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TECHNICAL REPORT

Intelligent Transport Systems (ITS); Pre-standardization study on co-channel co-existence between IEEE- and 3GPP- based ITS technologies in the 5 855 MHz - 5 925 MHz frequency band

Reference

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Foreword

This Technical Report (TR) has been produced by ETSI Technical Committee Electromagnetic compatibility and Radio spectrum Matters (ERM).

Modal verbs terminology

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1 Scope

The present document carries out studies on the feasibility of co-channel co-existence between ITS-G5 and LTE-V2X technologies based on solutions presented to CEPT. It defines methodologies and metrics required for performing the studies and evaluating the performance of the solutions studied. To find co-channel co-existence methods, which enable both technologies to use the same frequency channel in the same geographical area, while meeting the metrics defined.

The present document classifies co-channel co-existence methods depending on the observed metrics.

2 References

2.1 Normative references

Normative references are not applicable in the present document.

2.2 Informative references

References are either specific (identified by date of publication and/or edition number or version number) or non-specific. For specific references, only the cited version applies. For non-specific references, the latest version of the referenced document (including any amendments) applies.

NOTE: While any hyperlinks included in this clause were valid at the time of publication ETSI cannot guarantee their long term validity.

The following referenced documents are not necessary for the application of the present document but they assist the user with regard to a particular subject area.

[i.1] ETSI EN 302 665 (V1.1.1) (09-2010): "Intelligent Transport Systems (ITS); Communications Architecture".

[i.2] ETSI EN 302 663 (V1.3.1) (01-2020): "Intelligent Transport Systems (ITS); ITS-G5 Access layer specification for Intelligent Transport Systems operating in the 5 GHz frequency band".

[i.3] IEEE Std 802.11™-2020: "IEEE Standard for Information technology - Telecommunications and information exchange between systems - Local and metropolitan area networks-Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications".

[i.4] IEEE/ISO/IEC 8802-2-1998: "Information technology -- Telecommunications and information exchange between systems -- Local and metropolitan area networks -- Specific requirements -- Part 2: Logical Link Control".

[i.5] IEEE 802.11e™-2005: "IEEE Standard for Information technology - Local and metropolitan area networks - Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications - Amendment: Medium Access Method (MAC) Quality of Service Enhancements".

[i.6] ANSI/IEEE Std 802.1D™-1998: "IEEE Standard for Information technology - Telecommunications and information exchange between systems - Local and metropolitan area networks - Common specifications - Part 3: Media Access Control (MAC) Bridges".

[i.7] ETSI EN 303 613 (V1.1.1) (01-2020): "Intelligent Transport Systems (ITS); LTE-V2X Access layer specification for Intelligent Transport Systems operating in the 5 GHz frequency band".

[i.8] ETSI TS 136 213 (V15.9.0): "LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures (3GPP TS 36.213 version 15.9.0 Release 15)".

[i.9] ETSI TS 136 211 (V14.3.0): "LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical channels and modulation (3GPP TS 36.211 version 14.3.0 Release 14)".

[i.10] ETSI TS 136 300 (V14.3.0): "LTE; Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; Stage 2 (3GPP TS 36.300 version 14.3.0 Release 14)".

[i.11] ETSI TS 136 321 (V14.3.0): "LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Medium Access Control (MAC) protocol specification (3GPP TS 36.321 version 14.3.0 Release 14)".

[i.12] ETSI TS 136 101 (V14.4.0): "LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio transmission and reception (3GPP TS 36.101 version 14.4.0 Release 14)".

[i.13] 3GPP TR 36.885: "Study on LTE-based V2X services" (V14.0.0, Release 14)", June 2016.

[i.14] F. Berens, V. Martinez, and K. Moerman: "Survey on CAM statistics," presented at ETSI ITS workshop 2019.

NOTE: Available online: https://docbox.etsi.org/Workshop/2019/201903_ITSWS/SESSION03/NXP_Moerman.pdf.

[i.15] CAR2CAR Communication Consortium: "Survey on ITS-G5 CAM statistics," 2018.

NOTE: Available online: https://www.car-2-car.org/fileadmin/documents/General_Documents/C2CCC_TR_2052_Survey_on_CAM_statistics.pdf.

[i.16] ETSI EN 302 637-3 (V1.3.1) (04-2019): "Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 3: Specifications of Decentralized Environmental Notification Basic Service".

[i.17] ETSI EN 302 637-2 (V1.4.1) (04-2019): "Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 2: Specification of Cooperative Awareness Basic Service".

[i.18] 3GPP TR 36.843: "Study on LTE Device to Device Proximity Services; Radio Aspects (V12.0.1, Release 12)" March 2014.

[i.19] Report Recommendation ITU-R M.2135-1 (2009): "Guidelines for evaluation of radio interface technologies for IMT-Advanced".

[i.20] T.S. Rappaport: "Wireless Communications: Principles and Practice", second edition, Prentice Hall. .

[i.21] C. Sommer, and F. Dressler: "Using the right two-ray model? A measurement-based evaluation of PHY models in VANETs", in 17th ACM MobiCom, Poster Session, Las Vegas, NV, September 2011.

[i.22] Recommendation ITU-R P.1411-10 (08-2019): "Propagation data and predicition methods for the planning of short-range outdoor radiocommunication systems and radio local area networks in the frequency range 300 MHz to 100 GHz".

[i.23] ECC Report 68: "Compatibility studies in the band 5725-5875 MHz between fixed wireless access (FWA) and other systems," June 2005.

[i.24] ECC Report 250: "Compatibility studies between TTT/DSRC in the band 5805-5815 MHz and other systems," April 2016.

[i.25] ETSI TS 103 574 (V1.1.1) (11-2018): "Intelligent Transport Systems (ITS); Congestion Control Mechanisms for C-V2X PC5 interface; Access layer part".

[i.26] ETSI TS 102 687 (V1.2.1) (04-2018): "Intelligent Transport Systems (ITS); Decentralized Congestion Control Mechanisms for Intelligent Transport Systems operating in the 5 GHz range; Access layer part".

[i.27] IEEE Std 1609.4™-2016: "IEEE Standard for Wireless Access in Vehicular Environments (WAVE) - Multi-Channel Operation".

[i.28] ETSI TS 103 723 (V1.2.1) (11-2020): "Intelligent Transport Systems (ITS); Profile for LTE-V2X Direct Communication".

[i.29] 3GPP TS 36.101: "Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio transmission and reception (V16.4.0, Release 16)", December 2019.

[i.30] TGbd: "Project Authorization Request (PAR)", IEEE 802.11-18/0861r9.

NOTE: Available at https://mentor.ieee.org/802.11/dcn/18/11-18-0861-09-0ngv-ieee-802-11-ngv-sg-proposed-par.docx.

[i.31] G. Naik, B. Choudhury and J. Park: "IEEE 802.11bd & 5G NR V2X: Evolution of Radio Access Technologies for V2X Communications," in IEEE Access, 2019. doi: 10.1109/ACCESS.2019.2919489.

[i.32] M. H. C. Garcia et al.: "A Tutorial on 5G NR V2X Communications," in IEEE Communications Surveys & Tutorials, 2021. doi: 10.1109/COMST.2021.305701.

[i.33] ETSI TS 136 133 (V14.17.0): "LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Requirements for support of radio resource management (3GPP TS 36.133 version 14.7.0 Release 14)".

[i.34] ETSI EN 302 571 (V2.1.1): "Intelligent Transport Systems (ITS); Radiocommunications equipment operating in the 5 855 MHz to 5 925 MHz frequency band; Harmonised Standard covering the essential requirements of article 3.2 of Directive 2014/53/EU".

[i.35] ETSI TS 103 613: "Intelligent Transport Systems (ITS); Access layer specification for Intelligent Transport Systems using LTE Vehicle to everything communication in the 5,9 GHz frequency band".

3 Definition of terms, symbols and abbreviations

3.1 Terms

For the purposes of the present document, the following terms apply:

subframe: time interval equal to 1 ms

NOTE: This equals the "subframe duration" as defined in ETSI TS 136 211 [i.9].

superframe: consists of two time slots

time slot: integer multiple of consecutive subframes

3.2 Symbols

Void.

3.3 Abbreviations

For the purposes of the present document, the following abbreviations apply:

AC	Access Category
ACK	ACKnowledgement
AGC	Automatic Gain Control
AIFS	Arbitration InterFrame Space
AIFSN	AIFS Number
AP	Access Point
ARQ	Automatic Repeat reQuest
BE	Best Effort

BK	Background
BPSK	Binary Phase Shift Keying
BS	Base Station
BSS	Basic Service Set
BSSID	BSS identifier
C2C-CC	CAR2CAR Communication Consortium
CAM	Cooperative Awareness Message
CBR	Channel Busy Ratio
CCA	Clear Channel Assement
CDF	Cumulative Distribution Function
CEN	Comité Européen de Normalisation
CP	Cyclic Prefix
CRC	Cyclic Redundancy Check
CSI	Channel Sidelink Information
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
CSR	Candidate Single-subframe Resources
CTS	Clear To Send
CW	Contention Window
DA	Data Age
DCC	Decentralized Congestion Control
DCF	Distributed Coordination Function
DENM	Decentralized Environmental Notification Message
DIFS	Distributed InterFrame Space
DL	Data Link Layer
DMRS	DeModulation Reference Signals
DSRC	Dedicated Short Range Communication
EDCA	Enhanced Distributed Channel Access
EE	Excellent Effort
EED	End-to-End Delay
ES	Energy Signals
EVM	Error Vector Magnitude
FCS	Frame Check Sequence
GNSS	Global Navigation Satellite System
HARQ	Hybrid Automatic ReQuest
IBSS	Independent BSS
IN	Interface
IPG	Inter-Packet Gap
IQ	In-phase Quadrature phase
ITS	Intelligent Transport Systems
ITS-S	ITS Station
KPI	Key Performance Indicator
LDPC	Low Density Parity Check
LLC	Logical Link Control
LOS	Line-Of-Sight
LTE	Long Term Evolution
LTF	Long Training Field
LUT	LookUp Table
MAC	Medium Access Control
MCS	Modulation and Coding Scheme
MIB	Management Information Base
MPDU	MAC Protocol Data Unit
MSPS	Mega Symbols Per Second
NAV	Network Allocation Vector
NC	Network Control
NLOS	Non-Line-Of-Sight
NR	New Radio
OBU	OnBoard Unit
OFDM	Orthogonal Frequency Division Multiplexing
OSI	Open System Interconnect
PDU	Protocol Data Unit
PER	Packet Error Rate
PHY	Physical Layer

PLCP	Physical Layer Convergence Procedure
PPDU	PLCP Protocol Data Unit
PPS	Parts Per Second
PRR	Packet Reception Ratio
PSCCH	Physical Sidelink Control Channels
PSDU	PLCP Service Data Unit
PSSCH	Physical Sidelink Shared Channels
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RA	Receive Address
RB	Resource Block
RSRP	Reference Signal Received Power
RSSI	Received Signal Strength Indicator
RSU	RoadSide Unit
RTS	Requestion To Send
RX	Receiver
SC-FDMA	Single-Carrier Frequency Division Multiple Access
SCI	Sidelink Control Information
SDR	Software Defined Radio
SIFS	Short InterFrame Space
SINR	Signal to Interference and Noise Ratio
SPS	Semi-Persistent Scheduling
STF	Short Training Field
SUMO	Simulation of Urban Mobility
TB	Transport Block
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
TL	Time Length
TTI	Transmission Time Interval
TX	Transmitter
UP	User Priority
VI	Video
VO	Voice

4 Technical description of road ITS technologies

4.1 Introduction

The two studied road ITS technologies herein are ITS-G5 and LTE-V2X (3GPP Release 14) [i.2]. The technologies represent the access layer of the ITS communications architecture, see Figure 4.1, outlined in ETSI EN 302 665 [i.1]. The access layer consists of the physical layer (PHY) and the data link layer (DL) of the OSI model.

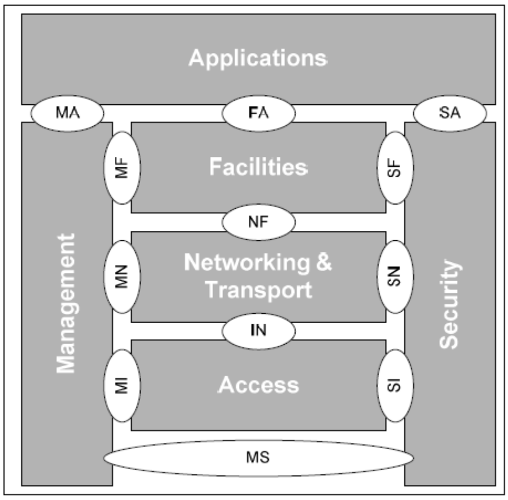


Figure 4.1: The ITS stations reference architecture [i.1]

4.2 ITS-G5

4.2.1 Introduction

ITS-G5 is outlined in ETSI EN 302 663 [i.2] describing the access layer of the ITS station reference architecture. The ITS-G5 access layer consists of:

- IEEE 802.11-2020 [i.3] operating outside the context of a basic service set (enabled by setting the MIB parameter `dot11OCBEnabled` to true).
- IEEE 802.2 Logical Link Control (LLC) [i.4].

IEEE 802.11-2020 outlines the PHY and the Medium Access Control (MAC) protocol used for vehicular ad hoc networking in ITS-G5. The PHY is based on Orthogonal Frequency Division Multiplexing (OFDM) and the MAC is using the Enhanced Distributed Channel Access (EDCA) functionality, see Clause 4.2.2 and Clause 4.2.3 for more technical details.

The IEEE 802.11-2020 [i.3] standard contains two basic network topologies: the infrastructure BSS and the independent BSS (IBSS). The former contains an Access Point (AP) and data traffic usually takes a detour through the AP even though two nodes are closely co-located. The IBSS is a set of nodes communicating directly with each other and this is also called *ad hoc* or peer-to-peer network. Both these topologies are aimed for nomadic devices and synchronization is required between nodes performed via beacons. Further, they are identified with a unique BSSID. Association and authentication are required in infrastructure BSS whereas in IBSS association is not used and communication can take place in an unauthenticated mode. With the introduction of 802.11p a new capability of the 802.11 is introduced, namely communication outside the context of a BSS, see Clause 4.3.17 of IEEE 802.11-2020 [i.3]. The communication outside of a BSS is enabled by setting the MIB variable `dot11OCBActivated` to true. In this mode authentication, association and security between nodes are disabled at the MAC sublayer. This implies that active and passive scanning of BSS and IBSS are disabled. The scanning on frequency channels for the node to join an existing network is no longer enabled. Therefore, the implementation when the MIB variable is set to `dot11OCBActivated` true in the vehicular environment requires predetermined frequency channels to be set in the management.

NOTE: The possibility to communicate outside the context of a BSS for vehicular communication was introduced in the IEEE 802.11p amendment. IEEE 802.11p was published in 2010 and it was enrolled into 802.11 in 2012, at which time the 802.11p amendment was classified as superseded. However, for the purpose of the present document, the notion "802.11p" will be used when referring to the vehicular components of IEEE 802.11-2020.

4.2.2 Physical layer

The OFDM PHY parameters of ITS-G5 are detailed in Clause 17 of IEEE 802.11-2020 [i.3]. ITS-G5 uses 52 orthogonal subcarriers in a channel bandwidth of 10 MHz, where 48 subcarriers are used for data and 4 are pilot carriers. The OFDM PHY layer of ITS-G5 can support eight different transfer rates by using different modulation schemes and coding rates. The support of 3 Mbit/s, 6 Mbit/s, and 12 Mbit/s is mandatory. The duration of an OFDM symbol is fixed to 8 µs, and consequently for different transfer rates the number of data bits per OFDM symbol varies. Table 4.1 outlines the different transfer rates together with coding and modulation schemes and data bits per OFDM symbol.

Table 4.1: Transfer rates, modulation schemes and coding rates used by ITS-G5

Transfer rate (Mbit/s)	Modulation scheme	Coding rate	Data bits per OFDM symbol	Coded bits per OFDM symbol
3	BPSK	1/2	24	48
4,5	BPSK	3/4	36	48
6	QPSK	1/2	48	96
9	QPSK	3/4	72	96
12	16-QAM	1/2	96	192
18	16-QAM	3/4	144	192
24	64-QAM	2/3	192	288
27	64-QAM	3/4	216	288

Figure 4.2 shows the format of a transmitted ITS-G5 packet, i.e. the physical layer convergence procedure (PLCP) Protocol Data Unit (PPDU). The PLCP Service Data Unit (PSDU) contains the data from the MAC layer including MAC header and trailer (collectively named MAC Protocol Data Unit, MPDU). The preamble is used for synchronizing the receiver. The signal field contains information about packet length and data rate of the data field. It has a length of 24 bits and is always transmitted in one OFDM symbol using BPSK with a coding rate of 1/2 (3 Mbit/s). In Table 4.2 details of the ITS-G5 PHY packet format are listed (see also Clause 17 of IEEE 802.11-2020 [i.3]).

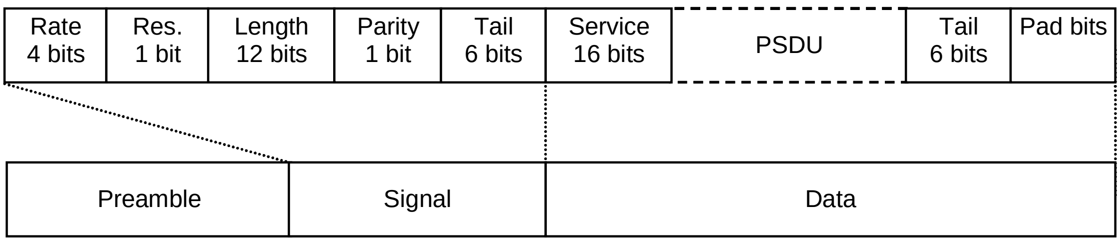


Figure 4.2: ITS-G5 packet format, i.e. PPDU, ready for transmission

Table 4.2: Explanation of the different fields of the PPDU

Field	Subfield	Description	Duration
Preamble	N/A	Consists of a short and a long training sequence.	32 µs
Signal	Rate	Transfer rate at which the data field in the PPDU will be transmitted.	8 µs
	Reserved	For future use.	
	Length	Length of the packet.	
	Parity	Parity bit.	
	Tail	Used to facilitate decoding and for calculation of rate and length subfields.	
Data	Service	Used for synchronizing the descrambler at receiver.	variable
	PSDU	The data from the MAC layer including header and trailer, i.e. MPDU.	
	Tail	Used for putting the convolutional encoder to zero state.	
	Pad bits	Bits added to fill up the last OFDM symbol of the packet.	

4.2.3 Medium access control

4.2.3.1 Introduction

The MAC algorithm decides when in time a node is allowed to transmit based on the current channel status and the MAC schedules transmission with the goal to minimize the interference in the system to increase the packet reception probability. The MAC algorithm deployed is called Enhanced Distributed Coordination Access (EDCA). It is based on the basic Distributed Coordination Function (DCF) but adds QoS attributes. DCF is a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) algorithm.

NOTE: The EDCA was introduced with the IEEE 802.11e [i.5] amendment and it added QoS to the DCF mechanism. IEEE 802.11e [i.5] was published in 2004 and it was enrolled into 802.11 in 2007, at which time the 802.11e document was classified as superseded.

In CSMA/CA a node starts to listen to the channel before transmission and if the channel is perceived as idle for a predetermined listening period the node can start to transmit directly. If the channel becomes occupied during the listening period the node will perform a backoff procedure, i.e. the node has to defer its access according to a randomized time period. In IEEE 802.11-2020 [i.3], the predetermined listening period is called either Arbitration Interframe Space (AIFS) or Distributed Interframe Space (DIFS) depending upon the mode of operation (EDCA or DCF). The former listening period is used when there is support for QoS.

4.2.3.2 Backoff procedure

The backoff procedure in 802.11 works as follows:

i) draw an integer from a uniform distribution [0, CW], where CW refers to the current maximum value of the contention window (the total number of integers to draw from is CW+1);

ii) decrease the backoff value only when the channel is free, one decrement per slot time (for a 10 MHz channel the slot time is 13 μs);

iii) upon reaching a backoff value of 0, transmit. In broadcast operation the node will only invoke the backoff procedure once during the initial listening period. When 802.11 is employed in unicast mode it acts as a stop-and-wait protocol and the transmitter will wait for an acknowledgment (ACK). If no ACK is received by the sender for some reason (the transmitted packet never reached the intended recipient, the packet was incorrect at reception, or the ACK never reached the sender), a backoff procedure will also be invoked.

For every attempt to send a specific packet (in broadcast mode there is only one attempt but in unicast mode it can be several attempts due to missing ACKs), the current size of the contention window, CW, will be increased from its initial value (CW_{min}) until it reaches a maximum value (CW_{max}). This feature of increasing the CW allows the network to recover from high utilization periods by spreading transmission attempts in time. After a successful transmission or when the packet had to be discarded because the maximum number of channel access attempts was reached, the CW will be set to its initial value again (CW_{min}).

If the channel becomes busy during the decrease of the backoff value once per 13 μs slot time the node has to suspend the countdown until the channel becomes free again. However, it should be noted that after every busy channel period the node will first wait an AIFS before the decrementation resumes.

NOTE: In broadcast mode the backoff procedure is only invoked once during the initial listening (AIFS) to the channel due to the lack of ACKs in broadcast transmissions. Therefore, the CW is always set to its minimum value, CW_{min}, and it will never be doubled.

More details about the backoff procedure are found in Clauses 10.3.3 and 10.3.4.3, of IEEE 802.11-2020 [i.3].

4.2.3.3 Medium access control

In Figure 4.3, simplified drawings of the channel access procedure as performed by 802.11 nodes is depicted for broadcast mode, Figure 4.3(a), and unicast mode, Figure 4.3(b).

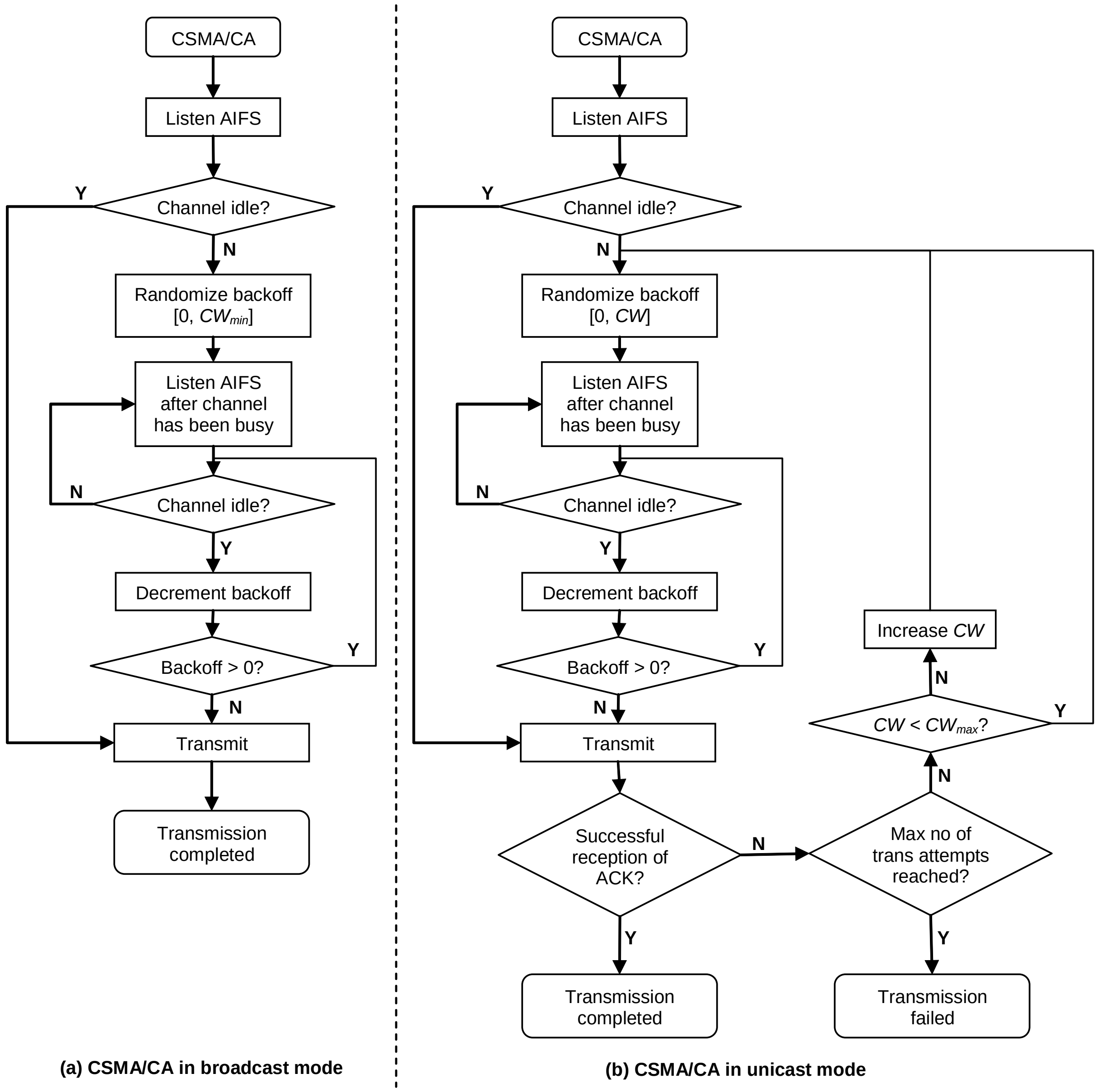


Figure 4.3: A simplified drawing of the channel access procedure in IEEE 802.11-2020 [i.3] in (a) broadcast and (b) unicast mode

More details about the channel access procedure are found in Clause 10 of IEEE 802.11-2020 [i.3].

4.2.3.4 EDCA parameters, AC and UP

EDCA is the official name of one of the MAC algorithms in 802.11, which is used by 802.11p. It is the DCF with inclusion of QoS, i.e. the CSMA/CA algorithm with the possibility to prioritize data traffic. In EDCA every node maintain queues with different AIFS values and CW sizes with the purpose of giving data traffic with higher priority increased probability to access the channel before data traffic with lower priority.

The QoS facility in 802.11 defines eight different User Priorities (UPs) and these are inherited from the ANSI/IEEE Std 802.1D [i.6] defining MAC bridges. The UPs from 802.1D are shown in Table 4.3 and they are mapped to four different Access Categories (ACs), i.e. queues, within the QoS facility. This mapping is shown in Table 4.3, where the lowest priority is 0 and the highest 7.

Table 4.3: Mapping of UPs in 802.1D to the ACs of QoS facility in 802.11

UP in 802.1D	Data traffic type in 802.1D	AC in 802.11	Data traffic type in 802.11
1	Background (BK)	AC_BK	Background
2	Spare (-)	AC_BK	Background
0	Best effort (BE)	AC_BE	Best effort
3	Excellent effort (EE)	AC_BE	Best effort
4	Controlled load	AC_VI	Video
5	Video (VI)	AC_VI	Video
6	Voice (VO)	AC_VO	Voice
7	Network control (NC)	AC_VO	Voice

NOTE 1: In 802.1D best effort traffic has the lowest priority 0 but the traffic type background has the priority of 1 even if this traffic type in reality has lower priority than the best effort type. For historical reasons the priority of the best effort traffic in 802.1D is not changed because of interoperability problems with legacy network equipment. This priority conflict is however solved in the QoS facility in 802.11.

The resulting AIFS for the ACs is calculated using the following formula:

$$AIFS[AC] = AIFSN[N] \times aSlotTime + aSIFSTime \tag{4.1}$$

where the *AIFSN* stands for AIFS number, which is an integer, *aSlotTime* and the *aSIFSTime* (short interframe space) are fetched from the PHY in use and they are fixed. Consequently, the AIFSN is the parameter determining the listening period (AIFS) for each queue (AC). In Table 4.4 the default values for AIFSN and CW is tabulated for the different ACs in 802.11p, found in Table 9-156 IEEE 802.11-2020 [i.3].

Table 4.4: The default values for the AIFSN and CW in 802.11p found in IEEE 802.11-2020 [i.3]

AC	CW_{min}	CW_{max}	*AIFSN*
AC_VO	*(aCWmin + 1) / 4 - 1*	*(aCWmin + 1) / 2 - 1*	2
AC_VI	*(aCWmin + 1) / 2 - 1*	*aCWmin*	3
AC_BE	*aCWmin*	*aCWmax*	6
AC_BK	*aCWmin*	*aCWmax*	9

NOTE 2: The default values may be changed through some other mean such as the advertisement, regulation or another controlling standard.

In Table 4.5, the different parameter values needed to determine MAC specific functions for 10 MHz channels of the OFDM PHY layer are tabulated. These values are fetched from Table 17-21 in IEEE 802.11-2020 [i.3].

Table 4.5: OFDM PHY specific parameters used in 802.11p found in IEEE 802.11-2020 [i.3]

Parameter	Value
aSlotTime	13 µs
aSIFSTime	32 µs
aCWmin	15
aCWmax	1 023

In Table 4.6, the resulting default values for 802.11p's ACs are tabulated using Table 4.4, Table 4.5 and Equation (1).

