEEE 802.11ac/ax) on the lower ITS-G5 band
  - …and LTE-U, resp. NR-U for Private 5G networks
Coexistence ITS-G5 – LTE-V2X – Problem Statement

- Typical Use Case

Solid red/green A/B block can be either:
- different cars (stationary view)
- or same car at different times (dynamic view)

- Potential Coexistence in Time Domain

Source: ETSI, TR 103 766
Coexistence ITS-G5 – LTE-V2X – Problem Statement

- The last symbol gap problem

Source: ETSI, TR 103 766
Coexistence ITS-G5 – LTE-V2X – Problem Statement

- The last symbol gap problem

Reminder: ITS-G5 EDCA values

<table>
<thead>
<tr>
<th>AC</th>
<th>(CW_{\text{min}})</th>
<th>(CW_{\text{max}})</th>
<th>AIFS</th>
<th>Intended use</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC VO</td>
<td>3</td>
<td>7</td>
<td>58 µs</td>
<td>High priority DENM</td>
</tr>
<tr>
<td>AC VI</td>
<td>7</td>
<td>15</td>
<td>71 µs</td>
<td>DENM</td>
</tr>
<tr>
<td>AC BE</td>
<td>15</td>
<td>1 023</td>
<td>110 µs</td>
<td>CAM</td>
</tr>
<tr>
<td>AC BK</td>
<td>15</td>
<td>1 023</td>
<td>149 µs</td>
<td>others</td>
</tr>
</tbody>
</table>

Source: ETSI, TR 103 766
Coexistence ITS-G5 – LTE-V2X – Problem Statement

- The last symbol gap problem

<table>
<thead>
<tr>
<th>AC</th>
<th>CW</th>
<th>AIFS*</th>
<th>Possible duration of the inner state machine*</th>
<th>Gap problem occurrence chances*</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC_VO</td>
<td>3</td>
<td>58 µs</td>
<td>([0, 1, 2, 3] \text{ CW} = [0, 13 \mu s, 26 \mu s, 39 \mu s])</td>
<td>50% (2 chances out of 4)</td>
</tr>
<tr>
<td>AC_VI</td>
<td>7</td>
<td>71 µs</td>
<td>([0, 1, 2 \ldots 7] \text{ CW} = [0, 13 \mu s, 26 \mu s \ldots])</td>
<td>12.5% (1 chance out of 8)</td>
</tr>
<tr>
<td>AC_BE</td>
<td>15</td>
<td>110 µs</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>AC_BK</td>
<td>15</td>
<td>149 µs</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

*the numbers in bold and italic are the values for which the last symbol gap problem can occur

Source: ETSI, TR 103 766
Potential Coexistence Strategies...

- **NAV setting and CTS-to-Self**

  ![Diagram showing NAV setting and CTS-to-Self](Image)

  After setting the NAV, the LTE-V2X transmission is protected from ITS-G5 interference.

- **LTE V2X PHY Header insertion**

  ![Diagram showing LTE V2X PHY Header insertion](Image)

  Source: ETSI, TR 103 766
Coexistence ITS-G5 – LTE-V2X – Evaluation

- **Scenario:**
  - Dense Highway; Normal CAM trigger

- **Observations:**
  - The maximum distance of ITS-G5 to achieve PER above 0.9 is reduced by 50% when 50% of vehicles adopt LTE-V2X.
  - No major impact on LTE V2X from ITS-G5

Source: A Bazzi, et al., Co-channel Coexistence: Let ITS-G5 and Sidelink C-V2X Make Peace, 2020
Coexistence ITS-G5 – LTE-V2X – Evaluation..

