Gefördert durch:

Bundesministerium
für Verkehr und
digitale Infrastruktur

aufgrund eines Beschlusses
des Deutschen Bundestages

Deliverable D3.1: Comparative Analysis of Candidate V2X Radio Technologies

Version: V1.0

October 23, 2018

Revision history

Revision	Date	Description
1.0	October 23, 2018	First release version

Contents

1 Scope

The objective of this document is to describe V2X use cases, requirements and performance evaluation criteria. It analyses and compares the features of existing radio technologies 802.11p and LTE, both cellular and sidelink. For the features relevant for use cases defined in the project, the document assesses the theoretical performance and on that basis draws conclusion on the suitability for the respective use cases. Furthermore the radio spectrum requirements are estimated, together with the required density of cellular base stations and R-ITS. The advantages of licenses over unlicensed spectrum for individual use cases are discussed as well.

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3 Definitions and Abbreviations

3.1 Definitions

Host Vehicle (HV): The vehicle whose driver is alerted or notified by a warning or notification indication by its InVehicleInformation system (e.g. visually and/or acoustically), as a result of the reception and processing of CAM’s and DENM’s from surrounding other vehicles.

PC5 transport: Transmission of V2X data from a source UE (e.g., a vehicle) to a destination UE (e.g., another vehicle, road infrastructure, a pedestrian, etc.) via ProSe Direct Communication over the PC5 interface between the UEs (sidelink).

Remote vehicle (RV): The collection of all vehicles in a traffic scenario which surround a considered Host Vehicle. The Remote Vehicles broadcast their positions and vehicle information periodically and also create special DENM warning messages in case of safety-relevant events.

Road Side Unit (RSU): An entity supporting V2I Service that can transmit to, and receive from a UE using V2I application. RSU is implemented in an eNB or a stationary UE.

Uu transport: Transmission of V2X data from a source UE (e.g., a vehicle) to a destination UE (e.g., another vehicle, road infrastructure, a pedestrian, etc.) via the eNB over the conventional Uu interface (uplink and downlink).

V2I Service: A type of V2X Service, where one party is a UE and the other party is an RSU both using V2I application.

V2N Service: A type of V2X Service, where one party is a UE and the other party is a serving entity, both using V2N applications and communicating with each other via cellular network (e.g. LTE or 5G) .

V2P Service: A type of V2X Service, where both parties of the communication are UEs using V2P application. For this service the vehicle-side UE is a V-ITS-S, the pedestrian-side (respectively VRU-side) UE is a P-ITS-S.

V2V Service: A type of V2X Service, where both parties of the communication are UEs using V2V application. . For this service both vehicle-side UEs represent V-ITS-S.

Vulnerable Road User (**VRU**): A road user, such as a pedestrian, a cyclist or a motorcyclist, bearing a greater risk of serious injury than vehicle occupants when involved in a traffic accident.

3.2 Abbreviations

3GPP	3rd Generation Partnership Project
5G	5th Generation
5GAA	5G Automotive Association
5G-PPP	5G Private Public Partnership
A9	Motorway A9
ACC	Adaptive Cruise Control
CACC	Corporative Adaptive Cruise Control
C2C-CC	CAR 2 CAR Communication Consortium
CAM	Cooperative Awareness Message as defined in ETSI a message vehicles issue in 1Hz to 10 Hz interval to send their at least position and heading to its surrounding using local communication (e.g. 802.11p
C-ITS	Cooperative Intelligent Transport Systems
C-V2X	Cellular V2X
CV2XBox	Cellular V2X Communication Module
CVRIA	Connected Vehicle Reference Implementation Architecture
DCC	Decentralized Congestion Control
DENM	Decentralised Environmental notification Message as defined in ETSI a message vehicles or infrastructure components send case any relevant warning shall be issued to nearby vehicles
DSRC	Dedicated Short Range Communications
EEBL	Emergency Electronic Brake Light (use case)
EIRP	Equivalent Isotropically Radiated Power
ERTICO	European Road Transport Telematics Implementation Coordination
ETSI	European Telecommunications Standards Institute
E-UTRA	Evolved UMTS Terrestrial Radio Access
EU	European Union
FCD	Floating Car Data
FCW	Forward Collision Warning
GLOSA	Green Light Optimal Speed Advisory
GNSS	Global Navigation Satellite System
HGV	Heavy Goods Vehicle
HW	Hardware
ICS	ITS Central Station
IEEE	Institute of Electrical and Electronics Engineers
ITS	Intelligent Transport System
IVI	In Vehicle Information as defined in SAE and CEN/ISO information on current (dynamic) sign display to be sent from infrastructure to vehicles
IRS	ITS Roadside station
IVS	In-Vehicle Signage

KPI	Key Performance Indicators
LTE	Long Term Evolution
MAC	Media Access Control (layer)
MDM	Mobility Data Marketplace
OEM	Original Equipment Manufacturer
PC5	ProSe Communication reference point 5.
PHY	Physical (layer)
ProSe	Proximity-based Services
PRR	Packet Reception Rate
PVD	Prove Vehicle Date as in discussion in CEN/ISO a message to allow vehicles to issue collected data to other vehicles or infrastructure
P-ITS-S	Personal ITS Station
REFSENS	Reference Sensitivity
R-ITS-S	Roadside Intelligent Transport System Station
RV	Remote Vehicle
RSU	Road Side Unit
SAE	Society of Automotive Engineers
SINR	signal-to-interference and noise ratio
SNR	signal-to-noise ratio
SPaT/MAP	Signal Phase and Time / Map Standard
SW	Software
SWD	Shockwave Damping Service Deployment
TCC	Traffic Control Center
TGW	Traffic jam ahead warning
UE	User Equipment
V2C	Vehicle to Cloud
V2I	Vehicle to Infrastructure
V2N	Vehicle to Network
V2P	Vehicle to Pedestrian
V2V	Vehicle to Vehicle
V2X	Vehicle to Everything
V-ITS-S	Vehicular Intelligent Transport System Station
VMS	Variable Message Sign
VRU	Vulnerable Road User
WAVE	Wireless Access in Vehicular Environments

4 General V2X Comparison

4.1 Scope and Overview

V2X communication around the globe is supported by different technologies and standards (ARIB-Japan, IEEE-US, ETSI-Europe, 3GPP-Global). C-V2X has been added as the 3GPP LTE - and in future 5G - based communication approach. The following sections will provide some more detailed insights into the specifics of the relevant European technologies which are based on C-ITS (ETSI) and C-V2X (3GPP). The following Table 4.1-1 and Table 4.1-2 provide an overview of C-ITS and 3GPP with respect to frequency bands and standards relevant for Europe based on [32] and augmented for the LTE C-V2X information.

Table 4.1-1: V2X Technologies in Europe: Bands

Band [MHz]	Channelization	In-use or Allocated	Applications
5470-5725 (ITS-G5C)	Dynamic Frequency Selection (DFS) of 10 MHz or 20 MHz service channel	Allocated	ITS applications based on V2I communication
5795-5815	Four 5 MHz channels	In-use	Road transport and telematics
5855-5925	One 10 MHz control channel and six 10 MHz service channels	Allocated	Non-safety applications [5855-5875 MHz (ITS-G5B)] safety applications [5875-5905 MHz (ITS-G5A)] future ITS applications [5905-5925 MHz]
LTE Bands: 1 [FDD 2100], 3 [FDD 1800], 7 [FDD 2600], 8 [FDD 900], 20 [FDD 800], 42 [TDD 3500]	Typically, 5, 10 or 20 MHz	In-use or allocated	V2N

Table 4.1-2: V2X Technologies in Europe: Standards and Scope

Standards		Scope
ETSI	3GPP (LTE)	
EN302571		Requirements for operation in [5855-5925] MHz
EN300674-1		Requirements for operation in [5795-5815] MHz
ES202663 (ITS-G5) ES202663 (ITS-G5)	TS36.321 TS36.21x (x=1,2,3,4)	MAC PHY
	TS33.303	3GPP PC5/ProSe security aspects
EN302665		Communication architecture
EN302636-3		Network architecture
EN302636-4-1		Geographical routing functionality
TS102636-4-2		Geographical routing based on ITS-G5
EN302636-6-1		Tx of IPv6 packets using geographical routing
EN302636-5-1		Transport layer
EN302637-2		CAM
EN302637-3		DENM
	TS36 series	Uu interface

As can be identified from Table 4.1-2 the 3GPP C-V2X focus is on providing the lower layer (MAC and PHY) functionality to be integrated with the ITS protocol stack and services specified by ETSI.

More details on the C-V2X technology and protocol stacks (PC5, Uu) can be found in the other relevant project descriptions, e.g., [30], and in Section 5 of this document.

4.2 Architectures and Reference Points

This section provides a quick review, overview and comparison of V2X technologies with reference to further sources of information. Figure 4.2-1 shows the high-level architecture with the relevant use case categories and the relevant interfaces provided by the technologies of ETSI and 3GPP, respectively.

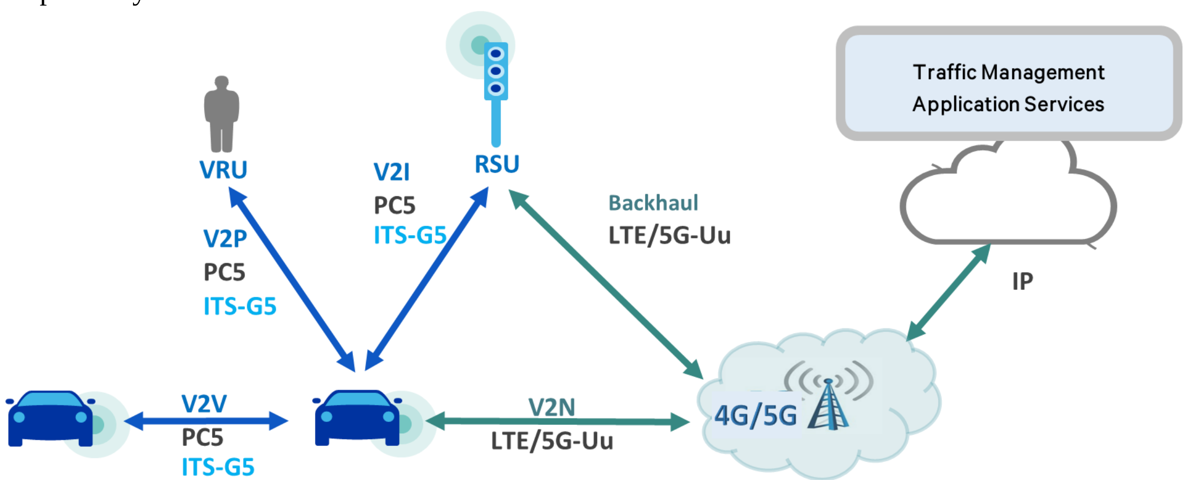


Figure 4.2-1 High Level Network Architecture and Technology/Protocol Support

The V2X specifications in 3GPP Release 14 and in ETSI, respectively, include up to two complementary communication interfaces. Direct communication such as vehicle-to-vehicle (V2V) is realized through PC5 (ProSe Communication reference point 5). The same holds for vehicle-to-pedestrian (V2P) and vehicle-to-infrastructure (V2I) communications. The respective ETSI protocol for these communications is ITS-G5 based on IEEE 802.11p as outlined in the previous section already.

In addition, the LTE - or in future the 5G NR - Uu connection complements any communication for the non-direct links within the (wide area) network for V2N cases. This connection might also be used as backhaul-link between road-side-units (RSU) and their (traffic management) center, acting as transparent IP connection. This interface is solely supported by the 3GPP LTE (4G) and 5G-NR Uu interfaces; ETSI does not provide an own interface for this but relies on the 3GPP interfaces in a hybrid fashion.

There are some commonalities but as well as some fundamental differences between the 3GPP PC5 based C-V2X and the ETSI ITS-G5 V2X approaches. The main difference exists in the lower layers of MAC and PHY, and the integration within the whole protocol stack up to the service/application layer mainly with respect to management and security. Section 5 is providing these insights and comparison in more detail.

5 Analysis of V2X Technologies

5.1 Introduction

The present section 5 describes the main functions and characteristics of the current candidate V2X radio technologies:

- DSRC/WAVE specified by the US Department of Transportation (U.S. DOT)
- ETSI C-ITS / ITS-G5 specified by ETSI by mandate of the European Commission
- 3GPP Rel-14 Cellular V2X based on LTE Uu and PC5 radio technologies

Both DSRC/WAVE and ETSI C-ITS / ITS-G5 are based on IEEE 802.11 WLAN radio technologies, namely a MAC/PHY variant of the 802.11a standard which is denoted IEEE 802.11p. Therefore, both technologies are colloquially often referred to as “WLAN-based” or “WiFi-based” V2X technologies. Section 5.2 introduces the overall protocol stacks of DSRC/WAVE and ETSI C-ITS / ITS-G5 and elaborates the commonalities and differences between these technologies.

Section 5.3 presents the main features of 3GPP Rel-14 LTE-based cellular V2X radio technologies examined in the ConVeX project, namely LTE Uu radio technology applied for V2N communications, and LTE PC5 (“sidelink”) radio technology for V2V/V2I/V2P communications.

Section 5.4 provides an analysis of the main performance characteristics of the considered V2X technologies.

5.2 802.11p-based Technologies

5.2.1 Introduction to 802.11p, DSRC and ITS-G5

The IEEE 802.11p specification has been developed as an amendment [31] to the IEEE 802.11 WLAN standard series of specifications. The goal of this effort was to introduce radio technology enhancements in order to support communication between vehicles (V2V) and between vehicle and road side infrastructure (V2I) at typical vehicle speeds.

IEEE 802.11p comprises a specification of the physical (PHY) layer and Media Access Control (MAC) layer processing. In fact, IEEE 802.11p represents a modified version of the IEEE 802.11a amendment which was designed for WLAN networks operating in the 5 GHz band (approx. 5.2 to 5.8 MHz) with nominal data rates up to 54 Mbps.

The application of 802.11p PHY/MAC technology with the Wireless Access for Vehicular Environments (WAVE) extensions to the MAC and upper layer ITS protocol stack is referred to as Dedicated Short Range Communications (DSRC). The term DSRC has been introduced in a customized version of the IEEE 802.11p MAC/PHY standards which has been published by ASTM International (originally founded as *American Society for Testing and Materials*, today an organization which corresponds to DIN e.V. in Germany) as ASTM E2213-03 specification [32]. This specification has been adopted by the US department of Transportation (U.S. DOT) for ITS services in the USA.

The overall DSRC/WAVE protocol stack is presented in more detail in Section 5.2.2.

In Europe, ETSI has created a V2X standard which is builds upon the IEEE 802.11p MAC/PHY standard and DSRC [32], which however adds a significant cross-layer function which affects the MAC and some upper layers, denoted as Decentralized Congestion Control (DCC). This modified version of 802.11p/DSRC is denoted as ETSI ITS-G5 technology. ETSI has also redefined other upper layer functionality substantially. The overall ETSI V2X standard is commonly denoted as ETSI C-ITS (Cooperative Intelligent Transport System). This standard is described in detail in Section 5.2.3.

Another technology which is based on DSRC [32] is employed for Electronic Fee Collection (EFC) services. This technology is denoted CEN DSRC in Europe. This standard is defined by CEN Technical Committee (TC) 278 and specified in EN 12253, EN 12795, EN 12834 [ISO 15628] and EN 13372 (see http://www.itsstandards.eu/efc).

CEN DSRC is briefly described in Section 5.2.4.

5.2.2 DSRC/WAVE Technology

5.2.2.1 IEEE 802.11 Architecture

Figure 5.2.2.1-1 shows the principal architecture model applicable to any IEEE 802.11 system, including 802.11p [57].

The smallest building block of a wireless LAN is a basic service set (BSS), which consists of some number of stations (STA) executing the same MAC protocol and competing for access to the same shared wireless medium. A BSS may be isolated or it may connect to a backbone distribution system (DS) through an access point (AP). The AP functions as a bridge and a relay point. In a BSS, client stations do not communicate directly with one another. Rather, if one station in the BSS wants to communicate with another station in the same BSS, the MAC frame is first sent from the originating station to the AP, and then from the AP to the destination station. Similarly, a MAC frame from a station in the BSS to a remote station is sent from the local station to the AP and then relayed by the AP over the DS on its way to the destination station. The BSS generally corresponds to what is referred to as a cell in the literature. The DS can be a switch, a wired network, or a wireless network.

When all the stations in the BSS are mobile stations, with no connection to other BSSs, the BSS is called an independent BSS (IBSS). An IBSS is typically an ad hoc network. In an IBSS, the stations all communicate directly, and no AP is involved. A simple configuration is shown in Figure 5.2.2-1, in which each station belongs to a single BSS; that is, each station is within wireless range only of other stations within the same BSS. It is also possible for two BSSs to overlap geographically, so that a single station could participate in more than one BSS. Further, the association between a station and a BSS is dynamic. Stations may turn off, come within range, and go out of range. An extended service set (ESS) consists of two or more basic service sets interconnected by a distribution system. Typically, the distribution system is a wired backbone LAN but can be any communications network. The extended service set appears as a single logical LAN to the logical link control (LLC) level. Figure 5.2.2.1-1 indicates that an access point (AP) is implemented as part of a station; the AP is the logic within a station that provides access to the DS by providing DS services in addition to acting as a station. To integrate the IEEE 802.11 architecture with a traditional wired LAN, a portal is used. The portal logic is implemented in a device, such as a bridge or router, that is part of the wired LAN and that is attached to the DS.

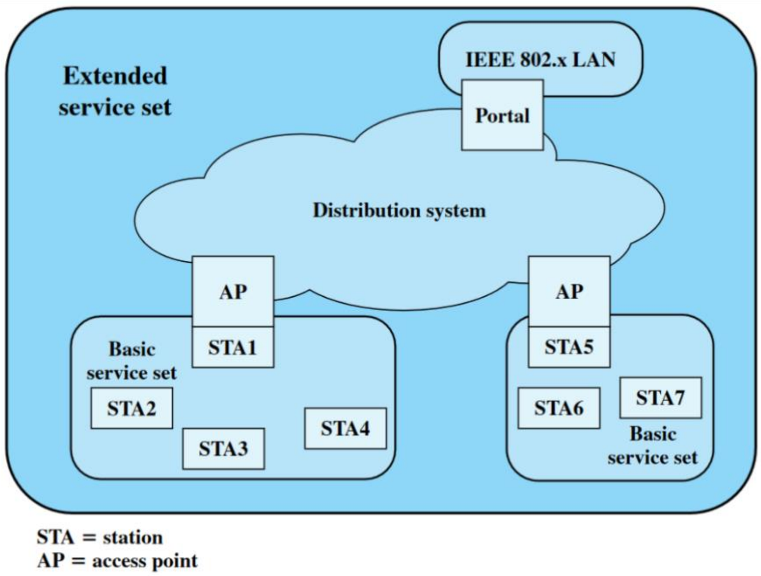


Figure 5.2.2.1-1: IEEE 802.11 architecture model

5.2.2.2 Main modulation and coding parameters

The IEEE 802.11p PHY layer is characterized by the modulation parameters listed as follows:

- Modulation and multiple access scheme: OFDM
  - symbol duration 8 µs (while 11a supports 4 µs), including the guard time interval 1.6µs (while 11a has 0.8µs)
  - subcarrier spacing of 156250 Hz (half of 11a)
  - 52 useful carriers per symbol (48 for data, 4 pilot) in 10 MHz (twice in 20 MHz)
  - BPSK/QPSK/16QAM/64QAM.
- 10 and 20 MHz bandwidth
- supports nominal bit rates (before channel coding) of 3/4.5/6/9/12/18/24/27 Mbps, i.e. half the rates of 802.11a (shown in the table below) due to doubled symbol duration

The OFDM carrier allocation is illustrated in Figure 5.2.2.2-1 [58]. The 52 useful plus 12 nulled carriers are mapped into a FFT constellation with N = 64 carriers. The green carriers are used for data, the red carriers represent pilot information. Since the spectrum of a sampled signal is periodic, the null subcarriers numbered 27 ... 37 correspond to the edge frequencies of a 10 MHz transmission channel. This enables use of band selection filters with moderate slope. Also, the DC carrier number 0 is not used for data transmission in order to prevent issues due to DC offsets.