Table 4.6: The resulting AIFS and CW sizes for 802.11p's ACs

AC	CW_{min}	CW_{max}	*AIFS*
AC_VO	3	7	58 µs
AC_VI	7	15	71 µs
AC_BE	15	1 023	110 µs
AC_BK	15	1 023	149 µs

More details about the EDCA mechanism is found in Clause 10 of IEEE 802.11-2020 [i.3].

4.3 LTE-V2X

4.3.1 Introduction

LTE-V2X is outlined in ETSI EN 303 613 [i.7] describing the access layer of the ITS station reference architecture.

4.3.2 Physical layer

LTE-V2X uses Single-Carrier Frequency-Division Multiple Access (SC-FDMA), and supports 10- and 20-MHz channels. Each channel is divided into subframes, Resource Blocks (RBs), and subchannels. Subframes are 1 ms long, as the LTE Transmission Time Interval (TTI). An RB is the smallest unit of frequency resource that can be allocated to a user. It is 180 kHz wide in the frequency domain and contains 12 subcarriers, which are 15 kHz each. LTE-V2X defines subchannels as a group of RBs in the same sub-frame, where the number of RBs per subchannel can vary. Subchannels are used to transmit data and control information. The data is transmitted in Transport Blocks (TBs) over Physical Sidelink Shared Channels (PSSCH), and the Sidelink Control Information (SCI) messages are transmitted over Physical Sidelink Control Channels (PSCCH) [i.8]. PSSCH and PSCCH are transmitted on the same subframe to reduce the impact of near-far issues and the issues related to the half-duplex operation. However, PSSCH and PSCCH may or may not be adjacent in the occupied RBs. Same power control parameters are used for both channels, however a 3 dB power spectral density boosting is applied for PSCCH to make sure that control information does not become the bottleneck.

A TB contains a full packet to be transmitted, e.g. a beacon or cooperative awareness message. A node intending to transmit a TB has also to transmit its associated SCI, also referred to as scheduling assignment. The SCI includes information such as the Modulation and Coding Scheme (MCS) used for transmitting the TB, the RBs it uses, and the resource reservation interval for Semi-Persistent Scheduling (SPS). The correct reception of SCI by other nodes is crucial for the decoding of the transmitted TB. LTE-V2X defines two subchannelization schemes - adjacent and non-adjacent - see Figure 4.4.

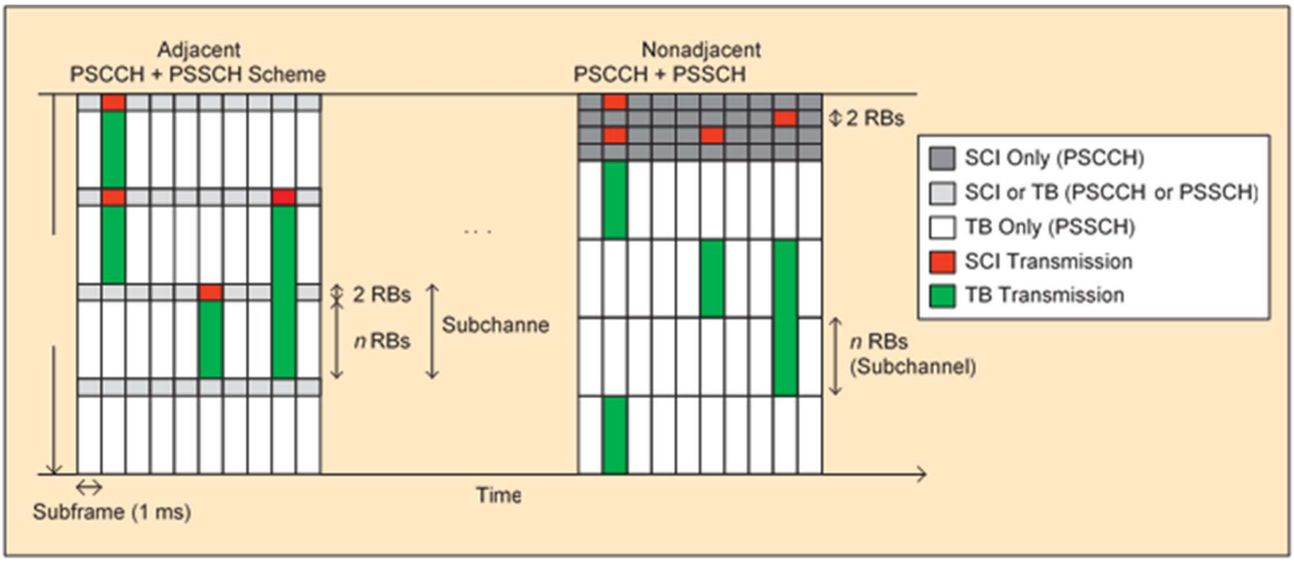


Figure 4.4: LTE-V2X subchannelization

In the *adjacent PSCCH + PSSCH scheme*, the SCI and TB are transmitted in adjacent RBs. For each SCI + TB transmission, the SCI occupies the first two RBs of the first subchannel utilized for the transmission. The TB is transmitted in the RBs following the SCI, and depending on its size can occupy several subchannels. In this case, it will also occupy the first two RBs of the following subchannels.

In the *nonadjacent PSCCH + PSSCH scheme*, the RBs are divided into pools. One pool is dedicated to transmit only SCIs, and the SCIs occupy two RBs. The second pool is reserved to transmit only TBs and is divided into subchannels. TBs can be transmitted using QPSK or 16-QAM, whereas the SCIs are always transmitted using QPSK. LTE-V2X uses turbo coding and normal cyclic prefix. LTE-V2X subcarriers have a total of 14 symbols per subframe, and four of these symbols are dedicated to the transmission of demodulation reference signals (DMRSs) to combat the Doppler effect at high speeds. DMRSs are transmitted in the third, sixth, ninth, and 12th symbol of each subcarrier per subframe, ETSI TS 136 211 [i.9].

The adjacent PSCCH + PSSCH scheme has been selected for mode 4 operation in ETSI EN 303 613 [i.7].

4.3.3 Medium access control

4.3.3.1 Introduction

Vehicles using V2X communications mode 4, select their radio resources independently from the control of cellular network. In ETSI EN 303 613 [i.7], the number of subchannels has been selected to be 5, therefore each subchannel contains 10 RBs. When the vehicles are in the cellular network coverage, the network decides how to configure the V2X channel and informs the vehicles about V2X configurable parameters through the Uu interface [i.10]. The message includes the carrier frequency of the V2X channel, the V2X resource pool, synchronization references, the subchannelization scheme, the number of subchannels per subframe, and the number of RBs per subchannel, among other things.

When the vehicles are not under the cellular network control, they autonomously select radio resources by using sensing with a semi-persistent transmission, which is a kind of "frequency domain listen before talk". Such transmission allows a node to take advantage of semi-periodic traffic arrival and uses past interference patterns to predict the future. The nodes utilize a preconfigured set of parameters to replace the sidelink V2X configurable parameters. The standard does not specify a concrete value for each parameter and the V2X resource pool indicates which subframes of a channel are utilized for V2X. The rest of the subframes can be utilized by other services, including cellular communications. The standard provides the option to divide the V2X resource pool based on geographical areas (referred to as zoning [i.10]). In this case, vehicles in an area can only utilize the resource pools which have been assigned to that areas.

4.3.3.2 Sensing based semi-persistent scheduling

Vehicles select in mode 4 their subchannels by using sensing-based Semi-Persistent Scheduling (SPS) scheme specified in Release 14 ETSI TS 136 300 [i.10], ETSI TS 136 321 [i.11]. A vehicle reserves the selected subchannel(s) for a few consecutive reselection packet-counter transmissions. This counter is randomly set between five and 15, and the vehicle includes its value in the SCI. After each transmission, the reselection counter is decremented by one. When it is equal to zero, additional resources need to be selected and reserved with probability (1-P). Each vehicle can set-up P between zero and 0,8. Additional resources also need to be reserved if the packet to be transmitted does not fit in the subchannel(s) previously reserved. The reselection counter is randomly chosen every time additional resources are reserved. Packets can be transmitted every 100 subframes [i.e. ten packets per second (10 pps)] or in multiples of 100 subframes (up to a minimum of 1 pps). Each vehicle includes its packet transmission interval in the resource reservation field of its SCI. Thanks to the semipersistent reservation of resources and the inclusion of the reselection counter and packet transmission interval in the SCI, other vehicles can estimate which subchannels are free when making their own reservation, which reduces packet collisions. The process for reserving subchannels is organized in three steps as explained in Figure 4.5.

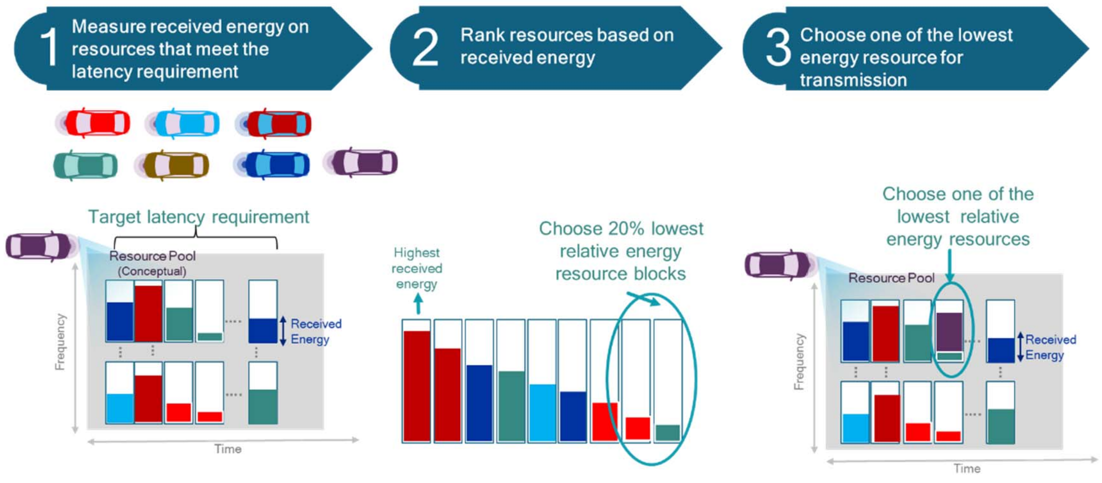


Figure 4.5: Mode 4 resource selection

The resource selection is as follows:

Step 1: Suppose that a vehicle, *V*, needs to reserve new subchannels at time, *T*. It can reserve subchannels between *T* and the established maximum latency (≤ 100 ms [i.12]). Within this time period, called selection window, the vehicle identifies candidate single-subframe resources (CSRs, also referred to as candidate resources) to be reserved by all groups of adjacent subchannels within the same subframe, where the SCI + TB to be transmitted will fit.

Step 2: Vehicle, *V*, analyses all the information it has received in the 1 000 subframes before *T* and creates a list, *L1*, of CSRs it could reserve. This list includes all the CSRs in the selection window except those that meet the following two conditions.

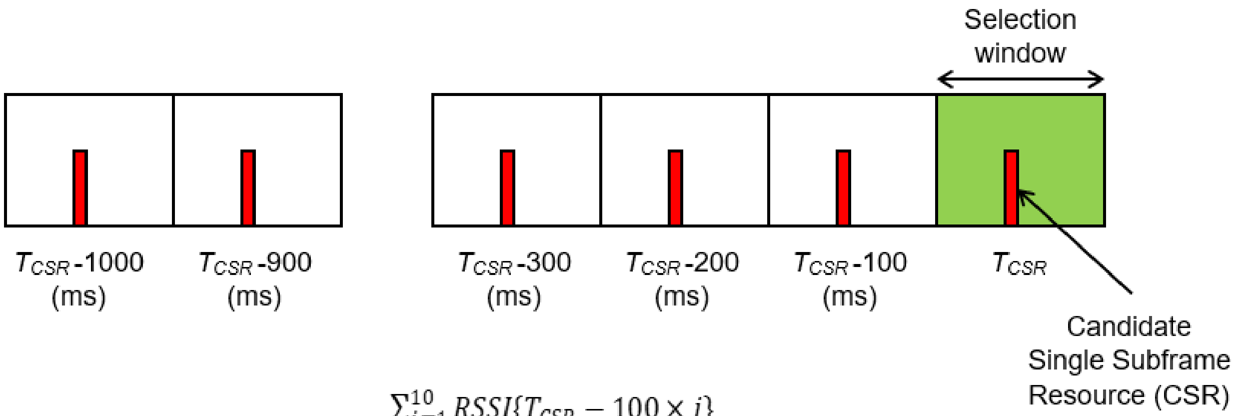
1) In the last 1 000 subframes, *V* has correctly received an SCI from another vehicle indicating that it will utilize this CSR at the same time *V* will need it to transmit any of its next reselection packet-counters.

2) *V* measures an average reference signal received power (RSRP) over the RBs utilized to transmit the TB associated to the SCI higher than a given threshold. The threshold depends on the priority of the packet. This priority is established by higher layers based on the relevance and urgency of the application. If V receives several SCIs from the same interfering vehicle reserving a given CSR, it will utilize the most recent one to estimate the average RSRP.

The above-mentioned conditions need to be simultaneously met for *V* to exclude a specific CSR. Vehicle *V* also excludes all CSRs of subframe *F* in the selection window, if *V* was transmitting during any previous subframe *F*-100 × j (j ϵ N, 1 ≤ j ≤ 10). It should be noted that *V* is not able to receive the transmissions of other vehicles in the subframe it is transmitting due to half duplex transmissions.

After Step 2 is executed, *L1* has to include at least 20 % of all CSRs in the selection window. If not, Step 2 is iteratively executed until the 20 % target is met. The RSRP threshold is increased by 3 dB in each iteration.

Step 3: Vehicle *V* creates a second list *L2* of CSRs. The total number of CSRs in *L2* has to be equal to 20 % of all CSRs in the selection window. *L2* includes the CSRs from *L1* (after Step 2) that experienced the lowest average received signal strength indicator (RSSI) over all its RBs. This RSSI value is averaged over all the previous T_{CSR}-100 × j subframes (j ϵ N, 1 ≤ j ≤ 10), see Figure 4.6. Vehicle *V* randomly chooses one of the CSRs in *L2*, and reserves it for the next Reselection Counter packet transmissions.



$$RSSI = \frac{\sum_{j=1}^{10} RSSI\{T_{CSR} - 100 \times j\}}{10}$$

Figure 4.6: The average RSSI of a candidate resource in Step 3

4.3.3.3 Hybrid automatic request

Hybrid Automatic Request (HARQ) is a mandatory feature in ETSI TS 103 723 [i.28]. It combines forward error correcting codes with ARQ error control and soft combining. The retransmission needs to be performed within 15 subframes of the original transmission.

4.4 New road ITS technologies

4.4.1 Introduction

During the drafting of the present document, new road ITS technologies have been or are being developed. These have not been subject for studying the co-channel co-existence herein but are mentioned briefly for completeness.

4.4.2 IEEE 802.11bd

The IEEE 802.11bd Task Group was created in January 2019 [i.30] to develop IEEE 802.11p further and the work is planned to be completed during autumn 2021. Its purpose is to support advanced use cases within connected and automated driving. New features developed in the IEEE 802.11bd task group are enhancements to the legacy waveform (retransmissions) as well as new optimized waveform which includes Low Density Parity Check (LDPC) encoding and midambles, support for 20 MHz channels and vehicle positioning etc. More details on IEEE 802.11bd can be found in [i.31]. The outcome of IEEE 802.11bd will be included in an update of the access layer standard ITS-G5.

4.4.3 5G-NR V2X

Release 16 of the 3GPP specifications (completed in June 2020) contains V2X communication using 5G New Radio (NR). It is complementing LTE-V2X and it supports advanced use cases and higher automation levels whereas LTE V2X supports basic active safety and traffic management [i.32]. 5G-NR V2X supports two modes of operation like LTE-V2X using the PC5 interface:

i) decentralized communication (mode 2); and

ii) supported by the Uu interface inside the coverage by a base station (mode 1).

5G-NR V2X has a new physical layer compared to LTE-V2X whereas the scheduling of transmissions for sidelink operation is similar for both technologies based on a synchronous network, while scheduling parameters allow for more flexibility. The additional flexibility and the support of a new feedback channel, enabling HARQ and CSI feedback as well as power control, might cause the NR V2X sidelink transmissions to behave significantly different from those of LTE-V2X sidelink. For more details on the 5G-NR V2X have a look in [i.31] and [i.32]. The 5G-NR V2X will be included in an update of the access layer standard LTE-V2X.

5 Problem statement

5.1 Introduction

The present document carries out studies on the feasibility of co-channel co-existence between ITS-G5 and LTE-V2X technologies. Uncoordinated transmissions from the 2 access technologies result in:

- Message collision: messages using different access technologies overlap in time, rendering either one or both messages invalid depending on the geographical position of the transmitting and receiving ITS stations, thus, leading to loss of data. This would undermine safety, which is not acceptable.
- Imbalance in channel access: one technology does not (sufficiently) release the channel for the other technology (i.e. not being granted the channel in a 'fair' way), leading to access starvation for the other technology. This would not be acceptable if both technologies were deployed in the same geographical area and had equal rights in accessing the available channels.

Further, each ITS station has its own radio horizon, impacting to which extent other vehicles are visible. As a result, without coordination each ITS station may have a very different view of the world with respect to the number of equipped vehicles (and hence channel busy ratio) and ratio between technologies. This can quickly vary over time. This is illustrated in Figure 5.1, where different world views of two vehicles (red and green vehicle, respectively) are shown, but this could also be time-varying perception by the same vehicle at two different locations close in time, t_1 and t_2. Co-channel co-existence mechanisms need to be robust against these locally different world views.

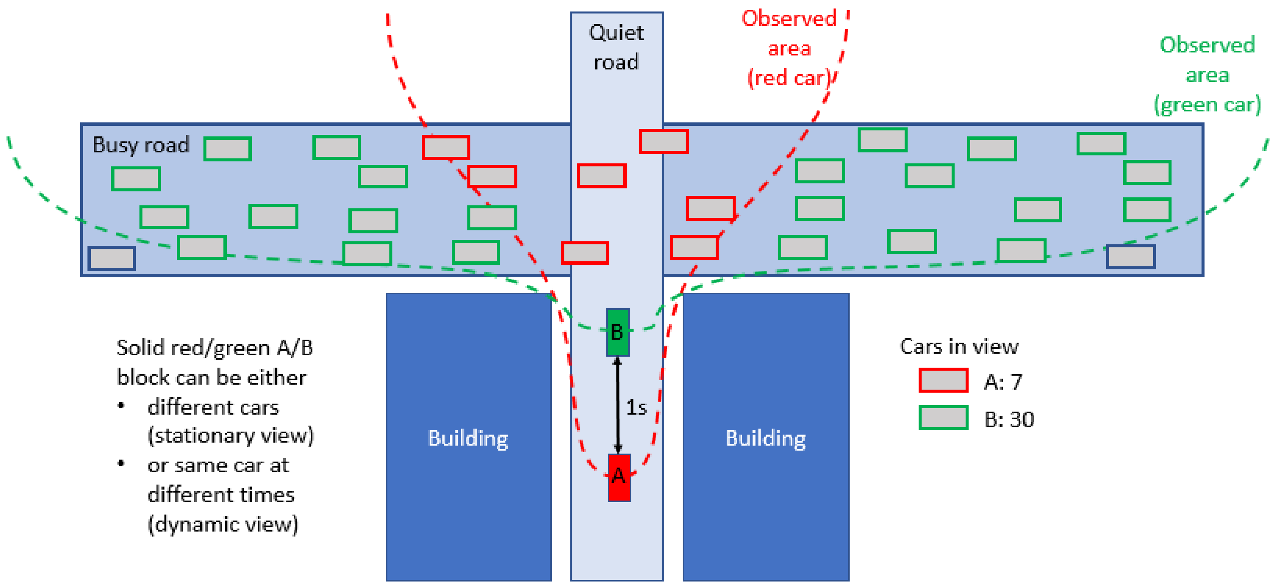


Figure 5.1: Perceived traffic from two positions (red and green)

To ensure a non-interfering operation of distinct radio communications technologies, orthogonality between corresponding transmissions is required. Orthogonality is typically achieved in the time, frequency, space and/or code domain. ITS-G5 uses the whole bandwidth of the channel (i.e. 10 MHz) for every transmission and cannot divide the channel resources in frequency. Different packet lengths are varied using more time for transmission given a specific Modulation and Coding Scheme (MCS) or varying the MCS. On the other hand, LTE-V2X has a fixed subframe of 1 ms and cannot vary the packet length in the time domain but instead in the frequency domain by changing MCS and number of subchannels. Thus, the possible division of channel resources between the two technologies needs to be performed in the time domain (time division multiplexing), see Figure 5.2.

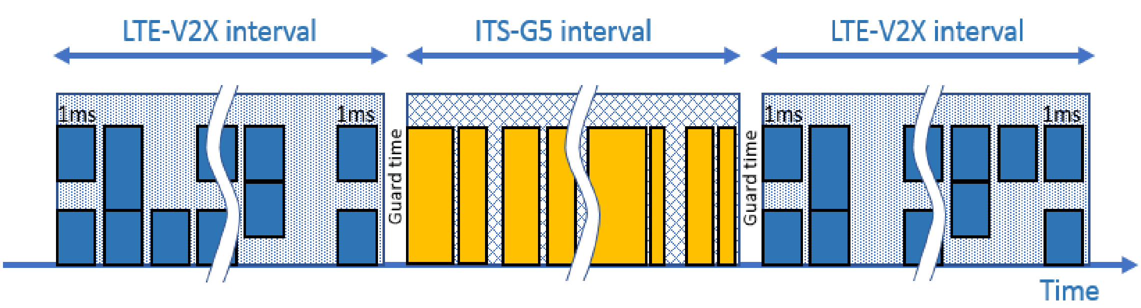


Figure 5.2: Example of how the two technologies share frequency channel in the time domain

5.2 Overlapping message transmissions

5.2.1 The last symbol gap problem

The "last symbol gap" problem is one of the mechanisms resulting in message collision between ITS-G5 and LTE-V2X, and is caused by the inter-subframe gap of LTE-V2X. The free gap between two subframes can be perceived by ITS-G5 as being a release of the channel, especially for high priority messages such as event-triggered Decentralized Environmental Notification Messages (DENMs).

NOTE: DENMs are triggered on behalf of an ITS application detecting an hazardous event. DENMs will be transmitted as long as there is an impending danger. DENMs are standardized in ETSI EN 302 637-3 [i.16]

The LTE-V2X subframe is divided into 14 OFDM symbols. The last OFDM symbol, sometimes referred to as "GAP" symbol is not transmitted to allow some time for the transmitters to return to receiver state before the start of the next subframe. This last OFDM symbol lasts exactly 1 024 + 72 IQ samples worth of time, sampled at 15,36 MSPS. This is approximately 71,35 µs and is denoted TL hereafter.

Figure 5.3 depicts how the channel is perceived by LTE and ITS-G5 stations, respectively, for a 2 ms period of time. Both subframes in Figure 5.3 contain transmissions and ITS-G5 has an opaque view of the channel since it cannot decode the LTE-V2X transmissions, it just detects the energy available. The last so-called GAP symbol by LTE-V2X is also depicted and during this period ITS-G5 can perceive the channel as free and it can perform a channel sensing (AIFS). This can lead to that ITS-G5 starts a transmission when a new subframe is starting.

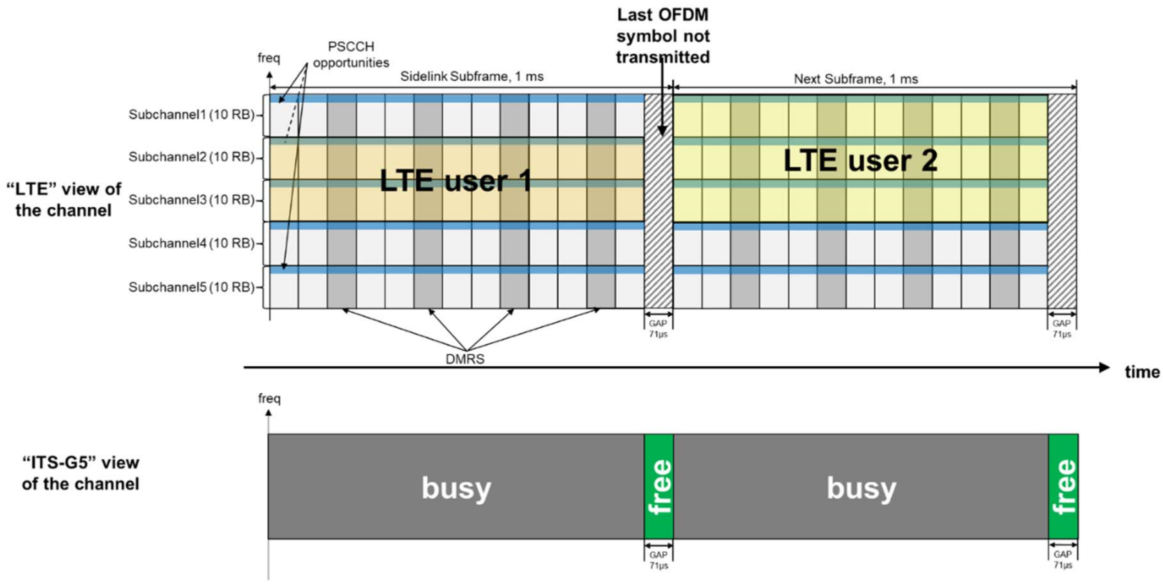


Figure 5.3: ITS-G5 can perceive the channel as free at LTE-V2X's GAP symbol in each subframe

Before being allowed to transmit, an ITS-G5 station listens on the channel for a predetermined listening period called the AIFS to assure the channel is free (see Clause 4.2.3 on details on ITS-G5 channel access mechanism). The length of the AIFS is depending on the message priority, to allow messages of higher priority access to the channel before messages of lower priority. In Table 5.1, the resulting AIFS and CW for ITS-G5 ACs are shown. As can be seen in this table, ITS-G5 can have AIFS (+ CW backoff time) smaller than TL for traffic classes AC_VO and AC_VI, thus the last LTE-V2X symbol can be used by ITS-G5 for performing an AIFS plus possible backoff time.

Table 5.1: AIFS and CW sizes for 802.11p's ACs

AC	CW_{min}	CW_{max}	*AIFS*	Intended use
AC_VO	3	7	58 µs	High priority DENM
AC_VI	7	15	71 µs	DENM
AC_BE	15	1 023	110 µs	CAM
AC_BK	15	1 023	149 µs	others

NOTE: In broadcast mode (used for road traffic safety applications), the *CW* is always set to its minimum value CW_{min}, see Figure 4.3. This CW is the upper bound of the back-off time slot, randomly chosen from the interval [0, CW]. Thus CW can be potentially zero (for AC_VO a probability of 25 %).

Figure 5.4 illustrates when ITS-G5 senses the channel during the last symbol of LTE-V2X, the AIFS is set to either AC_VO or AC_VI with zero or 13 µs backoff time. In the ITS-G5 view, when having a DENM message ready for transmission, ITS-G5 will start to sample the channel until no signal is detected. Now the slot is perceived free, and a DENM transmission is started after the AIFS period. LTE-V2X, not aware of ITS-G5, may start a transmission at almost the same time, resulting in an unavoidable collision impacting both the ITS-G5 message as well as the LTE-V2X message.

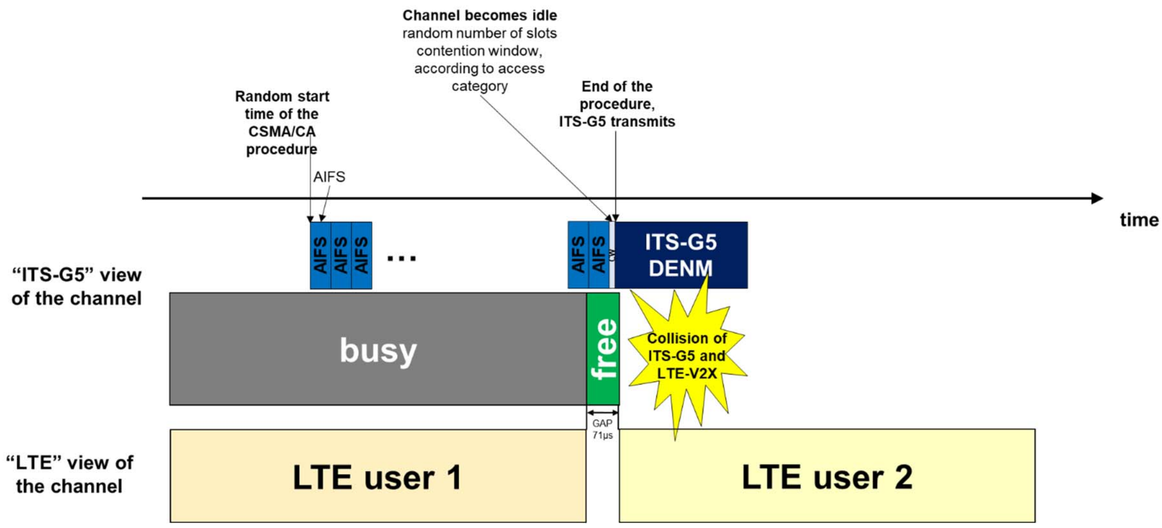


Figure 5.4: ITS-G5 initiates a transmission during the last symbol of LTE-V2X

The last symbol gap problem will occur for 50 % of the data traffic mapped to AC_VO for ITS-G5 and 12,5 % for data traffic mapped to the AC_VI under the circumstance that LTE-V2X stations transmit in consecutive subframes and ITS-G5 stations have data traffic belonging to the two traffic classes. Table 5.2 tabulates possible CW values and AIFS that can cause ITS-G5 to initiate an AC_VO or AC_VI transmission when the next subframe starts for LTE-V2X.