Scenario:
- Dense Highway; Periodic CAM Tx (more favorable to SPS)

Observations:
- Impact of LTE V2X on ITS-G5 is reduced; and conversely.
- Problem: not standard compliant (but Q’com compliant)

Source: A Bazzi, et al., Co-channel Coexistence: Let ITS-G5 and Sidelink C-V2X Make Peace, 2020
Part VI

FUTURE V2X - IEEE 802.11BD
In November 2016, the CAR 2 CAR initiated a WI on ITS-G5 Rel. 2

### Design directions:
- Enhanced channel usage (modulation, congestion control)
- Enhanced information exchange (Tx what is ‘required’)
- Enhanced PHY & MAC
- Enhanced Capacity
  - mmWAVE bands

### Input currently under discussions at the CAR 2 CAR
- Objectives:
  - > 5dB gain at 5GHz
  - 10x capacity at 60Hz
# 802.11 for Next Generation V2X Communication

- **IEEE 802.11 new Study Item created on March 9th 2018**
  - Following the proposal from the CAR 2 CAR
  - Take the state-of-art IEEE 802.11 technology (IEEE 802.11ac)
    - Add minor ‘magic’.
  - Potential Innovations:
    - LDPC codes
    - Space-Time Block Codes (STBC)
    - Higher Modulation & Capacity
    - Multi-Channel managements
    - Advanced Channel Estimation

- **Release**: rather fast, probably end 2022

---

## Disclaimer: All current C-ITS applications can be handled by ITS-G5. This new SI is to match the future 5G-V2X for next Generation C-ITS

### Table: Comparison of 802.11p and 802.11bd Features

<table>
<thead>
<tr>
<th>Feature</th>
<th>802.11p</th>
<th>802.11bd</th>
<th>Benefit from 802.11bd</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulation</td>
<td>BPSK, QPSK, 16-QAM, 64-QAM</td>
<td>BPSK, QPSK, 16-QAM, 64-QAM, 256 QUAM</td>
<td>33% increased throughput</td>
</tr>
<tr>
<td>Data subcarriers</td>
<td>48</td>
<td>48+52</td>
<td>8% increased capacity</td>
</tr>
<tr>
<td>MIMO</td>
<td>None</td>
<td>2xMIMO</td>
<td>2x higher capacity</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>10MHz</td>
<td>10MHz &amp; 20MHz</td>
<td>Improved sensitivity</td>
</tr>
<tr>
<td>Spectrum</td>
<td>5.9GHz</td>
<td>5.9GHz &amp; 60GHz</td>
<td>New application &amp; increased capacity</td>
</tr>
<tr>
<td>Channel Coding</td>
<td>BCC</td>
<td>LDPC</td>
<td>3db lower sensitivity = range extension</td>
</tr>
<tr>
<td>Adaptive Re-Transmit</td>
<td>None</td>
<td>1-3 retransmission (as a function of CBR)</td>
<td>Range extension/ higher reliability</td>
</tr>
<tr>
<td>Channel Tracking</td>
<td>Proprietary</td>
<td>Proprietary &amp; midband</td>
<td>Lower complexity receiver</td>
</tr>
<tr>
<td>Sub-carrier spacing</td>
<td>156.25kHz</td>
<td>312.5kHz, 156.25kHz, 78.125 kHz</td>
<td>Higher flexibility</td>
</tr>
<tr>
<td>MIMO</td>
<td>None</td>
<td>2xMIMO</td>
<td>2x higher capacity</td>
</tr>
</tbody>
</table>

---

WiFi V2X - IEEE 802.11bd

- **Frame Structuring**...
  - Baseline 802.11p header
  - L-STF  L-LTF  L-SIG  VHT-SIG-A  VHT-STF  VHT-LTF  VHT-SIG-B  DATA ....
  - NG 802.11p header

- **Midamble approach**

- **Coexistence**
  - Baseline 802.11p header
  - L-STF  L-LTF  L-SIG  VHT-SIG-A  VHT-STF  VHT-LTF  VHT-SIG-B  DATA ....
  - New 802.11bd header
  - Embedded
  - 802.11bd trailer
  - 16uS SIFS
  - 58uS 11p DIFS
  - Transparent
**WiFi V2X - IEEE 802.11bd**

- **Link Level Performance Evaluation...**
  - **Retransmission strategy**

- Should be understood as « Boolean OR of the CRC-pass results », we take the best of the 2 tries:
  - trans#1 FAIL + trans#2 FAIL = FAIL
  - trans#1 FAIL + trans#2 PASS = PASS
  - trans#1 PASS + trans#2 FAIL = PASS
  - trans#1 PASS + trans#2 PASS = PASS