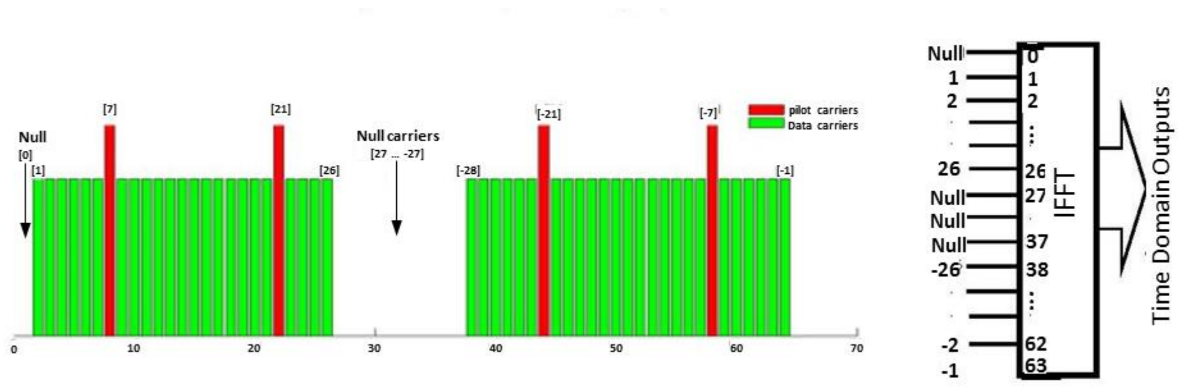


Figure 5.2.2.2-1: OFDM carrier format source: [42]

Channel coding: forward error correction (FEC) convolutional coding is used with coding rates of 1/2, 2/3, or 3/4.

Data Rate given in the first column of Table 5.2.2.2-1 can be calculated from the number of data bits per OFDM symbol divided by OFDM symbol length

Table 5.2.2.2-1: Parameters of 802.11p modulation and coding

Data Rate (Mbit/s)	Modulation	Coding rate	Coded bits per subcarrier	Coded bits per OFDM symbol	Data bits per OFDM symbol
3	BPSK	1/2	1	48	24
4.5	BPSK	3/4	1	48	36
6	QPSK	1/2	2	96	48
9	QPSK	3/4	2	96	72
12	16-QAM	1/2	4	192	96
18	16-QAM	3/4	4	192	144
24	64-QAM	2/3	6	288	192
27	64-QAM	3/4	6	288	216

5.2.2.3 802.11p Physical Layer frame format

Figure 5.2.2.3-1 shows the format of an IEEE 802.11p Physical Layer Protocol Data Unit (PPDU) which applies to 802.11p as well.

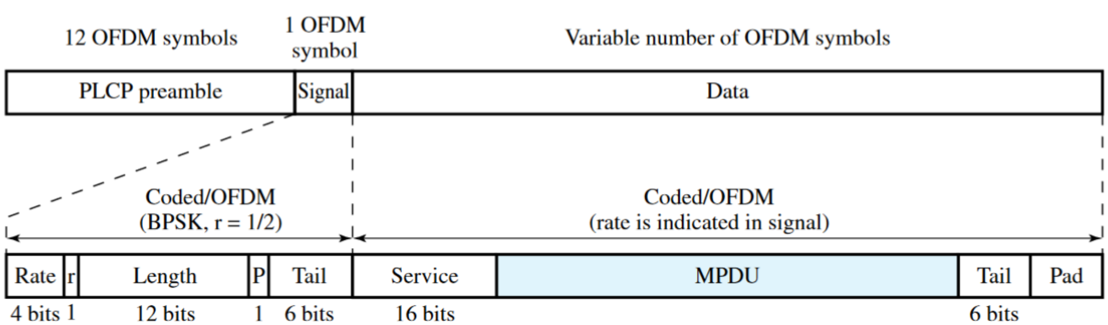


Figure 5.2.2.3-1: 802.11p Physical Layer frame format

In the transmitting direction. the physical layer (PHY) processes and transmits the medium access control (MAC) protocol data units (MPDUs) indicated by the MAC layer to PHY. In the receiving direction, the PHY delivers received data in the format of MPDUs to the MAC layer.

The 802.11 PHY is divided into two sublayers, the Physical Layer Convergence Protocol (PLCP) and Physical Medium Dependent (PMD) sublayers.

The PLCP sublayer provides the framing and signaling bits needed for OFDM for signal acquisition and synchronization. The PMD sublayer performs the encoding/decoding and modulation/demodulation operation.

The PLCP Preamble represents a training sequence comprised of 12 OFDM symbols employed for signal acquisition and synchronization at the receiver. Both the Preamble and the Signal fields are transmitted at a fixed data rate with BPSK modulation and rate 1/2 encoding. The purpose of the Signal field is to indicate the data rate (i.e. employed modulation and encoding) applied to the Data field. It of the consists of the following subfields:

Rate: Specifies the data rate at which the Data field of the frame is transmitted

r: Reserved (for future use)

Length: Number of octets in the MPDU

P: An even parity bit for the 17 bits in the Rate, r, and Length subfields

Tail: Tail bits (6 zero bits) applied at convolutional encoding of the Signal field

The Data field consists of a variable number bytes which are mapped to a variable number of OFDM symbols transmitted at the data rate specified in the Rate subfield. Prior to transmission.

The Data field consists of four subfields:

Service: Consists of 16 bits, with the first 7 bits set to zeros to synchronize the descrambler in the receiver, and the remaining 9 bits (all zeros) reserved for future use.

MAC PDU: Data unit handed down from the MAC layer to the physical layer, see Section 5.2.2.5.

Tail: Produced by replacing the six scrambled bits following the MPDU end with 6 bits of all zeros; used to reinitialize the convolutional encoder.

Pad: The number of bits required to make the Data field a multiple of the number of bits in an OFDM symbol (48, 96, 192, or 288).

The Signal field and Service subfield of Data together are denoted as PLCP header.

5.2.2.4 Multiple access mechanism

For IEEE 802.11 medium access, stations in “Outside the Context of BSS” - OCB mode employ the Enhanced Distributed Channel Access (EDCA). Client stations “outside the context of BSS” communicate directly with each other.

Setting of the MAC field *dot11OCBActivatedEnabled* to TRUE indicates that a station is used for WAVE operation (denoted *OCBActivated communication*).

EDCA is contention-based and applies Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). With CSMA/CA, a device listens to the channel before starting any own transmissions. If the channel is occupied, the station delays its own transmission by a random duration of time, denoted as backoff time, and then probes the channel again. Stations differentiate data, assign the data to access categories (ACs), and handle the data from different access categories with other CSMA/CA-related parameters, which effectively allows for data traffic prioritization [41].

The EDCA mechanism uses the IEEE 802.11 Distributed Coordination Function (DCF) to setup multiple queues for different QoS/priority. This mechanism allows up to eight levels of MAC-sublayer priority as specified in IEEE Std 802.11.

A brief summary of the IEEE 802.11p MAC and EDCA is given in Annex B.4 of ETSI TS 302 663 [46]. Details are specified in Section 5 of IEEE 1609.4 [36].

5.2.2.5 MAC Frame Format

Figure 5.2.2.5-1 shows the frame format of the IEEE 802.11 MAC protocol [57].

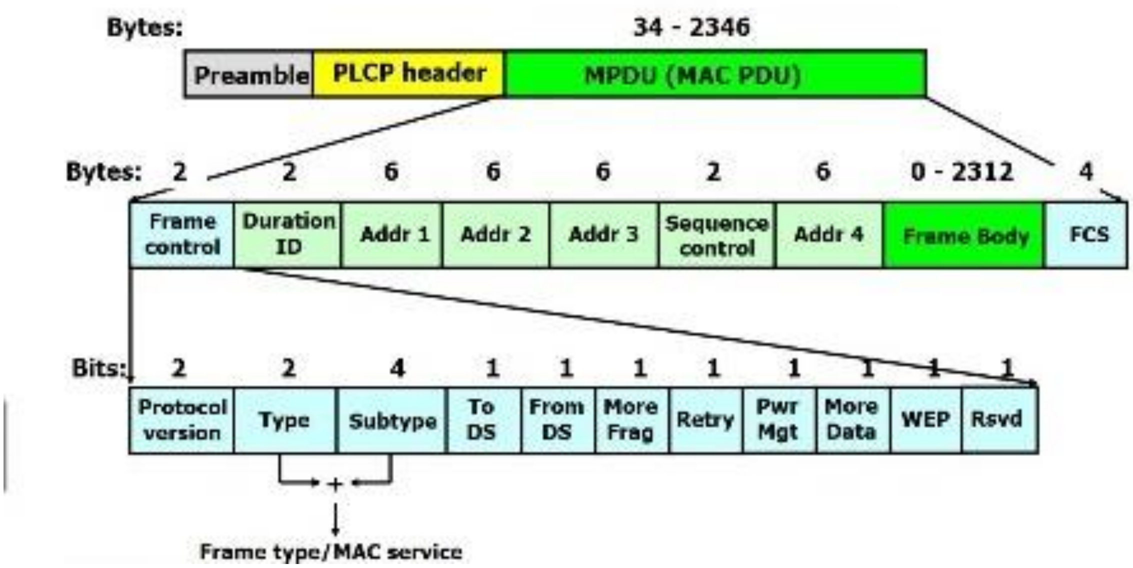


Figure 5.2.2.5-1: 802.11p frame format

The fields of the MAC PDU serve the following purpose [57]:

Frame Control: Indicates the type of frame (control, management, or data) and provides control information. Control information includes whether the frame is to or from a Distribution System (DS), fragmentation information, and privacy information. The two bytes frame control information includes the following on bit level (note that this information can be monitored e.g. with WireShark). This field is common to all IEEE 802.11 systems.

- Protocol version: 2 bits protocol version information
- Frame type/subtype: Indicates the type of a frame and the subtype of data frames. There are eight data frame subtypes, organized into two groups. The first four subtypes define

frames that carry upper-level data from the source station to the destination station. The four data-carrying frames are as follows:

  - Data: This is the simplest data frame. It may be used in both a contention period and a contention-free period.
  - Data + CF-Ack May only be sent during a contention-free period. In addition to carrying data, this frame acknowledges previously received data.
  - Data + CF-Poll: Used by a point coordinator to deliver data to a mobile station and also to request that the mobile station send a data frame that it may have buffered.
  - Data + CF-Ack + CF-poll : Combines the functions of the and into a single frame.
  - The remaining four subtypes of data frames do not in fact carry any user data.

- To DS: if set to 1 the frame is transmitted from a wireless station to the distribution system (DS) through the AP
- From DS: if set to 1 the frame is transmitted from a DS to a wireless station through the AP
- More Fragments: 0 this is the last fragment, 1 more fragment to follow
- Retry: 0 frame is not being retransmitted
- Power Management: 0 station (STA) will stay up (no power saving applied)
- More Data: 0 no data buffered, 1 data buffered
- Protection Flag (WEP): 0 data is not encrypted, 1 data is encrypted
- Order Flag (Rsvd): 0 not strictly ordered

Duration/Connection ID: If used as a duration field, indicates the time (in microseconds) the channel will be allocated for successful transmission of a MAC frame. In some control frames, this field contains an association, or connection, identifier.

Addresses: The number and meaning of the 48-bit address fields depend on context. The transmitter address and receiver address are the MAC addresses of stations joined to the BSS that are transmitting and receiving frames over the wireless LAN. The service set ID (SSID) identifies the wireless LAN over which a frame is transmitted. For an IBSS, the SSID is a random number generated at the time the network is formed. For a wireless LAN that is part of a larger configuration the SSID identifies the BSS over which the frame is transmitted; specifically, the SSID is the MAC-level address of the AP for this BSS (Figure 17.4). Finally, the source address and destination address are the MAC addresses of stations, wireless or otherwise, that are the ultimate source and destination of this frame. The source address may be identical to the transmitter address and the destination address may be identical to the receiver address.

Sequence Control: Contains a 4-bit fragment number subfield, used for fragmentation and reassembly, and a 12-bit sequence number used to number frames sent between a given transmitter and receiver.

Frame Body: Contains an MSDU or a fragment of an MSDU. The MSDU is a LLC protocol data unit or MAC control information.

Frame Check Sequence: A 32-bit cyclic redundancy check.

5.2.2.6 Overall DSRC/WAVE protocol stack

ITS communication standards in the US are built by combining IEEE 802.11p PHY/MAC with extensions defined in the series of Wireless Access for Vehicular Environments (WAVE) standards defined in the IEEE 1609 series of specifications.

IEEE Std 1609.0-2013 [33] describes the overall WAVE protocol architecture

IEEE Std 1609.4-2010 (Multi-Channel Operations) [36] specifies extensions to the IEEE 802.11 MAC layer protocol and includes the following features [33]:

- Channel timing and switching
- Use of IEEE 802.11 facilities, e.g., channel access, Enhanced Distributed Channel Access (EDCA), outside the context of a BSS (Basic Service Set)
- Use of IEEE 802.11 Vendor Specific Action and Timing Advertisement frames in a WAVE system
- MAC-layer readdressing in support of pseudonymity

IEEE Std 1609.3-2010 (Networking Services) [35] includes the following features:

- WAVE Service Advertisements and channel scheduling
- WAVE Short Message Protocol
- Use of existing protocols, e.g., LLC and IPv6, including streamlined IPv6 configuration
- Delivery of general management information over the air interface

IEEE Std 1609.2-2013 (Security Services for Applications and Management Messages) specifies

- communications security for WAVE Service Advertisements and WAVE Short Messages and additional
- security services that may be provided to higher layers.

IEEE P1609.5 (Communication Manager) [37] is an open project for addressing network management requirements.

IEEE P1609.6 (Remote Management Services) [38], is under development. It will include over-the-air management and alias features.

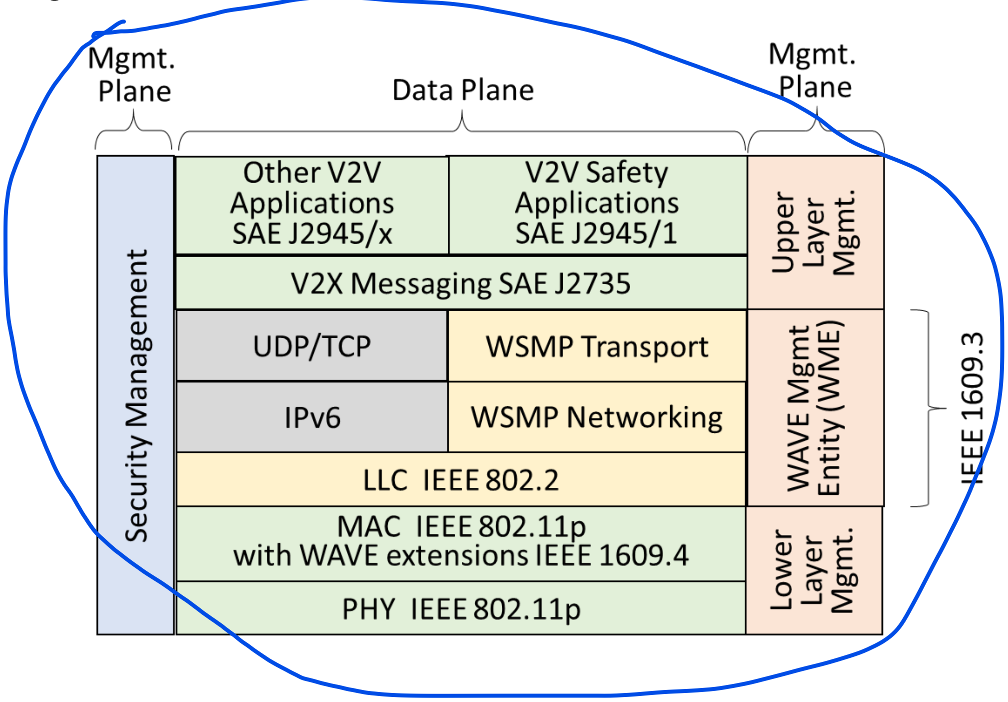


Figure 5.2.2.6-1: WAVE/DSRC protocol stack

The DSRC/WAVE messaging layer is defined in SAE J2735 [60]. The Basic Safety Messages (BSM) are specified in SAE J2945/1. Messages for non-safety related use cases will be specified in other specifications of the SAE J2945/x series in future.

Generally, messages are specified in ASN.1 syntax with Unaligned Packet Encoding Rules (UPER) message encoding. However other encoding styles (typically due to reuse from other standards) are encapsulated and supported in various places, see SAE J2735 [60].

The Logical Link Control (LLC) layer adds 2 bytes LLC header information. This enables differentiation between IPv6 and WSMP messages (see details in [35]).

5.2.3 ETSI ITS-G5/C-ITS Technology

5.2.3.1 Architecture

The overall architecture described in Section 5.2.2.1 also applies to ETSI ITS-G5 systems. The overall ETSI communications reference architecture is described in ETSI EN 302 665 [47].

5.2.3.2 Modulation and Coding

The modulation and coding scheme as described in Section 5.2.2.2 applies to the ETSI ITS-G5 physical layer.

5.2.3.3 Multiple access mechanism

The multiple access mechanism as described in Section 5.2.2.3 applies to the ETSI ITS-G5 physical layer.

5.2.3.4 MAC Frame Format

The MAC frame format as described in Section 5.2.2.4 applies to the ETSI ITS-G5 MAC layer. The main difference between the MAC protocols of DSRC/WAVE and ETSI ITS-G5 protocol stacks is that the Distributed Congestion Control (DCC) function is mandatory for ETSI ITS-G5 while it is optional for DSRC/WAVE.

5.2.3.5 Overall ETSI ITS-G5/C-ITS protocol stack

In the present document we use the term *ETSI Cooperative ITS (ETSI C-ITS)* to refer to the system specified by the series of specifications which are listed in ETSI TR 101 607 [44]. Note that this series is comprised of more than 80 documents. In this section, only a small subset of these specifications are referenced.

This series of specifications originates from work carried out by the ETSI Technical Committee ITS. The overall ETSI C-ITS protocol stack is shown in Figure 5.2.3.5-1.

The PHY and MAC layers are specified in ETSI ES 202 663 [45] and ETSI TS 302 663 [46].

The term ITS-G5 refers to a system compliant with the *Access layer specification for Intelligent Transport Systems operating in the 5 GHz frequency band* specified in [46]. ITS-G5 is based on IEEE 802.11-2012 which incorporates IEEE 802.11p-2010 [31].

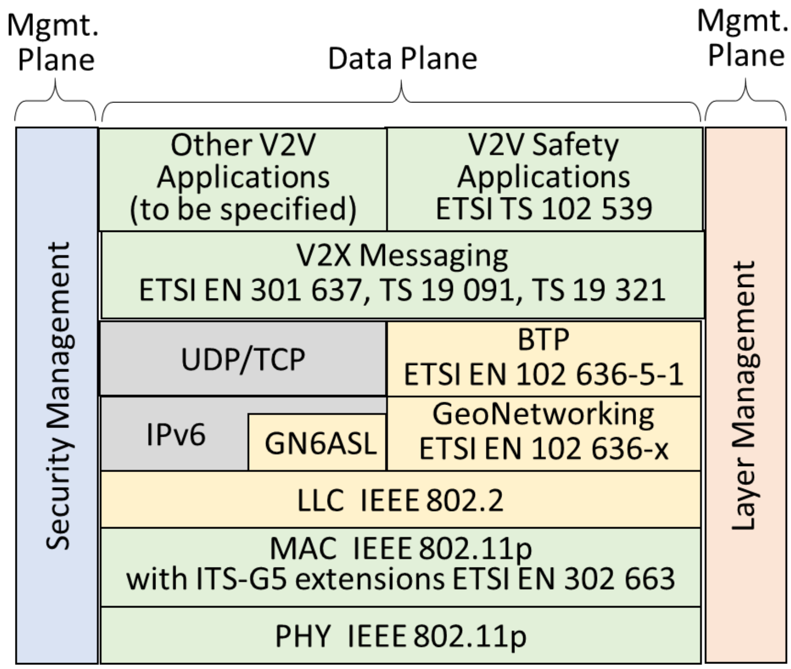


Figure 5.2.3.5-1: ETSI C-ITS protocol stack

The LLC header of 2 bytes has the same functionality as in DSRC. It includes source and destination addresses of service access points enabling differentiation between IP and GeoNetworking services. The GeoNetworking IPv6 Adaptation Sub-Layer (GN6ASL) enables transmission of TCP/UDP/IP packets over the GeoNetworking layer.

GeoNetworking layer allows different “packet types”: GeoUnicast, GeoBroadcast, GeoAnycast, topologically-scoped broadcast (TSB), Single-hop broadcast (SHB). The GeoUnicast, GeoBroadcast, GeoAnycast and TSB packet handling types provide support for multi-hop routing and addressing.

The principal format of a Protocol Data Unit (PDU) exchanged between the MAC and PHY layers when sending messages via the GeoNetworking layer (right-sided stack of Figure 5.2.3-1) is illustrated in Figure 5.2.3-2.

The GeoNetworking header consists of two main parts, the Common Header and the Extended Header. The common header is common to all GeoNetworking layer packet types. The extended header has a packet-type specific format. All details of the GeoNetworking header are specified in ETSI TS 102 636-4-1 [51].