Table 5.2: Occurrence of the last symbol gap problem

AC	*CW*	*AIFS* (see note)	Possible duration of the inner state machine (see note)	Gap problem occurrence chances (see note)
AC_VO	3	***58 µs***	[***0***,***1***,2,3] CW = [***0, 13 µs***, 26 µs, 39 µs]	***50 %*** (2 chances out of 4)
AC_VI	7	***71 µs***	[***0***,1,2…7] CW = [***0***, 13 µs, 26 µs…]	***12,5 %*** (1 chance out of 8)
AC_BE	15	110 µs	n/a	n/a
AC_BK	15	149 µs	n/a	n/a
NOTE: The numbers in bold and italic are the values for which the last symbol gap problem can occur.				

The frequency of an LTE-V2X transmission actually being scheduled will depend on the traffic situation and LTE-V2X scheduling mechanisms and will have to be analysed through simulation.

The occurrences of the last symbol gap problem in Table 5.2 are calculated assuming that the beginning of the AIFS channel sensing by ITS-G5 is aligned with the beginning of the LTE gap, i.e. the last symbol of LTE-V2X. There is an ON/OFF time mask defined for LTE-V2X in Clause 6.3.4G of [i.29]. For power off, a 20 µs transient period is allowed from the end of the 13th OFDM symbol into the guard period (i.e. 14th symbol). Therefore, the OFF power requirement is not valid in the first 20 µs and the power radiated within this time might still allow for a detection of LTE-V2X by ITG-G5. Figure 5.5 has been added for illustration stemming from Figure 6.3.4G.1-1 in [i.29].

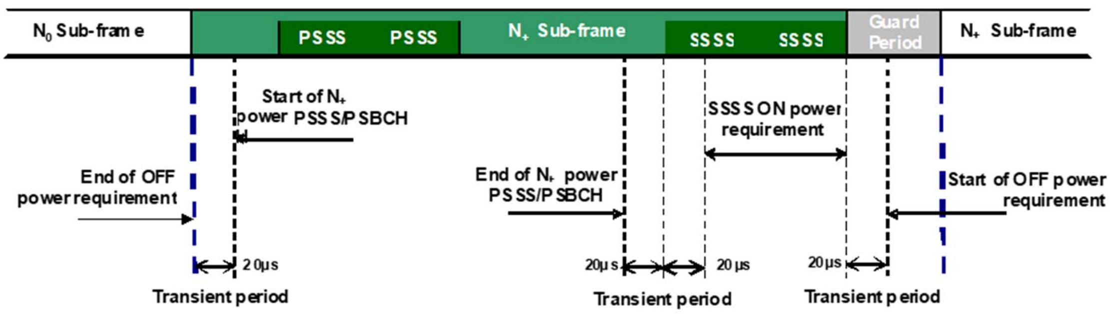


Figure 5.5: ON/OFF mask for LTE-V2X [i.29]

To this end, Table 5.2 shows the worst case occurrence of the gap problem and given the amount of energy during the 20 µs transient period, the severity of the gap problem occurrence for AIFS = 71 µs with CW = 0 as well as AIFS = 58 µs with CW = 1 might be a bit relaxed.

5.2.2 ITS-G5 cut off by LTE-V2X resuming transmission

In case the LTE-V2X system decides not to use one or more 1 ms subframes, the period in which the channel is available is now much longer than described in Clause 5.2.1, and ITS-G5 messages get access to the channel during subsequent subframe(s). A collision will occur if the LTE-V2X system "resumes" transmissions (in the sense the same or another LTE-V2X user will start the next transmission), as shown in Figure 5.6.

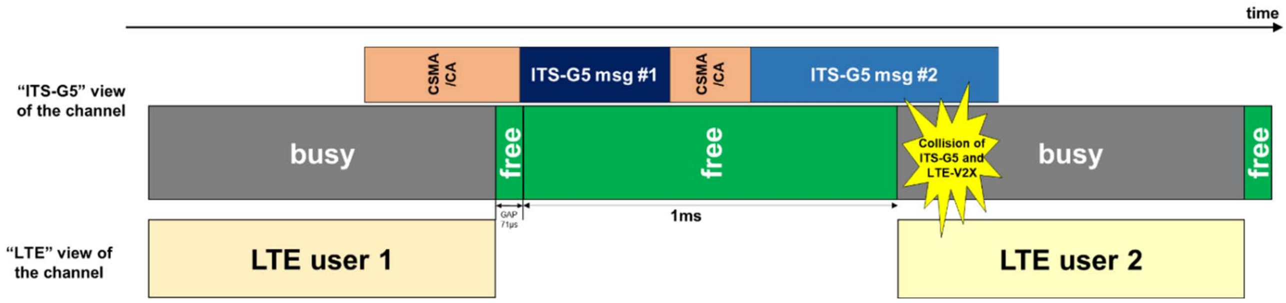


Figure 5.6: ITS-G5 stations can transmit messages from all traffic classes in unused LTE-V2X subframes

In the situation of a single unutilized subframe, 1,071 ms "free-from-LTE-transmissions" time (71 µs + 1 ms) is available. Thus, any traffic class of ITS-G5 messages can use the channel when it is idle for such a long time, not only DENM but for instance Cooperative Awareness Messages (CAMs).

NOTE: CAMs are triggered with 1 Hz - 10 Hz depending on vehicle dynamics and they are always present as long as the vehicle is turned on. CAM is standardized in ETSI EN 302 637-2 [i.17].

CAMs have sizes between 190 and 550 bytes, averaging 350 bytes in real test-drives (see Annex B). This translates into a packet duration approximately between 0,3 ms and 0,8 ms with an average duration of 0,5 ms (considering 350 bytes) given the default rate of 6 Mbit/s (QPSK, ½ rate).

The CSMA/CA procedure for CAMs can last between 110 µs (AIFS time) up to 279 µs (AIFS time + 15 CW, based on CW_{min} for class AC_BE). This means that in case of a CAM pending for transmission and a gap of a single LTE-V2X subframe, typically the first CAM gets through completely, but the second CAM (third in case of all CAMs are short) will suffer a collision towards the end of the transmission when the next LTE-V2X subframe containing a LTE-V2X transmission. Likewise, the LTE-V2X message will suffer from the ITS-G5 transmission, rendering either or both messages invalid depending on the geographical position of the ITS stations.

The exact statistical figures of occurrence of collisions need to be analysed, possibly via numerical simulations. However, for average ITS-G5 CAM sizes of 350 bytes, the cut-off problem typically occurs for the second CAM in case of one "free" LTE subframe and for the third and fourth CAM in the case of two consecutive "free" LTE subframes. Thus, it would be useful to group LTE-V2X messages into adjacent subframes to avoid the cut-off problem.

5.3 Basic principles for co-channel co-existence solutions

5.3.1 Fair sharing of time resources depending on relative traffic load

The available time resources of a channel are shared fairly between LTE-V2X and ITS-G5 depending on the relative traffic load which is observed in a given geographic location and at a given time. A corresponding parameterization typically varies over time and space depending on the locally observed share between LTE-V2X and ITS-G5 at a given point in time.

EXAMPLE: At a given geographic location and at a given time, it is assumed that 50 % of the traffic belongs to LTE-V2X and 50 % of the traffic belongs to ITS-G5. In such a case, each of the two systems will have 50 % of the time resources reserved for their respective transmissions.

5.3.2 Distributed channel access management

The division of channel resources between LTE-V2X and ITS-G5 is based on a distributed mechanism, i.e. no centralized control entity is required to coordinate between the systems.

NOTE: The requirements of Clauses 6.1.2 and 6.1.3 imply that a distributed mechanism is used to decide on the deterministic start time, end time and duration of the LTE-V2X and ITS-G5 transmission intervals. Furthermore, both systems, LTE-V2X and ITS-G5, will have the capability to detect the deterministic start time, end time and duration of the LTE-V2X and ITS-G5 transmission intervals.

5.3.3 Orthogonality of channel access

Both systems, LTE-V2X and ITS-G5, will limit any channel access to their respective LTE-V2X and ITS-G5 transmission intervals.

NOTE: The requirement implies that a channel access period is typically finite and well defined. A transmission is only scheduled in case that it will not exceed the channel access period.

5.3.4 Deterministic timing

The start time, end time and duration of the LTE-V2X and ITS-G5 transmission intervals are deterministic for a given geographic location and a given time.

NOTE: The timing parameterization is adapted in function of the observed relative traffic load of LTE-V2X and ITS-G5, respectively. Once the parametrization is agreed, the transmission intervals are deterministic, i.e. it is known in advance when an interval starts and ends.

5.3.5 Guard time between transmission intervals

A guard time is introduced between the LTE-V2X and ITS-G5 transmission intervals (and vice versa).

NOTE: The main purpose of this guard time is to avoid interference between both systems. Due to inaccurate time synchronization or the propagation delay, transmissions at the end of the reserved time for one of the systems can generate interference at the start of the time reserved for the other system. This guard time may enable a suitable switching of dual-mode transceivers.

6 Co-channel co-existence methods

6.1 Introduction

6.1.1 Background

Clause 6 outlines a set of co-channel co-existence methods between ITS-G5 and LTE-V2X, which will be scrutinized in subsequent clauses. All methods presented are based on sharing in the time domain since ITS-G5 uses always the whole bandwidth for transmission whereas LTE-V2X can also divide the resource in the frequency domain. The techniques presented range from a classical Time Division Multiplexing (TDM) approach with static division of time resources to dynamic based on the possibility to perceive technology distribution in a certain geographical area (e.g. through detection of signals).

6.1.2 Sharing in the time domain

Sharing in the time domain implies that the available time is divided into time slots, where one technology will occupy the whole bandwidth for a certain period of time (i.e. time slot). Figure 6.2 illustrates this. How the resources are used within each time slot interval is decided by the medium access control scheduling for each technology. ITS-G5 always uses the whole bandwidth and depending on payload the packet transmission duration is variable. LTE-V2X uses 1 ms chunks (i.e. subframe) and can further divide this into the frequency domain as depicted in Figure 6.1. There may be a guard time when transitioning from one technology time slot to another.

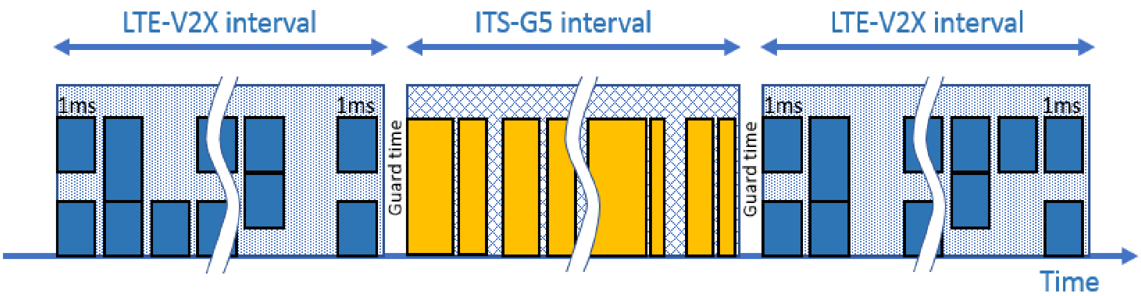


Figure 6.1: Example of how the two technologies share frequency channel in the time domain

To assess and describe the methods outlined in Clause 6.3, a common terminology needs to be introduced. In Figure 6.2, the notion of superframe together with time slots is introduced and in Table 6.1, the different parameters are described. The superframe boundary contains two "time slots", one for each technology. The time slot boundary will vary depending on for example equipment rate. The guard time is not depicted in Figure 6.3 and it is not clear if time needs to be spent on a pronounced guard time or inherent protocol mechanism is enough as guard times (e.g. AIFS for ITS-G5 or "guard period" in LTE-V2X).

NOTE: Time slot is the period of time one technology has access to the channel, denoted T_a and T_b in Figure 6.2. Subframe refers to the 1 ms time duration of an LTE-V2X transmission, see Figure 6.1.

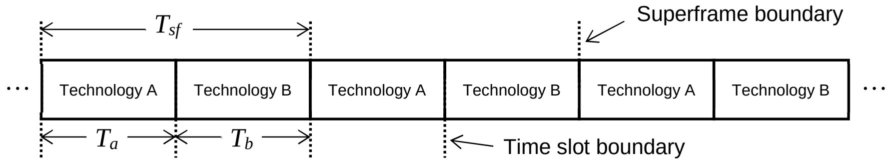


Figure 6.2: Superframe structure with two time slots, one for each technology

Table 6.1: Description of parameters in Figure 6.3

Parameter	Unit	Description
T_{sf}	ms	The length of the superframe.
T_a	ms	The length of the period technology A is allowed to use the channel for transmission denoted "time slot". Technology B is not allowed to access the channel during this time. T_a can vary depending on the method. $T_a + T_b = T_{sf}$. A guard time might be included in the beginning of T_a.
T_b	ms	The length of the period technology B is allowed to use the channel for transmission denoted "time slot". Technology A is not allowed to access the channel during this time. T_b can vary depending on method. $T_a + T_b = T_{sf}$. A guard time might be included in the beginning of T_b.

6.1.3 Limitations of sharing in the time domain

There are inherent protocol mechanisms for both technologies that put up limits on the time slot and superframe sizes that need to be considered when developing and investigating the co-existence methods.

In LTE-V2X mode 4, sensing-based Semi-Persistent Scheduling (SPS) is used to reserve the radio resources, i.e. subchannels, as outlined in Clause 4.3. An ITS station reserves the selected subchannel(s) for several subsequent transmissions. According to ETSI EN 303 613 [i.7], the parameter P_{step} in [i.8] is equal to 100 ms. The final SPS transmission periodicity is determined by $P_{step} \times P_{rsvp\_Tx}/100$, where the resource reservation interval $P_{rsvp\_Tx} \in \{20, 50, 100, 200, \ldots, 1\,000\}$ is determined by higher layers. The resource reservation interval P_{rsvp_Tx} is chosen by the LTE-V2X station depending on its scheduling decision. Therefore, packets utilizing the same subchannel(s) can be transmitted every 20 ms, 50 ms, 100 ms or in (integer) multiples of 100 ms up to 1 s. When combining the SPS algorithm with a TDM pattern, then the SPS reservations does not have to fall into the time reserved for the other technology. To be compatible with the SPS algorithm, the TDMA superframe duration has to be identical to or a (prime) divisor of the SPS transmission periodicity. All other superframe durations lead to the effect that although the first SPS reservation can be selected to fall within the LTE-V2X time slot, there is no guarantee that the reselected SPS resources that follow do not fall into the time reserved for the other technology. Table 6.2 lists the shortest five SPS transmission periodicities and the resulting superframe durations.

Table 6.2: SPS transmission periodicity and possible superframe durations

SPS transmission periodicity (ms)	Possible superframe durations (supported superframe durations in bold)
20	**2, 4, 5, 10, 20**
50	**2, 5, 10, 25, 50**
100	**2, 4, 5, 10, 20, 25, 50**, 100
200	**2, 4, 5, 8, 10, 20, 25, 40, 50**, 100, 200
300	**2, 3, 4, 5, 6, 10, 12, 15, 20, 25, 30, 50**, 60, 75, 100, 150, 300
…	…

In general, the longer the superframe duration, the higher the additional delay caused by the transmission. Since CAM packets can be generated periodically every 100 ms and DENM packets every 50 ms, the superframe duration needs to be less or equal than the smallest time interval between two packets. Otherwise, two or more packets, where only the last packet contains up-to-date information, need to be transmitted within one time slot. This would render the transmission of the outdated packet(s) redundant and a waste of radio resources. Even for 50 ms superframe duration, the packet delay will be significantly increased, depending on the time slot length allocated to the other technology. Therefore, for practical implementations, superframe durations smaller or equal to 50 ms should be chosen.

Table 6.2 summarizes in bold the possible combinations of the SPS transmission periodicity and the supported superframe durations up to 50 ms. It can be observed, that only superframe durations 2, 5, and 10 ms can be supported by all SPS transmission periodicities. In case 20 ms SPS transmission periodicity would be excluded, then also superframe durations of 25 and 50 ms are possible. To transmit CAM and DENM messages, excluding 20 ms SPS transmission periodicity might be possible. However, by restricting the available LTE-V2X SPS transmission periodicities, messages requiring a higher packet rate than 20 Hz will be impacted. Technologies relying on CA/CSMA would not be impacted by an exclusion of the 20 ms SPS transmission for such use cases.

LTE-V2X can enable HARQ retransmissions to increase robustness and above a vehicle speed of 160 km/h, HARQ retransmissions are mandatory (see ETSI EN 303 613 [i.7]). Therefore, HARQ retransmissions have to be ensured in a time-sharing scenario. According to the LTE-V2X specification in Clause 14.1.1.17 of ETSI TS 136 213 [i.8], when employing HARQ retransmissions, both transmissions, the initial transmission and the retransmission, have to occur within a window of 15 (contiguous) subframes, i.e. 15 ms. Depending on the combination of superframe and LTE-V2X time slot duration, the transmit opportunities for both transmissions might be significantly limited, especially in the case of short time slot durations. As soon as the time slot duration of the other technology is 15 ms or longer, both transmissions have to happen in the same time slot. In this case, for very short time slot durations both transmissions might need to be transmitted in the neighbouring or even adjacent subframes, since frequency multiplexing on the same subframe is not allowed see Clause 14.1.1.7 in ETSI TS 136 213 [i.8], therefore reducing the time diversity. Due to the reduced number of available resources, the SPS algorithm might have to accept higher RSRP thresholds to find available resources, which leads to overall higher interference between LTE-V2X transmissions and higher packet error rate.

For LTE-V2X, time slot and superframe durations in multiples of 1 ms, i.e. the fixed duration of one LTE-V2X subframe, ensure that the LTE-V2X time slot can be fully used. For ITS-G5, where the duration of each transmission depends on the payload size and the selected Modulation and Coding Scheme (MCS), there is no preference towards a specific time slot or superframe granularity. Therefore, choosing the time slot and superframe durations in multiples of 1 ms is optimizing the system efficiency. In case guard periods between both technologies are used, it is therefore beneficial to have the start and end time of the LTE-V2X transmission aligned with the 1 ms granularity.

For the minimum time slot duration, a compromise needs to be found. Depending on the packet size and selected modulation and coding scheme, ITS-G5 transmissions can take up to 4 ms according to Equation (2) in ETSI EN 302 663 [i.2]. Furthermore, also the time for AIFS and CW are required in the time slot before the transmission, which can account up to 1 ms depending on the priority class. Therefore, the minimum time slot duration for each technology should never fall below 5 ms since this would render certain ITS-G5 transmissions impossible and undermines HARQ retransmissions diversity for LTE-V2X, as described above. To ensure fairness for both systems, the minimal time slot duration has to be equal for both technologies. Since the superframe duration needs to be longer than the sum of the two time slot durations the superframe durations has to be at least 10 ms. The short superframe durations of 2 ms and 5 ms, which would be supported by all LTE-V2X SPS transmission periodicities, cannot be used due to the limitation of ITS-G5. Clause 6.2 elaborates further on superframe and time slot sizes.

Given the inherent protocol mechanisms of both technologies as outlined, only a set of sizes of the superframe is eligible:

- superframe duration: 10 ms, 25 ms, or 50 ms
    - 10 ms supports the following SPS periodicities {20, 50, 100, 200, …, 1 000},
    - 10 ms, 25 ms, and 50 ms, supporting the following SPS periodicities {50, 100, 200, …, 1 000}

Three different superframe duration (10 ms, 25 ms, and 50 ms) will be examined during simulations to find out which one is the most suitable for co-channel co-existence. The minimum time slot duration for each technology is set to 5 ms for numerical simulations in this study. In a real-world deployment, the superframe duration will be fixed and the time slot duration for each technology will be decided either static, semi-static, or dynamic. This is further discussed in Clause 6.2.3.

6.1.4 Presumptions

6.1.4.1 Half duplex constraint

Each ITS station regardless of access layer technology is operating in half-duplex operation, implying that it cannot receive messages or perform PHY layer measurements while it is transmitting messages.

6.1.4.2 Synchronization

All ITS stations have access to a Global Navigation Satellite System (GNSS) and thus, they can have common time source

LTE-V2X and ITS-G5 stations may have different time synchronization tolerance.

LTE-V2X is based on a synchronous network and LTE-V2X stations inherently have a tight requirement for accuracy in terms of frequency and time synchronization. The frequency accuracy requirement is specified in 3GPP TS 36.101 [i.29] to maximum 0,1 ppm jitter (i.e. ± 600 Hz), and the time accuracy requirement is specified in ETSI TS 136 133 [i.33] to maximum ±0,39 µs.

ITS-G5 is based on an asynchronous network, with messages including a preamble allowing the receivers to tune to the frequency and time of the transmitter. The synchronization requirements are thereby less stringent.

EXAMPLE: IEEE 1609.4-2016 [i.27] defines a channel switching mechanism, where ITS stations have a synchronization tolerance of 2 ms, and the time error can be as large as ±0,33 ms.

For simulation purposes in the present document, it is assumed that ITS-G5 stations have a time synchronization accuracy of 0,1 ms.

6.2 Configuration of time slot boundary

6.2.1 Static, semi-static and dynamic

The superframe duration will be fixed in a real-world deployment but the time slot boundary can be configured either statically, semi-statically, or dynamically, depending on the technology distribution. Description of the configurations are found in Table 6.3. The dynamic configuration could either be performed locally or globally, which will be further elaborated on in subsequent clauses.

Table 6.3: Description of possible configurations

Configuration	Description
Static	The available resources are divided between the two technologies offline and are constant throughout the lifetime of the ITS station. The static configuration is decided by regulators.
Semi-static	The available resources are divided between the two technologies offline but can be changed throughout the lifetime of the ITS station. The semi-static configuration is decided (and potentially revised) by regulators. This configuration requires the ability of performing software updates.
Dynamic	The available resources are dynamically shared considering the actual, local distribution of technologies among ITS stations: • Locally, the determination is performed on the fly by (some of) the ITS stations. • Globally, the determination is performed by a source outside the ITS station, called supervising entity. The supervising entity is responsible for aggregating traffic measurements performed by Base Stations (BS) and/or Roadside Unit (RSUs).

6.2.2 Dynamic local configuration of time slot sizes

In a dynamic local configuration scenario, the ITS stations determine the time slot sizes for each technology, in a distributed manner. Three superframe sizes are considered in present document: 10 ms, 25 ms, and 50 ms. More details on the superframe sizes are found in Clause 6.1.3. In a real-world deployment, the superframe size will be fixed to one of the proposed.

The superframe and time slot sizes are not known to ITS-G5 in Method B through Method E (described in more detail in Clause 6.3 and an overview provided in Table 6.3). In these methods, LTE-V2X stations signal to ITS-G5 stations to defer channel access using different approaches. LTE-V2X can perceive the amount of transmissions belonging to LTE-V2X, how this assessment is performed is detailed in Clause D.3. Both technologies need to adhere to congestion control mechanisms, implying that there will be an upperbound for the channel utilization by both technologies.

ITS-G5 will restrict the number of packets transmitted by each ITS-G5 station substantially when hitting a CBR of 62 % [i.26], and LTE-V2X has the same mechanism for when CBR values reaches 65 % [i.25].

LTE-V2X needs to know which 1 ms subframes in the future that are possible to use for scheduling upcoming transmissions. Given this, the LTE-V2X part for transmissions should be first in the superframe because then LTE-V2X always know from where to start. When the number of LTE-V2X station increases, indicated by the CBR_{LTE} (see Clause D.3), more and more 1 ms subframes can be added to the resource pool for eligible resources to select from.

The minimum time slot duration for each technology is set to 5 ms (see Clause 6.1.3) for numerical simulations in this study. For a superframe duration of 10 ms, the time slot duration will always be fixed for each technology.

For the superframe durations of 25 ms and 50 ms, the $Tech_{percentage}$ will determine the time slot duration for each technology, see Tables 6.4 and 6.5. Annex H provides two tables detailing all time slot duration values for different $Tech_{percentage}$ intervals for each superframe size.

Table 6.4: Time slot duration for each technology for a superframe of 25 ms

Superframe of 25 ms		
$Tech_{percentage}$	LTE-V2X	ITS-G5
[0:22[%	5 ms	20 ms
[22:26[%	6 ms	19 ms
…	…	…
[78-100] %	20 ms	5 ms

Table 6.5: Time slot duration for each technology for a superframe of 50 ms

Superframe of 50 ms		
$Tech_{percentage}$	LTE-V2X	ITS-G5
[0:11[%	5 ms	45 ms
[11:13[%	6 ms	44 ms
…	…	…
[89:100] %	45 ms	5 ms

6.2.3 Dynamic global configuration of time slot sizes

In a dynamic global configuration scenario, the available resources are dynamically shared considering the actual, local distribution of technologies among ITS stations. The scheduling of resources is performed by a source outside the ITS station, called supervising entity. The supervising entity is responsible for aggregating measurements performed by, e.g. Roadside Units (RSU), Base Stations (BS), as well as by the Onboard Units (OBU). The supervising entity will instruct (some of) the ITS stations about the TDM pattern to follow.

The methods to determine the TDM pattern locally and globally can be categorized as:

- small-area local short-term measurements;
- large-area long-term measurements; or
- based on a large-area database.

For each locally and globally defined TDM pattern, a geographic area as well as a validity duration are required. Depending on the intended requirements for both parameters, different solutions should be used, as depicted in Figure 6.3. Although a fast update and a fine geographical area are desired, a compromise needs to be found to enable a sustainable update rate, i.e. the right balance between spectral efficiency and implementation/deployment complexity.

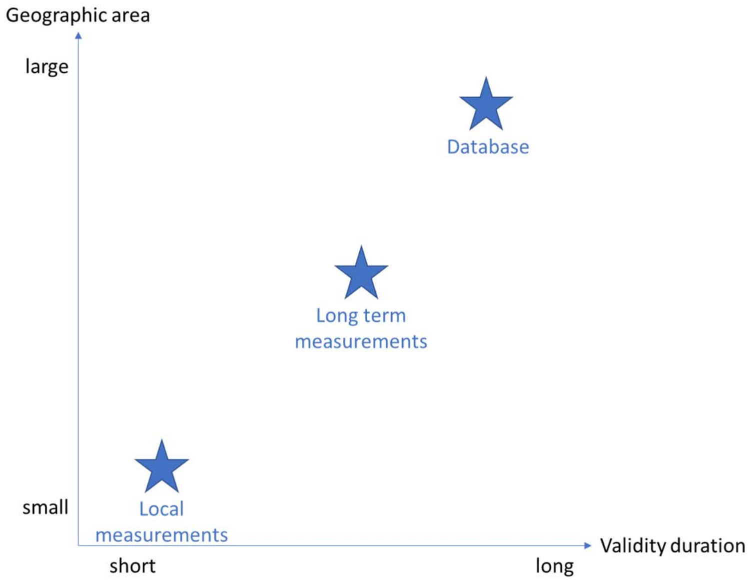


Figure 6.3: Validity duration and geographic area for different solutions to determine the TDM pattern dynamically and globally

The small-area local short-term measurements are summarized as follows:

- In a small geographic area, local measurements are continuously performed. The measurements can be performed by road-side units, base stations, as well as by on-board units, for example.
- An infrastructure/communication link is needed to quickly distribute the measurements to the supervising entity. A centralized or a number of distributed entities need to handle the handover of vehicles between the corresponding geographical areas.
- The TDM pattern should be valid for minutes or hours.
- The method requires a mandatory fast and reliable communication connection to distribute the measurements as well as the information about the dynamic TDM pattern. Therefore, the effort for this is method is very high.

The large-area long-term measurements are summarized as follows:

- In a wider geographic area, measurements are done regularly. The measurements can be performed by measurement vehicles or other equipment which is able to count the number of actively transmitting vehicles and their technology in a region.
- The measurements can be also done by several road-side units or base stations for a medium geographic area. They are stored in a database and are used to determine the TDM pattern. Also, here the supervising entity needs to handle the handover of vehicles between the wider geographical area.
- The TDM pattern should be valid for hours or days.
- This method requires neither a fast nor highly reliable communication connection to distribute the information to the vehicles. The effort for this method is therefore medium.