Source: IEEE 802.11bd – Fischer, Philippi, Martinez, NXP
WiFi V2X - IEEE 802.11bd

- Link Level Performance Evaluation...
  - Channel tracking vs. Midamble Channel Estimation (MCE)

- SNR vs PER
  - MCE M=4, similar performance to DACE
  - MCE M=8, worse performance than DACE

Source: I. Sarris, u-blox, IEEE 820.11-19/1104r1
WiFi V2X - IEEE 802.11bd

- Link Level Performance Evaluation...
  - BCC vs LDPC

- SNR vs PER
  - LDPC gives a 1-2 dB enhancement compared to DACE
  - Again, performance also depends on the MCE scheme used

Source: I. Sarris, ublox, IEEE 820.11-19/0310r0
WiFi V2X - IEEE 802.11bd

- **Packet-level Evaluation**
  - Ublox model embedded into ns-3 (BCC, MCE)

- **PRR vs Distance**
  - DOTBD provides between 20% and 50% range extension as function of the channel environment

Source: Sasi Paidimarri, I. Khan, J. Härri, Network-level evaluation of IEEE 802.11bd, 2021
Part VII

FUTURE V2X – NR V2X
A Tutorial on 5G NR V2X Communications

Martin H. Castellana Garcia, Alejandro Molina Cifuentes, Mate Bohus, Javier Gonzalez Balderrama Collin

IEEE Communications Surveys & Tutorials journal.
DOI 10.1109/COMST.2021.3057017
3GPP V2X - NR V2X

- **New Radio V2X**
  - 5G-V2X Rel. 16 and up..
  - Provide additional capacity for V2X use cases **not supported by LTE-V2X**

- **New Channel Multiplexing**
  - Slot rather than freq/time multiplexing between control and data channels

- **New Communication Types:**
  - Unicast
  - Groupcast

- **New Channel:**
  - Physical Feedback Channel (PSFCH)
    - Provides feedback on groupcast reception

- **New Numerology:**
  - NR-V2X mode 1 – Network Assisted
  - NR-V2X mode 2(a/d) – Ad-hoc (CH assist)
3GPP V2X - NR V2X

- NR SL PSSCH/PSCCH multiplexing

- New NR SL Feedback Channel

Source: Garcia et al., A Tutorial on 5G NR V2X Communications
3GPP V2X - NR V2X

- **New Preemption Strategy**...

- **Mini-Slots Approach**...

Source: Naik et al., IEEE 802.11bd & 5G NR V2X: Evolution of Radio Access Technologies for V2X Communications
3GPP V2X - NR V2X – Performance Evaluations

- Link Level Performance Evaluation...

Source: Anwar et al., On the Reliability of NR-V2X and IEEE 802.11bd
NR-V2X coexistence with LTE-V2X

Coexistence mechanisms

- **Time Division Multiplexing (TDM)**
  - Statically allocated (gNB+eNB)
  - Dynamically allocated (need geographic coordinates)

- **Frequency Division Multiplexing (FDM)**
  - In-band and out-of-band tx power adaptation required

Source: Garcia et al., A Tutorial on 5G NR V2X Communications
Part VIII

DISCUSSION – ROAD AHEAD AND CHALLENGES
V2X – Roadmap and Timeline

Source: Garcia et al., A Tutorial on 5G NR V2X Communications
V2X Services and IoT – Heterogeneous Backend

Edge IoT

Edge Geoservice

Intelligence ML/AI

MQTT broker

GeoServer

V2X-Manager

Event Manager

MQTT broker

Intelligence

Full Events

Real Time Service

Traffic Data

Subscription

Manager

ML/AI

Data Synchronization

Global Connectivity

Edge Connectivity

SENSOR

Network

Client

Cloud

Edge

Vehicles

Cross-domain hazard avoidance

Sensor/knowledge exchange (CPM/ML)
Personal IoT Networks – Heterogeneous Vehicular Networks

- From Vertical IoT ‘silos’ to decentralized IoT
  - Applications to vehicular sensors…
  - 3GPP TR 22.859 rel.17

source: 3GPP
Time Sensitive Vehicular Networks (TSVN)

- **TSN as Functional Safety enabler**
  - TSN expected for functional safety of dTLC
  - Fully distributed TSN model is defined in IEEE 802.1Qcc
  - Impact on 5G networks (Cellular IoT or D2D)
  - 3GPP TS 23.734 rel.17

![Diagram](source: 3GPP)
5G Cellular Multi-hop Network

- **UE-2-UE relaying…MACNET is back?**
  - 3GPP TR 22.866 rel. 17
  - 3GPP TR 38.836 rel. 17

source: 3GPP
So...what’s next ??