The Common Header has a length of 36 bytes, which includes a position vector of the sender of 28 bytes. Other fields include protocol version number, header types and subtype information, ITS station type, length of the payload field, traffic class, multi-hop routing information.

The Extended Header includes fields such as sequence number, lifetime, position information of source and destination, GeoNetworking address (see [51]) for details). Depending on the packet type, the extended header can become quite large, i.e. up to 88 bytes.

The GeoNetworking Security Header corresponds to the header field of the signedData message format as described in Section 6.5.3.5 of Deliverable D2.1. The security header is specified in ETSI TS 103 097 [65].

The Basic Transport Protocol (BTP) provides a connectionless transport service. It is specified in TS 102 636-5-1 [53] . This protocol is very similar to UDP [RFC 768].

MAC Header	Header	GeoNetworking Header	GeoNetworking Security Header (optional)	Payload (optional)

Figure 5.2.3.5-2: GeoNetworking packet structure (source: ETSI TS 102 636-4 [51])

5.2.3.6 Decentralized Congestion Control

ETSI TS 302 663 [46] mandates that Decentralized Congestion Control (DCC) mechanism is used for control of channel load and to avoid unstable behavior of the system, when used in the ITS-G5A, ITS-G5B and ITS-G5D bands.

DCC is a cross-layer function which requires special functionality on the MAC, the Network and the Facilities layers. Note that mandatory support of DCC represents a major difference between ITS C-ITS and the US WAVE/DSRC technologies. The overall cross-layer architecture of DCC is illustrated in Figure 5.2.3.6-1. The circled numbers refer to the Service Access Points (SAP) between protocol layers which are defined in ETSI 102 687 [48].

The DCC_access mechanism consists of the following building blocks:

- setup of transmit queues
- channel probing for Clear Channel Assessment (CCA)
- assessment of transmit statistics
- setup of various control loops

The EDCA/DCF mechanism is part of the DCC transmit queuing function.

The MAC-part of ITS-G5 DCC feature is specified in ETSI 102 687 [48]. Figure 5.2.3.6-2 shows the main DCC functions on the MAC layer.

The DCC mechanism aims to avoid channel congestion while maintaining fair resource allocation across all ITS Stations by control of four parameters: transmission (Tx) power, reception (Rx) sensitivity, messaging frequency and transmission data rate. Accordingly, DCC implements 4 different control loops:

- Transmit power control (TPC): this loop controls the range of transmission.
- DCC sensitivity control (DSC): this loop adapts the CCA sensitivity thresholds.
- Transmit rate control (TRC): this loop controls the frequency of periodically transmitted messages.

- Transmit data rate control (TDC): this loop controls the selection of Modulation and Coding Scheme (MCS).

Other DCC functions include

- Transmit access control (TAC), which sets up messaging queues and controls prioritization of message transmission, and
- Multiple channel operation, which controls the distribution of messages over multiple frequency channels, if available.

In order to combat channel congestion, Tx power and messaging frequency can be lowered, the Rx sensitivity can be enhanced and the modulation data rate can be increased, all to the effect of reducing the number of messages within the transmission range.

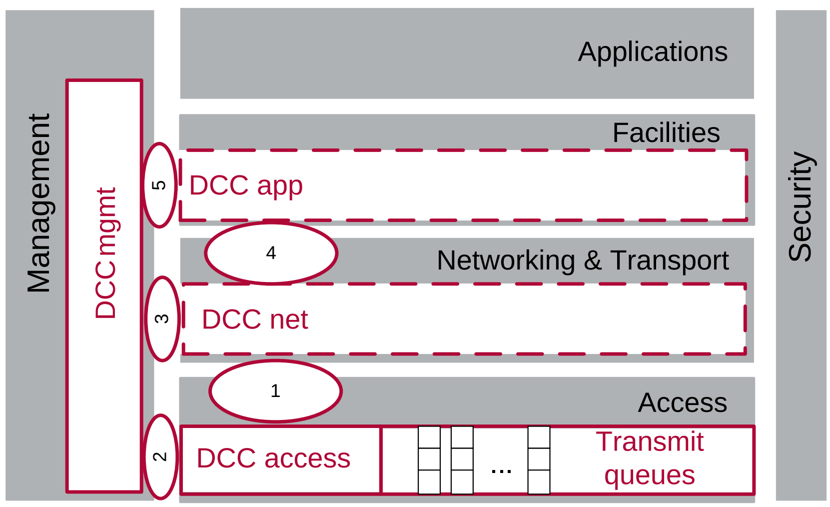


Figure 5.2.3.6-1: DCC Architecture (source: ETSI 102 687 [48])

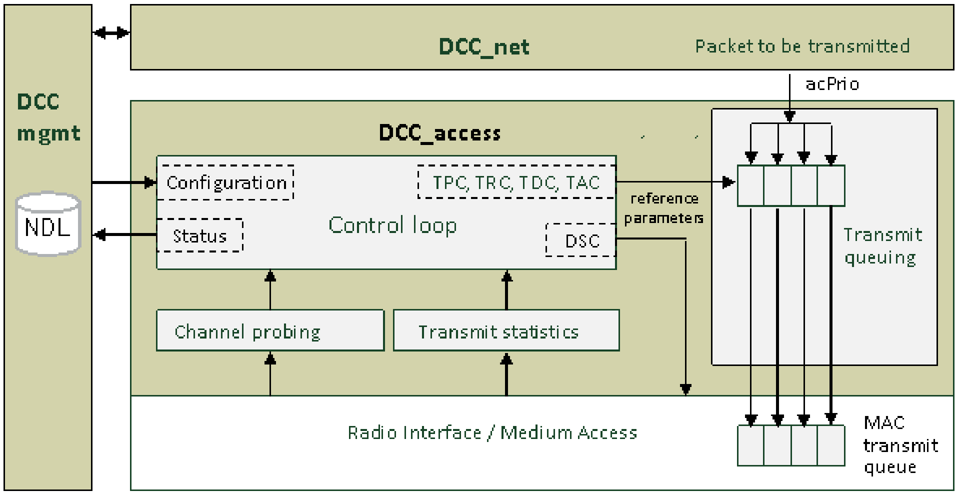


Figure 5.2.3.6-2: DCC_access functional view (source: ETSI 102 687 [48])

5.2.4 CEN DSRC Technology

CEN DSRC [32] is employed for Electronic Fee Collection (EFC) services. This technology is often denoted CEN DSRC in Europe. This standard is defined by European Committee for Standardization and specified in EN 12253, EN 12795, EN 12834 [ISO 15628] and EN 13372. These standards are not available for free. An overview on regulatory requirements is provided in [64].

The messaging layer complies with IEEE Std 1609.11-2010 (Over-the-Air Electronic Payment Data Exchange Protocol for ITS) [39].

An example use case illustrating electronic fee collection is provided in C.2 of IEEE 1609.0. The essential radio parameters of CEN DSRC are summarized in Table 5.2.4-1

Table 5.2.4-1: Parameters of CEN DSRC radio technology

Parameter	CEN DSRC
Band	5 795 – 5 815 GHz (20 MHz)
Number of Channels	4
Channel Bandwidth	5 MHz
Data Rate	Downlink: 500 Kbps Uplink: 250 Kbps
Range	15 - 20 m
Modulation	RSU TX: 2-ASK OBU TX: 2-PSK

When using V2X technology in the 5.9 GHz band, it must be ensured that CEN DSRC systems operated along the route are not experiencing any harmful interference within their communication range. The mobile V2X stations must be able to detect that they are approaching a CEN DSRC system and possibly lower their TX power. The permitted emission limits are defined in ETSI EN 302 571 [56].

5.3 LTE

An overview of LTE and the functionality most relevant for V2X is provided in [30].

LTE-based V2X communications can be realized over the uplink/downlink interface (Uu interface) or the sidelink interface (PC5). For downlink traffic on the Uu interface, both unicast and multicast/broadcast transport may be utilized to deliver the message within the area of interest. However, in the test network, multicast/broadcast is not supported.

Figure 5.3.x shows the high level view of the non-roaming architecture for PC5 and LTE-Uu based V2X communication [68].

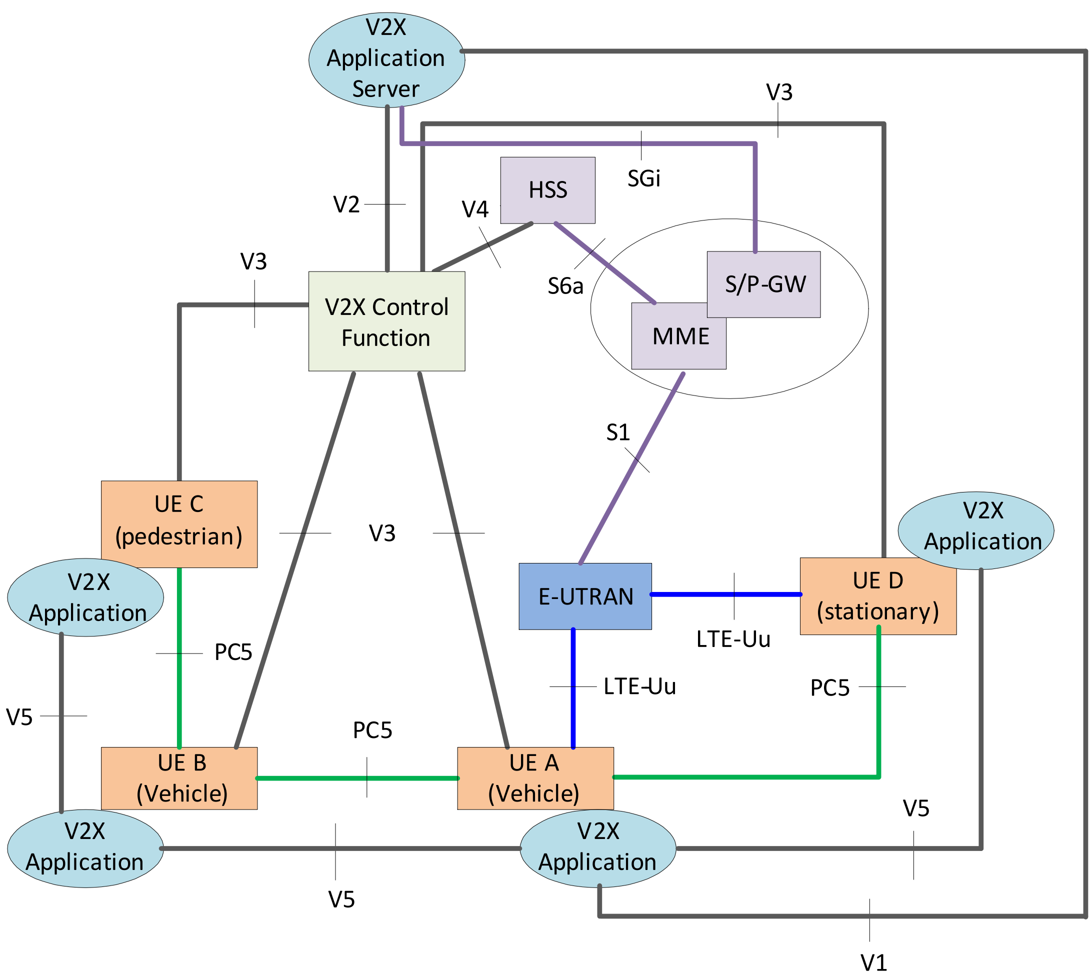


Figure 5.3-1: Non-roaming reference architecture for PC5 and LTE-Uu based V2X communication

Figure 4.2.2-1a and figure 4.2.2-1b show the high level view of the reference architectures with MBMS for LTE-Uu based V2X communication. V2X Application Server may apply either MB2 or xMB reference points when managing MBMS service related information via BM-SC, MB2 reference point as defined in TS 23.468 [7] provides functionality related to group communication and xMB reference point as defined in TS 26.346 [11] provides functionality overall for any content and also supports security framework between content provider and BM-SC.

Reference points

V1: The reference point between the V2X application in the UE and in the V2X Application Server. This reference point is out of scope of this specification.

V2: The reference point between the V2X Application Server and the V2X Control Function in the operator's network. The V2X Application Server may connect to V2X Control Functions belonging to multiple PLMNs.

V3: The reference point between the UE and the V2X Control Function in UE's home PLMN. It is based on the service authorization and provisioning part of the PC3 reference point defined in clause 5.2 of TS 23.303 [5]. It is applicable to both PC5 and LTE-Uu based V2X communication and optionally MBMS and LTE-Uu based V2X communication.

V4: The reference point between the HSS and the V2X Control Function in the operator's network.

V5: The reference point between the V2X applications in the UEs. This reference point is not specified in this release of the specification.

V6: The reference point between the V2X Control Function in the HPLMN and the V2X Control Function in the VPLMN.

PC5: The reference point between the UEs used for user plane for ProSe Direct Communication for V2X Service.

S6a: In addition to the relevant functions defined in TS 23.401 [6] for S6a, in case of V2X Service S6a is used to download V2X Service related subscription information to MME during E-UTRAN attach procedure or to inform MME subscription information in the HSS has changed.

S1-MME: In addition to the relevant functions defined in TS 23.401 [6] for S1-MME, in case of V2X Service it is also used to convey the V2X Service authorization from MME to eNodeB.

LTE-Uu: The reference point between the UE and the E-UTRAN.

V2X Control Function

The V2X Control Function is the logical function that is used for network related actions required for V2X. There is only one logical V2X Control Function in each PLMN that supports V2X Services.

NOTE 1: If multiple V2X Control Functions are deployed within the same PLMN (e.g., for load reasons), then the method to locate the specific V2X Control Function (e.g., through a database lookup, etc.) is not defined in the specification.

V2X Control Function is used to provision the UE with necessary parameters in order to use V2X communication. It is used to provision the UEs with PLMN specific parameters that allow the UE to use V2X in this specific PLMN. V2X Control Function is also used to provision the UE with parameters that are needed when the UE is "not served by E-UTRAN" (Mode 4).

The V2X Control Function may also be used to obtain V2X USDs for UEs to receive MBMS based V2X traffic, through V2 reference point from the V2X Application Server.

The case of roaming UEs is not considered in the ConVeX system, however solutions are elaborated in [68]

The V2X Control Function is not used in the ConVeX system. The necessary parameters are preconfigured on the UEs (modem part of ITS stations).

UE

The UE may support the following functions:

- Exchange of V2X control information between UE and the V2X Control Function over the V3 reference point.
- Procedures for V2X communication over PC5 reference point and/or LTE-Uu reference point.
- Configuration of parameters for V2X communication (e.g., destination Layer-2 IDs, radio resource parameters, V2X Application Server address information). These parameters can be pre-configured in the UE, or, if in coverage, provisioned by signalling over the V3 reference point to the V2X Control Function in the HPLMN.

The Layer-2 IDs are used to distinguish V2X services e.g. PSID or ITS-AIDs of the V2X application [40].

MBMS and the related nodes and interfaces are not used in convex system.

V2X Application Server

The V2X Application Server (V2X AS) may support the following capabilities:

- Receiving uplink data from the UE over unicast.
- Delivering data to the UE(s) in a target area using Unicast Delivery and/or MBMS Delivery.
- Several capabilities related to MBMS, which is not used in the ConVeX system.

MME

In addition to the functions defined in TS 23.401 [6] and TS 23.246 [8], in case of V2X the MME performs the following functions:

- Obtains subscription information related to V2X as part of the subscription data.
- Provides indication to the E-UTRAN about the UE authorization status on V2X use.

5.3.1 LTE side link (PC5 interface)

An overview of the LTE side link (PC5 interface) and the functionality most relevant for V2X is provided in [30] section 6.1.

The PSSCH is variable in size (as described within the SCI) and can be transmitted with QPSK or 16QAM modulation (according to the MCS).

For each MCS index, Table 8.6.1-1 of [70] gives the TBS index and modulation order, which is equal to the number of encoded bits per symbol and subcarrier. For the PC5 interface, the maximum order is 4. From the TBS index and the number of physical resource blocks (PRB) the TB size can be obtained from Table 7.1.7.2.1-1 of [70]. For 10 MHz bandwidth there are 50 PRBs. Assuming a transport block is used in every subframe of 1 ms, finally the resulting data rate can be calculated and the results are shown in Table 5.3.1-1. From the number of encoded bits/symbol and the fact that there are 600 subcarriers for 10 MHz and 9 OFDM symbols per subframe available for data transmission, the encoded bit rate (after turbo coding) can be calculated. The ratio of bit rates before and after coding denotes the code rate. The resulting code rate are also shown in Table 5.3.1-1.

9 OFDM symbols used for data transmission includes the first OFDM symbol, which is also called the AGC symbol, because within this symbol the receiver performs automatic gain control to adjust its amplification and ADC settings to the received power. Depending on implementation the receivers may not be able to make any use of the signal received during the AGC symbol for the channel decoding, so effectively it receives only 8 symbols, which can be translated to a higher code rate. The 3GPP performance requirements in [94] are in fact based on the assumption that only 8 symbols are received. For this reason, in Table 5.3.1-1 we state the code rate for both 8 and 9 symbols.

Comparing the LTE PC5 data rates to the ones of DSRC in section 5.2.2.2, the PC5 rates are lower. The reason is the higher overhead in DSRC for channel access time, preamble and PLCP header and cyclic prefix. DSRC, however, supports 64QAM modulation, which in LTE PC5 is only supported from Release 15. Since the ConVeX project focuses on Release 14, use of 64QAM on PC5 is not taken into account here.

Table 5.3.1-1: Relation of MCS index, data rate, code rate and encoded bits/symbol

MCS Index	data rate [Mb/s]	code rate excl. AGC symbol	code rate incl. AGC symbol	encoded bits / symbol
0	1.4	0.15	0.13	2
1	1.8	0.19	0.17	2
2	2.2	0.23	0.20	2
3	2.9	0.30	0.27	2
4	3.6	0.38	0.33	2
5	4.4	0.46	0.41	2
6	5.2	0.54	0.48	2
7	6.2	0.65	0.57	2
8	7.0	0.73	0.65	2
9	8.0	0.83	0.74	2
10	8.8	0.92	0.81	2
11	8.8	0.46	0.41	4
12	9.9	0.52	0.46	4
13	11.4	0.60	0.53	4
14	13.0	0.68	0.60	4
15	14.1	0.73	0.65	4
16	15.3	0.80	0.71	4
17	16.4	0.85	0.76	4
18	18.3	0.95	0.85	4
19	19.8	1.03	0.92	4
20	21.4	1.11	0.99	4

5.3.2 LTE cellular link (Uu interface)

An overview of the LTE cellular link (Uu interface) and the functionality most relevant for V2X is provided in [30] section 6.2.

5.4 Comparison of features

Table 5.4.-1 compares some key features of the 802.11p and LTE cellular and sidelink physical layer that also can provide some insights into the reasons of performance differences.

Table 5.4.-1: Key features of the 802.11p and LTE cellular and sidelink physical layer

Feature	**LTE cellular**	**LTE sidelink**	**802.11p**
unicast (acked) / broadcast (unacked)	unicast and broadcast in DL	broadcast (optionally 1 "blind" retransmission)	broadcast
multiple access	scheduled by eNB in time and frequency	Mode 3: Scheduled by eNB Mode 4: Distributed to UEs using resource pools configured by eNB(in coverage) or preconfigured (out coverage) Sync aiming at slotted transmission among UEs in communication range. Optimized for avoiding collisions for periodic transmissions. 1s sensing, selecting resources with lowest energy and not used by others for higher prio messages. Sensing updating includes a randomization.	Distributed, CSMA/CA with service priority dependent random backoff (ECDA) asynchronous transmission Hidden node problem can lead to collisions. No medium occupancy history taken into account.
synchronization	UE sync to eNB using PSS/SSS with 1ms period	Mode 3: UE sync to eNB Mode 4 out of coverage: GNSS	UE sync to preamble of PPDU.
modulation type	UL: DFT-S OFDM DL: OFDM	DFT-S OFDM	OFDM

modulation order	UL: up to 64QAM DL: up to 256QAM	up to 16QAM typically QPSK ½	up to 64QAM typically QPSK ½
link budget (TxPwr, RxSens QPSK for AWGN)	downlink: TxPwr: 46 dBm REFSENS (Band 7 2.6 GHz FDD): -95 dBm (10 MHz) -92 dBm (20 MHz) uplink: [94] TxPwr: 23 dBm REFSENS: -101 dBm	[94] TxPwr: 23 dBm REFSENS for 3.5 Mb/s (QPSK 1/3): -90.4 dBm (V2X Band 47, i.e. 5.9 GHz, QPSK)	TxPwr: 23 dBm between -82 dBm (QPSK 1/2) and -83 dBm (BPSK 3/4) [96] One product specification: Typ. Sensitivity for 6 Mb/s (QPSK 1/2): -95 dBm [95] for AWGN: -88 dBm for fading, 50 km/h
OFDM symbol time	67.7 us + 4.7 us CP (7.1% overhead)	67.7 us + 4.7 us CP (7.1% overhead)	8 us incl. 1.6 us CP (25% overhead)
Subcarrier spacing	15 kHz	15 kHz	156250 Hz
# subcarriers/ 10 MHz	600	600	64
bandwidth	1.4, 3, 5, 10, 15, 20 MHz	10 MHz or 20 MHz	10 MHz or 20 MHz
occupied bandwidth	90% (edges unoccupied)	90% (edges unoccupied)	81.25%
TTI	1ms	1ms	depending on message size and MCS
RS / pilot density	time: 4 per TTI frequency: every 4. subcarrier	time: 4 per TTI (3 for synch subframe) frequency: every subcarrier	time: every symbol 4 subcarriers of 52

From the table it is visible that LTE with 600 subcarriers uses much more than 802.11p. With state-of-the-art technology this is not a cost driver. The lower subcarrier spacing achieved with LTE results in longer OFDM symbols. This in turn has the advantage that a cyclic prefix long enough to cover the delay spread in a typical V2X propagation channel represents lower overhead. Table 5.4 shows that the CP overhead is 7.1% in the case of LTE versus 25% overhead in the case of 802.11p.