The databases are summarized as follows:

- For each city/county/state, cars are registered in a central register. Those registers contain very detailed information about each car. From those databases it is possible to determine the technology distribution for a large geographic area.
- Since the information will change very slowly in those databases, the TDM pattern should be valid for days or months.

- The database of vehicles and technologies can be regularly cross-checked with mobile operators' data to provide the exact region where the vehicles are located.
- This method can be easily implemented and a public database, similar to the database used for CEN DSRC protection, can be used to convey this information to all vehicles. Therefore, the effort for this method is low.

To also enable the access to the channel for vehicles that have no access to the dynamic TDM pattern, a minimum time slot duration can be allocated to each technology. Vehicles without information about the dynamic TDM pattern are then limited to this minimum time slot duration. This minimum time slot duration will be also used as the fall-back configuration when transitioning from one geographical area to another.

How a dynamic global configuration might look in reality needs further elaboration and it is out of scope of the present document.

6.3 Co-channel co-existence methods

6.3.1 Method A: Classic TDM method

6.3.1.1 Introduction

This method is based on a classical Time Division Multiplexing (TDM) approach in which a time domain partition is used to assign resources to the two road ITS technologies a priori. The basic idea is to define the superframe length, with deterministic start and end times which is known by both technologies, as shown in Figure 6.4. To facilitate the discussion, it is assumed that the superframe is divided in two time slots, one for each technology.

Depending on if/how often the partitions of time between the technologies are updated, different approaches are possible:

- The **static** implementation of this approach would be a fixed TDM pattern in which the two technologies equally share the medium in time domain. In this case, the time slot boundary between the two technologies is fixed and the partition of the resources does not change over time. Within each time slot, one or multiple users within the same technology group may access the medium for transmission according to the technology intrinsic access method.
- **Semi-static** TDM would be that the time slot boundary between the two technologies can be periodically updated based on some mechanism as the one described in Clause 6.3.1.1. The updated could be triggered based on different conditions (e.g. traffic conditions in a specific area) and with a different periodicity. In any case, the time scale of update is much longer compared to a dynamic scheme.
- In the **dynamic** approach, the technologies adapt the time slot boundary based on the current equipment rate.

In summary, the key aspects of the method based on TDM partitions are the following:

- It is required that both technologies have a common time reference. This can be provided by, e.g. Global Navigation Satellite System (GNSS).
- An overall frame structure (*superframe*) is known to both technologies.
- A contiguous portion of the superframe timing is allocated to each technology (T_i). Each technology is allowed to transmit only in its allocated partition. The TDM configuration (pattern) is repeated in every superframe. The time slots which are dedicated to one technology are contiguous.
- Guard intervals at the end of each partition can be introduced to account for synchronization inaccuracies.

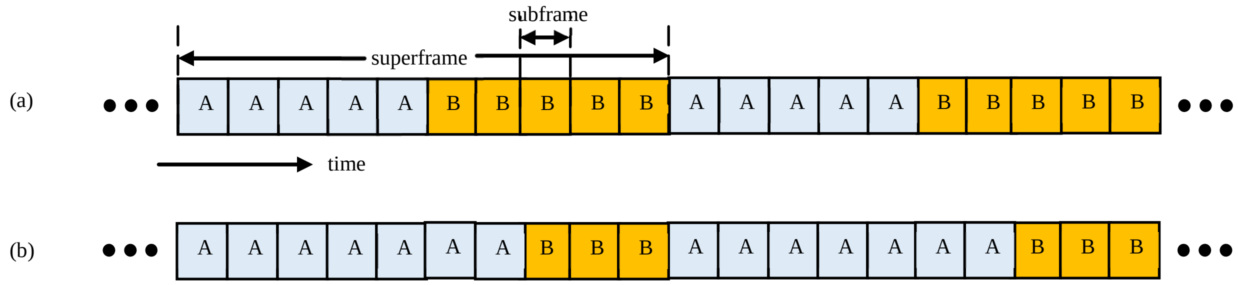


Figure 6.4: Time division between technologies A and B

6.3.1.2 Semi-static TDM pattern update

A static TDM configuration would lead to channel underutilization when the traffic load distribution between technologies changes. As these changes do not happen abruptly over time and geographical area, a semi-static update of the TDM configuration, where the TDM pattern is periodically updated to match the technologies traffic load over a certain geographical area is proposed. The focus is on the mechanism which allows an efficient update of the TDM pattern rather than on the trigger of the updates.

TDM configuration updates are broadcasted via signalling from base stations and/or RSUs. Alternatively, it is also possible to send the updates out-of-band via, e.g. the cellular network connectivity. All vehicles receive during the full superframe, except while transmitting. This is required to detect transmissions from vehicles which are out of coverage.

Every TDM configuration update sent by the network (e.g. RSU) can be safely considered as valid for a period of time called *TDM_config_expiration_time* and limited by an optional geographical area information. The validity of the TDM configuration applies even when the ITS station goes out of network coverage. When the *TDM_config_expiration_time* of the last received TDM configuration expires or the geographical area is left, the ITS station cannot assume that this configuration is still valid. In that case, the ITS station falls back to a default TDM configuration that restricts only its TX (but not RX) resource pool.

The default TDM configuration restricts only the subframes over which the station may transmit. The station always tracks all subframes for transmissions of interest as if no TDM was applied, since the current (and unknown) TDM might as well provide all subframes to the same technology. Therefore, the station may end up receiving signals over subframes that are excluded from its TX partition. There are several possible approaches for the design of the default configuration:

- Matching the distribution/penetration of technologies over a large-scale geographical area
- Splitting the resources equally (50 - 50) between technologies
- Using a conservative reservation (e.g. transmit only on 20 % of subframes) to avoid the possibility of transmitting in a subframe reserved for the other technology (with the potential cost of underutilization of resources)

6.3.1.3 Dynamic TDM pattern update

The semi-static method described in Clause 6.3.1.2 might require an external entity to update the TDM configuration. In a dynamic TDM method each station will use local measurements to determine which technology is used in each subframe. In contrast to other dynamic approaches, in this method all stations, i.e. LTE-V2X as well as ITS-G5, need to derive the TDM pattern to be followed.

ITS-G5 stations can distinguish signals originating by LTE-V2X from ITS-G5 transmissions, e.g. by employing the cyclic prefix method described in Clause D.2.1. Since LTE-V2X transmissions are confined to subframes, as indicated in Figure 6.4, one possible method is to decide based on the cyclic prefix method for each slot if it is used by LTE-V2X. The method to determine the dynamic local configuration of superframe structure and time slot described in Clause 6.3.3.2 can be also applied to derive the TDM pattern for ITS-G5 stations. In case self-detection of ITS-G5 signals is used, the $Tech_{percentage}$ will be calculated accordingly.

For LTE-V2X, the metrics described in Clause D.3 could be used to determine the technology distribution metric $Tech_{percentage}$. Based on this metric, Clause 6.2.2 can be applied.

It should be noted that the enhancements described in Clause 6.3.1.5 can also be applied with the dynamic TDM pattern update. This will ensure that the probability for collisions due to overlapping TDM patterns is significantly reduced.

The dynamic TDM pattern update could also be used as a fall-back method for the semi-static TDM pattern update, described in Clause 6.3.1.2, if a station is out of coverage and therefore not able to receive an updated/valid TDM pattern.

6.3.1.4 Alternative method to detect LTE-V2X transmission boundaries

As outlined in Clause 6.3.1.2, for the classic TDM method access to a common time reference is required. LTE-V2X stations always have access to a common time reference, therefore the following method is a good option for ITS-G5 stations to acquire synchronization. Assuming that T_{sf} , the superframe length, is pre-stored or signalled and optionally also T_a or T_b are pre-stored or signalled to the station, then it is possible to detect the superframe and transmission boundaries between the two technologies by local measurements. ITS-G5 stations estimate the location of LTE-V2X transmissions inside the superframe and derive the time slot boundary between technologies as well as the superframe boundary.

ITS-G5 stations construct a virtual time map of LTE-V2X transmissions leveraging the fact that LTE-V2X transmissions will repeat with a periodicity of T_{sf} , i.e. the super-frame length. Finally, the virtual time map informs ITS-G5 stations of the boundaries between both technologies.

To build the map, the station needs to observe and measure the channel for a time T_{meas}, which should be a multiple of T_{sf}. During this time the ITS-G5 station uses preamble detection to detect the presence of other ITS-G5 stations and energy detection to detect LTE-V2X transmissions in subframes of duration T_{sf} / N_c, where N_c denotes the number of subframes per superframe. The ITS-G5 station will mark each measurement as:

- Pass: if the measurement returns either energy below a threshold or an ITS-G5 preamble could be successfully detected
- Fail: if the measurement returns energy above a threshold but ITS-G5 preamble could not be detected

After collecting all the measurements, the ITS station will combine the chunks to estimate the transmission boundaries. This is done by combining the measurements for all chunks that are multiples of the superframe duration T_{sf}. Exploiting the fact that the chunks belonging to one technology are contiguous, the boundaries can be estimated between both technologies. If T_a or T_b are known, then only the superframe boundary needs to be estimated and additional averaging of the chunks can be performed to further improve the estimation accuracy, especially in the cases of low traffic conditions.

A possible extension to further reduce the number of measurements is a two-step approach. Here, after having obtained a coarse timing estimate using a lower number of chunks N_c, the fine timing estimate is derived in the second step. By using much shorter chunks than in the first step, but limited to the short period before and after the boundary detected in the first step, the same principle is used to refine the estimation accuracy.

As outlined in Annex A, the remaining uncertainty in timing can be compensated by avoiding transmissions at the turn-around times.

6.3.1.5 Enhancement to Method A

This clause describes enhancement to Method A. It comprises the following additions to the default Method A:

- Both technologies only transmit when the start and end of the packet transmission are contained within the time slot of each technology. This implies that ITS-G5 stations are not allowed to transmit if the end of their packet would overlap with the beginning of the next superframe. This echoes the description outlined in Annex F.
- Packet generation for ITS-G5 station is artificially delayed, proportionally to the ITS-G5 available part, for all ITS-G5 packets. The Figure 6.5 provides an overview of the proportionality of the of delay for all ITS-G5 packets.

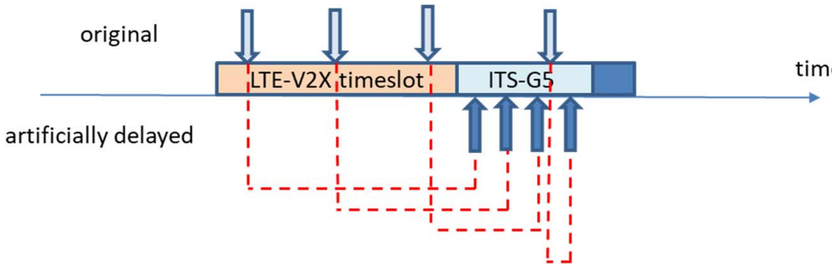


Figure 6.5: Proportional delay applied to all ITS-G5 packets

The procedure for determining the time t_{new} until which the packet will be delayed as $t_{new} = t_b + \Delta_y$ is as follows:

- Denote t_a the start of the LTE-V2X time slot, and t_b the start of the ITS-G5 time slot.
- Denote T_g the guard time that is not available for transmission at the end of the ITS-G5 time slot, due to potential overlapping with the next superframe:
  - T_g is defined as the duration of the ITS-G5 packet to be transmitted. It comprises the preamble and the data section of the packet. It does not comprise channel access time (AIFS and CW).
- Define the reference start as $t_a - T_g$.
- Packet is generated at time *t*.
- Compute Δ_x, the time difference between *t* and the guard time beginning: $\Delta_x = t - (t_a - T_g)$.
- Compute T_{G5}, the available part of the ITS-G5 time slot: $T_{G5} = T_b - T_g$.
- Compute Δ_y, the time offset to be applied from ITS-G5 beginning: $\Delta_y = \Delta_x \times \frac{T_{G5}}{T_a + T_b}$.
- The packet will be delayed until $t_{new} = t_b + \Delta_y$,

  i.e. $t_{new} = t_b + \frac{(t-(t_a-t_g))\times(T_b-T_g)}{T_a+T_b}$.

An illustration of t_{new} is found in Figure 6.6.

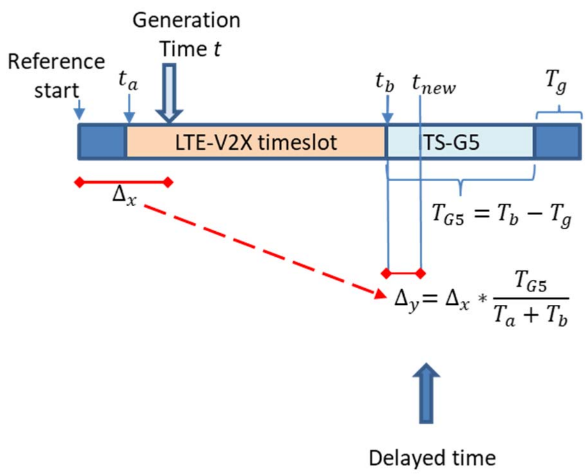


Figure 6.6: Illustration of new packet time t_{new}

6.3.2 Method B: Energy signals

6.3.2.1 Introduction

In this method, LTE-V2X stations follow a superframe structure with a specific time slot boundary and LTE-V2X stations use Energy Signals (ES) to prevent ITS-G5 stations from transmitting during specific periods of time. Thus, the core idea of the method is to partition the time resources in a Time Division Multiplexing (TDM) manner into time slots that alternately grant exclusive access to the channel for LTE-V2X and ITS-G5, respectively. More precisely, during the LTE-V2X time slots, the ITS-G5 stations should refrain from accessing the channel and only LTE-V2X stations are allowed to transmit their messages and vice versa. Similar to the approach used in Method A, the time partition between LTE-V2X and ITS-G5 could be static, semi-static or adjusted dynamically for example based on traffic load distribution between the two technologies. For the time sharing to work properly without interference, a concept of energy signals is introduced to prevent ITS-G5 stations from accessing the channel during LTE-V2X time slots.

With a proper configuration of the "resource pool", the access of the LTE-V2X stations to the channel can be restricted to the LTE-V2X periods. This mechanism is already possible with the existing specifications. Current 802.11p specification can prevent ITS-G5 stations from accessing the channel during the LTE-V2X periods only if it is ensured that the channel does not remain free (idle) for a duration longer than a pre-defined duration. This method introduces energy signals allowing a LTE-V2X station to block the channel access during the periods dedicated for LTE-V2X transmissions. These signals should fill the gap created by the guard band between two consecutive LTE-V2X transmissions, by the unused LTE-V2X subframes, or to block the channel shortly before the starting of the LTE-V2X dedicated phase. An example of different usages of the energy signals is illustrated in Figure 6.7.

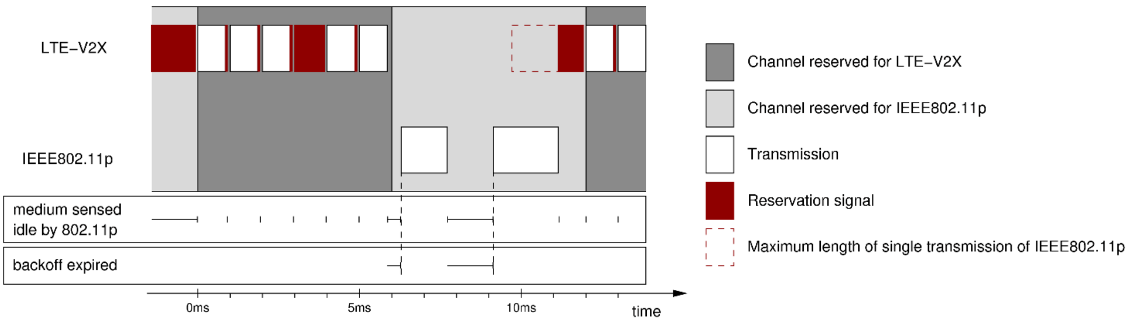


Figure 6.7: Energy signals sent before the beginning of LTE-V2X Phase, in unused subframes and in the guard band

These energy signals are short signals which are sent without payload to instruct ITS-G5 stations to defer the channel access at the beginning of a dedicated LTE-V2X subframe.

6.3.2.2 Energy signal type 1

Three different types of energy signals to reserve the channel at different phases are proposed. In Type1, energy signals are sent during unused LTE-V2X subframes within the LTE-V2X time slot. During the LTE-V2X time slot, at the start of each TTI, each LTE station measures the channel and if the measured received signal-strength falls below a certain threshold, the LTE station will send the energy signal, to block ITS-G5 from using this particular subframe. The required measurement is taken at the very beginning of the subframe in a period that is no longer than the interface spacing period of 802.11p to prevent ITS-G5 devices from resuming contention during the phase reserved for LTE-V2X transmissions.

6.3.2.3 Energy signal type 2

Energy signal type 2 is blocking ITS-G5 transmissions sent before the beginning of the next LTE-V2X time slot. At the end of ITS-G5 time slot and before the start of the subsequent LTE-V2X time slot, ITS-G5 devices need to be blocked from transmitting data. This is achieved by LTE-V2X devices sending energy signals just before the start of the LTE-V2X time slot. The length of the signal can be configured so that it can only prevent new ITS-G5 transmission to start at the end of their time slot but does not interfere with ongoing transmissions.

6.3.2.4 Energy signal type 3

Energy signal type 3 uses the guard period, which is part of the 14th OFDM symbol at the end of an LTE-V2X subframe.

Such energy signals are transmitted by LTE-V2X stations to block neighbouring ITS-G5 devices from starting transmissions during the guard period between two consecutive LTE subframes.

The configuration of the energy signals could specify different parameters such as start of the ES transmission, duration of the signal (the duration is set depending on the ES type and can also vary for the same type), frequency resources used for the ES transmission (ES signals can be sent using all the subchannels or may occupy only a small part of the frequency resources), transmitter of the energy signal (depending on the situation one or many devices can transmit the ES simultaneously), transmission threshold (indicates which energy level measured at the channel below which an ES should be sent), and lastly, the transmit power.

6.3.3 Method C: ITS-G5 PHY header insertion

6.3.3.1 Introduction

This method suggests using the superframe structure where LTE-V2X and ITS-G5 have exclusive right to channel in their time slot as found in Figure 6.3. ITS-G5 is not aware of the superframe structure but defer from access to the channel when LTE-V2X transmits the ITS-G5 PHY header to announce upcoming LTE-V2X transmissions. Further, the insertion of the PHY header could also be used to avoid the phenomenon called the "last LTE symbol gap", see Clause 5.2.1. LTE-V2X is aware of the superframe structure and schedules transmissions in its time slot (containing several subframes) as opposed to ITS-G5. The proposed insertion of the ITS-G5 PHY header consists of preamble and SIGNAL field, which natively contains the information about the duration of a ITS-G5 transmission and it is always present in ITS-G5. Figure 6.8 presents an overview of the ITS-G5 PHY layer protocol data unit and which part that would be used by LTE-V2X to signal an upcoming packet transmission.

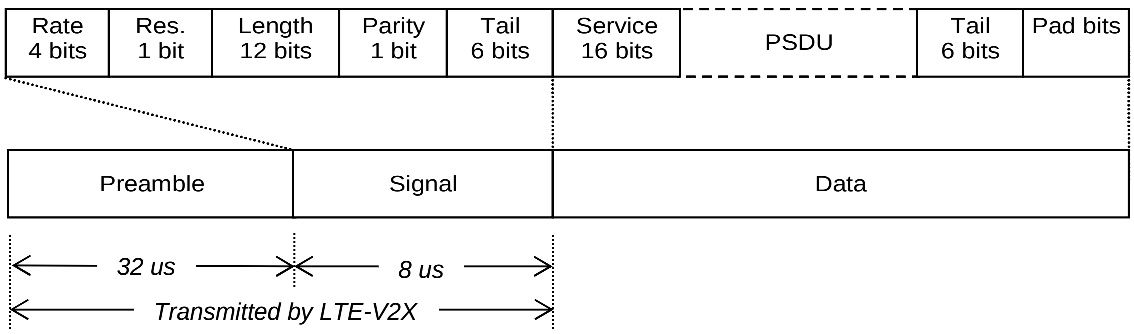


Figure 6.8: Shows what LTE-V2X transmits from the ITS-G5 PHY header

Figure 6.9 shows an example how the ITS-G5 header consisting of the preamble and a signal field can be used to reduce the interference probability to LTE-V2X transmissions and vice versa to ITS-G5 transmissions.

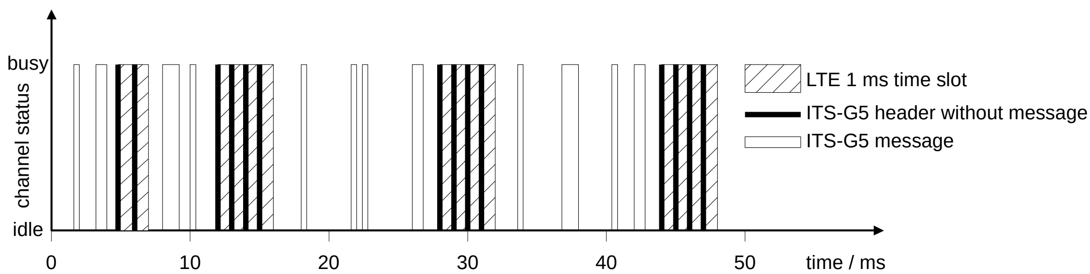


Figure 6.9: Example of an ITS-G5 header sent right before an LTE-V2X message to reserve the channel

The inclusion of the ITS-G5 PHY header could either be done by patching the first LTE symbol or/and exploit unused guard symbol of around 71 µs at the end of each 1 ms transmission time. More technical details around the ITS-G5 PHY header insertion is found in Annex A.

Since LTE-V2X stations do not sense the channel right before transmitting and the channel access timing of ITS-G5 transmissions cannot be predicted from the past, there can still be an overlap (interference) with already ongoing ITS-G5 transmissions. The header insertion method will at least reduce the interference by avoiding ITS-G5 to start a transmission when the LTE-V2X transmission cannot be detected with the simple energy detector. This improves the collision probability to a value better than a pure ALOHA medium access control, but it will be worse than the collision probability for a more advanced CSMA/CA medium access control.

6.3.3.2 Option 1: Single LTE-V2X transmission protection

In this configuration of Method C, LTE-V2X stations know the superframe structure and time slot boundaries, whereas ITS-G5 stations are unaware. LTE-V2X stations will transmit the ITS-G5 PHY header making an immediate reservation of the channel for 1 ms. When ITS-G5 stations receive this information, they defer access to the channel for the announced period of time. LTE-V2X stations can receive their time slot configuration either from a source outside the station or locally as outlined in Clause 6.2. It should be noted that in this option ITS-G5 can start transmissions during what they perceive as unused subframes of the LTE-V2X time slot which could cause an overlap between unfinished ITS-G5 transmissions with transmissions in the next subframe, see Figure 6.10.

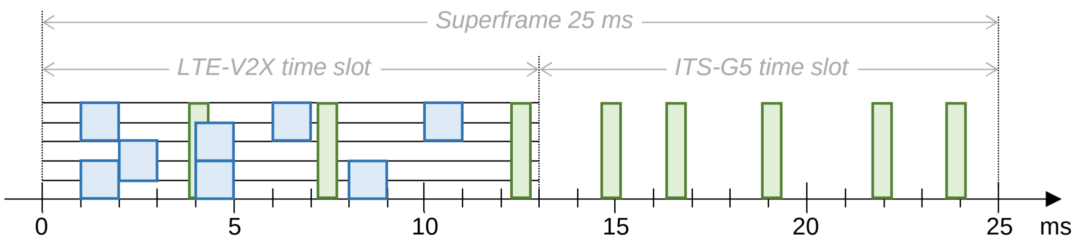


Figure 6.10: Illustration of packet transmissions for Method C Option 1 given a superframe of 25 ms with 13:12 time slot distribution

6.3.3.3 Option 2: Multiple LTE-V2X transmission protection with enhancement

In this configuration of Method C, LTE-V2X stations know the superframe size and time slot boundaries. The purpose with this configuration is to make ITS-G5 stations aware about when their time slot starts to also utilize the possibility for artificially spread ITS-G5 transmissions in their time slot as described in Clause 6.3.1.5. LTE-V2X stations receive their time slot configuration from a source outside the station as outlined in Clause 6.2.1.

When LTE-V2X stations transmit the ITS-G5 header, they reserve the present and subsequent subframes until the end of the LTE-V2X time slot (or upper bounded to a large value, e.g. 10 ms). The reservation mechanism is further detailed in Annex A, see for example Figure A.5.

ITS-G5 stations store the information about the time slot size of LTE-V2X to learn about the current division of the superframe and store this information for a while even though no ITS-G5 headers are received from LTE-V2X stations (further detailed in Annex A).

This option is based on the following assumptions:

1) ITS-G5 stations have knowledge about the superframe size (e.g. 25 ms, 50 ms) in order for ITS-G5 stations to avoid sending messages that may overlap with the beginning of the next superframe and hence, the time slot of LTE-V2X

2) ITS-G5 stations need to distinguish between ITS-G5 headers transmitted by ITS-G5 stations from those transmitted by LTE-V2X stations

6.3.4 Method D: Reservation messages

This method requires that all ITS stations are using ITS-G5 transceivers for sending reservation messages on the frequency channel and an ITS station equipped with dual radio can reserve resources for its other radio technology by broadcasting messages on the shared frequency channel. Figure 6.11 shows an example on resource reservations embedded in ITS-G5 messages (e.g. CAMs) that announce when, e.g. LTE-V2X will use the channel.

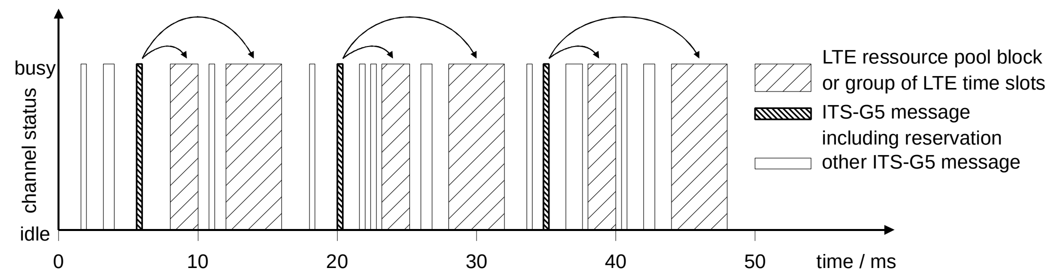


Figure 6.11: Example of ITS-G5 resource reservations (e.g. embedded in an ITS-G5 CAM) that each contain a list of two LTE-V2X transmit reservations

A list of channel reservations (containing time and duration values) can be announced in a reservation message. The reservation message could be, e.g. put into a data container of the CAM (like the protected zone message - see [i.17]).

The receiving ITS station can use this information in several ways. It can queue all ITS-G5 transmissions that will not be finished before the reserved time slot and when using an additional radio technology (e.g. LTE-V2X) it can also facilitate scheduling transmission of this other radio technology to avoid (self) interference. Because in an ad hoc broadcast network each individual resource pool scheduler has no global view of the available resources, and semi-persistent scheduling (as used in LTE-V2) assumes periodic messages, the reservation messages can inform the scheduler also about upcoming non-periodic transmissions.

6.3.5 Method E: Combination of ITS-G5 PHY header insertion and reservation messages

This method combines the ITS-G5 PHY header insertion described in Clause 6.2.3 with the reservation messages introduced in Clause 6.3.4. The motivation for combining these two methods is that existing ITS-G5 stations are not capable of decode the reservation message.

Figure 6.12 shows the combination of reservation messages (e.g. ITS-G5 CAMs) for LTE-V2X together with ITS-G5 PHY headers insertion.

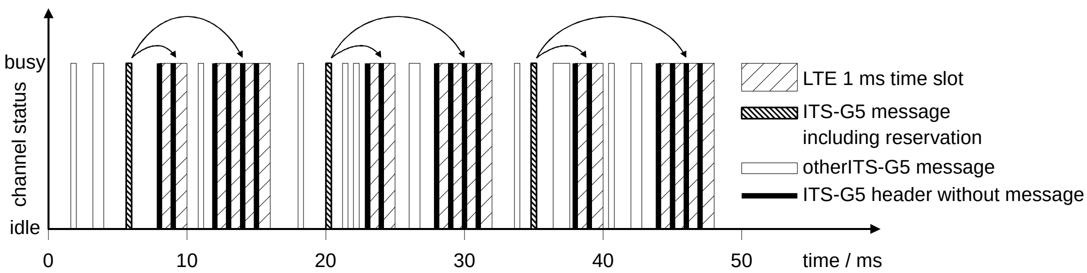


Figure 6.12: Example of an ITS-G5 resource reservation message in combination with an ITS-G5 header sent right before an LTE-V2X message to reserve the channel

6.3.6 Method F: LTE-V2X applying IEEE 802.11 NAV setting

6.3.6.1 Introduction

Assuming a coexistence based on deterministic timing, and static, semi-static and dynamic time slot configurations, this method assumes that the LTE/NR-V2X system will take over the overall timing management of all technologies including LTE-V2X and ITS-G5. This is proposed to be achieved through the setting of the IEEE 802.11 Network Allocation Vector (NAV), which is a virtual carrier-sensing mechanism that limits the need for physical carrier-sensing at the air interface in order to improve power efficiency. The MAC layer frame headers contain a duration field that specifies the transmission time required for the frame (i.e. indicating the time for which the medium will be busy). The vehicles (or other stations) will listen on the wireless medium to read the duration field; then, they will set their NAV, i.e. an indicator for an ITS-S on how long it has to abstain from accessing the medium. In the IEEE 802.11 standard (and thus potentially also for ITS-G5), the NAV indicates the time period which is intended to be held by the ITS-S, and can be a maximum of 32,767 µs.