- **Back to Square One !!**
  - …well, not completely..

- **Roadmap for V2X communications**
  - ETSI Standards for multi-technology: **completed**
  - ETSI first interoperability: **successful**
  - Latest results of ITS-G5 vs. LTE V2X: **comparable results**
  - Coexistence studies: **progressing**...

- **Real Challenge now is...** **corporate decision**
  - Should LTE V2X be actually deployed?
    - No forward compatibility – cars will need to update their V2X devices to get NR V2X
    - NR V2X first prototype – most likely 2022...

- **Next (current) Challenges:**
  - 3GPP Rel. 17 – brand new world !!
    - **Multi-hop** Cellular Ad-Hoc Networks
    - **Wireless** Time Sensitive Networking (TSN) (i.e. deterministic networks)
    - V2X & IoT
Back to the Future: V2X Roadmap and Timeline

V2X for Connected Vehicles: 2019 - Ready to Roll !!

Het-V2X for Connected Automated Vehicles: The Future is bright !!

Two technologies are an advantage: can provide redundancy and be more resilient to failure and attacks !!

Jérôme Härri, EURECOM, haerri@eurecom.fr
# ETSI ITS Innovative Work Items

- **TR 102 638**
  - BSA Release 2 (incorporation of the new services)

- **TS 102 890-2 (EN 302 890-2)**
  - Facility Position and Time

- **TS 103 141**
  - Facility Communication Congestion Control

- **TR 103 298**
  - Platooning pre-standardisation study

- **TR 103 299**
  - C-ACC pre-standardisation study

- **TR 103 300-1**
  - VRU pre-standardisation study

- **TS 103 300-2**
  - VRU Architecture

- **TS 103 300-3**
  - VRU Service

- **TR 103 562**
  - Informative Report Collective Perception

- **TS 103 324**
  - Collective Perception Service

- **TS 103 561**
  - Maneuver Coordination Service

- **TR 103 579**
  - standardisation study

- **TR 103 439**
  - Charging/Tolling applications via ITS-G5 pre-

- **TR 103 579**
  - Multi Channel Operation study
## LTE V2X - List of Standards (all Rel. 14)

### V2X
- TS 36.101 - User Equipment (UE) radio transmission and reception
- TS 23.285 - Architecture enhancements for V2X services
- TS 22.185 - Service requirements for V2X services;
- TS 22.186 - Enhancement of 3GPP support for V2X scenarios;
- TS 24.386 - User Equipment (UE) to V2X control function; protocol aspects

### RRC signaling
- TS 36.331 – E-UTRA Radio Resource Control (RRC); Protocol specification

### PDCP Procedures
- TS 36.323 – E-UTRA Packet Data Convergence Protocol (PDCP) specification

### MAC layer Procedures
- TS 36.321 – E-UTRA Medium Access Control (MAC) protocol specification

### Physical Layer Procedures
- TS 36.211 – E-UTRA Physical Channels and Modulations
- TS 36.212 - E-UTRA Multiplexing and channel coding
- TS 36.213 – E-UTRA Physical layer procedures
- TS 36.214 – E-UTRA Physical Layer - measurements
Selected Reference Papers

- ETSI, TR 103 766 V0.0.9, **Co-channel co-existence between ITS-G5 and LTE-V2X**, 2020
- ETSI, TR 103 667 V0.0.4, **Study on Spectrum Sharing between ITS-G5 and LTE-V2X technologies in the 5 855 MHz-5 925 MHz band**, 2020
- Garcia et al., **A Tutorial on 5G NR V2X Communications**, IEEE Communication Surveys and Tutorials, 2021