6 Performance Assessment

6.1 Link Level Performance

As already explained in section 5.3, LTE cellular link (Uu interface), LTE sidelink (PC5 interface) and IEEE 802.11p DSRC have different link level designs, e.g. coding scheme and frame structure. The link level performance is usually evaluated by Block Error Rate (BLER) under different conditions, e.g. Signal to Noise Ratio (SNR) and relative speed.

6.1.1 BLER vs SNR

Reference [66] has presented a link level performance comparison between LTE-V2X PC5, i.e. LTE-V in Figure 6.1.1-1, Figure 6.1.1-2 and Figure 6.1.1-3, and DSRC based on simulation. Both LTE-V2X PC5 and DSRC UEs are assumed to use same modulation scheme, coding rate, carrier frequency, fast fading model, noise figure and number of antennas. BLER values for different SNRs and receiving powers are evaluated. Detailed simulation parameters are shown in Appendix A.1. The difference between random and fixed carrier frequency offset, i.e. CFO in the figures, is negligible in this context.

Figure 6.1.1-1, Figure 6.1.1-2 and Figure 6.1.1-3 provide the simulation results for scenarios with different relative speeds. Line of Sight (LOS) propagation is also assumed. As usual, BLER decreases when SNR/receive power increases. For both PC5 and DSRC the SNR required for a specific BLER hardly depends on the message size, but for PC5 the required received power does. The paper does not provide an explanation, also not for why this is not the case for DSRC. Possibly it has been assumed that in the case of PC5 with its frequency-domain multiplexing on PRB basis, for the larger message a wider bandwidth is allocated, thereby leading to a larger received power of about 2 dB for the same SNR, whereas the fact that in the case of DSRC the message extends over a longer period of time is not revealed in this type of results.

Comparatively, under the same relative speed condition DSRC requires higher SNR/receive power to reach the same BLER as LTE-V2X PC5, for the target BLER of 5% at 30 km/h – 120 km/h as much as 4 – 5 dB more, whereas for 500 km/h LTE degrades more than DSRC so that the advantage decreased to 2 – 3 dB. For this high speed the performance however depends heavily on the employed receiver algorithms and all details are not disclosed in the source. The paper also does not explain why the differences in required receive power between DSRC and PC5 are even larger, for the 30 km/h 8 - 10 dB depending on message size. Possibly for DSRC the power is aggregated over the entire 10MHz channel (excluding guard band) whereas for PC5 only a subset of the 10MHz bandwidth is occupied, whereas the fact that the PC5 transmission time is with the LTE subframe length of 1ms longer than for DSRC does not impact this type of results. In essence, the receive power results are significantly less meaningful to compare efficiency than the SNR results, so we propose to focus on the latter.

According to the author, the superiority of LTE-V2X PC5 may be owing to the fact that turbo code used in LTE-V2X PC5 outperforms convolutional code used in DSRC. Other factors could be the ones discussed in section 5.4.

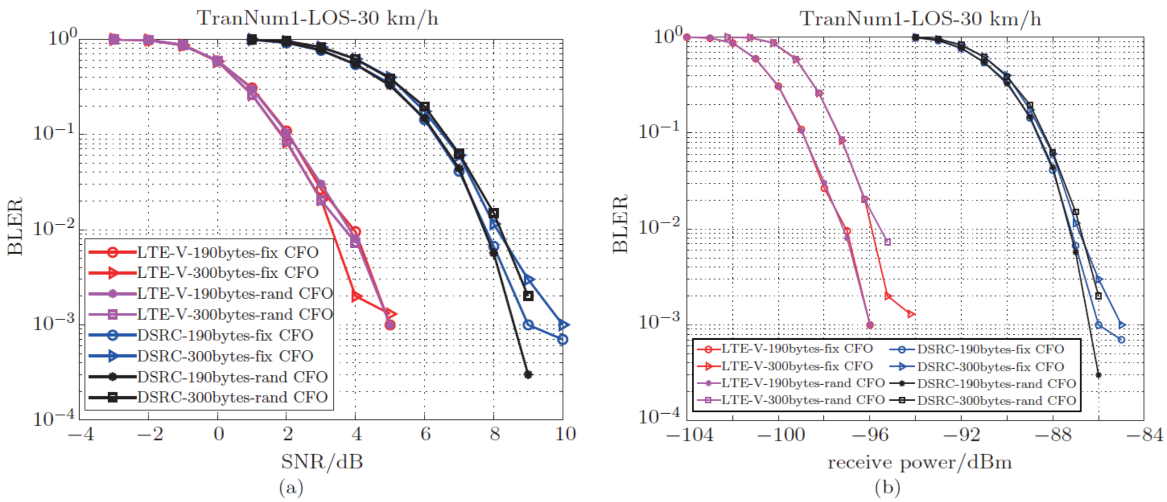


Figure 6.1.1-1: Link level performance comparison between LTE V2X and DSRC (urban case: LOS; relative speed 30 km/h). (a) SNR-BLER; (b) receiving power-BLER

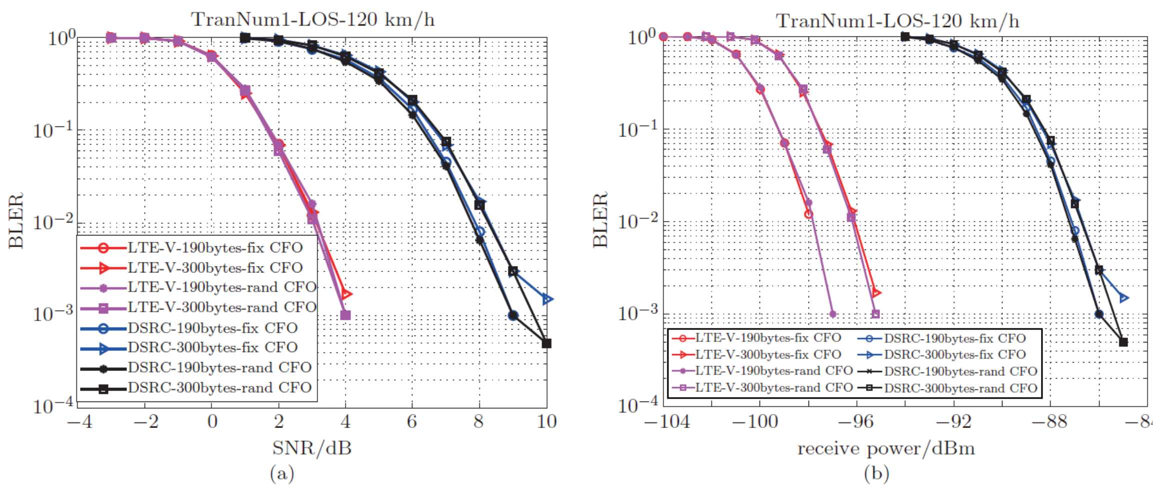


Figure 6.1.1-2: Link level performance comparison between LTE V2X and DSRC (urban case: LOS; relative speed 120 km/h). (a) SNR-BLER; (b) receiving power-BLER

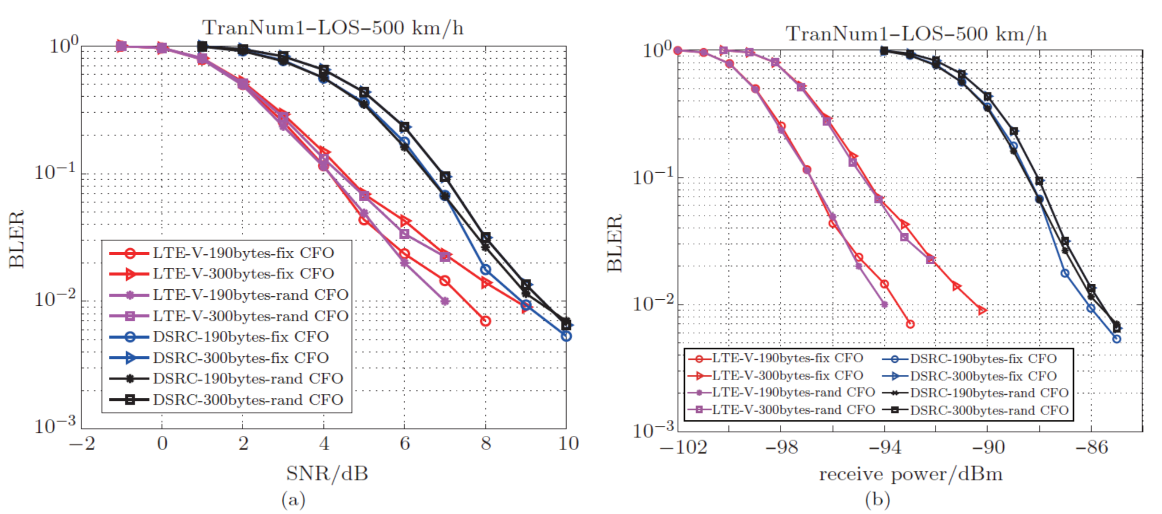


Figure 6.1.1-3: Link level performance comparison between LTE V2X and DSRC (freeway case: LOS; relative speed 500 km/h). (a) SNR-BLER; (b) receiving power-BLER

6.1.2 BLER vs Relative Speed

In vehicular environment, the high relative speed is one of the most challenging issue resulting in frequency offset and reception failure.

To overcome this problem, LTE-V2X sidelink increases the number of DMRS from two in LTE D2D to four [30]. These DMRS help to estimate the channel and compensate the frequency offset to a certain extent. Similarly, DSRC uses short and long training sequences to estimate and compensate the frequency offset. Therefore, it can be seen in Figure 6.1.1-1 and Figure 6.1.1-2, that when relative speed raises from 30 km/h to 120 km/h, performances of LTE-V2X sidelink and DSRC almost remain unchanged.

On the other hand, LTE-V2X sidelink by nature is more sensitive to frequency offset than DSRC. This is because LTE-V2X sidelink has subcarrier spacing of 15 kHz which is smaller than 156.25 kHz subcarrier spacing in DSRC. As a result, LTE-V2X sidelink can tolerate ± 0.1 ppm frequency error while DSRC can operate with frequency error between ± 20 ppm. It can be observed in Figure 6.1.1-3 that when relative speed is up to 500 km/h, both LTE-V2X sidelink and DSRC suffer from a severe Doppler effect and their performances degrade. In addition, the superiority of LTE-V2X sidelink becomes less obvious. However, the performance degradation for relative vehicle speed 500 km/h, appears to be rather pessimistic compared to results experienced in ConVeX field trials. It is planned to revisit the issue of performance degradation at high relative vehicle speed in the follow-up deliverable D3.2.

6.2 System Level Performance

Different from link level performance, system level performance focuses on the E2E performance, e.g. packet reception ratio (PRR) and latency, under more realistic scenarios considering communication distance and vehicle density etc. In this sense, MAC layer design is the key factor causing different system level performances and will be discussed in this section.

6.2.1 PRR vs Distance

Reference [27] compared the reliability performance for V2X CAM message transmission using LTE multicast, LTE-V2X PC5 mode 3, LTE-V2X PC5 mode 4 and DSRC respectively. The performances of the different vehicular communication alternatives are evaluated in the two scenarios as below:

- **Urban slow scenario:** models a dense urban deployment with 3 horizontal streets and 3 vertical streets with 175 vehicles/cell travelling at low speeds, i.e.15 km/h.
- **Freeway fast scenario**: models a 6-lane highway deployment resulting in 54 vehicles/cell travelling at high speeds i.e. 140 km/h.

During the simulation, all vehicles generate, send, and receive CAMs. CAMs are generated at regular interval of 100 ms. For every five messages, the first message has size 300 bytes followed by four messages of size 190 bytes. Detailed simulation parameters are given in Appendix A.2.

The simulation results are shown in Figure 6.2.1-1 and Figure 6.2.1-2. In general, reliability decreases when transmitter and receiver UEs are far away from each other. More precisely, LTE multicast has the best reliability performance than others, LTE-V2X PC5 mode 3 reaches a slightly higher PRR than LTE-V2X PC5 mode 4, and DSRC has the lowest PRR among them.

In addition to the link level performance as addressed in section 5.3 and 6.1, MAC layer design plays a significant role in terms of reliability. MAC layer for DSRC is EDCA and CSMA/CA based, where UE accesses the medium randomly with a back-off mechanism to avoid a certain level of collision. Sensing based Semi Persistent Scheduling (SPS) is used for LTE-V2X mode 4. SPS is designed for periodic message transmissions, e.g. CAM, and one UE is aware of the resource utilization via sensing and decoding SCI from other UEs. Hence, LTE-V2X mode 4 can do more efficient scheduling with the knowledge of resource reservation for future transmission. Since scheduling is conducted by eNodeB in LTE-V2X mode 3, collisions due to hidden node problem in mode 4 can be avoided and therefore a relatively higher PRR can be achieved. In LTE-V2X PC mode 3 and mode 4, it's allowed to let two UEs far away from each other transmit using the same resources and the interference is assumed to be minimized. In contrast, the same resource will not be reused in the same cell, as a result, receiver UE in LTE multicast suffers less interference and can reach a higher PRR.

It's worth mentioning that in this study, PRR is compared with the distance between two UEs, however, it's the distance between UE and eNodeB that matters in LTE multicast scenario. Hence, it can be observed that reliability for LTE multicast is lower than others for urban slow scenario when distance between UEs are smaller than 80m.

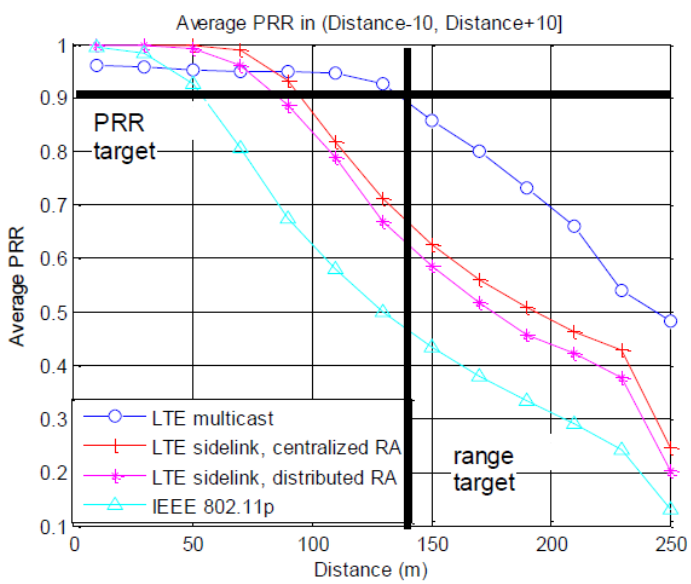


Figure 6.2.1-1: Comparison between different technologies at required vehicle density, i.e., 175 vehicles/cell in Urban Slow scenario at 6 GHz carrier

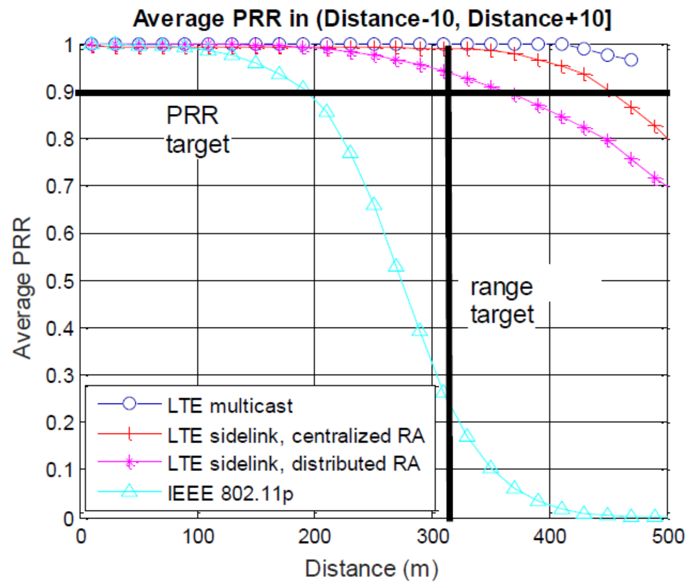


Figure 6.2.1-2: Comparison between different technologies at required vehicle density, i.e., 54 vehicles/cell in Freeway Fast scenario at 6 GHz carrier

6.2.2 PRR vs Traffic Load

Reference [69] conducted performance comparison between LTE, i.e. LTE cellular unicast, and DSRC under different traffic load conditions. The simulation scenario is set to be a 5x5 Manhattan grid with a number of vehicles transmitting a beacon message periodically (for both cases, LTE and DSRC) and the communication range is assumed to be 250 meters as described in Appendix A.3. Various traffic load is generated in the simulation by adapting two parameters, i.e. the beacon transmission frequency and the number of vehicles.

Figure 6.2.2-1and Figure 6.2.2-2 show the reliability performances of DSRC based and LTE based vehicular network respectively. It can be seen in Figure 6.2.2-1 that PRR, i.e. Packet Delivery Ratio in the figure, declines when there are more vehicles, i.e. “n” in the figure, transmitting at the same time or when vehicles are transmitting with a higher beacon transmission frequency. The reason is that the collision issue in CSMA/CA based MAC protocol becomes more severe with a higher traffic load. Additionally, DSRC is a broadcast system without ACK/NACK feedback, thus lost packet will not be retransmitted.

For LTE cellular unicast, a transmission only occurs when there are free resources available, in other words, vehicles within the same cell will not experience packet loss due to transmission collision. Besides, the HARQ process is enabled in LTE cellular unicast. A retransmission will be triggered if the packet is not received successfully and retransmission attempts are limited by a maximal number depending the configuration. As shown in Figure 6.2.2-2 if messages are delivered via LTE cellular unicast, PRRs above 96% can be achieved and they reduce slightly when increasing the beacon transmission frequency while a more observable reduction happens when increasing the number of vehicles in the simulation.

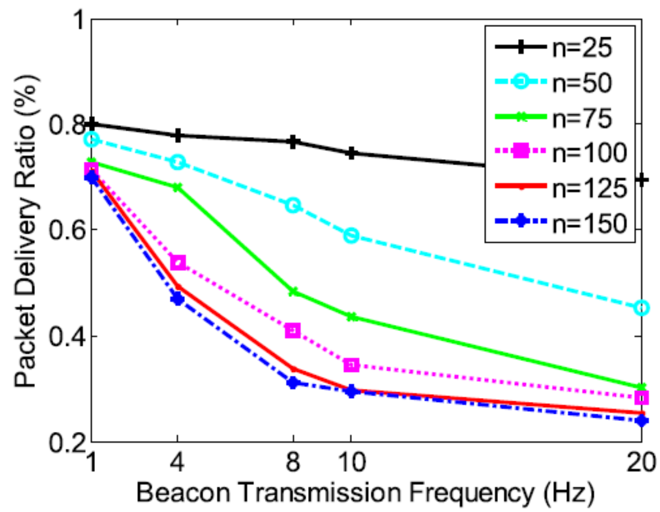


Figure 6.2.2-1: Packet delivery ratio (%) vs. beacon transmission frequency (Hz), IEEE 802.11p-based vehicular network

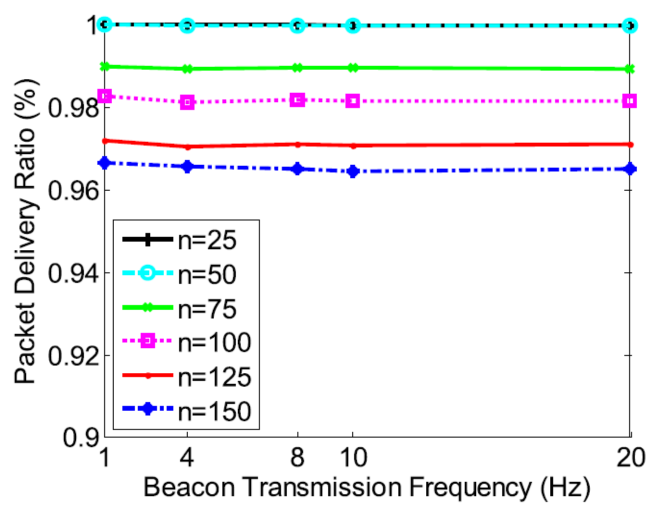


Figure 6.2.2-2: Packet delivery ratio (%) vs. beacon transmission frequency (Hz), LTE-based vehicular network

6.2.3 Latency vs Traffic load

The latency performance is also studied in [69]. It is shown in Figure 6.2.3-1 that the End-to-End delay raises dramatically from 1 ms to over 2000 ms when DSRC is used and the traffic load is high. The result reflects the analysis in 5.2 that if the cannel is busy, potential transmissions in DSRC must back-off a certain amount of time until the channel is idle again. Therefore, with a higher traffic load, a longer back-off time is expected. In comparison, every transmission is scheduled by eNodeB in LTE network and unnecessary back-off time can be saved. As a result, the End-to-End delay remains reasonably low even with a high traffic load as depicted in Figure 6.2.3-2.