The basic idea is that the ITS-G5 stations will behave as a "hidden terminal" during the LTE-V2X transmissions and will refrain at accessing the channel. The total time an IEEE 802.11-based station will defer access is the NAV time plus the configured AIFS time.

In a conventional distributed CSMA/CA protocol, the process to resolve the "hidden terminal problem" is implemented as follows: The transmitter sends a Request-To-Send (RTS) and the receiver waits one SIFS before sending the Clear-To-Send (CTS) signal. Alternatively, a Clear-To-Send-To-Self (CTS-To-Self) signal may be sent including the duration field, which will be then used to set the NAV. Then, the transmitter will wait for another SIFS before sending the payload data. Afterwards, the receiver will wait a SIFS before sending ACK. Following this reasoning, the NAV is the duration from the first SIFS to the ending of ACK. During this time the medium is considered busy. The basic principle is as follows: one LTE-V2X stations broadcasts an IEEE 802.11 sequence (such as CTS-To-self, RTS, CTS, RTS/CTS, etc.), which will make the ITS-G5 stations to set their NAV, in order to get protection during the LTE-V2X transmission period.

Not all LTE-V2X stations need to issue the NAV setting signal and there are multiple possible rules to establish which station will issue the signal, preventing all ITS-G5 stations to transmit during the LTE-V2X time slot. For example, during the Semi-Persistent Scheduling (SPS) procedure, the LTE-V2X station which allocated a specific resource in the available resource pool, will be also the one eligible to issue the NAV setting signal.

Although not all LTE-V2X stations need to issue the NAV setting signal, all of them do need to know the technology distribution or the exact time split between the two technologies. For static and semi-static superframe configuration, the timing updates are provided offline or externally by means of other entities in the system. For the dynamic superframe configuration, the LTE-V2X stations could use the metrics described in Clause D.3 to determine the technology distribution metric. Based on that the mapping between technology distribution and slot duration presented in Clause 6.2.2 can be employed.

Figure 6.13 illustrates the basic principles. Prior to an LTE-V2X transmission, the LTE-V2X station issues a NAV setting request applying the corresponding signalling as defined in IEEE 802.11 as a mandatory feature. Consequently, the LTE-V2X time slot will be protected from ITS-G5 transmissions occurring at the same time. At the end of the LTE-V2X transmission, the NAV is automatically released, no additional signalling is required. Then, the ITS-G5 stations will be able to access the medium applying its standard protocol until the next NAV is issued by LTE-V2X.

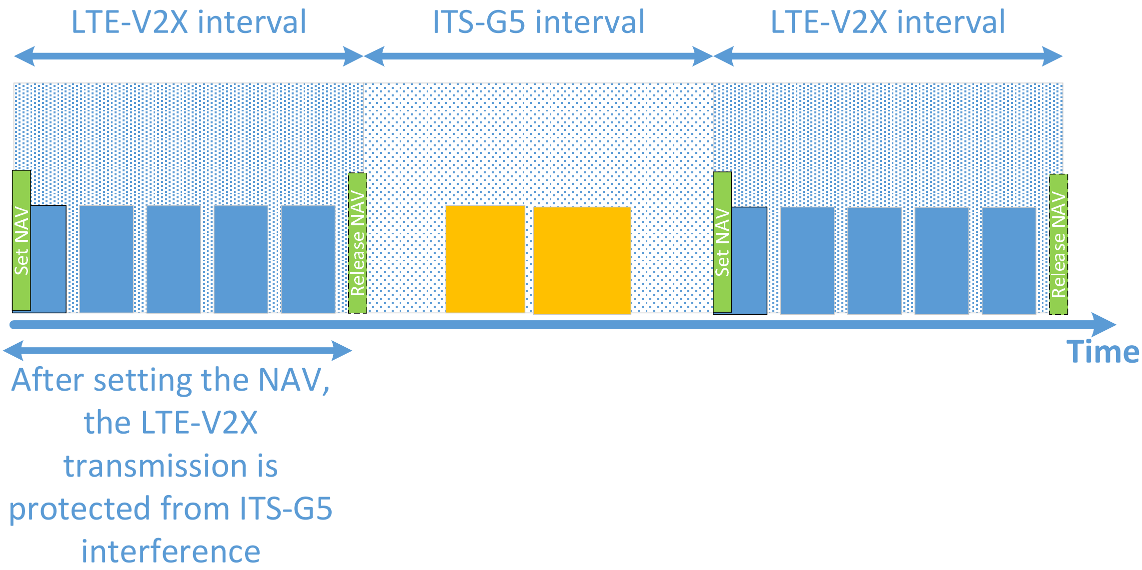


Figure 6.13: Example of how to achieve coexistence between ITS-G5 and LTE-V2X through appropriate setting of the Network Allocation Vector (NAV) by the LTE-V2X system

6.3.6.2 CTS-to-Self as NAV setting signal

Figure 6.14 shows an example of the basic operation of the protection mechanism using the CTS-To-Self signal. Although the LTE-V2X station sends the CTS-to-itself, all ITS-G5 stations on the vicinity are required to listen to CTS frames and update the NAV accordingly.

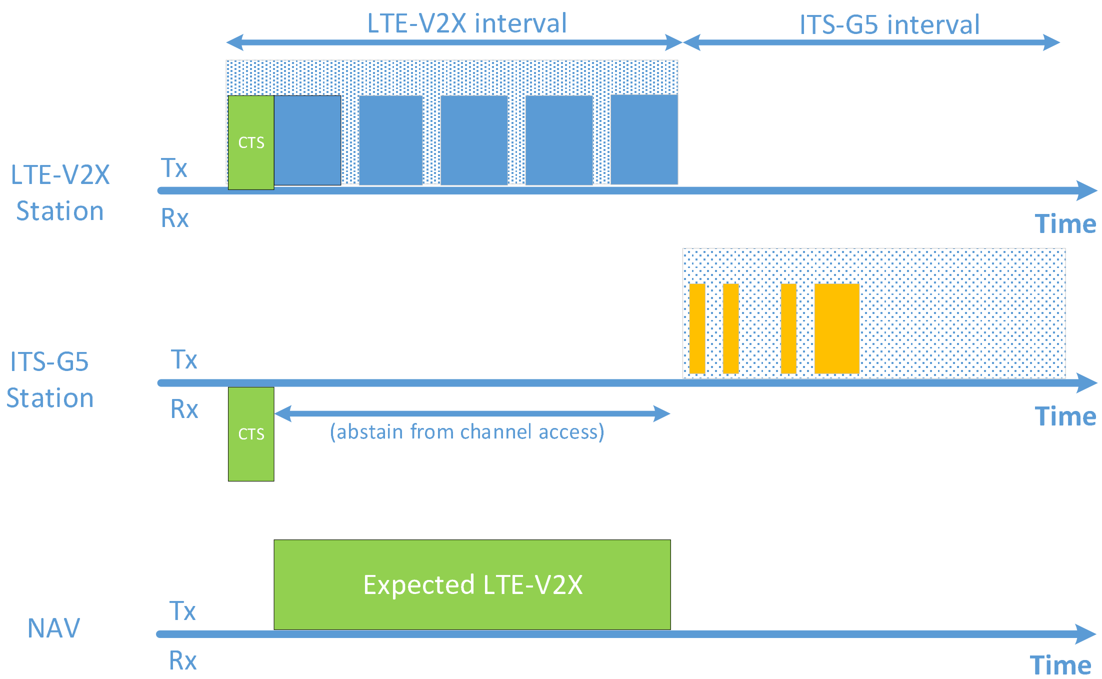


Figure 6.14: Example of NAV activation by sending a CTS-to-Self signal

The IEEE 802.11 specification defines the CTS content on the MAC layer, i.e. MAC layer Protocol Data Unity (MPDU), in Clause 9.3.1.3 in IEEE 802.11-2020 [i.3] it is detailed and it is also depicted in Table 6.6.

Table 6.6: CTS frame format

2 octets	2 octets	6 octets	4 octets
Frame Control	Duration	RA (Receive Address)	FCS (Frame Check Sequence)

The following is found in IEEE 802.11-2020 [i.3]. More details on employing the transmitter's MAC address and a potential solution can be found at the end of this clause. The total CTS frame size is then 14 octets or 112 bits. In the PPDU, the overhead of service plus tail to the CTS frame (PSDU) are added and end up with 134 bits as "data" in the PPDU.

The symbol interval in IEEE 802.11p is 8 µs (6,4 µs symbol duration + 1,6 µs guard interval) and the number of symbols necessary to transmit one CTS-to-Self depends on the choice of the transfer rates, i.e. modulation scheme and coding rate employed (MCS).

Table 6.7 provides the supported transfer rates and MCS, as well as the corresponding total number of (uncoded and coded) bits per OFDM symbols and the corresponding necessary number of OFDM symbols N_{NAV} to transmit the NAV setting signal, i.e. the CTS-to-Self frame in this case. The support of 3 Mbit/s, 6 Mbit/s, and 12 Mbit/s is mandatory for IEEE 802.11p and ITS-G5. To ensure robustness of the reception of the NAV setting signal it is recommended that the default MCS is QPSK ½, corresponding to a data rate of 6 Mbit/s.

Table 6.7: Number of symbols necessary for transmitting the NAV setting

Transfer rate (Mbit/s)	Modulation scheme	Coding rate	Data bits per OFDM symbol	Coded bits per OFDM symbol	Number of OFDM symbols for NAV (N_{NAV})
3	BPSK	1/2	24	48	6
4,5	BPSK	3/4	36	48	4
6	QPSK	1/2	48	96	3
9	QPSK	3/4	72	96	2
12	16-QAM	1/2	96	192	2
18	16-QAM	3/4	144	192	1
24	64-QAM	2/3	192	288	1
27	64-QAM	3/4	216	288	1

The duration of each component of the physical structure is outlined in Table 6.8.

Table 6.8: The duration of the physical structure components

PHY Preamble	Signalling information	MAC content
32 µs (4 OFDM symbols)	8 µs (1 OFDM symbol)	N_{NAV}×8 µs

The total duration of the CTS-to-Self signal will in that case be 88 µs, 64 µs and 56 µs for the mandatory IEEE 802.11p MCS BPSK ½, QPSK ½ and 16-QAM ½, correspondingly.

The NAV setting time is given in the "Duration" Field of 16 bits specified in Clause "9.2.4.2 Duration/ID field" in IEEE 802.11-206 [i.3], which indicates the duration of the LTE-V2X transmission interval plus suitable guard periods. The minimum value is 0 and the maximum 32,767 µs.

In Clause 6.2.2, there are examples of the time slot duration for each technology for different superframe durations. The "Duration" field in those examples is given by the duration of the LTE-V2X transmission interval. The ITS station, transmitting the NAV, will configure this field based on the local measurements of the technology distribution based on the metrics presented in Clause D.3 for the dynamic configuration. For the static and semi-static, the field will be configured offline or from information obtained from external entities.

The receiving ITS-G5 station should refrain from transmitting during the corresponding LTE-V2X time slot.

To protect the privacy of the CTS-to-Self transmitting station, the MAC address field should not be filled with its own MAC address, but rather with some general address that can be used by all LTE-V2X stations, such as all zeros, for example. As an alternative, since the MAC address is irrelevant for this specific use of the CTS-to-Self as NAV setting signal, the RA field could be completely omitted (the main information conveyed is the duration of the NAV) shortening the CTS-to-Self signal.

In this modified shorter CTS-to-Self signal, the modified CTS frame is outlined in Table 6.9.

Table 6.9: Modified shortened CTS-to-Self signal Type 1

2 octets	2 octets	4 octets
Frame Control	Duration	FCS (Frame Check Sequence)

Another option, instead of omitting the RA field, is to extend the Duration field by N_d additional octets, where N_d=0,…,6. With that modification the NAV setting would allow for longer time slots for the LTE-V2X stations than 32 ms. By following a similar mapping as the original one, the maximum NAV duration, i.e. for N_d=6, the Duration field would be 8 octets long and give an unrealistic time slot. N_d=0 corresponds to the modified short CTS-to-Self signal Type 1 as outlined in Table 6.9. For N_d=1, i.e. one additional octet in the Duration field, a maximum time slot of more than 8 s is possible and it is denoted modified short CTS-to-Self signal Type 2. The new CTS frame is represented in Table 6.10.

Table 6.10: Modified short CTS-to-Self signal Type 2

2 octets	3 octets	4 octets
Frame Control	Duration	FCS (Frame Check Sequence)

The total new CTS frame size is then 9 octets or 72 bits reducing the total number PHY data to 94 bits. The total duration of the short CTS-to-Self signal Type 2 will remain 72 µs, 56 µs and 48 µs equal to Type 1, for the mandatory MCS BPSK ½, QPSK ½ and 16-QAM ½.With the modified short CTS-to-Self signal Type 2 time slot durations up to 8 s are possible.

Based on the modified short CTS-to-Self signal Type 2, a third modification of the CTS-to-Self signal is possible. In this option, called modified CTS-to-Self Type 3, the full CTS frame with 14 octets is transmitted, however, the Duration field is extended to three octets and the remaining 5 octets of the RA field are reserved for future use. This third option for the CTS frame is presented in Table 6.11.

Table 6.11: Modified CTS-to-self signal Type 3

2 octets	3 octets	5 octets	4 octets
Frame Control	Duration	Reserved	FCS (Frame Check Sequence)

The total duration of the modified CTS-to-Self signal Type 3 is the same as the original provided in Table 6.9.

6.3.6.3 Selection of an LTE-V2X station to issue the NAV setting signal

Among all LTE-V2X stations within a given coverage area, only a single LTE-V2X station should issue the NAV setting signal. The question is thus how to negotiate/identify the one LTE-V2X station which will be tasked to issue the NAV setting signal among the multitude (possibly hundreds) of coexisting LTE-V2X station within a given coverage area.

One observation is that LTE-V2X stations typically share the available resource by allocating to themselves specific subchannels within the available or preconfigured resource pools at specific times in the so-called semi-persistent scheduling (SPS) scheme as illustrated Figure 6.15.

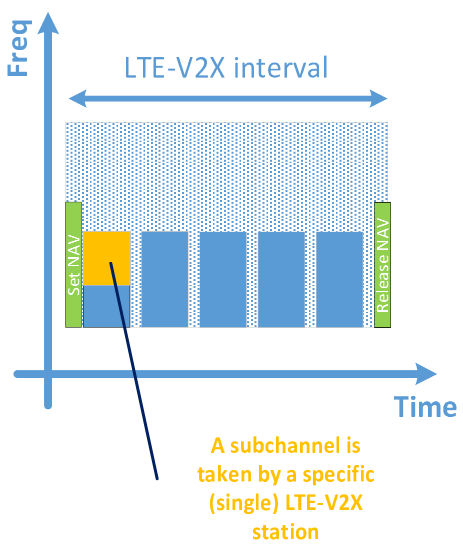


Figure 6.15: Example of LTE-V2X station's allocation of resources

The LTE-V2X station issueing the NAV setting signal will be selected as function of its subchannel allocation in the previous LTE-V2X frame (or one of the previous LTE-V2X frames). In one typical example, the rule is that the LTE-V2X station is selected (to issue the NAV setting signal at the beginning of the NEXT LTE-V2X superframe) which has occupied the subchannel in the "upmost left corner" (i.e. highest occupied frequency and earliest occupied time) of all occupied subchannels.

Other rules are of course feasible, for example using the "lowest left corner" (i.e. lowest occupied frequency and earliest occupied time) of all occupied subchannels, "upmost right corner" (i.e. highest occupied frequency and latest occupied time) of all occupied subchannels, "lowest right corner" (i.e. lowest occupied frequency and latest occupied time) of all occupied subchannels and everything in between.

It is important that the first OCCUPIED subchannel is used for the above rules. To give an example using the "lowest left corner" (i.e. lowest occupied frequency and earliest occupied time) rule, the corresponding subchannel may relate to a transmission any time within the LTE-V2X transmission interval if previous resources remain unused as illustrated in Figure 6.16.

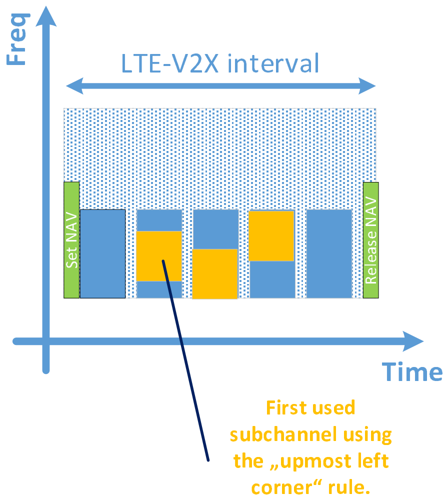


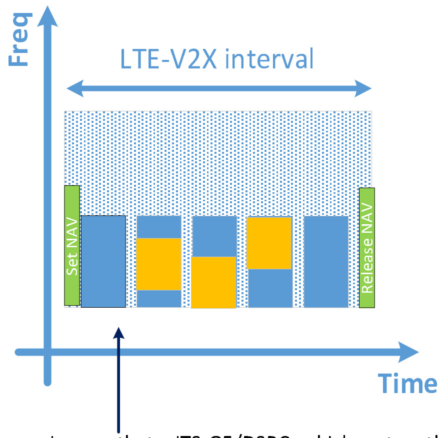
Figure 6.16: First used subchannel in the "upmost left corner" rule

In Figure 6.16, the LTE-V2X station performing the first transmission in the "upmost left corner" of the available resources will thus be tasked to issue the NAV setting signal in the beginning of the next LTE-V2X interval to prevent ITS-G5 from accessing the channel.

This principle of how to select which LTE-V2X station will transmit a specific IEEE 802.11 signal can be applied to any type of header that is valid for the transmission of several LTE-V2X stations.

6.3.6.4 New ITS-G5 station entering NAV setting range

Also, the case that new ITS-G5 vehicles may enter the coverage area of a specific transmission (of the NAV setting signal) needs to be addressed. In case that the new vehicles arrive during the LTE-V2X transmission interval, it may not have received the NAV setting signal and may start transmitting during the LTE-V2X period as illustrated in Figure 6.17.



In case that a ITS-G5/DSRC vehicle enters the coverage area AFTER the transmission of the NAV setting signal, then the protection for LTE is not activated for this specific ITS-G5/DSRC vehicle. It may thus start transmitting during the LTE interval.

Figure 6.17: ITS-G5 stations have not received the NAV setting signal

To address the case illustrated in Figure 6.17, it is proposed that an ITS-G5 vehicle needs to wait (before accessing the medium) for the reception of a NAV and thus the start of a new full LTE transmission interval. Only afterwards, when the new ITS-G5 interval starts, the vehicle may start transmitting. However, after waiting for a predetermined number of intervals (e.g. 2 - 3 intervals) without reception of a NAV setting signal, the ITS-G5 vehicle may still access the medium. This situation may occur if there are no LTE-V2X equipped vehicles nearby.

6.3.7 Method G: Load-based approach

NOTE: This method is based on observations from simulations of other co-channel coexistence methods. Therefore, it was included after simulation studies were completed and no further simulations of this approach could be performed before the drafting ended but it is included for completeness.

This approach uses already an inherent feature of V2X technologies, namely, to assess the CBR on a channel. CBR assessment is central to the DCC algorithm for providing feedback to the station about the current channel load situation and react when the channel load increases beyond predefined limits. This method suggests to restrict the channel load further in order to keep interference between technologies sharing the same channel on an acceptable level. The acceptable level is not yet defined and this needs to be investigated and decided upon. Both ITS-G5 and LTE-V2X include a congestion control mechanism as part of their access layer controlling the channel load to not increase above approximately 60 %.

The probability of interference between different technologies increases as the equipment rates grow if no coordination between them takes place. The idea is to provide channel load limits on the shared communication channel leaving headroom to keep the probability of concurrent transmissions between different technologies low. The more coordinated the channel access is between technologies (e.g. when using a co-channel co-existence method) the less headroom is needed. Consequently, uncoordinated channel access needs more headroom to reduce the interference probability. In its simplest form, ITS-G5 and LTE-V2X can reduce their respective CBR level to keep the interference intra-technology low when no coordination exist, see Figure 6.18(a). When coordination between technologies exist, the headroom decreases as shown in Figure 6.18(b) because then interference between technologies is coordinated. In this sense, this approach is different from pure co-channel coexistence methods, because it does not aim at coordinating access layers, but limits the probability of interference.

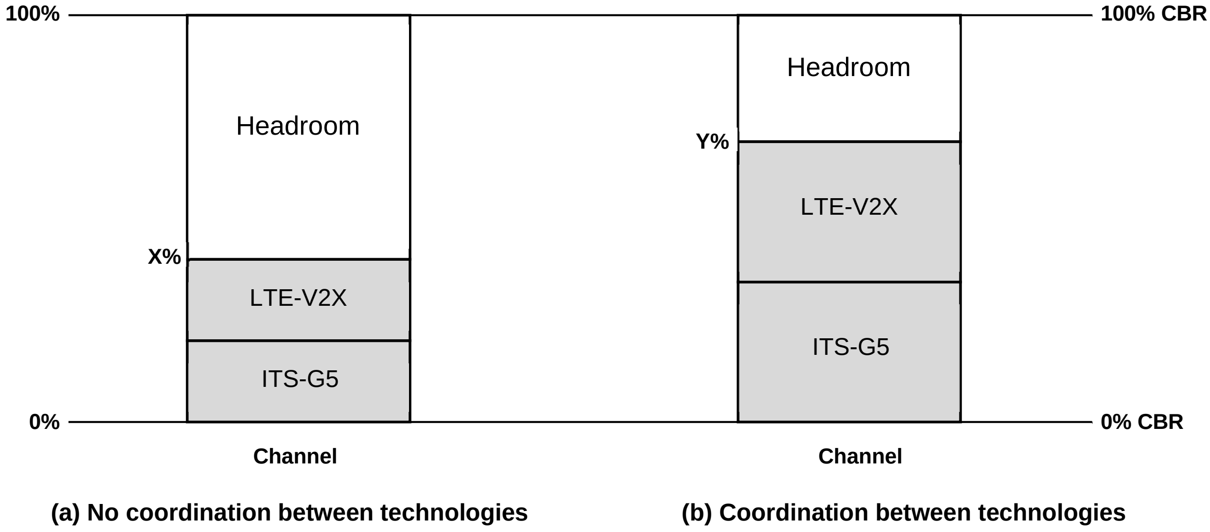


Figure 6.18: Illustration on the load-based approach

7 Evaluation

7.1 Key performance indicators

7.1.1 Packet reception ratio

For one transmission packet with index *n*, the Packet Reception Ratio (PRR) for a given communication range interval of interest is calculated as X_n / Y_n, where Y_n is the number of receiving vehicles that are located within that communication range from the transmitter, and X_n is the number of vehicles with successful reception among those Y_n vehicles.

The average PRR for said communication range interval is calculated as $(X_1+X_2+X_3+....+X_N)$ / $(Y_1+Y_2+Y_3+....+Y_N)$ where *N* denotes the number of messages in simulation relevant for this average PRR measurement.

To visualize the communication range of the different system configurations and features, the PRR is plotted as a profile over the distance from the transmitter. The distance bin width used is 20 m.

7.1.2 Data age

Data Age (DA) or information age is defined as the age of the information in the last correctly received sample of data in a receiving ITS station. Data age, T_{age}, is calculated according to Equation 7.1.

$$T_{age} = t - t_{tsLR} \pm t_{sync}, \qquad (7.1)$$

where t the current time, t_{tsLR} is the timestamp (i.e. generation time) of the last successfully received message and t_{sync} is the synchronization error between the sending and receiving vehicles, where the unit is second. The DA is evaluated for transmitter-receiver pairs, whose distance is within the interval [0, 300] metres. A constant sampling interval of 10 ms is used to measure regularly the age of information at each receiver. Figure 7.1 shows an illustration of data age.

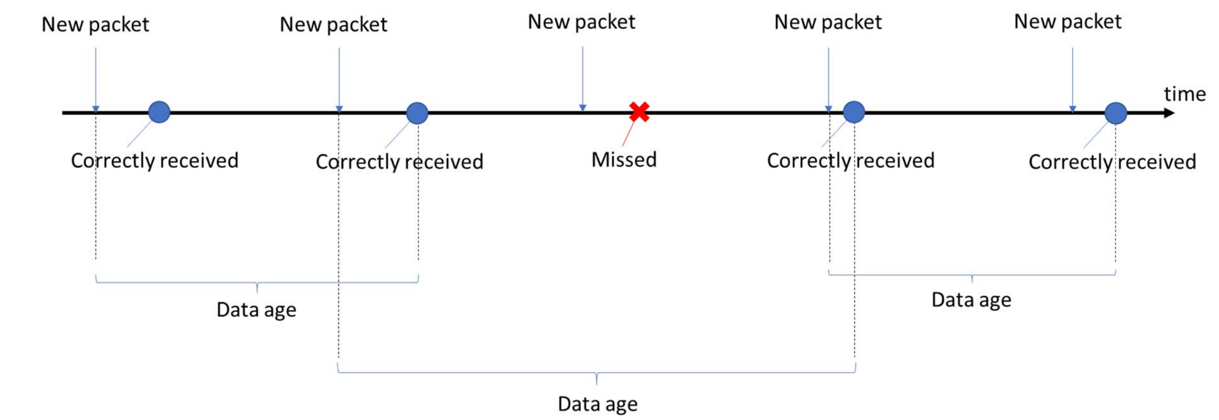


Figure 7.1: Data Age (DA)

7.1.3 End-to-end delay

End-to-end delay (E2E delay) measures the time from when a packet is passed to the access layer of the sending ITS stations until the packet is successfully received at the receiving ITS station. For packets that are not received, it is not measured. Apart from generally minimal processing delays on transmitter and receiver side, the E2E delay is dominated by the scheduling delay of the MAC layer (i.e. channel access delay). The E2E delay is evaluated for transmitter-receiver pairs, whose distance is within the interval [0, 300] metres. A constant sampling interval of 10 ms is used to measure regularly the age of information at each receiver. Figure 7.2 illustrates the E2E delay.

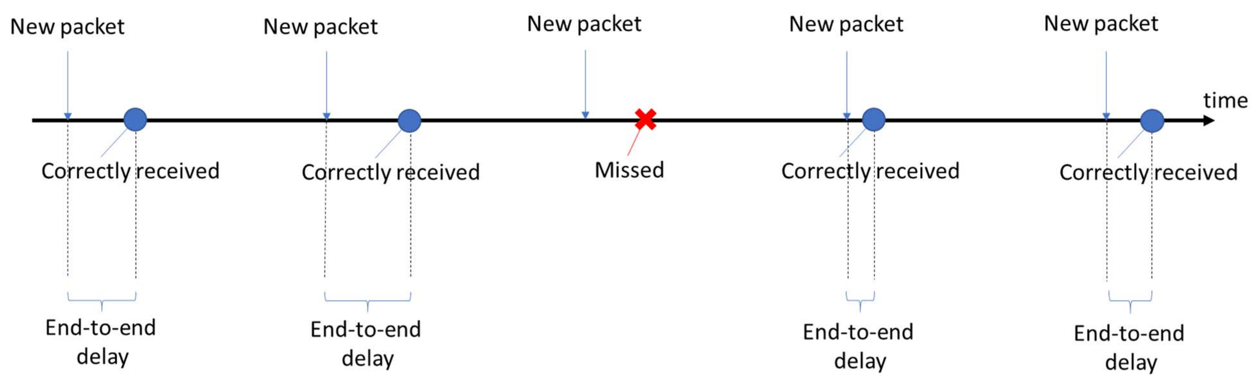


Figure 7.2: End-to-end delay

7.1.4 Inter-packet gap

The Inter-Packet Gap (IPG) is the time difference between the instant when a packet is correctly decoded by the receiver, and the instant when the previous packet had been correctly decoded by the receiver, see Figure 7.3. The difference between IPG and DA is that IPG does not take into account the channel access delay. The IPG is evaluated for transmitter-receiver pairs, whose distance is within the interval [0, 300] metres.

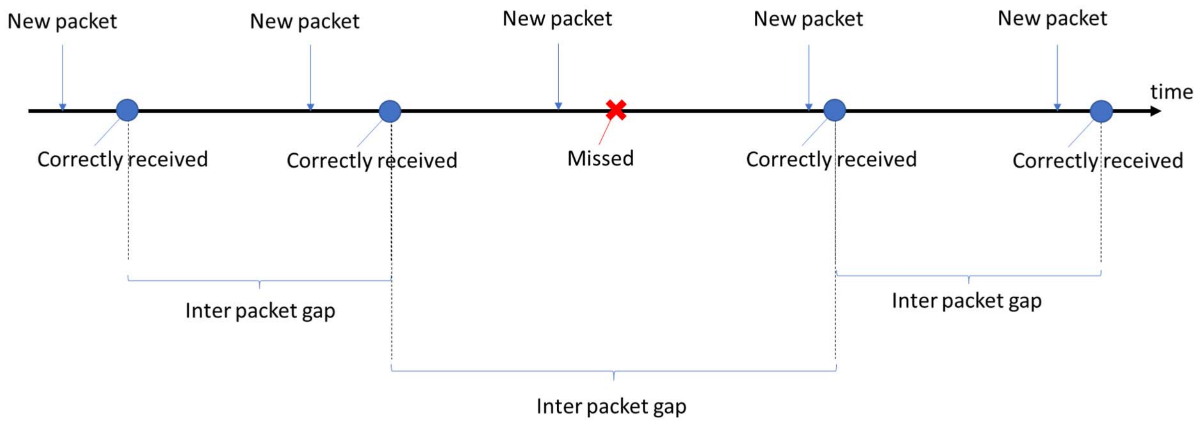


Figure 7.3: Inter-packet gap

7.2 Simulation framework

7.2.1 Introduction

To evaluate the methods described in Clause 6 with respect to the evaluation criteria as described in Clause 8, simulations of the various methods in three different traffic scenarios are performed. This way, insight is gained in parameters such as channel busy ratio, number of vehicles visible, impartiality of technology and impact on safety. The results are presented in Clause 7.3.

7.2.2 Road traffic scenarios

7.2.2.1 Introduction

Two different road traffic scenarios forms the basis of the simulations - urban and highway. The latter will be further divided into fast and slow scenarios, where the fast highway scenario has fewer vehicles travelling at a higher speed and the slow vehicle scenario contains more vehicles travelling at lower speeds.

Transmission of Cooperative Awareness Messages (CAM) based on vehicle dynamics will be the default data traffic model. To capture triggering of Decentralized Environmental Notification Messages (DENM), a special set of road traffic scenarios have been created. These are further detailed in Clause 7.2.2.4.

7.2.2.2 Urban scenario

In the urban scenario vehicles are moving slow and non-of-light-sight (NLOS) links between vehicles around corners of building are considered. This topology is known as a Manhattan grid when vehicles are moving along roads situated between blocks of buildings.

Each road is formed by 4 lanes, 2 lanes in each direction. There are 9 blocks of buildings, which leads to a topology consisting of 4 horizontal roads and 4 vertical roads. The distance between two parallel roads is set to 433 m, see Figure 7.4. The configuration of this scenario is found in Table 7.9.

Three variants of this configuration with different number of vehicles on the road: 100, 200 and 300 vehicles, is considered.

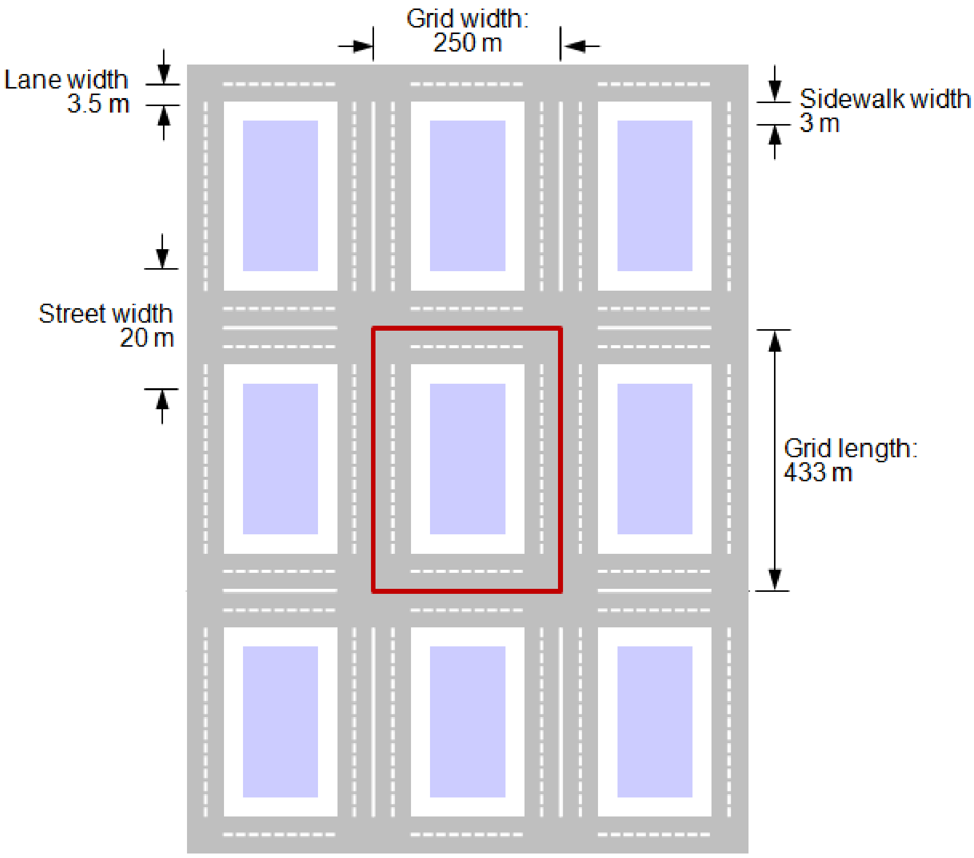


Figure 7.4: Road configuration for urban case based on 3GPP TR 36.885 [i.13]

Table 7.1: Details of vehicle drop and mobility model in 3GPP TR 36.885 [i.13]

Parameter	Urban case
Number of lanes	2 in each direction (4 lanes in total in each street)
Lane width	3,5 m
Road grid size by the distance between intersections	433 m × 250 m. Note that 3 m is reserved for sidewalk per direction (i.e. no vehicle or building in this reserved space)
Simulation area size	Minimum 1 299 m × 750 m
Vehicle density	Average inter-vehicle distance in the same lane is 2,5 s × absolute vehicle speed. Baseline: The same density/speed in all the lanes in one simulation.
Target vehicle speed	15 km/h, 60 km/h
NOTE: The "Target vehicle speed" is selected instead of a max vehicle speed due to that traffic and network simulators may set a target speed for all vehicles, in reality, not all vehicles will follow exactly that speed. In mobility simulators, this is handled automatically (with default settings of parameters 'sigma' and 'speedDev'). In network simulators, which are auto-generating the vehicles' movements, to capture these small variations, each station may have a different maximum speed obtained from a random distribution with Gaussian statistic with average set as the target speed and standard deviation set to one tenth of the same value (e.g. 140 km/h mean and 14 km/h standard deviation).	

7.2.2.3 Highway scenario

7.2.2.3.1 Fast highway scenario

A highway with 6 lanes, 3 lanes in each direction, is considered. The length of the highway is ≥ 2 km, see Figure 7.5. All vehicles move with the same max speed and three vehicle densities are considered for this configuration:

- 70 km/h, with 245 vehicles

- 140 km/h with 123 vehicles
- 250 km/h with 70 vehicles

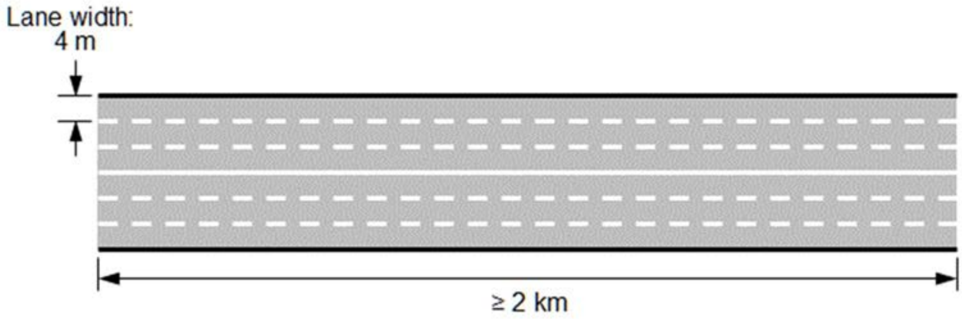


Figure 7.5: Road configuration for freeway case based on 3GPP TR 36.885 [i.13]

7.2.2.3.2 Slow highway scenario

This models a high vehicle density and thus, the DCC mechanism is tested. In this scenario, the vehicles move on a highway of length 600 m, composed of 3 lanes in each direction, see Figure 7.6. To reach a high vehicle density, the maximum speed is set to 50 km/h. There different vehicle densities are considered for the slow highway scenario: 100, 200 and 300 vehicles.

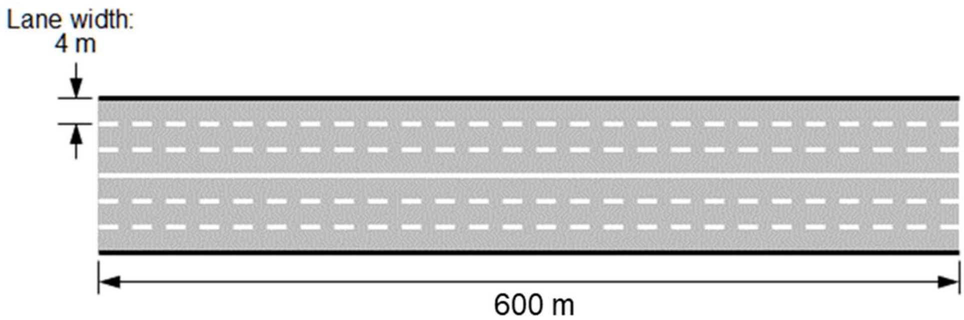


Figure 7.6: Road configuration for slow highway case

Table 7.2: Details of vehicle drop and mobility model

Parameter	Highway slow	Highway fast
Number of lanes	3 in each direction (6 lanes in total in the freeway)	
Lane width	4 m	
Road grid size by the distance between intersections	N/A	
Simulation area size	Freeway length = 600 m. Wrap around should be applied to the simulation area.	Freeway length ≥ 2 000 m. Wrap around should be applied to the simulation area.
Vehicle density	Average inter-vehicle distance in the same lane is 2,5 s × absolute vehicle speed. Baseline: The same density/speed in all the lanes during one simulation.	
Target vehicle speed (see note in Table 7.1)	50 km/h	140 km/h, 70 km/h

NOTE: There are Eclipse Sumo™ generated mobility traces available for the simulations, see Annex C.

7.2.2.4 High-priority DENM generation scenarios

7.2.2.4.1 Introduction

Dangerous events will trigger the transmission of DENMs, as opposed to normal driving situations that typically only trigger CAM. Such notifications are important, as they might highlight safety-of-life situations and the vehicles in the vicinity need to be informed rapidly and reliably about such an accident or hazardous locations.

To ease the simulations production, and keep the number of Eclipse Sumo™ traces to a reasonable number, it is proposed to use the previously described scenarios as a baseline, and simply add a pair of stationary vehicles transmitting high-priority DENMs, on top of the other vehicles (an alternative option is to replace the last two stations of the Eclipse Sumo™ traces with such pair of stationary vehicles).

The location of the pair of stationary vehicles transmitting high-priority DENM is detailed in Clause 7.2.2.4.2 to Clause 7.2.2.4.4. The origin of the x and y coordinates is assumed to be the most bottom left corner of the road(s).

7.2.2.4.2 Fast highway

Two stationary vehicles are placed in the fast highway scenario transmitting DENMs throughout the simulation. The placement is as follows (see Figure 7.7):

- Stationary vehicle 1: x = 800 m, y = 26 m
- Stationary vehicle 2: x = 805 m, y = 26 m

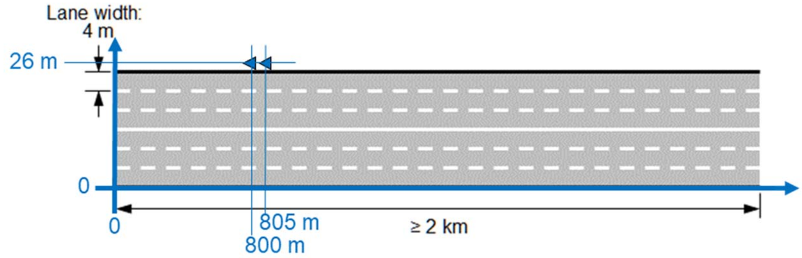


Figure 7.7: Placement of two stationary vehicles in the fast highway scenario

7.2.2.4.3 Slow highway

Two stationary vehicles are placed in the slow highway scenario transmitting DENMs throughout the simulation. The placement is as follows (see Figure 7.8):

- Stationary vehicle 1: x = 200 m, y = 26 m
- Stationary vehicle 2: x = 205 m, y = 26 m

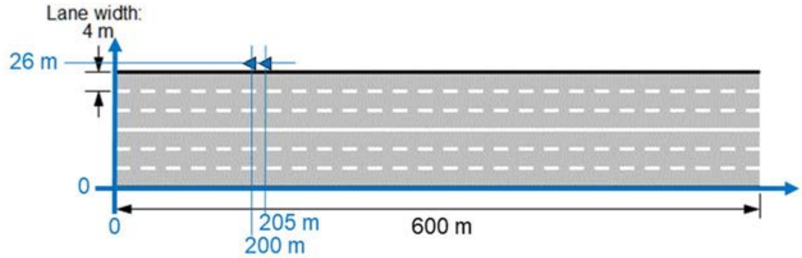


Figure 7.8: Placement of two stationary vehicles in the slow highway scenario

7.2.2.4.4 Urban

Two stationary vehicles are placed in the urban scenario transmitting DENMs throughout the simulation. The placement is as follows (see Figure 7.9):

- Stationary vehicle 1: x = 550 m, y = 875 m
- Stationary vehicle 2: x = 555 m, y = 875 m

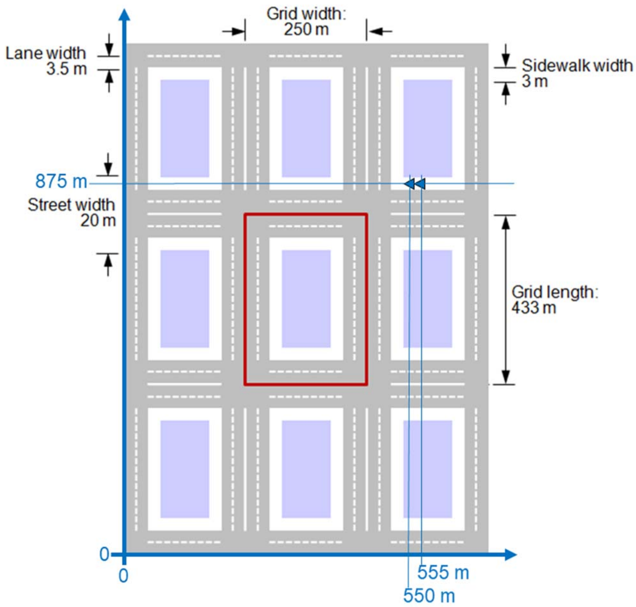


Figure 7.9: Placement of two stationary vehicles in the urban scenario

7.2.2.5 Vehicle Drop

Details of vehicle drop and mobility models are from 3GPP TR 36.885 [i.13]. Vehicles are placed on roads according to the spatial Poisson process. The vehicle density is determined by assumption on the vehicle speed, and the vehicle locations should be updated every 100 ms in the simulation. In the urban case, also probabilities for turning left or right, or going straight in intersections are included see Table 7.3.

Table 7.3: Probabilities for maneuvers in intersections for urban scenario

Maneuver	Probability [%]
Turning left	25
Turn right	25
Go straight	50

7.2.2.6 Number of vehicles and traffic mixes for numerical simulations

Several coexistence methods (e.g. Method A semi-static, Method C semi-static variant, and Method F) are based on TDM schemes where the detailed partitioning of the superframe is provided by a supervising entity. It is envisioned that the TDM partitioning will be defined for a given geographical area and may evolve over time.

Such global TDM schemes have an inherent notion of commonality over time and geography. On the one hand, this may be beneficial since such collocated stations always obey the same TDM scheme, although on the other hand the commonality over time and geography might lead to local mismatches between the reality of the road-traffic and the global TDM instructions. For a realistic assessment of the performance of those co-existence methods, numerical simulations need to be conducted including an offset on the targeted vehicles traffic mix.

Table 7.4 provides details on the number of vehicles pertaining to each technology and the intended technology mixes for conducting numerical simulations. There is an ideal technology mix perfectly matching the number of vehicles for each technology in the simulation (rows with white shading in Table 7.4). Furthermore, to each ideal technology mix also technology mixes with a slight deviation in either direction are to be investigated (rows with grey shading in Table 7.4). The deviating numbers are derived assuming that when placing vehicles of technology A with a probability p and vehicles of technology B with a probability $(1 - p)$ into an area, the distribution of the vehicles can be described by a binomial distribution, and further assuming that the approximation of the binomial distribution according to the law of large numbers can be approximated by a normal distribution. More details on the theoretical derivation of those numbers are provided in Annex G.

Table 7.4: Number of vehicles assigned to each technology, for different total number of vehicles

		Number of vehicles in simulations pertaining to either LTE-V2X or ITS-G5											
Ideal mix [%]		70		100		123		200		245		300	
LTE-V2X	ITS-G5	LTE-V2X	ITS-G5	LTE-V2X	ITS-G5	LTE-V2X	ITS-G5	LTE-V2X	ITS-G5	LTE-V2X	ITS-G5	LTE-V2X	ITS-G5
0	100	0	70	0	100	0	123	0	200	0	245	0	300
		7	63	11	89	13	110	22	178	27	218	33	267
		14	56	20	80	24	99	39	161	48	197	59	241
25	75	18	52	25	75	31	92	50	150	61	184	75	225
		21	49	30	70	37	86	61	139	74	171	91	209
		32	38	45	55	55	68	89	111	109	136	134	166
50	50	35	35	50	50	62	61	100	100	123	122	150	150
		38	32	55	45	68	55	111	89	136	109	166	134
		49	21	70	30	86	37	139	61	171	74	209	91
75	25	52	18	75	25	92	31	150	50	184	61	225	75
		56	14	80	20	99	24	161	39	197	48	241	59
100	0	70	0	100	0	123	0	200	0	245	0	300	0
		63	7	89	11	110	13	178	22	218	27	267	33
NOTE: The whitemarked rows show the ideal technology mix corresponding to a perfect match of the resources in the superframe given the different number of vehicles in simulations whereas the greymarked rows are slightly deviating from the ideal situation, see Annex G.													

7.2.3 Channel model

Channel models includes one or several components such as propagation pathloss model, shadowing distribution, shadowing standard deviation, decorrelation distance, and fast fading. For the propagation pathloss, several models have been developed and used in V2X studies and publications. This includes:

- Free space pathloss, two-ray ground reflection [i.20], and log-distance two-ray ground models [i.21].
- The pathloss models found in Equation (6) or Equation (12) in Recommendation ITU-R P.1411-10 [i.22].
- WINNER+ model, often used in 3GPP studies, and defined in 3GPP TR 36.885 [i.13].
- ECC models, such as the three slope propagation model from ECC Report 68 [i.23] which is further refined in section 3.2 of ECC Report 250 [i.24].

The three slope propagation model from ECC Report 68 [i.23] distinguishes three parameter sets for the pathloss calculation: urban, suburban, and rural.

Figure 7.10 depicts the different propagation pathloss models. Here, for the two-ray ground reflection model a perfect horizontal E-field polarization and ground reflection is assumed and for the WINNER+ model an effective antenna height of $h_e = 1{,}5$ m is used. The channel models Recommendation ITU-R P.1411-10 [i.22], Equation (6), WINNER+ B1 LOS and ECC Report 68 [i.23] three slope suburban result in very similar pathloss values.

More details and the equations for the pathloss models can be found in Annex E.

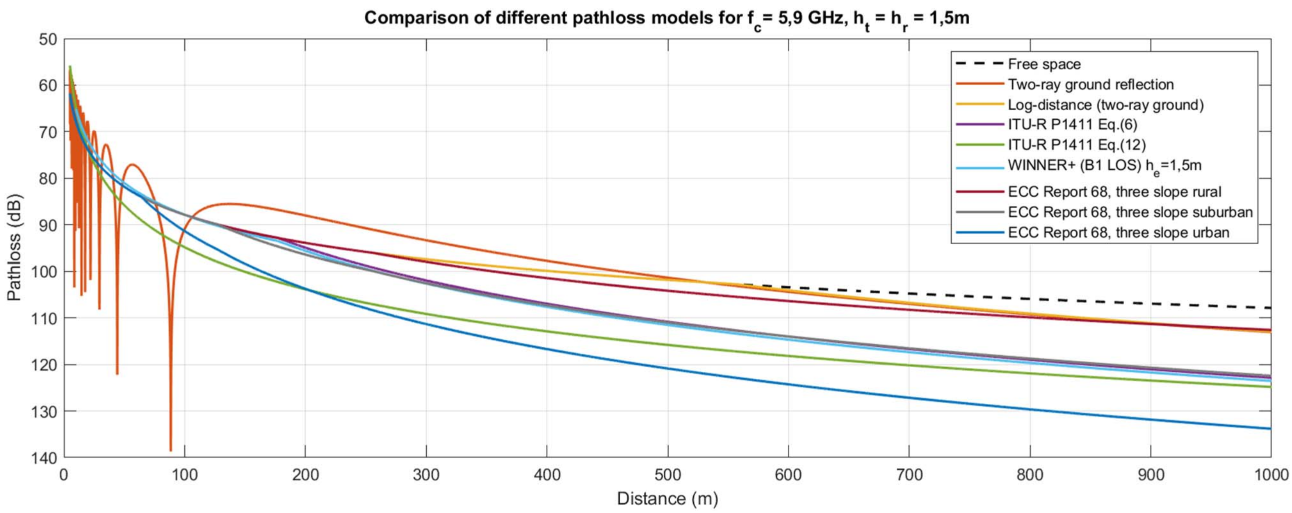


Figure 7.10: Comparison of different pathloss models

For the present document, the channel model described in Clause A.1.4 of 3GPP TR 36.885 [i.13] has been selected, and its pathloss component is the WINNER+ as shown in Figure 7.6. Table 7.5 provides assumptions for the channel model. More details on update rate etc. of this model can be found in Clause A.1.4. of 3GPP TR 36.885 [i.13]. Detailed formulas of the channel models in 3GPP TR 36.885 [i.13] are detailed in Report Recommendation ITU-R M.2135-1 [i.19].

Table 7.5: Assumptions for vehicle-to-vehicle channel in 3GPP TR 36.885 [i.13]

Parameter	Urban scenario	Highway scenario
Pathloss model	WINNER+ B1 Manhattan grid layout (note that the antenna height should be set to 1,5 m). Pathloss at 3 m is used if the distance is less than 3 m.	LOS in WINNER+ B1 (note that the antenna height should be set to 1,5 m.). Pathloss at 3 m is used if the distance is less than 3 m.
Shadowing distribution	Log-normal	Log-normal
Shadowing standard deviation	3 dB for LOS and 4 dB for NLOS	3 dB
Decorrelation distance	10 m	25 m
Fast fading	NLOS in Clauses A.2.1.2.1.1 or A.2.1.2.1.2 in 3GPP TR 36.843 [i.18] with fixed large scale parameters during the simulation.	

7.2.4 Data traffic generation

7.2.4.1 Message size

The message size is fixed to 350 bytes throughout the simulation times both for CAMs and DENMs. The message size is defined as the size of the Protocol Data Unit (PDU) delivered by the Networking and Transport Layer to the Access Layer via the IN interface, as per the ITS-S reference architecture defined in ETSI EN 302 665 [i.1], see also Figure 4.1 in the present document. Annex B outlines the rationale for selecting 350 bytes as the message size.

Additional sizes of 190 and 550 bytes representing the minimum and maximum messages size, respectively, can optionally be simulated.

7.2.4.2 Time intervals

If the simulation environment is capable of reproducing the CAM triggering conditions (derived from geographical traces), the time intervals are derived automatically from the scenario (highway, urban etc.), and are mainly depending on the speed of vehicle.

If the simulation environment is not capable of reproducing the CAM triggering conditions, the time intervals are set upfront according to the speed of the vehicle.

For the scenario where also DENMs are transmitted (see Clause 7.2.2.4), the message rate is fixed to 20 Hz for the stationary ITS stations.

7.3 Results

7.3.1 Observations

7.3.1.1 ITS-G5 channel busy ratio levels

The CSMA/CA procedure of ITS-G5 stations instructs a power threshold of -85 dBm over which the channel may be considered busy when a ITS-G5 preamble is detected. Using the WINNER+ propagation model (see Clause 7.2.3.) with 23 dBm transmit power and 3 dBi antenna gain settings, the received power is above -85 dBm for a distance of up to 223 m.

For all the scenarios considered, even in the slow highway scenario that is supposed to model congestion, CBR levels stay at low levels, well below the 0,62 threshold. Consequently, Decentralized Congestion Control (DCC) measures are not activated in the set of simulations defined in the present document. Figure 7.11 and Figure 7.12 show CBR levels for two different scenarios. The packet length used for the results is 350 bytes and the packets are transmitted with 6 Mbps (QPSK, r = ½).

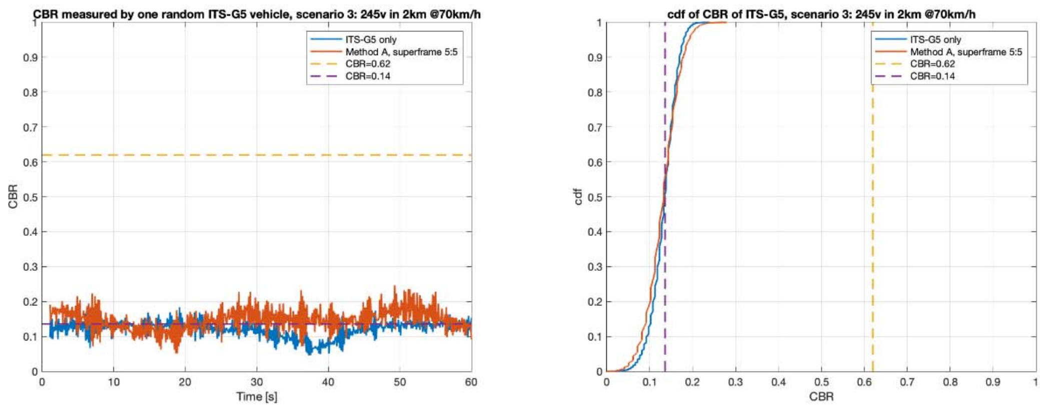


Figure 7.11: CBR statistics for fast highway with 245 vehicles at 70 km/h

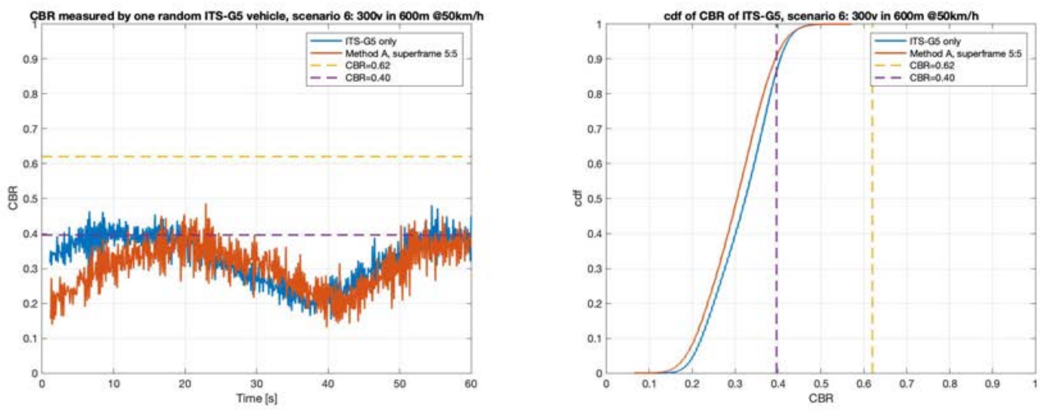


Figure 7.12: CBR statistics for slow highway with for 300 vehicles at 50 km/h

7.3.1.2 Superframe sizes and time slot configurations

Clause 6.1.3 concludes on three superframe sizes: 10 ms, 25 ms, and 50 ms. These sizes can be supported by the SPS algorithm for LTE-V2X. The time slot configuration for each technology is outlined in Clause 6.2.2, where the 10 ms superframe suggests a 5 ms time slot for each technology. During initial simulations, it became evident that the 10 ms superframe will only work when there is a 50 % technology distribution (i.e. 50 % ITS-G5 stations and 50 % LTE-V2X). Due to this, simulations containing 10 ms superframe size have not been further conducted and studied.