As pointed out by the author, the vehicle density considered in [69] is relatively small, and the results may probably differ when a much higher vehicle density is applied. For instance, the delay in LTE unicast downlink will be heavily impacted when there are more target receivers.

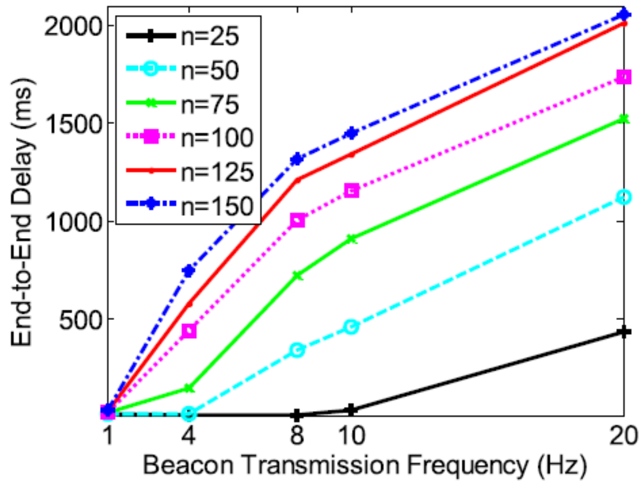


Figure 6.2.3-1: E2E delay (ms) vs. beacon transmission frequency (Hz), IEEE 802.11p-based vehicular network

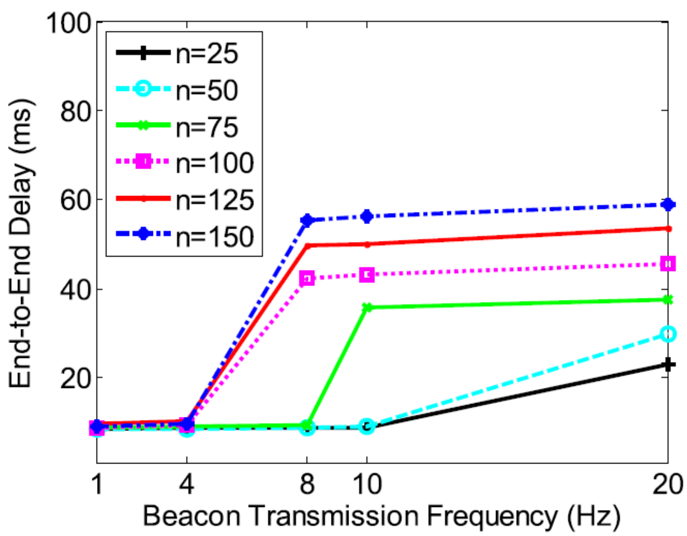


Figure 6.2.3-2: E2E delay (ms) vs. beacon transmission frequency (Hz), LTE-based vehicular network

6.2.4 Throughput vs Traffic Load

The actual throughput of one system can be evaluated by multiplying the transmitted data rate with the achieved reception ratio. The throughput performances of LTE and DSRC in study [69] can be deduced from Section 6.2.2.1 as shown in Figure 6.2.4-1 and Figure 6.2.4-2.Due to the low reliability performance of DSRC, the actual achieved throughput is also significantly lower than LTE network.

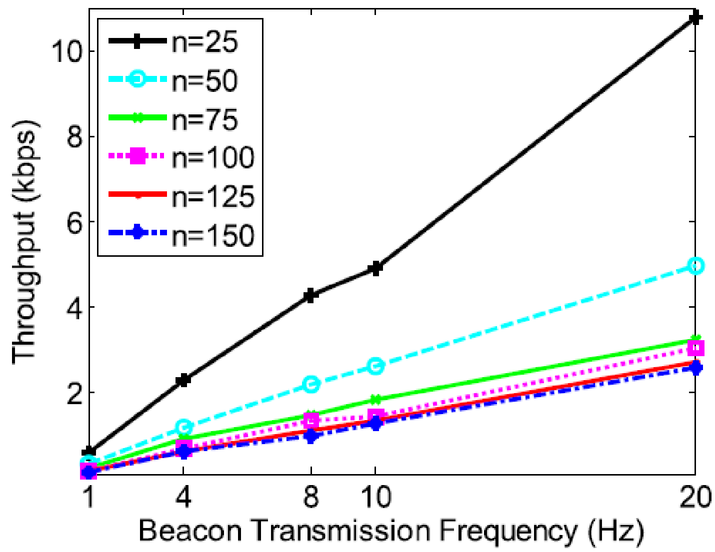


Figure 6.2.4-1: Throughput (kbps) vs. beacon transmission frequency (Hz), IEEE 802.11p-based vehicular network.

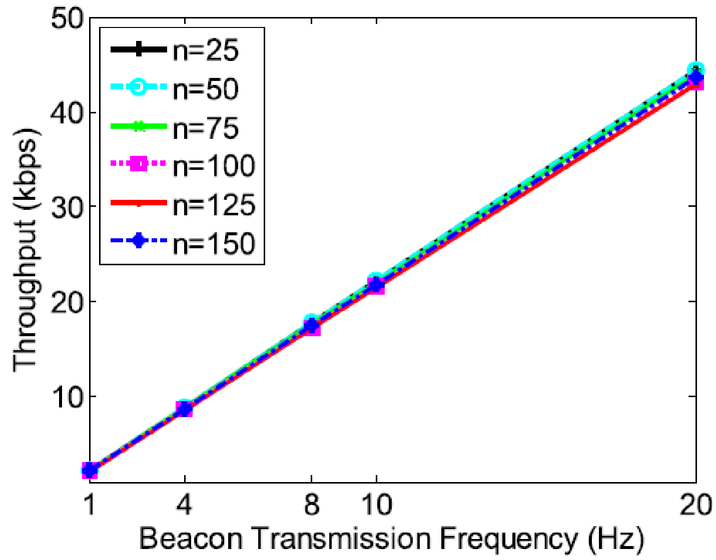


Figure 6.2.4-2: Throughput (kbps) vs. beacon transmission frequency(Hz), LTE-based vehicular network.

7 Suitability for ConVeX Use Cases

The objective of this chapter is to analyze the suitability of the radio technologies ETSI-ITS, C-V2X PC5 and C-V2X-Uu for the use cases defined in the ConVeX project.

Therefore, for each use case the critical requirements related to these radio technologies need to be defined.

The following table shows a summary of the requirements and how each technology covers them.

Table 7-1: Suitability for ConVeX Use Cases

Use Case	Critical Requirement	ETSI-C-ITS	C-V2X PC5	C-V2X Uu
FollowMe Information	Range and vehicle speed	not defined / not applicable (yet)	targeted use case (by design)	feasible (with larger delays especially suitable for distances out of PC5 range)
Cloud Based Sensor Sharing	Coverage area, high number and variety of sensor devices	no network support defined	could support device to device hopping	best suited, large coverage area
Blind Spot / Lane Change Warning	Short range, short delay, vehicle speed	Feasible	feasible, higher speeds	not suited
Do Not Pass Warning	Range (Passing Alert Distance, PAD) and vehicle speed	PAD=625 m e.g. HV/OLRV: v = 100 km/h ARV: v= 60 km/h [97]	PAD=1250 m e.g. HV/OLRV: v = 100 km/h ARV: v= 80 km/h [97]	can potentially extend range for early discovery of RVs
Emergency Electronic Brake Lights	Short range, short delay	Feasible	feasible, larger range; may support even higher vehicle speeds	can extend range for remote RVs, larger delays
Intersection Movement Assist	Range (obstructions), delay	lower range in case of Non-LOS (lower max. allowable path loss)	larger range in case of Non-LOS (higher max. allowable path loss)	not considered
Left Turn Assist	Range, obstructions, delay, vehicle speed	lower range in case of Non-LOS (lower max. allowable path loss), lower RV	larger range in case of Non-LOS (larger max. allowable path loss), higher RV	not considered

		speeds	speeds	
Vulnerable Road User Warning	Detectability of users	feasible but not defined yet	reliable detection within intended short range	not considered
Shockwave Damping	Range, traffic density	Lower range, higher density of RSU per area	higher range for vehicles and RSUs, lower density of RSUs per area	can extend range for remote RVs
In-Vehicle Information	Range (obstructions), vehicle speed, traffic density	Feasible, higher density of RSU for high speeds?	larger range, higher max. allowable path loss	can extend range of communicating devices
Road Works Warning	Range (obstructions), vehicle speeds, traffic density	lower range, higher delays, lower vehicle speeds	larger range, higher vehicle speeds	can extend range of communicating devices, higher delays
See Through	Data rates, range (obstructions), delays, vehicle speeds	lower range, higher delays, lower vehicle speeds	larger range, lower delays, higher vehicle speeds	can extend range of communicating devices, higher delays
Network Availability Prediction	Service availability and reliability, area	can support device to device communication, restricted service area	can support device to device communication, restricted but larger service area	proven service availability and reliability in large area

In the following part a few more differentiating aspects of the communication technologies, ETSI-C-ITS, C-V2X PC5 and C-V2X Uu are listed and described.

- ETSI-C-ITS
    - Allows direct car-to-car communication within a typically low to medium range distance (up to 50 m for urban and 300 m for highway) and low to medium vehicle speeds not optimally suited for the very high speed motorway scenarios up to 250 km/h or relative car speeds of up to 500 km/h.
- C-V2X PC5
    - Expected to allow direct car-to-car communication within a superior range distance and higher vehicle speeds (up to 250 km/h) and thus is best suited to fulfill the wide range of speed and road scenario requirements listed earlier.
- C-V2X Uu
    - LTE - and in future 5G - operated networks typically allow larger signal coverage areas (depending on the underlying network layout) but might be somewhat limited in very rural environments. Any involvement of such infrastructure will lead to additional end-to-end delays compared to a direct car-to-car communication. Considering these aspects, C-V2X Uu seems best suited for support of use cases characterized by large(r) coverage requirements at the expense of lower end-to-end delay requirements.

FollowMe Information

Compared to a clearly safety related use case the FollowMe Information Use Case can work with longer update cycles. In order to maintain the main functionality of receiving the path and position information of the HV in closer proximities, a feasible latency with a reasonable information update rate a certain level of quality of service should be available up to high vehicle speed. Since the main use case should contain a car following another one a relative speed of 250 km/h should be target.

With an increased distance between the cars the position and path information could also be forwarded by a cloud-based infrastructure in a lower frequency and a less accurate set position information.

Cloud Based Sensor Sharing

Since the use case does not aim for handling/solving an explicit driving maneuver (e.g. emergency break), but instead to share information on road users, forming a baseline for coordinated driving, the latency has to be low enough so that a movement prediction does not deviate too much from the real progression of events under normal driving circumstances. A stable latency and high reliability are more important. Thus, IEEE 802.11p is not suitable for the use case because of its unpredictable transmit back off time, while a cellular communication (incl. multicast) fulfils the requirements much better, and PC5 is in principle also suitable.

However, the cloud-based sensor sharing use case requires a backhaul communication to the cloud instance for data aggregation & fusion. This is most efficiently solved over a cellular network, which may also offer a cellular broadcast for efficient message dissemination in the downlink in case of a lot of road users. On the other hand, a cellular broadcast may (depending on the configuration) come with significant extra delay, which should be avoided. Furthermore, a long backhaul connection should be avoided, which adds several 10ms latency, but a deployment directly at the radio edge is not needed.

Blind Spot / Lane Change Warning

The critical requirement for this use case is the short end-to-end delay between detection of the RV in the blind spot of the HV and the notification of the driver of the HV. The shorter this delay, the more time to react for the driver of the HV is left. Direct V2V communication is clearly the most efficient communication technique here. V2N communication via the Uu interface involving further network elements is detrimental to this. The range requirements of this use case are short to medium distances between RV and HV, essentially depending of the driven absolute speeds of RV and HV on the one side and the relative speeds between RV and HV on the other side. The speed range can be from 0 km/h for cars leaving a parking lot up to 250 km/h for Motorway scenarios.

Do Not Pass Warning

Here the most relevant requirement will be the maximum feasible range of communication while allowing speeds up to around 100 km/h for rural passing scenarios. The larger the allowable distance between HV and RV for reliable exchange of CAM messages between the involved cars will be the more time is available to avoid risky maneuvers. V2N assistance might enlarge the relevant detection area given that network coverage is available.

Emergency Electronic Brake Lights

Similar to the blind spot warning use case the short end-to-end delay between the emergency breaking event of the RV and the notification of the driver of the HV is most important. The typical distance between RV and the (closest) following HV will be around half the distance in meters of the driven vehicle speeds (following the German rule of thumb of the security distance between two cars). For a critical Motorway scenario of 250 km/h this would mean a distance of 125 m. For other cars following at larger distances the RV, V2N involvement can considerably increase the covered relevant notification area.

Intersection Movement Assist

The most critical requirement for this use case will be the short end-to-end delay of the communication between RV and HV in all intersection scenarios with line-of-sight (LOS) and non-line-of-sight (NLOS) transmission and reception cases. Especially in cases where buildings or other objects and obstructions are impacting the human assessment as well as propagation of radio waves the fast and reliable communication between RV and HV is essential. The typical vehicle speeds within the zero or low range are less of a concern, and mainly depending on the signage with “Stop” or “Yield” signs and traffic situation and density.

Left Turn Assist

The requirement argumentation for the left turn assist use case follows mainly the ones given in the previous intersection movement use case. One typical difference might be the driven vehicle speeds, as it can be expected that in more left turn scenarios the driven HV speed might be higher than in the intersection use case, but again depending on the actual left turn scenario, traffic situation and density.

Vulnerable Road User Warning

For this use case the high reliability of detecting a vulnerable road user is most critical. Any obstructions and path loss impacts (e.g., placing a user’s device within a backpack, bag, boxes, clothes, etc.) should not lower the detection reliability of the device carrying user.

Shockwave Damping

In order for the shockwave damping algorithm to work a gapless coverage of a highway section is optimal. Critical traffic situations are typically linked to a high density of vehicles. Thus, the RSU is required to have a long range for sending IVIM and receiving CAMS even in presence of many OBUs, meaning less RSU devices per section are needed.

In-Vehicle Information

IVIM must not only be received at high vehicle speeds in a free traffic flow situation but also in a traffic jam or near traffic jam situation. A higher RSU range increases the coverage efficiency, i.e. less installed devices per distance. Ideally the effect of obstacles like gantries, trees or trucks has only a limited effect on the RSUs range and visibility.

Road Works Warning

For this use case the same applies as in the “In-Vehicle Information” use case for DENMs instead of IVIM.

See Through

See Through aims at scenarios with lower relative speeds in intersection and vehicle scenarios where the vehicles are in close proximity and a similar orientation. Especially on the infrastructural side a broadcast of the video stream seems reasonable.

To keep a certain level of usability the video information should be transmitted within less than 300ms end-to-end delay on application level without any noticeable loss of critical packets (e.g. key frames)

High latency and/or an entire breakdown of the communication must be detectable.

Network Availability Prediction

The C-V2X technology is envisaged to support ultra-reliable low latency communication scenarios (for e.g., road safety warnings) with strict requirements in terms of reliability and latency. This requires a shift of the system design from the traditional throughput oriented to the one based on dependability. The current generation of wireless networks (including C-V2X) assumes the availability of a Reliable Transmission Link (RTL) and on the top employs redundancy techniques (for e.g., retransmissions) in order to increase the probability of successful transmission. However, this may change in the future revisions where the URLLC service/application relies on the wireless communication only in those instances in which the RTL is guaranteed with a certain probability (also referred to as Ultra-Reliable Requirement).

In this regard, the purpose of this use case is to predict the RTL availability for the future timeslots based on the historical data from metrics such as predicted SINR, RSSI, RSRP etc. This is done by using the Machine Learning (ML) schemes and in particular the Recurrent Neural Networks (RNNs) since the prediction itself can be formulated as a time series forecasting problem.

Depending upon the type of connection, two prediction time windows can be foreseen

NAP aims to predict the link availability for the future timeslots based on historical data from metrics such as post equalized SINR, RSSI, RSRP etc. Depending upon the type of connection (V2V or V2N), two prediction time windows can be foreseen

- Prediction over Short Term (PST) - Suited for V2V / V2I and V2N connectivity where the availability of the network needs to be predicted for short time windows. This requires local temporal knowledge about the previous transmissions in order to make a prediction (channel tracking). An example use case benefitting from such a short term prediction is platooning where the inter platoon distance is varied according to the network conditions
- Prediction over Long Term (PLT) - Suited for V2N connectivity where the availability of the network needs to be predicted for a longer time window. An example of use cases requiring such long term prediction are over-the-air software update (as in the case of Tesla vehicles)

NAP requires real-time vehicle data such as speed, location etc. and very low feedback reporting delays (in the order of 2-5 ms). It may not be applicable to communication scenarios with no feedback channel (e.g. broadcast) and to vehicles with a very high relative velocity due to the short term nature of the connection. The feedback channel is assumed to be perfect.

8 Radio Spectrum Aspects

8.1 Current allocation of spectrum for ITS services

8.1.1 Introduction

This section provides information on spectrum allocations for ITS services in Europe and in the US.

8.1.2 Europe

In Europe, the frequency bands 5470 MHz to 5725 MHz, 5795 to 5815 MHz and 5855 MHz to 5925 MHz are assigned to ITS applications. The regulatory framework is defined by a series of ECC decisions, ECC Recommendations and EU Commission Decisions, see [73] - [78]. This ITS band allocation in Europe is illustrated in Figure 8.1.2-1.

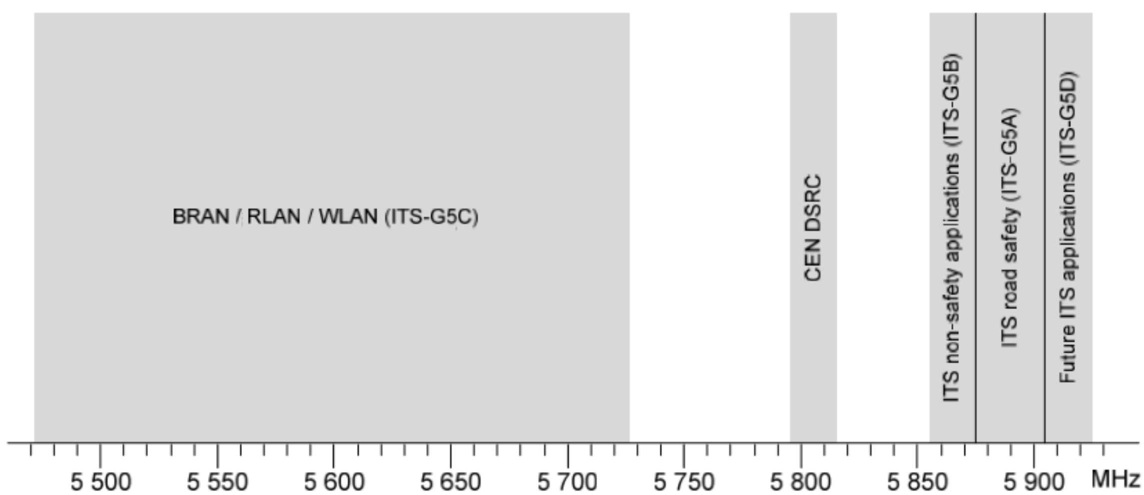


Figure 8.1.2-1: ITS band allocation in Europe in the 5 GHz range [79]

ETSI EN 302 663 [79] specifies the frequency allocation when deploying ETSI ITS-G5 systems in Europe in addition with a number of system-specific details and described as follows.