7.3.2 Simulations

7.3.2.1 Parameter settings

Only CAMs have been used throughout all simulations and the triggering has been based on the speed of the vehicle set upfront in simulations. The actual speed of each vehicle is randomly selected from a normal distribution with the mean corresponding to the average speed and a standard deviation of one tenth of the average speed. The high-priority DENM generation scenarios described in Clause 7.2.2.4 have not been subject to simulations. The CAM size has been fixed to 350 bytes, which is a mean of different CAM sizes (see Clause 7.2.4.1).

The slow and fast highway scenarios (see Clause 7.2.2.3) have been predominantly used in simulations with varying vehicle densities, the urban scenario outlined in Clause 7.2.2.2 has not been investigated. Table 7.6 provides the vehicle density per kilometre of highway and the maximum speed of vehicles. It also provides the data traffic generated on average in each scenario given the vehicle densities and maximum speed. This is included for providing an understanding of how much data traffic that is presented to the network each second. The data traffic generated is what the vehicles will generate when no decentralized congestion control is present. There might be vehicles locally exceeding the CBR limit triggering DCC but the occurrence of if and when DCC is activated has not been studied nor recorded.

Table 7.6: Average number of generated packets every second per kilometre of highway

		Scenario	No of vehicles	Length of road	No of vehicles per kilometre	Speed of vehicles	CAMs per second	Average number of generated CAMs/s/km
Highway	Fast	#1	70	2 000 m	35	250 km/h	700	350
		#2	125	2 000 m	62	140 km/h	1 215	607
		#3	245	2 000 m	123	70 km/h	1 147	574
	Slow	#4	100	600 m	167	50 km/h	347	580
		#5	200	600 m	333	50 km/h	694	1 156
		#6	300	600 m	500	50 km/h	1 041	1 735

NOTE 1: The number of generated CAMs is the data traffic generated by all vehicles in each scenario regardless of which technology they are using. It has been derived by taking the speed for each scenario which results in a specific CAM generation (number of CAMs/s) and this figure has been multiplied with the number of vehicles and then normalized to number of packets per second for one kilometre of road.

NOTE 2: The column "No of vehicles" tabulates the number of vehicles in the simulations. In Scenario #1-#3 the number of vehicles are spread over a stretch of road of 2 km, whereas for Scenario #4-#6 the number of vehicles provided here is for a stretch of road of 600 m. The road traffic scenarios are detailed in Clause 7.3.2.

For completeness also the CAM packet generation rate given a specific vehicle speed is shown in Table 7.7. CAMs are generated with 1 Hz - 10 Hz, i.e. a packet interval between 1s to 100 ms. For speeds above 150 km/h, the fastest packet generation is always 10 Hz and below 20 km/h the generation is always 1 Hz.

Table 7.7: Packet generation for different vehicle speeds

Speed [km/h]	Packet generation [Hz]	Time interval between packets [s]
0	1,00	1,000
10	1,00	1,000
20	1,39	0,720
30	2,08	0,480
40	2,78	0,360
50	3,47	0,288

Speed [km/h]	Packet generation [Hz]	Time interval between packets [s]
60	4,17	0,240
70	4,68	0,206
80	5,56	0,180
90	6,25	0,160
100	6,94	0,144
110	7,64	0,131
120	8,33	0,120
130	9,03	0,111
140	9,72	0,103
≥ 150	10,00	0,100

The settings for ITS-G5 are outlined in Table 7.8 and AC_BE is used for transmitting CAMs (see Table 4.6).

Table 7.8: ITS-G5 parameter setting for CAMs

Parameter	Value	Description
AIFS	110 µs	Listening period before transmission can commence.
CW size	16	The uniform distribution between [0,15] used for selecting backoff time.
MCS	QPSK, ½ rate	The default transfer rate of 6 Mbps selected for transmissions of CAMs. Also denoted MCS 2.
Carrier sensing threshold	-65 dBm	This threshold is for detecting any signal with a received energy above -65 dBm. The minimum carrier sensing threshold for detecting other ITS-G5 stations using QPSK, ½ rate is -88 dBm according to [i.3].

The settings for LTE-V2X are outlined in Table 7.9 and there are two different configurations for parts of the parameters called "Configuration 1" and "Configuration 2". These are both valid configurations according to ETSI EN 303 613 [i.7].

Table 7.9: LTE-V2X parameter setting for CAMs

Common parameters			
Parameter	Value	Description	
Subchannel size	10	There are 10 resource block pairs in each subchannel. There are five subchannels per subframe.	
Configuration	Adjacent	In the adjacent PSCCH + PSSCH scheme, the SCI and TB are transmitted in adjacent RBs.	
Differing parameter settings			
Parameter	Configuration 1	Configuration 2	Description
MCS	7 (3 subchannels) for CAM	11 (2 subchannels) for CAM	
HARQ	Disabled/Enabled	Enabled for all scenarios	HARQ determines if a packet is retransmitted or not. Configuration 1 enables HARQ for Scenario #1 in Table 7.14 of [i.7].
No of HARQ transmission	2	2	Determines the number of times a packet is transmitted.
Keep probability (*k*)	0,5	0,8	The probability that current reserved subchannel are kept when changing resources.
Subchannel sensing threshold	-110 dBm	-108 dBm	The value for determining if a subchannel is perceived as occupied or not.
Resource selection window	100 ms	90 ms	The size of the window used for determining new resources.
NOTE: ETSI EN 303 613 [i.7] describing the access layer technology LTE-V2X only mandates HARQ turned on for high-speed scenarios. During the drafting of the present document, ETSI TS 103 723 [i.28] (outlining a profile of LTE-V2X) was approved. This mandates HARQ to be turned on always for LTE-V2X.			

The settings for the channel model and transceiver properties are outlined in Table 7.9, where some parameters differ in settings called "Configuration 1" and "Configuration 2". Simulations are run with either "Configuration 1" from Table 7.9 and Table 7.10 or "Configuration 2" from the same tables.

Table 7.10: Channel model and transceiver parameter setting

<table>
<tr><th colspan="4">Common parameters</th></tr>
<tr><th>Parameter</th><th>Value</th><th colspan="2">Description</th></tr>
<tr><td>Channel bandwidth</td><td>10 MHz</td><td colspan="2">The channel bandwidth for transmissions is set to 10 MHz.</td></tr>
<tr><td>Antenna gain</td><td>3 dBi</td><td colspan="2">The antenna gain at TX and RX.</td></tr>
<tr><td>Propagation model</td><td>WINNER+, Scenario B1</td><td colspan="2">Details on the channel model are found in Clause 7.2.3. Only highway scenarios have been simulated, i.e. Scenario B1.</td></tr>
<tr><td>Shadowing</td><td>Variance 3 dB, decorrelation distance 25 m</td><td colspan="2">The selection of shadowing is based on the highway scenario.</td></tr>
<tr><th colspan="4">Differing parameter settings</th></tr>
<tr><th>Parameter</th><th>Configuration 1</th><th>Configuration 2</th><th>Description</th></tr>
<tr><td>Transmit power ITS-G5</td><td>23 dBm (13 dBm/MHz)</td><td>22 dBm (12 dBm/MHz)</td><td rowspan="2">The power leaving the antenna.</td></tr>
<tr><td>Transmit power LTE-V2X</td><td>20,8 dBm (13 dBm/MHz)</td><td>22 dBm (16 dBm/MHz)</td></tr>
<tr><td>Noise figure</td><td>6 dB</td><td>9 dB</td><td>Degradation caused by components in the receiving signal chain.</td></tr>
<tr><td>Cable loss</td><td>n/a</td><td>3 dB</td><td>The loss in cables on both TX and RX.</td></tr>
</table>

7.3.2.2 Successful reception of messages

Configuration 1 and Configuration 2 of the simulation configuration outlined in Table 7.9 and Table 7.10 use slightly different Packet Error Rate (PER) for successful reception. In Figure 7.13, the PER curves are shown for Configuration 1 being ITS-G5 MCS 2 and LTE-V2X MCS 7 (see Table 7.16 and Table 7.9).

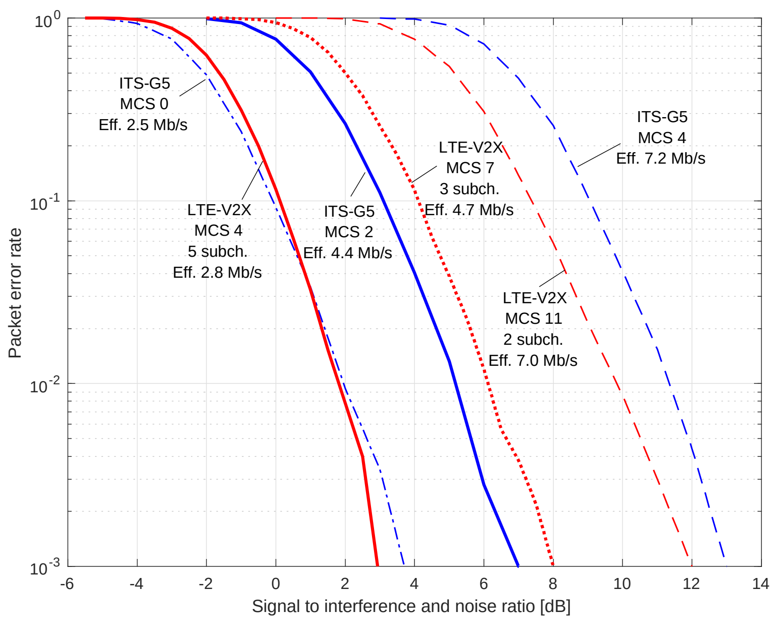


Figure 7.13: PER curves for successful decoding of messages for Configuration 1

In Figure 7.14, the PER curves for Configuration 2 are depicted where LTE-V2X uses MCS 11 and HARQ turned on.

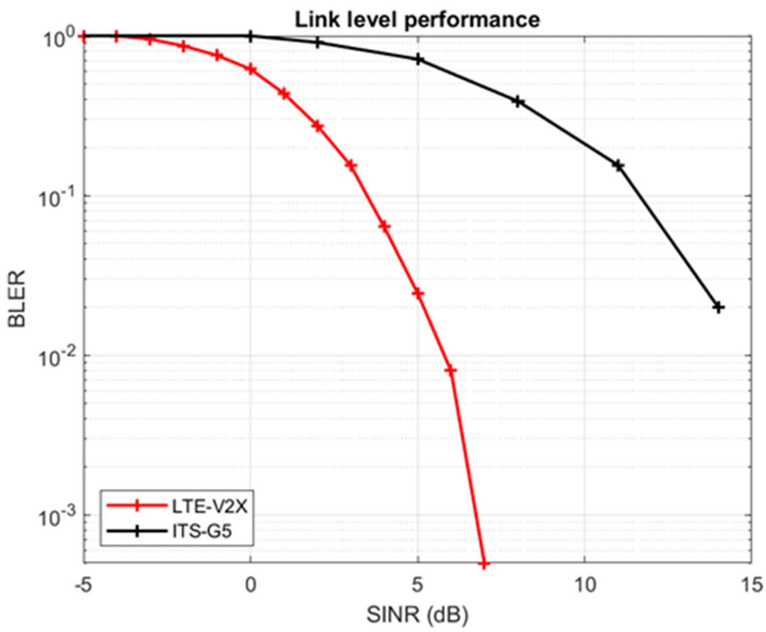


Figure 7.14: PER curves for successful decoding of messages for Configuration 2

7.3.2.3 Baseline performance

7.3.2.3.1 Introduction

This clause presents simulation results when ITS-G5 and LTE-V2X are both operating on the same frequency channel without any co-channel co-existence methods deployed. This will serve as a baseline for simulations with co-channel co-existence methods. The results presented are from the fast highway scenario with two different vehicle densities, i.e. Scenario #1 and Scenario #3 in Table 7.6. The specifics around Configuration 1 and Configuration 2 are fetched from Table 7.9 and Table 7.10.

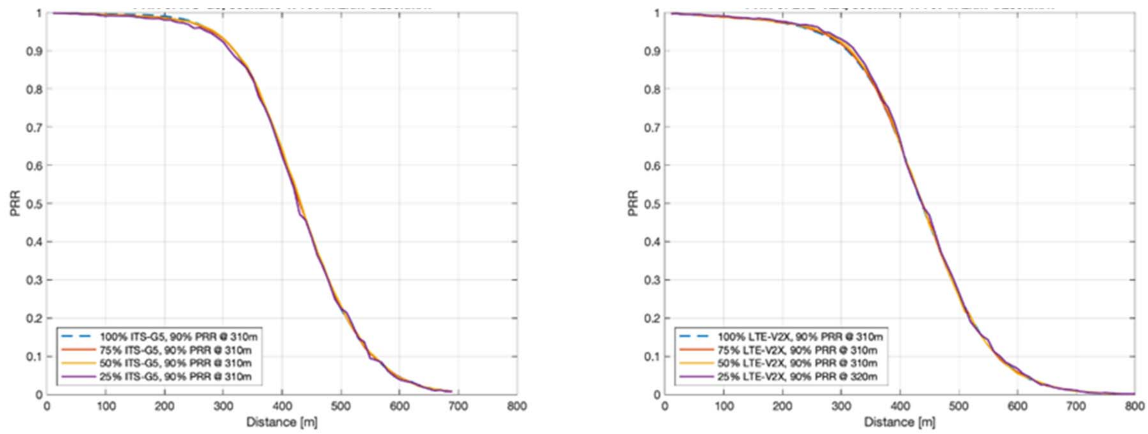
The fast highway with two different vehicle densities are divided between the two technologies as outlined in Table 7.11 for different technology mixes. The high vehicle density of 245, will generate almost 600 packets/s/km of highway and the lowest vehicle density scenario of 70 vehicles has around 350 packets/s/km of highway.

Table 7.11: Number of vehicles pertaining to either LTE-V2X or ITS-G5

Technology mix [%]		70		245	
LTE-V2X	ITS-G5	LTE-V2X	ITS-G5	LTE-V2X	ITS-G5
0	100	0	70	0	245
25	75	18	52	61	184
50	50	35	35	123	122
75	25	52	18	184	61
100	0	70	0	245	0

7.3.2.3.2 Configuration 1

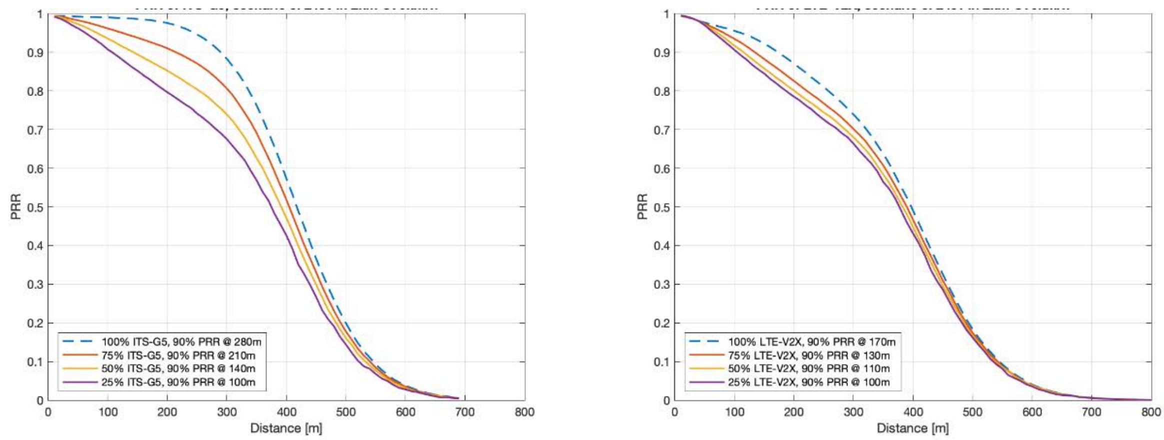
The Packet Reception Rate (PRR) for the fast highway scenario with 70 vehicles pertaining to either LTE-V2X or ITS-G5 for the technology mixes as outlined in Table 7.9 is shown in Figure 7.15. No co-channel co-existence method is deployed.



(a) ITS-G5 **(b) LTE-V2X**

Figure 7.15: 70 vehicles in the fast highway scenario (Scenario #1 in Table 7.6)

PRR when increasing the number of vehicles to 245 for the fast highway scenario is depicted in Figure 7.16. In this scenario, the performance degrades for both technologies when they are both present.



(a) ITS-G5 **(b) LTE-V2X**

Figure 7.16: 245 vehicles in the fast highway scenario (Scenario #3 in Table 7.6)

The End-to-End Delay (EED) for the two scenarios is not affected see a summary in Table 7.12. This due to that the EED only addresses successful receptions.

Table 7.12: End-to-end delay

	EED probability >90 %	
Mix of stations	**ITS-G5**	**LTE-V2X**
100 % ITS-G5 - 0 % LTE-V2X	1 ms	n/a
75 % ITS-G5 - 25 % LTE-V2X	1 ms	90 ms
50 % ITS-G5 - 50 % LTE-V2X	1 ms	90 ms
25 % ITS-G5 - 75 % LTE-V2X	< 1 ms	90 ms
0 % ITS-G5 - 100 % LTE-V2X	n/a	90 ms

Data Age (DA) increases when the number of vehicles increases, see a summary in Table 7.13. The data age also captures the packets not successfully decoded.

Table 7.13: Data age

	DA probability > 90 %			
	ITS-G5		LTE-V2X	
Mix of stations	70 vehicles	245 vehicles	70 vehicles	245 vehicles
100 % ITS-G5 - 0 % LTE-V2X	0,1 s	0,24 s	n/a	n/a
75 % ITS-G5 - 25 % LTE-V2X	0,1 s	0,29 s	0,19 s	0,47 s
50 % ITS-G5 - 50 % LTE-V2X	0,1 s	0,39 s	0,19 s	0,45 s
25 % ITS-G5 - 75 % LTE-V2X	0,1 s	0,41 s	0,19 s	0,39 s
0 % ITS-G5 - 100 % LTE-V2X	n/a	n/a	0,19 s	0,32 s

The Inter-Packet Gap (IPG) increases when the number of vehicles increases, see a summary in Table 7.14. The IPG also captures the packets not successfully decoded. IPG does not accommodate the channel access delay whereas DA includes this.

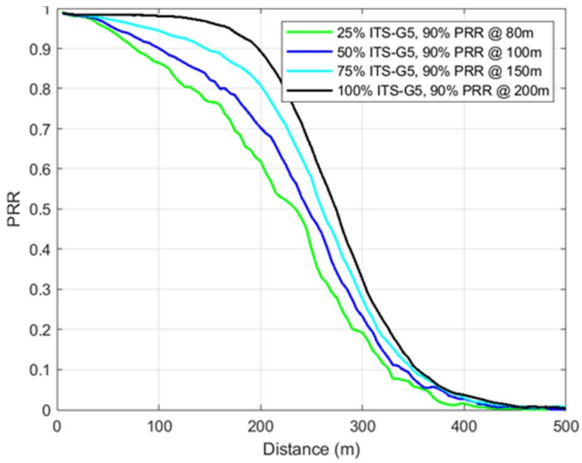
Table 7.14: Inter-packet gap

	IPG probability > 90 %			
	ITS-G5		LTE-V2X	
Mix of stations	70 vehicles	245 vehicles	70 vehicles	245 vehicles
100 % ITS-G5 - 0 % LTE-V2X	0,1 s	0,24 s	n/a	n/a
75 % ITS-G5 - 25 % LTE-V2X	0,1 s	0,29 s	0,1 s	0,4 s
50 % ITS-G5 - 50 % LTE-V2X	0,1 s	0,39 s	0,1 s	0,4 s
25 % ITS-G5 - 75 % LTE-V2X	0,1 s	0,41 s	0,1 s	0,3 s
0 % ITS-G5 - 100 % LTE-V2X	n/a	n/a	0,1 s	0,3 s

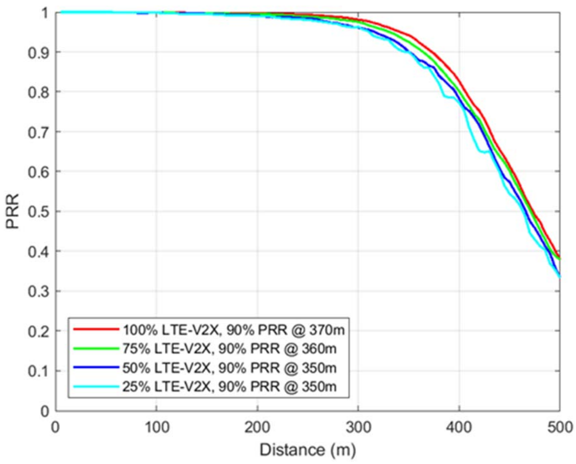
However, it should be noted that data age and inter-packet gap need also to be put in relation to the generation rate of packets. In the higher vehicle density case, vehicles will generate a new packet around every 200 ms given a speed of 70 km/h and in the lower vehicle density case the vehicles will generate with around 10 Hz, i.e. a new packet every 100 ms.

7.3.2.3.3 Configuration 2

The PRR for the scenario with 70 vehicles pertaining to either LTE-V2X or ITS-G5 for the technology mixes as outlined in Table 7.9 is shown in Figure 7.17 using Configuration 2 from Table 7.9 and Table 7.10. No co-channel co-existence method is deployed.



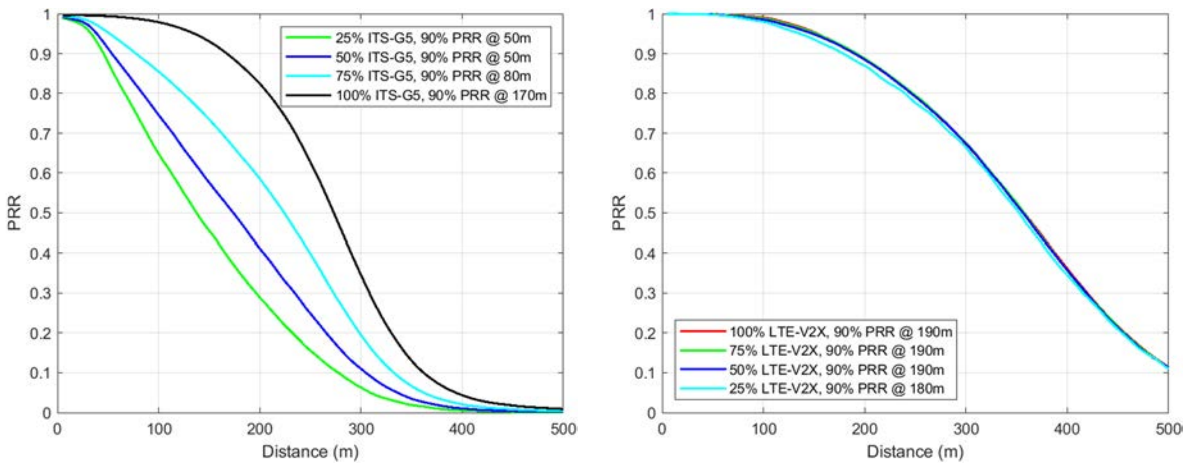
(a) ITS-G5



(b) LTE-V2X

Figure 7.17: 70 vehicles on the fast highway scenario (Scenario #1 in Table 7.6)

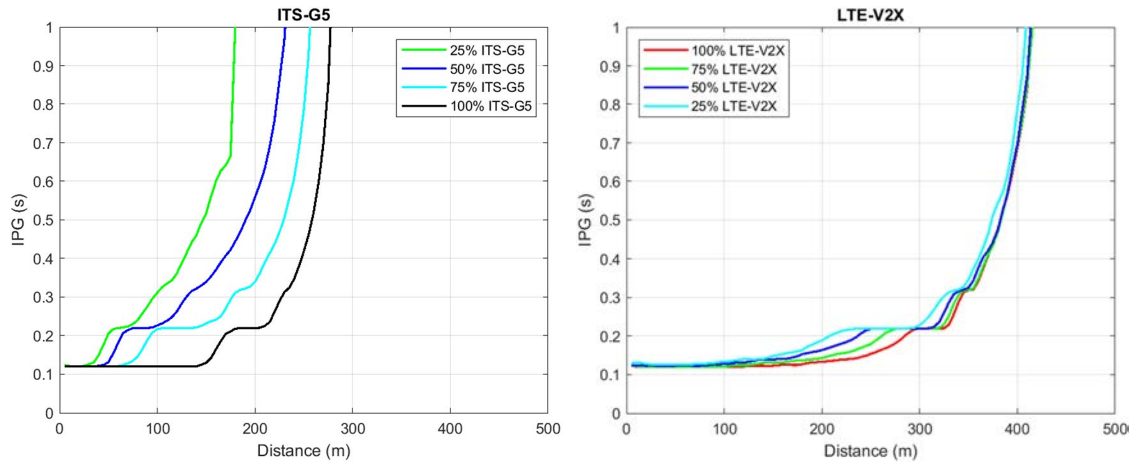
PRR when increasing the number of vehicles to 245 for the fast highway scenario is depicted in Figure 7.18. In this scenario, the performance degrades for ITS-G5 but LTE-V2X does not suffer from the same degradation when ITS-G5 stations are present. The PRR does not change for the different technology mixes for LTE-V2X.



(a) ITS-G5 **(b) LTE-V2X**

Figure 7.18: 245 vehicles in the fast highway scenario (Scenario #3 in Table 7.6)

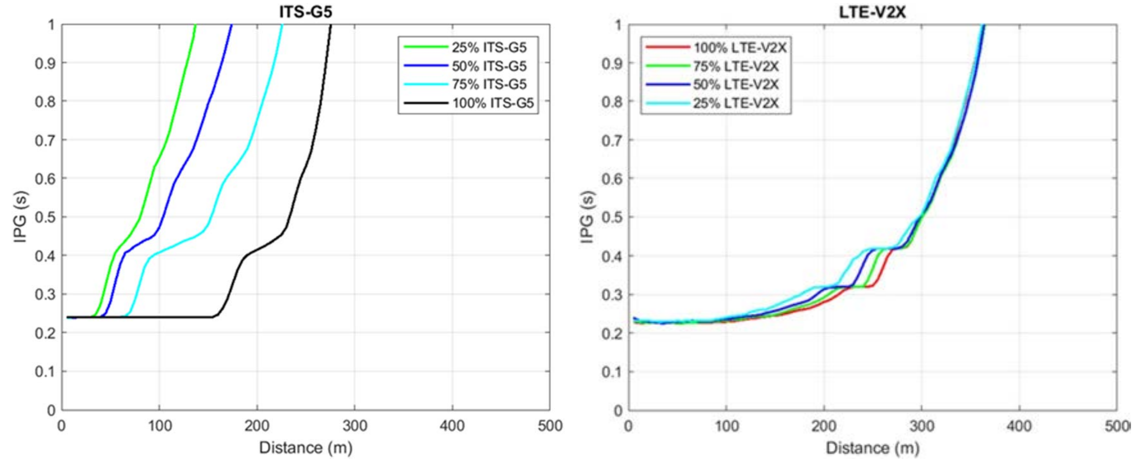
The IPG for the 70 vehicles scenario is depicted in Figure 7.19 and the IPG increases for ITS-G5 when the number of LTE-V2X stations increases. LTE-V2X has more or less a constant IPG.



(a) ITS-G5 **(b) LTE-V2X**

Figure 7.19: IPG for 70 vehicles on the fast highway scenario (Scenario #1 in Table 7.6)

The IPG for the 245 vehicles scenario is depicted in Figure 7.20 and the IPG increases for ITS-G5 when the number of LTE-V2X stations increases. LTE-V2X has more or less a constant IPG.



(a) ITS-G5 **(b) LTE-V2X**

Figure 7.20: IPG for 245 vehicles on the fast highway scenario (Scenario #3 in Table 7.6)

7.3.2.3.4 Wrap up

As expected, when the number of vehicles increases, the performance will decrease especially for ITS-G5 in terms of the PRR. The HARQ transmissions turned on in Configuration 2 will increase robustness for LTE-V2X compared to in Configuration 1, which might explain that the PRR for different technology mixes remains the same. EED is the same for all scenarios since this is only looking into successful reception of packets. IPG and DA increases with more vehicles, but more vehicles imply lower speed and increased time between packet generations.

7.3.2.4 Method A

7.3.2.4.1 Enhancement to Method A

Simulations have been conducted when artificially delaying ITS-G5 transmissions to avoid concurrent transmission attempts following a busy channel period and when extending the Contention Window (CW) size to spread the backoff times among ITS-G5 stations. Details on how the artificial delay are found in Clause 6.3.1.5. The following simulation results have been performed using "Configuration 2" from Table 7.9 and Table 7.10. A perfect time synchronization is assumed for both technologies and they are aware of the current Time Division Multiplexing (TDM) pattern, i.e. superframe size and time slot for each technology. The fast highway scenario has been used with a vehicle density of 123 vehicles (Scenario #2 in Table 7.6) corresponding to around 600 generated packets/s/km of road. In Table 7.15, the number of vehicles pertaining to either LTE-V2X or ITS-G5 for the vehicle density of 123 is tabulated.