The **ITS G5A band** (5,875 GHz to 5,905 GHz) contains the channels CCH, SCH1 and SCH2. They are dedicated to road safety related service. The usage of the CCH, SCH1 and SCH2 channels is under control of the decentralized congestion control (DCC).

The Control Channel (CCH) is basically dedicated to cooperative road safety. It is the default channel for the transmission of DP1 and DP2 messages. The transmissions of messages using different DCC profiles (DP3 to DP8) on the CCH are allowed in the DCC state "RELAXED". In this DCC state the channel is not crowded and therefore no restrictions occur.

The Service Channel 1 (SCH1) is the default channel for announcing and offering ITS services for safety & road efficiency under the DCC state ACTIVE and RESTRITIVE of the CCH. The transmissions of other message-types on the SCH1 are allowed if channel conditions according to the restrictions in the present document permit.

The Service Channel 2 (SCH2) is the second service channel on ITS G5A and is used as an alternate channel for traffic safety-related services. Due to its frequency band allocation between the CCH and the SCH1 and the resulting potential adjacent channel interference issues, the flexibility of the deployment of the SCH2 is limited. The limitations are taken into account in the requirement descriptions for the SCH2.

The **ITS G5B band** (5,855 GHz to 5,9875 GHz) contains the channels SCH3 and SCH4. It is considered for general purpose ITS services (e.g. road efficiency, service announcements, multi-hopping, etc.). The ITS G5B band is not allocated European wide. Thus, local usage restrictions might apply.

The **ITS G5C band** (5 470 MHz to 5 725 MHz), a.k.a. the RLAN/WLAN/BRAN band, is

regulated in EN 301 893 [91], which conditions are given in Commission Decisions 2005/513/EC and 2007/90/EC.

The **ITS G5D band** (5 905 MHz to 5 925 MHz) is set aside for future usage of ITS road traffic applications and it is allowed to be used by ITS-G5 compliant stations as specified in ETSI EN 302 663 [79].

Table 8.1.2-1 ITS bands allocated in Europe

ITS Band	Frequency range	Usage	Regulation	Harmonized standard
G5D	5 905 MHz to 5 925 MHz	Future ITS applications	ECC Decision [75]	EN 302 571 [80]
G5A	5 875 MHz to 5 905 MHz	ITS road safety	Commission Decision [78]	
G5B	5 855 MHz to 5 875 MHz	ITS non-safety applications	ECC Recommendation [73]	
G5C	5 470 MHz to 5 725 MHz	RLAN (BRAN, WLAN)	ERC Decision [74] Commission Decisions [76] and [77]	EN 301 893 [91]

Table 8.1.2-2 shows the channel allocation and transmit power limits for ITS systems deployed in Europe. Note that the data in this table is obtained from ETSI EN 302 663 [79]. However, the TX power limits have been aligned with the latest version of EN 302 571 [9], which is more up to date.

Table 8.1.2-2 Channel allocation and power limits in Europe

Channel Type	Center frequency	IEEE 802.11-2012 channel	Channel spacing	Default data rate	TX power limit	TX power density

	(MHz)	number	(MHz)	Mbit/s	(dBm EIRP)	limit (dBm/MHz)
G5-CCH	5 900	180	10	6	33	23
G5-SCH2	5 890	178	10	12	33	23
G5-SCH1	5 880	176	10	6	33	23
G5-SCH3	6 870	174	10	6	33	23
G5-SCH4	5 860	172	10	6	33	23
G5-SCH5	5 910	182	10	6	33	23
G5-SCH6	5 920	184	10	6	33	23
G5-SCH7	As described in EN 301 893 for the band 5 470 to 5 725 MHz	94 to 145	several	Dependent on channel spacing	33 (DFS master) 33 (DFS slave)	23
NOTE: With respect to emission limit/power density limit, the more stringent requirement applies						

8.1.3 USA

In the US, the FCC has allocated spectrum of 75 MHz bandwidth from 5850 to 5925 MHz for vehicle to vehicle and vehicle to infrastructure communication as shown in the figure 8.1.3-1.

The maximum permitted transmit power (and antenna EIRP) depends on the channel and is shown in Table 8.1.3-1.

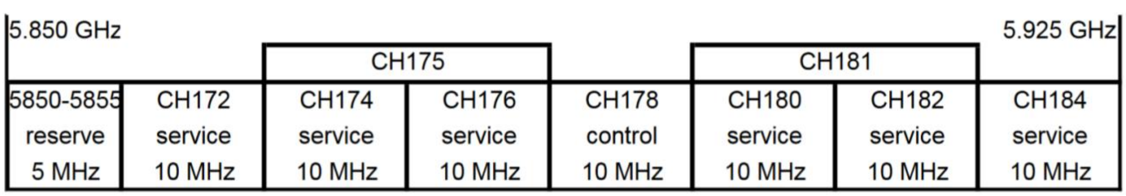


Figure 8.1.3-1: Band allocation for DSRC in the 5.9 GHz Band in the US [FCC]

Table 8.1.3-1: Maximum EIRP in the 5.9 GHz Band in the US [FCC]

Channel No.	Frequency Range (MHz)	Max. EIRP (dBm)	Channel Use
170	5850-5855		Reserved
172	5855-5865	33	Service Channel
174	5865-5875	33	Service Channel
175	5865-5885	23	Service Channel
176	5875-5885	33	Service Channel
178	5885-5895	33 / 44.8	Control channel
180	5895-5905	23	Service Channel
181	5895-5915	23	Service Channel
182	5905-5915	23	Service Channel
184	5915-5925	33 / 40	Service Channel

8.2 Spectrum requirements for ITS services using direct V2X communication

8.2.1 Introduction

In this section, we describe methodologies suitable for estimation of the overall amount of radio spectrum required to reliably support ITS services employing direct communication between vehicles (V2V), vehicles and RSUs (V2I) and between vehicles and pedestrians (V2P).

The amount of radio spectrum required depends principally on the type of ITS services to be supported (including number and size of the messages and their statistical distribution), the performance characteristics of the employed radio technology (spectrum efficiency, targeted communication range), and the density of ITS stations (i.e. vehicles, RSUs and VRUs) for typical road traffic scenarios, such as e.g. highway and urban street scenarios.

Focusing on ITS basic safety messages, V2X traffic consists of periodically sent CAMs and event-based triggered DENMs. The vast majority of messages will be CAMs.

There are also additional non-safety related message types (see ETSI TS 103 301 [92]), e.g. in-vehicle information massage (IVIM), road/lane topology and traffic maneuver message (MAPEM), and signal phase and timing extended message (SPATEM) which contribute to the spectrum requirement.

The spectrum bandwidth BW_{req} *(Hz)* required to serve a given traffic load in a radio network can be represented as the ratio of the required overall communication traffic data rate C_{req} (bit/s) and spectrum efficiency *SE* (bit/s/Hz):

$$BW_{req} = \frac{C_{req}}{SE} \quad (1)$$

The required overall network communication traffic data rate C_{req} is also denoted *required system capac*ity. The offered traffic load C_A is the aggregated data rate of all users of a communication channel. In order to serve the offered traffic load at a finite delay, the condition

$$C_{req} \geq C_A \quad (2)$$

must be met. A radio network is congested (overloaded) if its capacity C is lower than the offered traffic load. The required system capacity can be further expressed as follows by introducing a resource utilization efficiency, $0 \leq \alpha \leq 1$:

$$C_{req} \geq C_A/\alpha \geq C_A \tag{3}$$

The resource utilization efficiency expresses the fact that

(a) not all radio resources can be utilized for message transmissions of the stations inside resource reuse range D_{RR},

(b) additional protocol and signaling overhead needs to be taken into account.

Even if ideal scheduling of transmissions is assumed, i.e. no collisions due to simultaneous transmission attempts, the utilization factor is typically smaller than 1 in a radio system due to required overhead. Both, offered traffic load C_A and spectrum efficiency SE are random variables which depend on many parameters. The offered traffic load depends on the number and geographical distribution of the ITS stations, as well as the statistical distribution of the ITS messages and of their length (in bytes). Spectrum efficiency depends on the radio access technology, modulation and coding scheme, the random radio propagation characteristics and the target QoS requirements (see section 8.2.2).

8.2.2 V2X scenarios and propagation model

This section provides a description of typical V2X scenarios (urban street and highway scenarios) and radio performance aspects relevant to the analysis of the spectrum requirements.

The required spectrum depends on

- Size and frequency of transmitted messages (“packets”)
- Number of ITS stations (vehicles, RSUs, VRUs) transmitting messages (density per area unit)
- Geographical distribution and mobility of the ITS stations
- Target performance characteristics (PRR, delay, communication range)
- Radio propagation characteristics
- Spectrum efficiency of the radio technology for the given scenario

Consider a scenario as illustrated schematically in Figure 8.2.2-1. Assuming isotropic radio propagation, the signal transmitted by a vehicular ITS station V1 can be received by stations which are located within a circular area of radius D_R around the transmitter (stations V2 and V3). We denote D_R as the V2V *communication range*. The distance D_R may be determined such that all are served at a desired target level of QoS performance.

QoS performance can be defined in terms of a desired target Packet Reception Rate (*PRR*) of e.g. 95 % and a probabilistic limit on the transmission latency L.

Any vehicles inside the circle of radius D_R can be considered to be served adequately. The circle of radius D_R defines the *service area* around a considered reference ITS station.

The performance of a V2V transmission system is furthermore impacted by ITS stations which contribute to interference on any of the receiving stations within range D_R. This is illustrated in Figure 8.2.2-1 with a second circle of radius D_{RR}. ITS stations (V8, V9, V10) outside of D_{RR} are considered to not produce harmful interference to stations inside the considered communication range. Note that stations separated by at least the distance D_{RR} from each other could all transmit simultaneously without producing harmful interference onto a receiver located at the edge of the respective transmission range (i.e. the receiver in the most unfavorable radio condition).

The carrier sensing range D_{CS} is the maximum distance between two ITS stations where the one station is able to sense if the other station is transmitting. To avoid harmful transmission collisions, it is necessary to operate at a carrier sensing range which is at least equal to the resource reuse distance, i.e. $D_{CS} \geq D_{RR}$.

In 802.11p based systems, only a single ITS station inside the resource reuse range D_{RR} can transmit at a given time. Any simultaneous transmissions of two or more stations would cause a collision and cause loss of both colliding messages.

The 3GPP PC5 interface allows resource allocations where multiple stations can transmit simultaneously when different frequency resources of the resource pool are employed.

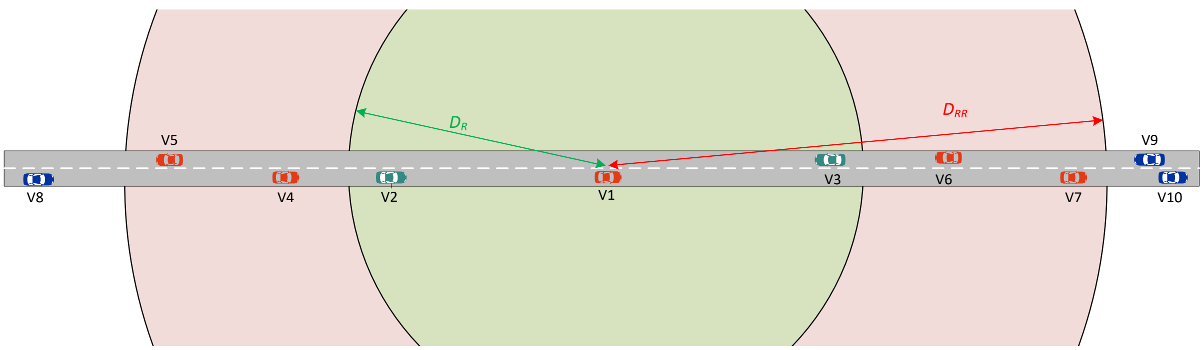


Figure 8.2.2-1: V2V propagation scenario

Table 8.2.2-1 lists the parameters and their definitions which are relevant to estimation of V2X spectrum requirements.

Table 8.2.2-1: Symbols and Definitions used in spectrum requirement estimations

Name	Symbol	Definition
Required system capacity	C_{req}	System capacity in bit/s required to serve all communications at the desired target QoS
Latency limited data rate	C_L	Instantaneous peak data rate due to critical latency requirement
Aggregated data rate	C_A	Overall aggregated transmission data rate in a long-time scale and periodic manner
Communication Range	D_R	Maximum distance between transmitter and receiver allowing reception at the target QoS level (defined in terms of PRR and delay)
Carrier Sensing Range	D_{CS}	The maximum distance between ITS station allowing sensing of transmission
Resource Reuse Distance	D_{RR}	The minimal distance between two stations which can transmit simultaneously on the same radio resources without causing intolerable interference.

Message size	S	V2X message (packet) size in bits or bytes per packet
Message frequency	F	Frequency of periodically transmitted V2X messages in packets per second
Number of vehicles within resource reuse distance	N	The number of transmitting ITS stations contributing to the overall offered traffic load
Channel Bandwidth	BW_{ch}	Bandwidth of a single radio transmission channel in Hz
Required Bandwidth	BW_{req}	Required total spectral bandwidth to serve a given offered traffic load in the V2X radio communication system
Spectrum Efficiency	SE	The amount of bit rate transmitted per Hz
Required Signal to Interference and Noise Ratio (SINR)	$SINR_{req}$	For a certain technique, it represents the needed SINR to achieve the target *PRR*
SINR at the edge of communication range	$SINR_R$	For a certain technique, it represents the actual SINR at the edge of the communication range
Resource utilization efficiency	A	Fraction of radio resources available for message transmission (in practice <1 due to non-ideal scheduling and overhead required for message acquisition)
Vehicle density	P	Average number of vehicles per meter (for unidimensional geographic distribution)
Latency constraint	L	Maximum tolerable latency in seconds

Figures 8.2.2-2 and 8.2.2-3 illustrate two typical traffic scenarios frequently used for assessment of offered traffic load, a highway and an urban street junction scenario, respectively.

A highway scenario as shown in Figure 8.2.2-2 is typically a straight road section with 2 to 6 lanes per direction. The distance between vehicles depends on the speed. In a “dense traffic” scenario a vehicle speed of 70 km/h is assumed. In a “sparse traffic” scenario a vehicle speed of 140 km/h is assumed. The distribution of vehicles is typically represented as a Poisson point distribution in each lane with 2.5 s mean time ahead between two cars. This corresponds to ~50 m and ~100 m in the dense and sparse traffic scenarios, respectively.

Assuming a communication range of D_R = 400 m, each lane may include on average 800/50 = 16 or 800/100 = 8 vehicles in the dense and sparse highway scenarios, respectively, within communication range. Assuming $D_{RR} = 2D_R$, there are on average 32 and 16 cars located inside the frequency reuse distance relevant for calculation of the offered traffic load. Considering 6 lanes, there are in total N = 192 and 96 cars inside D_{RR} in the dense and sparse scenarios, respectively.

Considering the transmission of CAM (indicating position locations of the vehicles) only, a transmission frequency of F =10 messages/s (i.e. message period 100 ms), and an average message length S = 300 bytes/message, the offered traffic load can be calculated as

$$C_A = N \cdot S \cdot F \quad (4)$$

which amounts to 192·2400·10 bps = 4.61 Mbps and 2.3 Mbps in the dense and sparse highway scenarios, respectively.

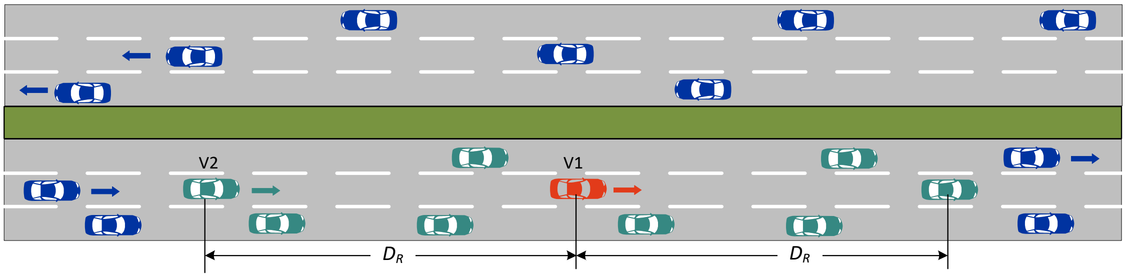


Figure 8.2.2-2: Illustration of highway scenario

The example metropolitan street junction (without flyovers), as schematically illustrated in Figure 8.2.2-3, shows 3 lanes in each direction. Assuming a communication range of D_R = 50 m and a resource reuse distance of D_{RR} = 2 D_R = 100 m.

Assuming car length of 4.5 m and distance between cars of 2.8 m, there will be 14 cars per lane per D_{RR} = 100 m which results in a total number of 14 · 3 (lanes) · 2 (drive directions) · 2 (courses) = 168 cars inside D_{RR}. Note that this example corresponds to the calculation of the traffic on two crossing straight streets independent of each other. The traffic inside of the junction's cross-section is approximated with this approach.

The offered traffic load amounts in this example to C_A = 168·2400·10 bps = 4.032 Mbps.

If the assumed resource reuse distance D_{RR} would be doubled, then also the offered traffic load doubles.

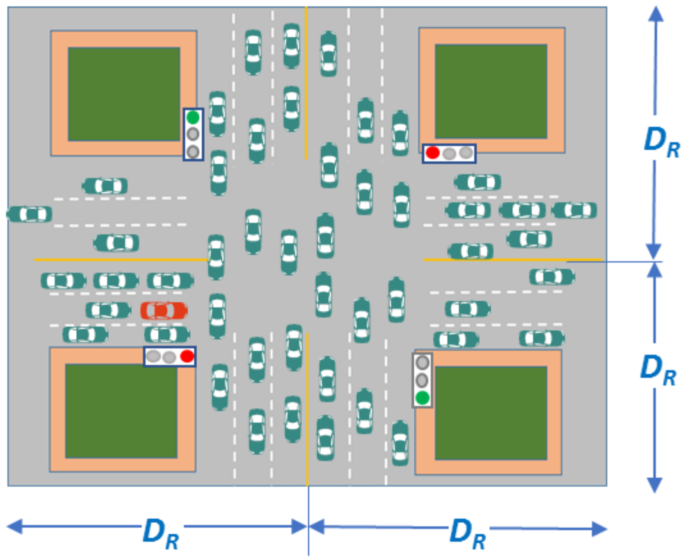


Figure 8.2.2-3: Urban street junction scenario

8.2.3 Deterministic method

This section presents a simple deterministic methodology for the estimation of the bandwidth requirement of V2X services. In this approach, offered traffic load C_A and spectrum efficiency SE in equation (1) are simply assumed to represent deterministic rather than stochastic numbers, which are known a-priori. This approach is denoted as *traffic loading mapping approach* in [84].

The analysis is based on the following assumptions:

1) The traffic load generated by each ITS station is equal and simply calculated based on a fixed message size S (bits) and a constant periodic message frequency F (packets/s).
2) All transmissions are broadcast type (no pairing, no unicast): transmit power is assumed to be chosen such that the station most distant from the transmitter is served at the desired QoS within a given range D_R.
3) All stations transmit with a fixed modulation and coding scheme (MCS) appropriate to serve all stations at the desired QoS within a given range D_R. QoS is defined in terms of PRR and maximum delay requirement.
4) Multi-user transmit multiplexing in the time-domain only, i.e. only one user is allowed to transmit on a given frequency channel at a given time.

From assumption 1) the offered traffic load can be calculated as

$$C_A = \sum_{n=1}^{N} S_n \cdot F_n = N \cdot S \cdot F \qquad (5)$$

where N is the number of ITS stations within the resource reuse distance D_{RR}, $S = S_n$ is the constant message size and $F = F_n$ is the constant message frequency.

Based on assumptions 1), 2) and 3), spectrum efficiency is calculated as

$$SE_{tx} = \frac{R_{tx}}{BW_{ch}} \tag{6}$$

where R_{tx} is the nominal transmission data rate associated with the selected MCS and BW_{ch} is the nominal channel bandwidth of 10 MHz.

The spectral efficiency in (6) is indexed with "tx" and referred to as *spectral efficiency at the transmitter*. This is reasonable because its amount depends solely on the characteristics of the used modulation and coding scheme employed by the transmitter. Characteristics of radio propagation and of reception performance are not incorporated in the calculation of SE_{tx}.

The bandwidth requirement can be calculated from equation (1) to (6) as

$$BW_{req} \geq \frac{N \cdot S \cdot F}{SE_{\mathrm{tx}} \cdot \alpha} \tag{7}$$

Example for 802.11p-based systems in urban traffic scenario:

Calculation of the offered traffic load:

CAM size (as assumed in 5GAA studies [84]): S = 300 bytes = 2400 bits

The packet size S is assumed to include lower layer protocol overhead (approx. 40 bytes + security overhead).

Offered traffic load for the urban scenario in Figure 8.2.2-3 has been derived in Section 8.2.2 as C_A = 4.032 Mbps.

Calculation of the spectrum efficiency:

Assuming MCS associated with data rate R_{tx} = 6 Mbps (QPSK, r = 1/2), presumed to be suitable for the coverage range D_R = 50 m of the urban scenario in Figure 8.2.2-3 for the given QoS requirements.

SE_{tx} = 6 Mbps / 10 MHz = 0.6 bps/Hz (48 bits per OFDM symbol and transmit time 8 us/OFDM symbol)

On the MAC layer, MAC protocol information of 34 Bytes is added to each CAM message payload (see Section 5.2.2.5). On the PHY layer, a 16 bit Service field and 6 tail bits are added (see Section 5.2.2.3). The overall packet size on the PHY layer amounts to (300+34)·8 + 22 = 2694 bits. This packet is mapped onto 57 OFDM symbols.

Each individual PHY packet requires an additional overhead of 13 symbols for PLCP (see section 5.2.2.3). The PLCP overhead can be converted into a resource utilization efficiency of α = 50/63 = 0.79.

Calculation of the spectrum requirement:

Calculating the spectrum requirement from eq. (4) yields:

$BW_{req} \geq$ 4.032 Mbps/0.6 bit/Hz/0.79 = 8.51 MHz

Example for C-V2X LTE sidelink in urban traffic scenario:

The LTE sidelink employs a fixed time interval of 1 ms (i.e. a subframe) to transmit data packets. Sidelink transmission allows flexible mappings of data packets onto the symbols of a subframe. The mapping may be done such that only a fraction of the channel bandwidth is utilized. The remaining portion of spectrum can for instance be used for transmissions of multiple ITS stations in a frequency division multiplex (FDM) fashion. Alternatively, the mapping could be such that the entire spectrum is utilized by a single packet. In this case, however, very strong encoding of the data bits can be applied, i.e. requiring a lower SINR to achieve reliable packet reception performance. Derivation of the spectrum requirement with the deterministic method as given in equation (7) is therefore somewhat tricky for LTE sidelink if the result should allow a comparison with the result obtained for 802.11p. In the following example we make the assumption that both systems transmit a data packet at the same modulation order (i.e. QPSK) and approximately the same coding rate of 1/2. In this case the LTE sidelink does not use the full available channel bandwidth and allows FDM. The result of this calculation does not take into account that the SINR requirement for LTE sidelink can be expected to be lower due to usage of a better encoding scheme (i.e. turbo coding versus convolutional coding in 802.11p).

Offered load: C_A = 4.032 Mbps (see example above)

Calculation of the spectrum efficiency:

We assume that at the desired edge of the communication range, the SINR is large enough to use MCS=6. According to Table 5.3.1-1 this implies QPSK with code rate 1/2 is used, such that SE_{tx} can be determined to be 0.52 bps/Hz.

The sidelink MAC layer adds a header of 10 Bytes (see 3GPP TS 36.321 [71]). The ITS message with MAC header then has a size of 310 Bytes (2480 bits), which can be mapped onto a Transport Block of size 2600 bits, requiring 25 Resource Blocks (RBs) for transmission at MCS=6, see [70]. In addition 2 RBs are required for the Physical Sidelink Control CHannel PSCCH, so that in total 27 RBs are transmitted per message.

The spectrum efficiency number of SE_{tx} = 0.52 bps/Hz from Table 5.3.1-1 applies to transmission of 50 RBs. The resource utilization efficiency can be determined from the MAC and PSCCH overhead $\alpha = 300/310 \cdot 25/27 = 0.90$ can therefore be assumed, provided all available subframes are utilized for data transmission (i.e. for ideal scheduling).

Calculation of the spectrum requirement:

Calculating the spectrum requirement from eq. (6) yields:

$BW_{req} \geq 4.032$ Mbps/0.52 bps/Hz/0.9 = 8.61 MHz

8.2.4 System simulation based method

In the simulation based method, vehicular traffic is simulated for selected scenarios according to a statistical model (e.g. Poisson point distribution of a given density). Then packet transmission for each of the vehicles involved in the traffic scenario is simulated applying statistical radio propagation channel models and appropriate link-to system-level mapping methods by which static signal-to-interference and noise ratios (*SINR*) are converted into *PRR* performance. By realistic modelling of V2V message generation for each vehicle, carrier sensing and of the medium access mechanisms, it is also feasible to investigate the delay performance. Simulation techniques used by 3GPP working groups are described in detail in 3GPP TR 36.885 [86].

For instance, for a highway street scenario as shown in Figure 8.2.2-2, a straight road section of about 3500 m length is typically considered. The length of the investigated road section in such simulations should be at least twice the resource reuse distance D_{RR} and larger than twice the target communication range D_R.

A critical parameter in such simulations is the SINR required to achieve a target PRR-performance. This parameter depends primarily on the characteristics of the propagation channel, the MCS of the transmitted signal, as well as the assumed receiver technology. In simulations a typical assumption on receiver technology is that Minimum Mean Square Error with Interference Rejection Combining (*MMSE-IRC*) receivers with 2 receive antennas are employed.

For a given vehicular traffic distribution and a given communication traffic model, the result can be determined as a curve showing PRR and/or delay performance versus the available frequency bandwidth (e.g. for *n* available 10 MHz frequency channels, or other channel bandwidth allocations).

8.2.5 Theoretical spectrum efficiency based model

The method described in this section has been proposed in [82].

As described in section 8.2.3, the spectrum demand can be evaluated by dividing required capacity C_{req} (bit/s) using spectrum efficiency SE (bit/s/Hz) as in equation (1).

Since communication requirements are critical for V2X use cases and have significant impact on spectrum demand, the evaluation framework shall include those factors. The remainder of this subsection describes a framework based on equation (1) while taking required communication range, reliability, and latency into consideration.

First, the required system capacity C_{req} (bit/s) is calculated by equation (2) to (6). It equals to the maximum among latency limited data rate C_L and aggregated transmission data rate C_A times required reliability defined in terms of Packet Reception Rate PRR (%) and then divided by resource utilization ratio $\boldsymbol{\alpha}$. C_L represents the instantaneous peak data rate due to critical latency requirement and is greater than or equal to the ratio between the V2X message of size S (bits) and the latency constraint L (s) for transmitting the message over the air, as shown in (8). In case various messages are used in the V2X system, the C_L shall be determined by the most demanding message, i.e. the message having the highest C_L value. C_A stands for aggregated data rate in a long-time scale and periodic manner. It is the product of message size S, message generation frequency F (Hz) and number of vehicles N as given in (9). N vehicles are assumed to fully utilize the spectrum and it equals to vehicle density ρ (vehicles/m) times resource reuse distance D_{RR} (m). In direct V2X communication, the time-frequency channel resource can be reused in the spatial domain, provided that the co-channel interference at the desired receiver does not exceed the acceptable level. D_{RR}, which is expressed in meters, is the distance between two vehicles that use the same channel resource. The maximum among C_L and C_A represents the required transmission data rate, while the actually required system capacity is the transmission date rate times the required reliability PRR.

$$\boldsymbol{C_{req}} = \frac{\boldsymbol{max\{C_L, C_A\} \cdot PRR}}{\boldsymbol{\alpha}} \tag{8}$$

$$\boldsymbol{C_L \geq \frac{S}{L}} \tag{9}$$

$$\boldsymbol{C_A = S \cdot F \cdot N} \tag{10}$$

$$\boldsymbol{N = \rho \cdot D_{RR}} \tag{11}$$

Assuming an additive white Gaussian noise (AWGN) channel, the spectrum demand lower bound BW_{AWGN}, which is technology agnostic, can be determined by (11). Note that (11) represents the information-theoretic Shannon bound on the capacity of an AWGN channel [89]. SNR_R is the reference signal-to-noise-ratio (SNR) for which the channel capacity C_{req} can be obtained for an AWGN.

$$\boldsymbol{BW_{AWGN}} = \frac{\boldsymbol{C_{req}}}{\boldsymbol{log_2(1 + SNR_R)}} \tag{12}$$

The reference SNR in equation (12) can be expressed as

$$\boldsymbol{SNR_R} = \frac{\boldsymbol{C_{req}}}{\boldsymbol{BW_{AWGN}}} \cdot \frac{\boldsymbol{E_b}}{\boldsymbol{N_0}} \tag{13}$$

where E_b and N_0 are the bit energy and noise spectral density, respectively.

To evaluate the spectrum demand when using a specific technique, e.g. DSRC or LTE-PC5, we can first determine the spectrum efficiency SE_{tx} at the transmitter side as defined in subsection 8.2.3.

Note that SE_{tx} is calculated by dividing the nominal payload data rate C_N (bit/s) by the occupied bandwidth W (Hz) according to the specification of the V2X technology. It denotes the spectral efficiency solely due to the modulation and coding scheme parameters without considering the reliability performance at receivers.

Considering reception failure due to noise and interference and the mismatch between the required reliability and the achieved reliability, the effective spectrum efficiency at receiver side can be estimated as (13).

$SINR_{req}$ is the required SINR to achieve the target PRR for a given MCS and given radio channel characteristics, and $SINR_R$ is the actual SINR at the edge of the communication range. Note that the reference SINR can be expressed similarly to equation (13), where the noise spectral density N_0 is replaced by an equivalent noise spectral density N_0', which includes the interference power density. The ratio $\frac{log_2(1+SINR_R)}{log_2(1+SINR_{req})}$ expresses the spectrum efficiency improvement/degradation due to SINR margin, e.g. modulation scheme adaptation, additional bit energy spent for reference signals and retransmission. For instance, assuming highway scenario, MCS = 6, 2.5 dB $SINR_{req}$ is required to reach 95% reliability while the actual $SINR_R$ can be 0dB and the corresponding PRR is 90%..

To compensate the low reliability caused by low SINR, one can select a lower MCS index to have more robust coding scheme or transmit the same packet multiple times, e.g. blind retransmission. In any case, the spectrum efficiency will be reduced in order to have a higher reliability. With the assumed system scenario, $SINR_R$ can be derived based on channel modelling. PRR requirement varies according to use cases, e.g. ranges from 90% to 99.999% in 3GPP TS 22.185 [87]. The corresponding $SINR_{req}$ for PRR = 95% depends on the applied technology, e.g. LTE sidelink or DSRC, and transmission parameters, e.g. MCS. A more detailed example will be given later in this section.

$$SE_{rx} = SE_{tx} \cdot PRR \cdot \frac{log_2(1 + SINR_R)}{log_2(1 + SINR_{req})} \tag{14}$$

In the end, the demanded minimum spectrum bandwidth can be expressed as (15). The selection of D_{RR} is crucial to the overall system spectrum demand: A larger D_{RR} value results in a lower co-channel interference level at receivers, i.e. a higher SINR value, and reduces the demand of spectrum BW. On the other hand, considering constant vehicle density, a larger D_{RR} value increases the number of vehicles requiring distinct channel resource blocks resulting in an overall higher system spectrum demand. The optimal value of D_{RR} minimizes the overall spectrum demand for the given vehicle density and the required communication reliability. In practice, when the V2X system uses a channel access algorithm based on channel sensing, the value of D_{RR} is usually controlled by adapting the sensing threshold of channel busy status, e.g. the clear channel assessment (CCA) threshold in IEEE 802.11p system.

$$BW = \frac{C_{req}}{SE_{rx}} = \frac{max\left\{\frac{S}{L}, \rho \cdot D_{RR} \cdot S \cdot F\right\}}{SE_{tx} \cdot \alpha} \cdot \frac{log_2(1 + SINR_{req})}{log_2(1 + SINR_R)} \tag{15}$$

One example is given to evaluate the spectrum demand for highway dense traffic scenario described in section 8.2.2 using LTE-V2V technique. Thus, message size S = 300 Bytes or 2400 bits, message frequency F = 10 Hz, vehicle density for 6 lane highway ρ = 0.12 vehicles/m, maximum latency L = 100 ms. Assuming 1/2 code rate QPSK is used, SE_{tx} can be determined to be 0.52 bps/Hz. The required SINR (dB) to reach 95% reliability requirement is about 2.5 dB for highway line of sight (LOS) scenario and 8 dB for urban non-line of sight (NLOS) scenario [66]. With required communication range D_R,which is set to 400 m for highway scenario and 50 m for urban scenario, and resource reuse distance of D_{RR}, the experienced $SINR_R$ at the edge of communication range can be derived using the WINNER+B1 model defined in 3GPP TR 36.885 [86]. For simplicity, only the nearest interferer is considered and $SINR_R$ can be expressed as equation (16) where P_{tx} is the transmission power of 23 dBm, P_N is the noise power of -104 dBm, H is the channel path loss coefficient which is a function of communication distance, e.g. $H(D_R)$ represents the channel coefficient for UE at the edge of communication range.

$$SINR_R = \frac{P_{tx} \cdot H(D_R)}{P_{tx} \cdot H(D_{RR} - D_R) + P_N} \tag{16}$$

Knowing other system parameters, equation (15) becomes a function of resource reuse distance D_{RR}:

$$BW = \frac{max\left\{\frac{2400}{0.1}, \rho \cdot 2400 \cdot 10 \cdot D_{RR}\right\}}{0.52 \cdot 0.9} \cdot \frac{log_2\left(1 + SINR_{req}\right)}{log_2(1 + SINR_R\,(D_{RR}))} \qquad (17)$$

Figure 8.2.5-1 illustrates how spectrum demand for scenarios described in section 8.2.2 varies when different D_{RR} is used. For highway scenario, when D_{RR}=1060 m the minimum spectrum demand of 7.17 MHz can be found. For urban scenario, when D_{RR} = 230 m the minimum spectrum demand is 7.72 MHz.

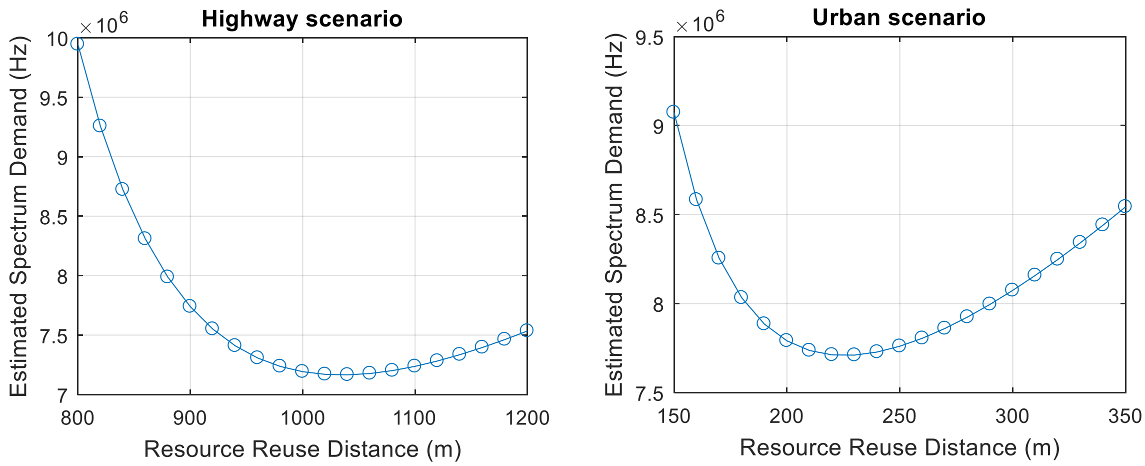


Figure 8.2.5-1: Example spectrum demand estimation

8.2.6 Queuing theory based approach

Another approach to assess V2X spectrum requirements can be derived from queuing theory. This methodology has been proposed first in [88]. It is especially suitable for taking delay performance requirements into account in the analysis, also allowing differentiation between service categories with different delay requirements.

A model frequently employed to analyze packet data transmission systems is denoted $M/G/1$ queue. In this model, the packet arrival process is modeled as a Poisson point distribution (M refers to memoryless or Markovian), i.e. packets arrive randomly with exponential interarrival time distribution. In that, the model is not typical for CAM, which is has more regular interarrival times. This could lead to an increased spectrum requirement, unless some coordination or randomization of the message generation is used. The server is modeled as a statistical process with general distributed service time (G refers to general distribution) and the number of servers is 1. This is a simplification in that - in the case of LTE - multiple UEs can be multiplexed in the frequency domain, so in fact for LTE the spectrum requirements obtained by this methodology tend to be overestimated to some extent.

In this context, the server is represented by the given radio resource which allows to serve a single message transmission at a given time. If the radio resource is busy, transmissions of other users must wait in a queue until the resource is free again. The model does not take into account that in the case of LTE, the transmission is slotted, i.e. a packet has to wait for the next slot and is delivered only at the end of a slot regardless of how much of the slot it occupies. However, this is relevant only for delay requirements on the order of the slot duration.

From the statistical distribution of the queuing delay experienced by each user, a delay requirement can be defined in terms of the probability that a target maximum delay is not exceeded.

The following input parameters are required. For each service category, $k = 1\ldots K$, determine

- offered traffic load $C_{A,k}$ in bit/s,
- mean message size S_k in bits/message,
- required mean latency L_k.

It is assumed that the service category with index $k = 1$ refers to the highest, $k = K$ to lowest priority (this means that the delay requirement for service category $k = 1$ is the strongest).

Offered traffic represents the total traffic (in bit/s) of all transmissions of a specific service category within the area defined by resource reuse distance D_{RR}, see Figure 8.2.2-1. Each type of C-V2X message (e.g. CAM, DENM, IVIM etc.) can be represented as a different services category in this model. The various service categories are indexed with the index $k = 1\ldots K$ in the following.

Dividing offered traffic $C_{A,k}$ by messages size S_k results in the traffic intensity λ_k ("packets per second"), also denoted as packet arrival rate:

$$\lambda_k = \frac{C_{A,k}}{S_k} \tag{18}$$

The system capacity $C_{req,k}$ needed to fulfil the delay requirement of service category k can be calculated as follows. The priority level demanding the highest capacity denotes the total required system capacity, since for the case that the QoS requirements of the most demanding service category are fulfilled, the requirements of the other service categories are even exceeded. Therefore, the overall required system capacity C_{req} is given by:

$$C_{req} = max\left(C_{req,1}, C_{req,2}, \ldots, C_{\mathrm{req},K}\right) \tag{19}$$

When considering non-preemptive packet priorities, it is assumed that each packet is completely served before the current radio resource allocation is changed. This is a valid assumption, because in many cases interrupting the service of a packet causes loss of radio resources already spent for that packet.

The mean packet latency L_k for service category k is the sum of mean waiting time and mean service duration. For a M/G/1 non-preemptive priority queue, the mean packet latency can be expressed as a function of the required system capacity C_{req} as follows [16]:

$$L_k\left(C_{req}\right) = \frac{\sum_{\mathrm{k}=\mathbf{1}}^{\mathrm{K}} \lambda_k S_k^{(2)}}{2\left(C_{req} - \sum_{i=1}^{k} \lambda_i S_i\right)\left(C_{req} - \sum_{i=1}^{k-1} \lambda_i S_i\right)} + \frac{S_k}{C_{req}} \tag{20}$$

This expression is used for determining the system capacity $C_{req,k}$ required to satisfy the QoS condition $L_k(C_{req,k}) = L_k$. i.e. regarding the left hand side of (20) as a QoS input and solving it for $C_{req,k}$, which is then a solution of the cubic equation:

$$a_k x^3 + b_k x^2 + c_k x + d_k = 0 \tag{21}$$

with coefficients a_k, b_k, c_k and d_k according to:

$$a_k = 2L_k \tag{22}$$
$$b_k = -2\left(L_k\left(\sum_{i=1}^{k}\lambda_i S_i + \sum_{i=1}^{\mathrm{k}-1}\lambda_i S_i\right) + S_k\right)$$
$$c_k = 2\left(L_k\left(\sum_{i=1}^{k}\lambda_i S_i\right)\left(\sum_{i=1}^{\mathrm{k}-1}\lambda_i S_i\right) - S_k\left(\sum_{i=1}^{k}\lambda_i S_i + \sum_{i=1}^{\mathrm{k}-1}\lambda_i S_i\right)\right) - \sum_{i=1}^{\mathrm{K}}\lambda_i S_i^{(2)}$$
$$d_k = -2S_k\left(\sum_{i=1}^{k}\lambda_i S_i\right)\left(\sum_{i=1}^{k-1}\lambda_i S_i\right)$$

For the solution of cubic equations good symbolic solution is available by using for example Cardano's formula. Mathematically, equation (21) has three solutions. To determine the correct solution among these three, the stability border of the queuing system has to be considered, i.e.:

$$\sum_{i=1}^{k-1}\lambda_i S_i < C_{req,k} \tag{23}$$

In order to deliver the packets with finite packet delay, the system capacity cannot be smaller than the aggregated offered load given in (18).

The spectrum requirement can be derived by the capacity C_{req} (bit/s) obtained with (19) and spectrum efficiency (bit/s/Hz) using equation (1). The spectrum efficiency can be estimated with equation (7) or equation (15). Using SE_{tx} in (5) results in

$$BW_{req} = \frac{C_{req}}{SE_{tx}\cdot\ \alpha} \tag{24}$$

The benefit of this bandwidth estimation methodology is that it allows to take into account the requirements of multiple service categories.

Example:

K = 2 service categories: k = 1 for DENM, k = 2 for CAM

Traffic intensity λ_k of each service category:

λ_1 = 125 packets per second,

λ_2 = 3360 packets per second (as in the example in section 8.2.2 for the urban street junction scenario)

Packet size S_k of each service category:

S_1 = 4000 bits/packet, S_2 = 2400 bits/packet

Offered load $C_{A,k} = \lambda_k \cdot S_k$ of each service category:

$C_{A,1}$ = 0.5 Mbps, $C_{A,2}$ = 4.032 Mbps

Latency requirement of each service category:

L_1 = 0.001 s (1 ms)

L_2 = 0.1 s (100 ms)

Note that in this example the latency requirement L_1 is set extremely stringent in order to emphasize that a challenging requirement on delay can have a strong impact on the required capacity even when the offered traffic load $C_{A,1}$ is rather low in relation to the offered load of a service category with much less stringent delay requirements.

Resolving equation (20) for k = 1 and k = 2 yields the main result:

$C_{req,1}$ = 5.8418 Mbps, $C_{req,2}$ = 4.5924 Mbps

Thus from (18), we obtain $C_{req} = C_{req,1}$ = 5.8418 Mbps.

Using (5) for calculation of the bandwidth requirement and the assumptions used in the example in 8.2.3 for the 802.11p-based system:

BW_{req} = 5.8418 Mbps/0.6 bit/Hz/0.71= 13.71 MHz

Using (5) for calculation of the bandwidth requirement and the assumptions used in the example in 8.2.3 for the C-V2X sidelink:

$BW_{req} \geq$ 5.8418 Mbps/0.52 bps/Hz/0.9= 12.48 MHz

Comparing the above results with the ones in section 8.2.3 (i.e. BW_{req} = 9.46 MHz for 802.11p and 8.61 MHz for C-V2X sidelink) it can be concluded that a strong latency requirement imposed for a delay-critical servicer can increase the spectrum requirement substantially.

If the latency requirement in the above example is lowered to 10 ms for the DENM messages, there is no significant increase of the spectrum requirement compared to the examples in Section 8.2.3.

8.2.7 Conclusions on spectrum requirements

Our spectrum analysis indicates that for typical traffic scenarios a single 10 MHz channel can be likely sufficient to serve the communication traffic load due to basic safety messages (i.e. CAMs and DENMs) as long as message delay requirements are not set extremely strong.

The results also show that the spectrum demand of C-V2X sidelink technology can be expected to be around 10% lower than required for ITS-G5, due to improved spectrum efficiency and reduced overhead. This applies even if the expected advantage of C-V2X with regard to receiver sensitivity and SINR requirement is not taken into account. We expect that the advantage of C-V2X will increase substantially when incorporating receiver sensitivity and SINR requirement into the analysis. This will be further analyzed in the follow-up deliverable D3.2.

However, as new use cases will likely be added in future it is evident that the spectrum demand will increase beyond 10 MHz of available spectrum.

For C-V2X systems larger bandwidth requirement can be handled either by allocating a single channel with 20 MHz contiguous bandwidth or allocating two channels with 10 MHz each. In the latter case, ITS-stations may need to be able to receive multiple frequency channels concurrently. For 3GPP C-V2X, this feature is part of Release-15.

8.3 Coexistence of DSRC and C-V2X systems

8.3.1 Regulatory aspects

The frequency band 5855 - 5925 MHz (see Table 8.1.2-1) is subject to the following harmonisation measures in Europe:

The European Commission has harmonised the band 5875-5905 MHz for safety-related applications of Intelligent Transport Systems in the European Union via the legally binding Commission Decision 2008/671/EC [78].

ECC Decision (08)01 [74] indicates in addition that CEPT administrations shall consider within a future review of Decision 2008/671/EC [78] the designation of the frequency sub-band 5905-5925 MHz for an extension of ITS spectrum.

ECC also recommends, via ECC Recommendation (08)01 [73], that CEPT administrations should make the frequency band 5855 - 5875 MHz available for ITS non-safety applications.

The ETSI Harmonized Standard EN 302 571 [80], defines requirements for operation of ITS equipment in 5855-5925 MHz frequency band, covering the essential requirements of article 3.2 of the Radio Radio Equipment Directive (RED), 2014/53/EU [90]. According to ECC DEC (08)01 [74] and ECC REC (08)01 [73], ITS equipment complying with EN 302 571 [80] are exempt from individual licensing for operating in this band.

The principle of technology neutrality in the European spectrum regulations implies that any radio technology which can demonstrate conformance with the essential requirements of the Radio Equipment Directive (e.g. through compliance with EN 302 571 [80]) is permitted to operate in the 5855 - 5925 MHz frequency band.

8.3.2 Spectrum sharing between C-V2X and ETSI ITS-G5

As has been described in section 5, C-V2X and ETSI ITS-G5 systems employ different PHY and MAC protocols. As such these two technologies cannot employ simultaneously the same frequency channel in the same geographical area without interfering each other harmfully.

There are two technical solutions to enable operation of both technologies in the ITS frequency band:

1) Time division multiplexing (TDM)
2) Frequency division multiplexing (FDM)

<ins>Time division multiplexing (TDM)</ins>

Sharing of the same frequency channel may be feasible if the two technologies are operated in TDM fashion. There are two options to implement this:

a) Fixed time allocation for each technology
b) Dynamic time allocation with sensing of channel status

Fixed time allocation means that fixed time slots based on absolute GPS timing are assigned to either technology. Dynamic time allocation means that either technology needs to be able to sense if a station using the same or different radio technology is already transmitting. This however would include the capability to decode the information for how long the channel is busy.

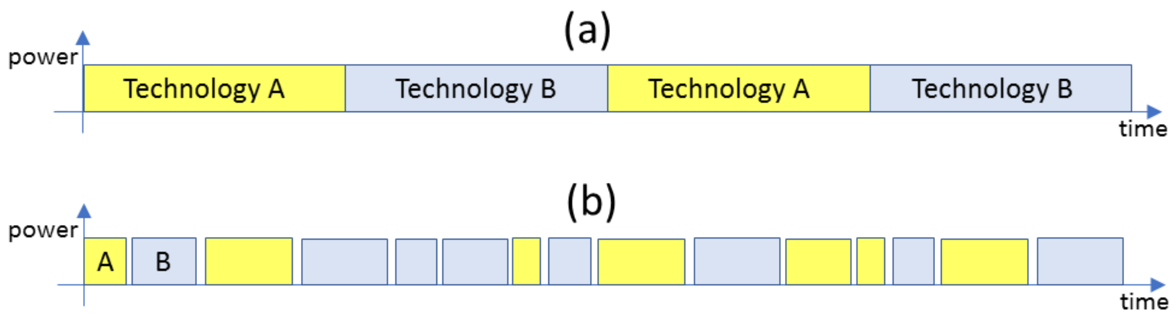


Figure 8.3.4-1: Spectrum sharing in TDM fashion: a) fixed time slot allocation, b) dynamic timeslot allocation

Frequency division multiplexing (FDM)

Different frequency channels are assigned to either radio technology. Some channels can be assigned such that use of a specific technology is preferred while other channels can be assigned dynamically depending on the geographical needs. An example [93] of spectrum allocation is shown in Figure 8.3.4-2. The channel 5875 – 5885 MHz may be assigned to be used preferably by technology A, which could e.g. be ETSI ITS-G5. The channel 5895 – 5905 MHz may be assigned to be used preferably by technology B, which could e.g. be 3GPP LTE-based C-V2X. The channel 5885 – 5895 MHz could be assigned flexibly depending on the needs given in a specific geographical area, for instance based on detect-and-vacate mechanisms.

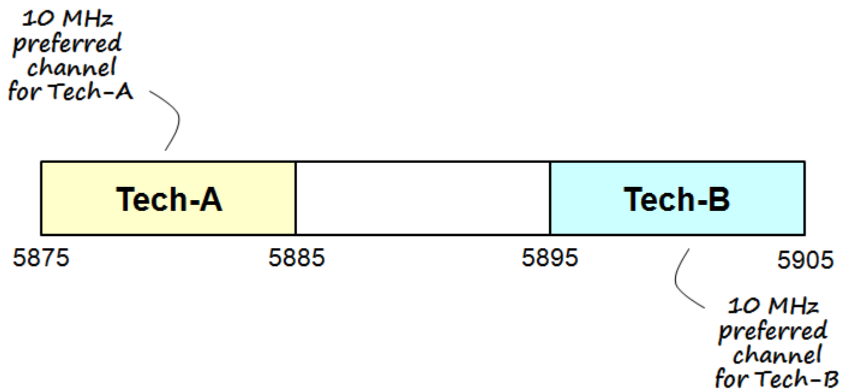


Figure 8.3.4-2: Assignment of frequency channels to radio technologies [93]

8.3.3 Spectrum sharing framework proposed by 5GAA

The 5GAA is proposing a spectrum sharing framework in Europe [93] which in short term should start with the FDM solution shown in Figure 8.3.5-1, where a preselected 10 MHz channel each is assigned to either technology, C-V2X and ETSI ITS-G5. These channels should be employed for safety-related use cases.

In a second step, as the deployment of the two technologies matures, technical solutions such as *mutual detect-and-vacate* can be put in place to enable access to the remaining parts of the 5875 - 5905 MHz band and eventually to the entire 5855 - 5925 MHz band, with a reduced likelihood of harmful co-channel interference as illustrated in Figure 8.3.5-1.

In this scenario, Technology A equipment would operate without any special measures in 5875-5885 MHz. If Technology A equipment wished to transmit in 5885-5895 MHz, then it would need to monitor activity on this channel, and proceed with transmissions if and only if Technology B transmissions are not detected. A symmetrical procedure would apply to Technology B. If Technology B equipment wished to transmit in 5885-5895 MHz, then it would need to monitor activity on that channel, and proceed with transmissions if and only if Technology A transmissions are not detected.

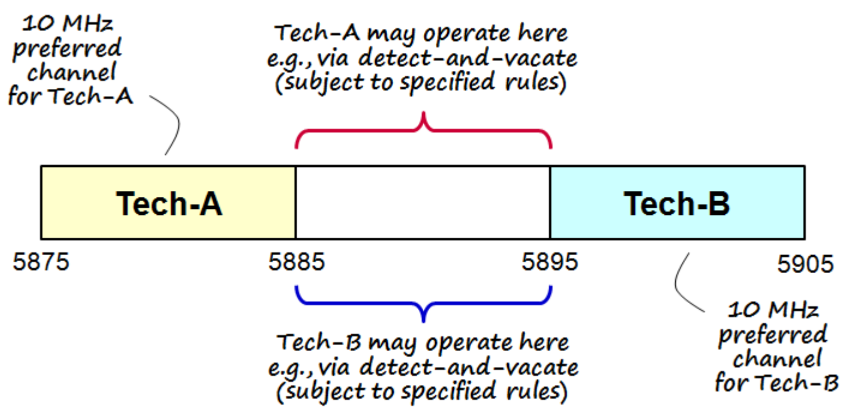


Figure 8.3.5-1: Spectrum sharing via preferred channels complemented by mutual detect-and vacate in the middle 10 MHz channel [93]

In a third step, *extended* detect-and-vacate solution for C-V2X and ITS-G5 can be employed as illustrated in Figure 8.3.5-2. In this scenario, Technology A equipment would operate without any special measures in 5875 - 5885 MHz. If Technology A equipment wished to transmit in 5885 - 5905 MHz, then it would need to monitor activity on these channels, and proceed with transmissions if and only if Technology B transmissions are not detected. A symmetrical procedure would apply to Technology B. This mechanism essentially combines FDM and slow dynamic TDM mechanisms of spectrum allocation.

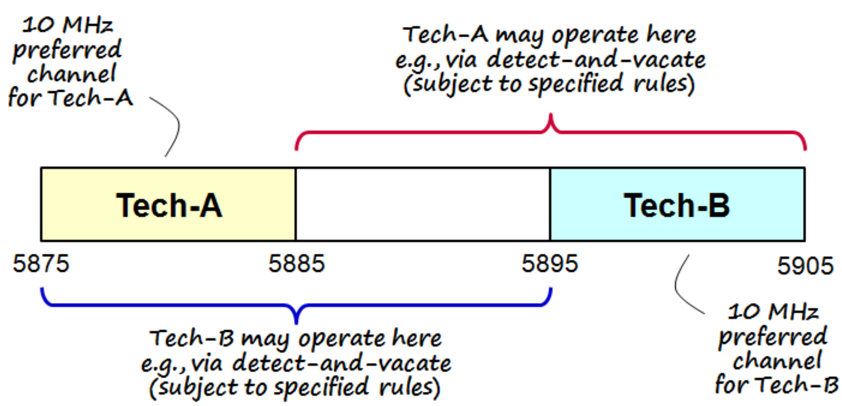


Figure 8.3.5-2: Spectrum sharing via preferred channels complemented by mutual detect-and vacate extended to the lower and upper 10 MHz channels [93]

Reference [93] suggests that suitable sharing mechanisms should be specified in ETSI EN 302 571 [80] on the basis of the results of studies to be undertaken at ETSI, and as captured in a respective technical report.

The 5GAA proposal does not suggest a regulatory approach toward segmentation of the band. The use of preferred 10 MHz channels by the two technologies is intended to be a short-term solution to be adopted by the industry for the avoidance of mutual harmful co-channel interference. This initial solution can be complemented in the longer term with the stepwise approach of introducing a dynamic spectrum sharing solution with suitable mutual detect-and-vacate mechanisms to enable fair access to the whole of 5855 - 5925 MHz band.

The steps of the approach proposed in [93] are the following:

- Initially, assignment of preferred channels for C-V2X and ITS-G5 (with each of the 5875 - 5885 and 5895 - 5905 MHz channels paired with one of either C-V2X or ITS-G5);
- Shared use of the middle channel (5885 - 5895 MHz);
- Shared use of all channels of the 5855 - 5925 MHz band.

9 Summary and Conclusions

In this document we have provided an analysis of V2X technologies. We have presented an overview of 802.11p-based technologies and LTE for V2X, both the cellular LTE radio technology and sidelink technology. We have compared side-by-side key features of the physical layer, where 802.11p had disadvantages from high cyclic prefix overhead and guard bands and very relaxed requirements on receiver sensitivity and older channel codes (convolutional), whereas LTE has high pilot overhead.

Link level simulation result have shown that LTE has 4 - 5 dB lower SINR requirements for relative speeds up to 120 km/h and 2 - 3 dB for 500 km/h. This translates into a much larger range of LTE, 90 m vs. 50 m in urban and 450 m vs. 200 m for the freeway scenario, as shown by system simulations.

Estimated spectrum requirements for LTE are 10% lower than for DSRC, whereby based on the link-level differences, larger LTE spectrum requirement advantages can be expected and the analysis should be further developed for the follow-up deliverable D3.2.

Appendix

Appendix A Simulation setup

Appendix A.1 Link Level Simulation 1

Simulation parameters

Simulation Parameters	LTE-V2X PC5	DSRC
Modulation	QPSK	QPSK
Coding rate	½	½
Carrier frequency	5.9 GHz	5.9 GHz
Number of antennas	1 TX and 2RX antennas	1 TX and 2RX antennas
Noise figure	9 dB	9 dB

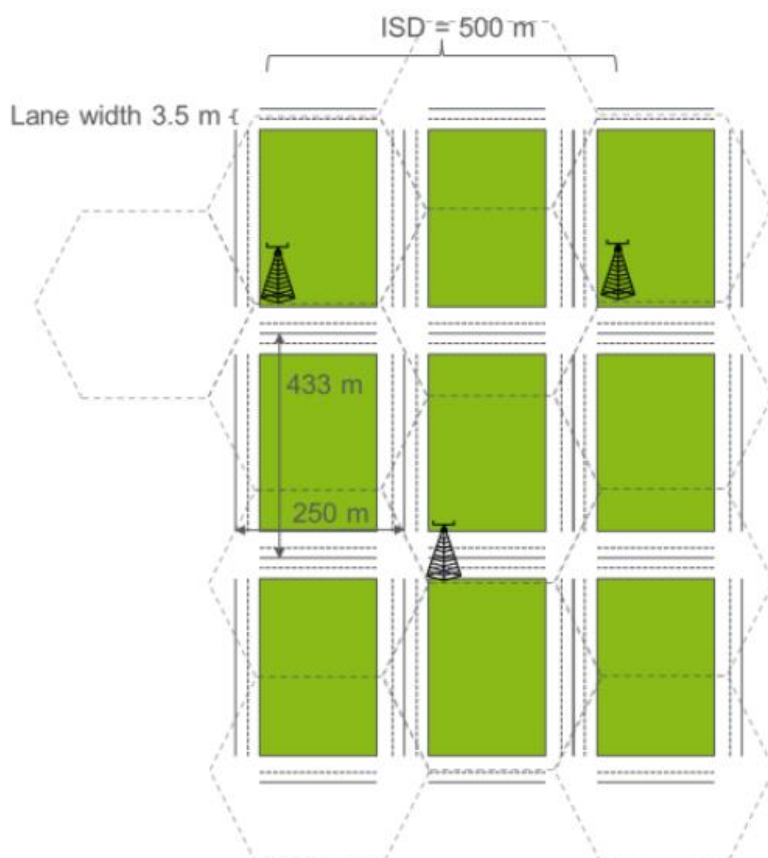
Appendix A.2 System Level Simulation 1

Simulation parameters

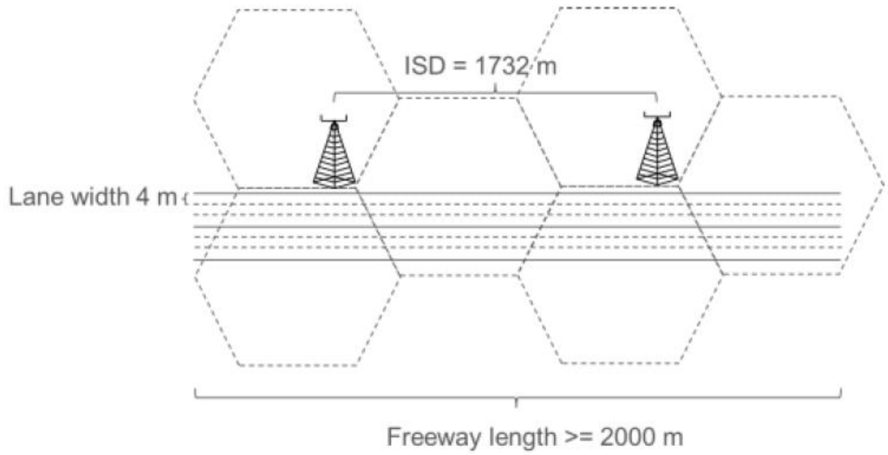
Simulation parameters	Values
Cellular layout	Urban slow: 21 cells, ISD 500M, Manhattan Grid Freeway fast: ISD 1732 m, length >= 2km
Channel bandwidth	10 MHz
Carrier frequency	6 GHz
Modulation	Broadcast: QPSK ½ Unicast: adaptive MCS

Data traffic	Urban: 2 Hz CAM Freeway: 10 Hz CAM
Tx power	eNB: 46 dBm UE: 23 dBm
Required communication range	Urban: 150 m Freeway: 320 m
Required PRR	90%
Vehicle density	Urban: 175 vehicles/cell Freeway: 54 vehicles/cell

Road configuration for urban scenario



Road configuration for highway scenario



Appendix A.3 System Level Simulation 2

Simulation parameters

Simulation parameters	Values
Number of vehicles	25, 50, 75, 100, 125, 150
Vehicle average speed	20, 40, 60, 80, 100 km/h
Beacon transmission frequency	1, 4, 8, 10, 20 Hz
Packet size	256 Bytes
Carrier frequence	IEEE 802.11p: 5.8 GHz LTE DL: 2110 MHz LTE UL: 1710 MHz
Channel bandwidth	10 MHz
Transmission power	IEEE 802.11p: 25 dBm LTE eNB: 40 dBm LTE UE: 20 dBm

Road configuration