Table 7.15: Number of vehicles pertaining to either LTE-V2X or ITS-G5

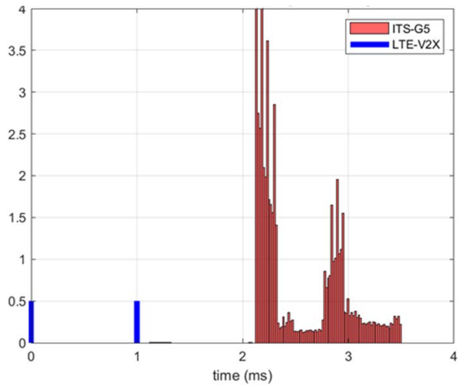
Technology mix [%]		123	
LTE-V2X	**ITS-G5**	**LTE-V2X**	**ITS-G5**
0	100	0	123
25	75	31	92
50	50	62	61
75	25	92	31
100	0	123	0

Different superframe sizes have been used for investigating the effects of concurrent ITS-G5 transmissions following a busy period, CW size, and the suggested artificial delay. Table 7.16 details the superframe sizes together with corresponding number of vehicles for each time slot. There is a perfect match between time slots and vehicles.

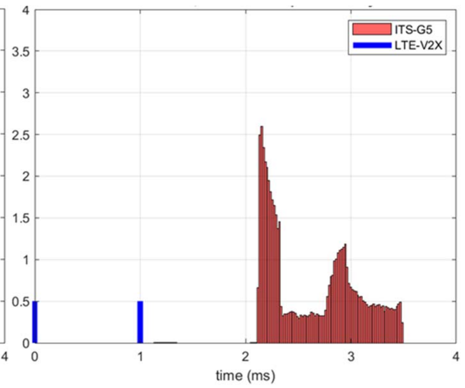
Table 7.16: Investigated superframe sizes

	Time slots		Number of vehicles		
Superframe size	**LTE-V2X**	**ITS-G5**	**LTE-V2X**	**ITS-G5**	**Denoted**
4 ms	2 ms	2 ms	62	61	(4,2,2)
10 ms	5 ms	5 ms	62	61	(10,5,5)
20 ms	10 ms	10 ms	62	61	(20,10,10)
20 ms	5 ms	15 ms	31	92	(20,5,15)
20 ms	15 ms	5 ms	92	31	(20,15,5)

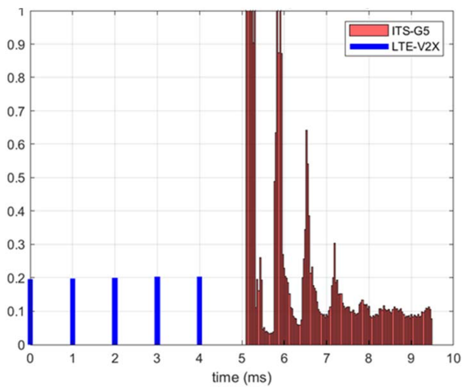
The effects of the packet delay mechanism are depicted in time histograms in Figure 7.21 for the (4,2,2), (10,5,5), and (20,10,10) settings. It is observed that the packet delay introduced reduces the occurrences of concurrent ITS-G5 packet transmissions.



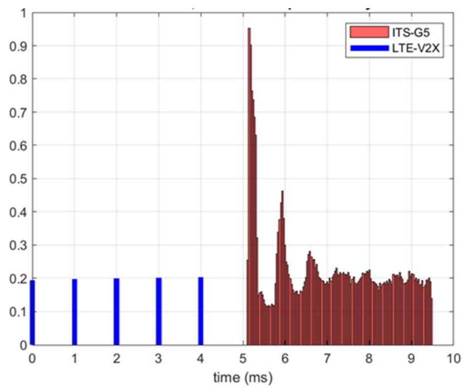
(a) No delay, (4,2,2)



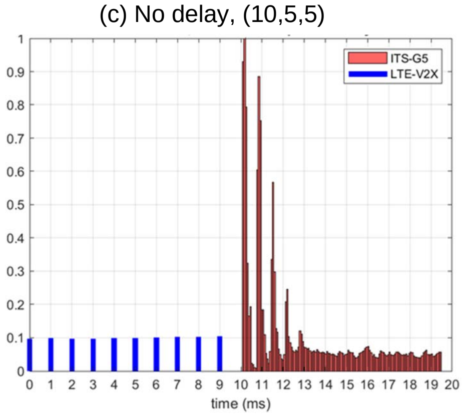
(b) Delay, (4,2,2)



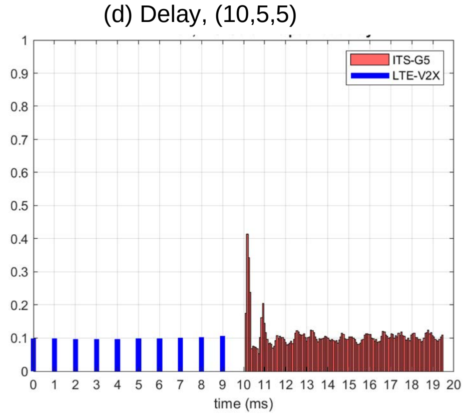
(c) No delay, (10,5,5)



(d) Delay, (10,5,5)



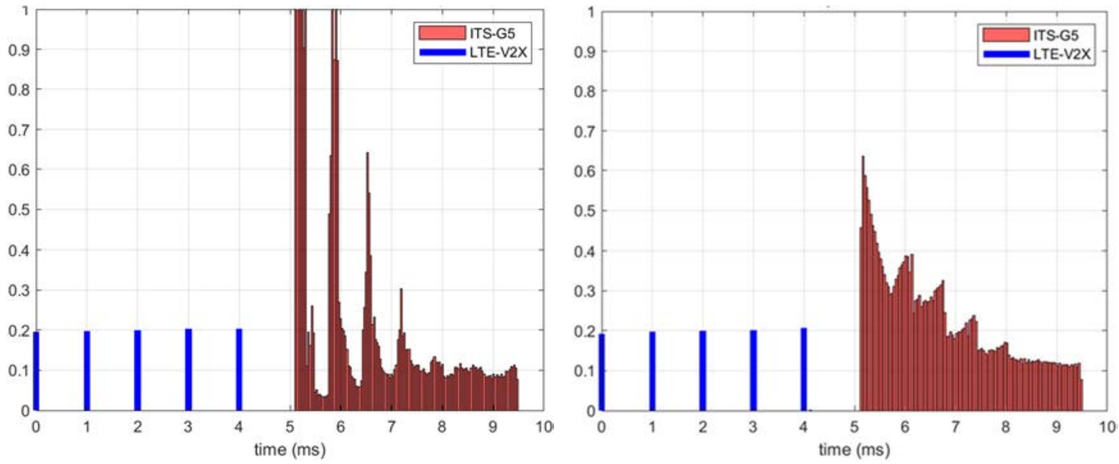
(e) No delay, (20,10,10)



(f) Delay, (20,10,10)

Figure 7.21: Histograms on the effects of delaying ITS-G5 transmissions

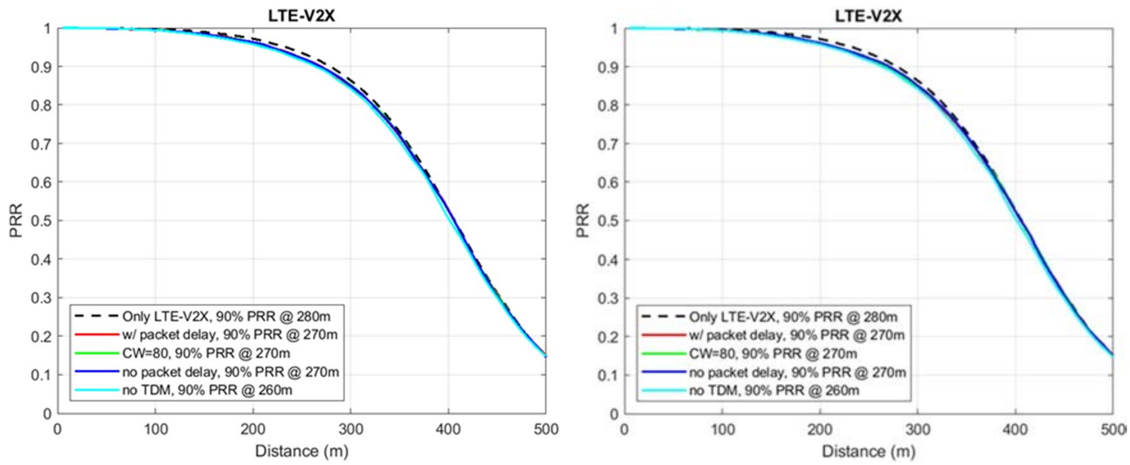
The effects of increasing the CW size from original 16 to 80 is depicted in Figure 7.22. It can be observed that the concurrent ITS-G5 transmissions are reduced.



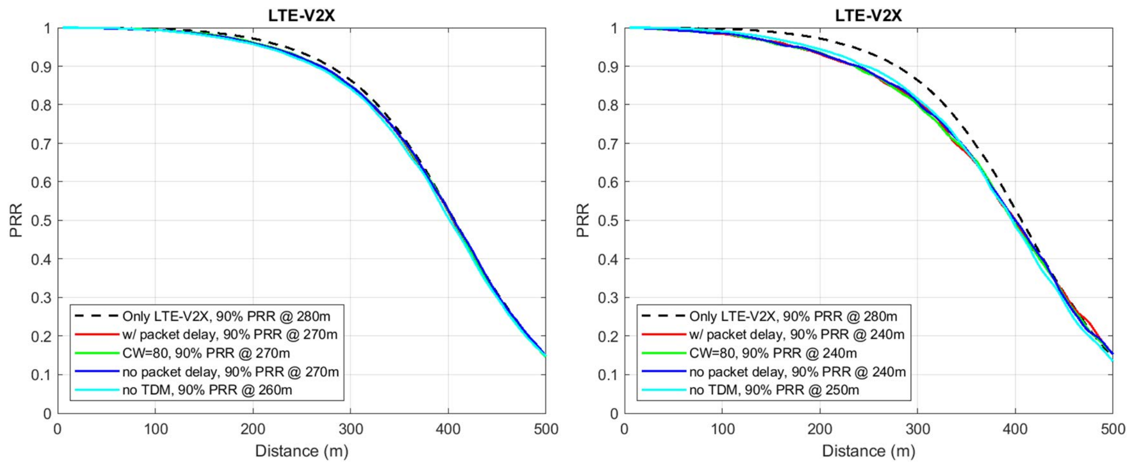
(a) No delay, (10,5,5) (b) CW size of 80, (10,5,5)

Figure 7.22: Histograms on the effects of increasing the CW size to 80

PRR for LTE-V2X for the different superframe sizes are depicted in Figure 7.23. The dashed black line is showing only LTE-V2X on the channel (upper-bound performance) and cyan line shows when no superframe is available. There is a slight performance degrade for LTE-V2X in the situation with (20,5,15) when LTE-V2X has 25 % of the available resources and the available resources to select from for transmissions in the superframe are restricted.



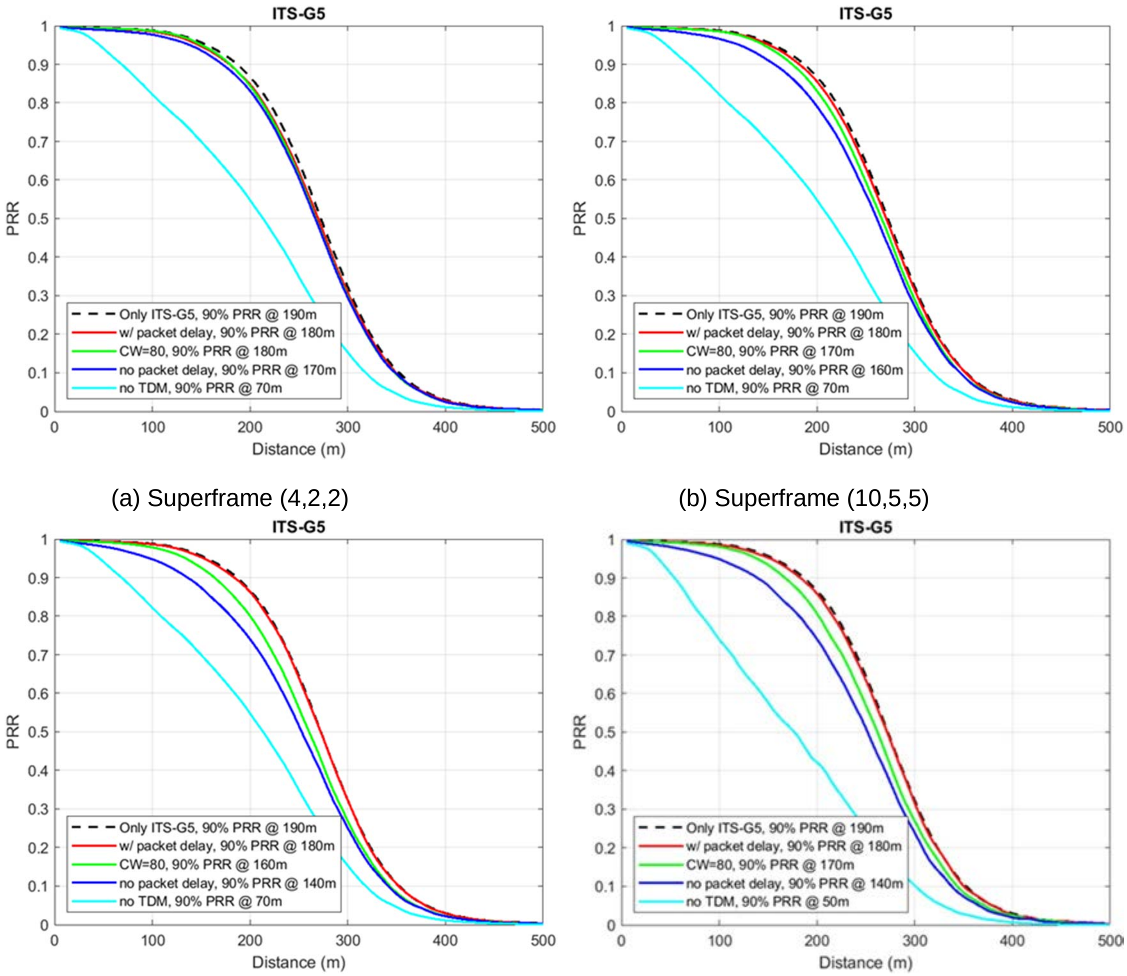
(a) Superframe (4,2,2) (b) Superframe (10,5,5)



(c) Superframe (20,10,10) (d) Delay, (20,5,10)

Figure 7.23: PRR for LTE-V2X for the different superframe sizes

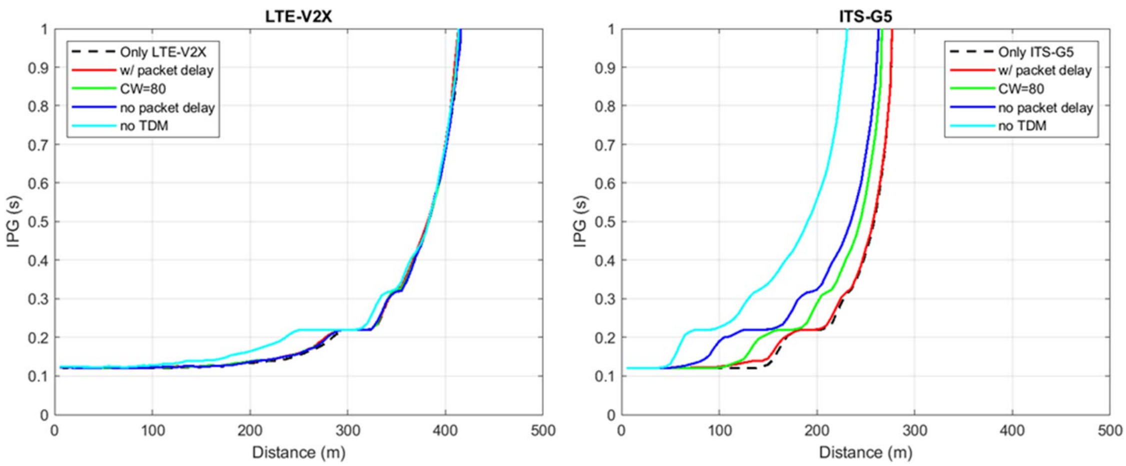
PRR for ITS-G5 for the different variants presented herein: no packet delay, packet delay, and increased CW size. When introducing packet delay, ITS-G5 performs almost the same as if only ITS-G5 had been on the channel and increased CW size is also better when not having any packet delay introduced at all.



(c) Superframe (20,10,10) (d) Superframe (20,15,5)

Figure 7.24: PRR for ITS-G5 for the different superframe sizes

The IPG for both technologies are more or less the same regardless of superframe size. In Figure 7.25, IPG for LTE-V2X and ITS-G5 are depicted for the superframe setting of (20,10,10).



(a) LTE-V2X (b) ITS-G5

Figure 7.25: IPG for a superframe setting of (20,10,10)

7.3.2.4.2 Mismatch between TDM pattern and technology mix

Clause 7.3.2.6 addresses the aspects when there is a mismatch between the TDM pattern and corresponding time slot for each technology compared to the actual technology penetration. Simulations have been conducted for investigating the effect of this mismatch in the fast highway scenario (Scenario #2 in Table 7.6) with 123 vehicles under Method A. "Configuration 2" from Table 7.9 and Table 7.10 has been used. In Table 7.17, the technology mix 0 % -100 % for a vehicle density of 123 and mismatch values are tabulated together with some explanation and colour coding of legends for the result figures.

Table 7.17: Technology mix and mismatch

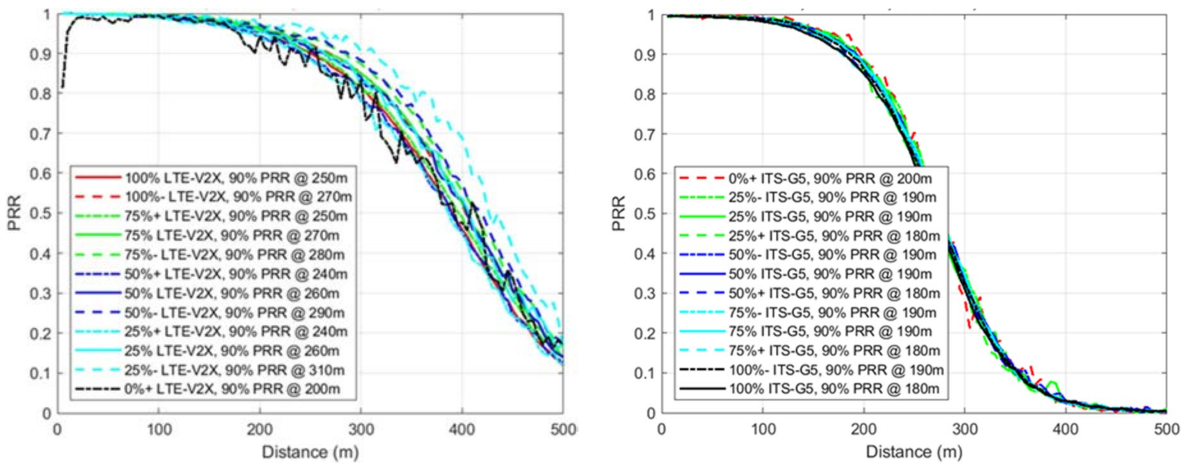
Technology mix [%]		123		Legend in figures		Explanation
LTE-V2X	ITS-G5	LTE-V2X	ITS-G5	LTE-V2X	ITS-G5	
0	100	0	123	n/a	100%	According to TDM scheme.
		13	110	0%+	100%-	LTE-V2X stations present despite 0 % according to TDM scheme.
25	75	24	99	25%-	75%+	Less LTE-V2X stations and more ITS-G5 stations compared to TDM scheme.
		31	92	25%	75%	According to TDM scheme.
		37	86	25%+	75%-	More LTE-V2X stations and less ITS-G5 stations compared to TDM scheme.
50	50	55	68	50%-	50%+	Less LTE-V2X stations and more ITS-G5 stations compared to TDM scheme.
		62	61	50%	50%	According to TDM scheme.
		68	55	50%+	50%-	More LTE-V2X stations and less ITS-G5 stations compared to TDM scheme.
75	25	86	37	75%-	25%+	Less LTE-V2X stations and more ITS-G5 stations compared to TDM scheme.
		92	31	75%	25%	According to TDM scheme.
		37	86	75%+	25%-	More LTE-V2X stations and less ITS-G5 stations compared to TDM scheme.
		110	13	100%-	0%	ITS-G5 stations present despite 0 % according to TDM scheme.
100	0	123	0	100%	n/a	According to TDM scheme.

The superframe size has been fixed to 50 ms. In Table 7.18, the time slots for each given technology mix are provided.

Table 7.18: Time slots for different technology mixes

	Technology mix [%]		Time slots [ms]	
Superframe size	LTE-V2X	ITS-G5	LTE-V2X	ITS-G5
50 ms	0	100	5	45
	25	75	13	37
	50	50	25	25
	75	25	37	13
	100	0	45	5

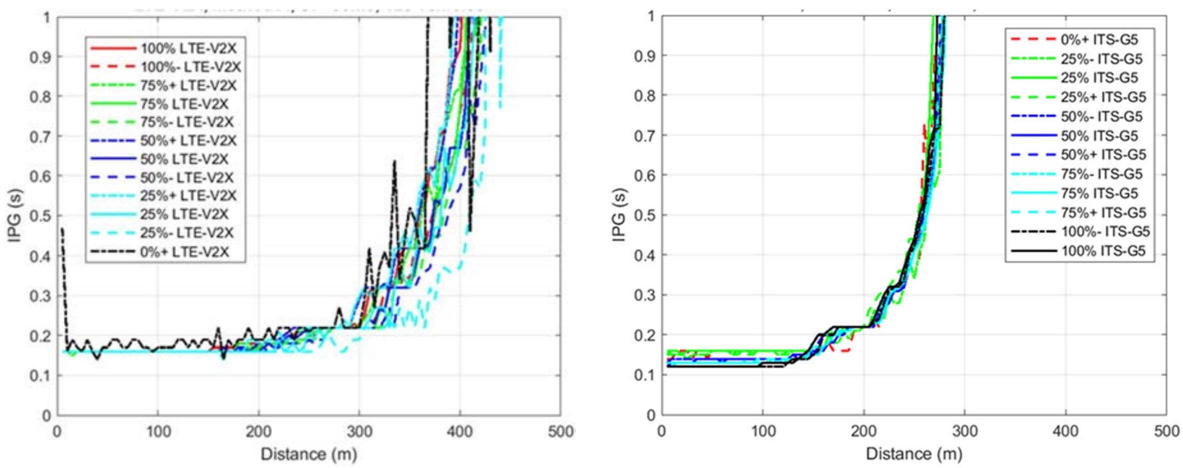
The PRR is shown in Figure 7.26. ITS-G5 is hardly affected by the mismatch whereas the PRR for LTE-V2X is a bit more spread. In the scenarios when only one technology is supposed to present but there are a few stations of the other technology provides not sufficient statistics. This is why those two cases provide a bit shaky results.



(a) LTE-V2X (b) ITS-G5

Figure 7.26: PRR for mismatch between time slots and technology mix

The IPG is depicted in Figure 7.27. A bit shaky results for "0 %+ LTE-V2X" and "0 %+ ITS-G5" given less statistics. For ITS-G5, the IPG is almost the same for all cases whereas there is a bit of spread for LTE-V2X.



(a) LTE-V2X (b) ITS-G5

Figure 7.27: IPG for mismatch between time slots and technology mix

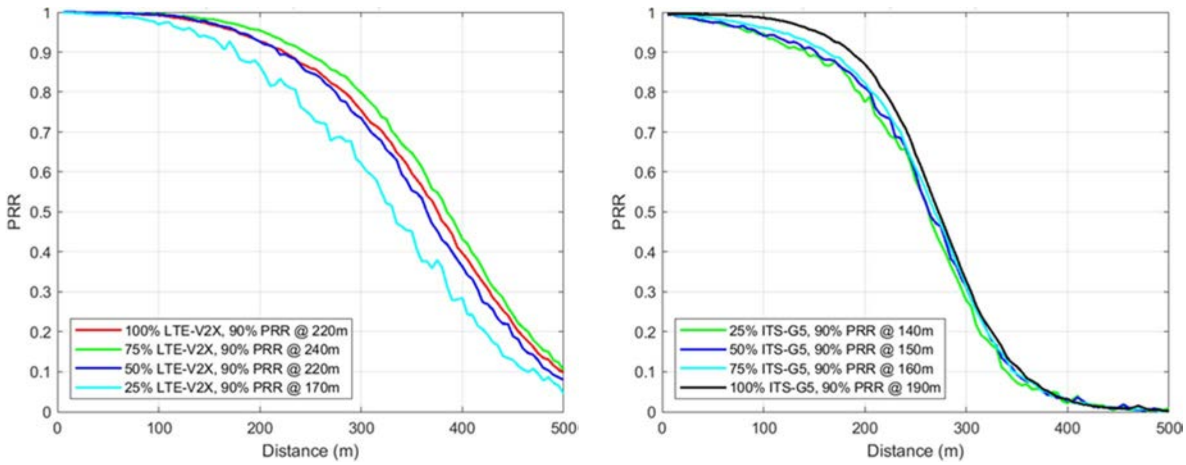
7.3.2.4.3 Semi-static Method A

In these simulation results, the semi-static Method A has been used where both ITS-G5 stations and LTE-V2X stations have the same knowledge about the superframe size and time slots for each technology. ITS-G5 also implements the enhancement with packet delay following the busy channel as outlined in Clause 6.3.1.5 (results from simulations detailing this is found in Clause 7.3.2.4.1). "Configuration 2" from Table 7.9 and Table 7.10 has been used together with the fast highway scenario "Scenario #2" from Table 7.6 containing 123 vehicles generating approximately 600 packets/s/km. The time slots for each technology together with the technology mixes are tabulated in Table 7.19 and two different superframe sizes have been used, i.e. 25 ms and 50 ms.

Table 7.19: Time slots for different technology mixes

	Technology mix [%]		123 vehicles		Time slots [ms]	
Superframe size	**LTE-V2X**	**ITS-G5**	**LTE-V2X**	**ITS-G5**	**LTE-V2X**	**ITS-G5**
25 ms	0	100	0	123	5	20
	25	75	31	92	6	19
	50	50	62	61	13	12
	75	25	92	31	19	6
	100	0	123	0	20	5
Superframe size	**LTE-V2X**	**ITS-G5**	**LTE-V2X**	**ITS-G5**	**LTE-V2X**	**ITS-G5**
50 ms	0	100	0	123	5	45
	25	75	31	92	13	37
	50	50	62	61	25	25
	75	25	92	31	37	13
	100	0	123	0	45	5

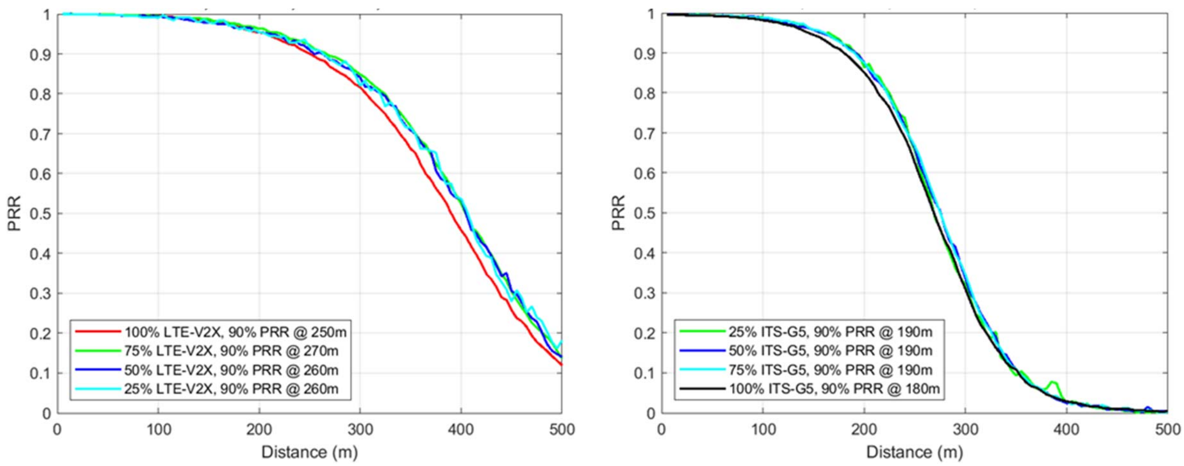
The PRR for a superframe size of 25 ms is depicted in Figure 7.28 for both technologies.



(a) LTE-V2X (b) ITS-G5

Figure 7.28: PRR for semi-static Method A with superframe size 25 ms (Scenario #2 from Table 7.6)

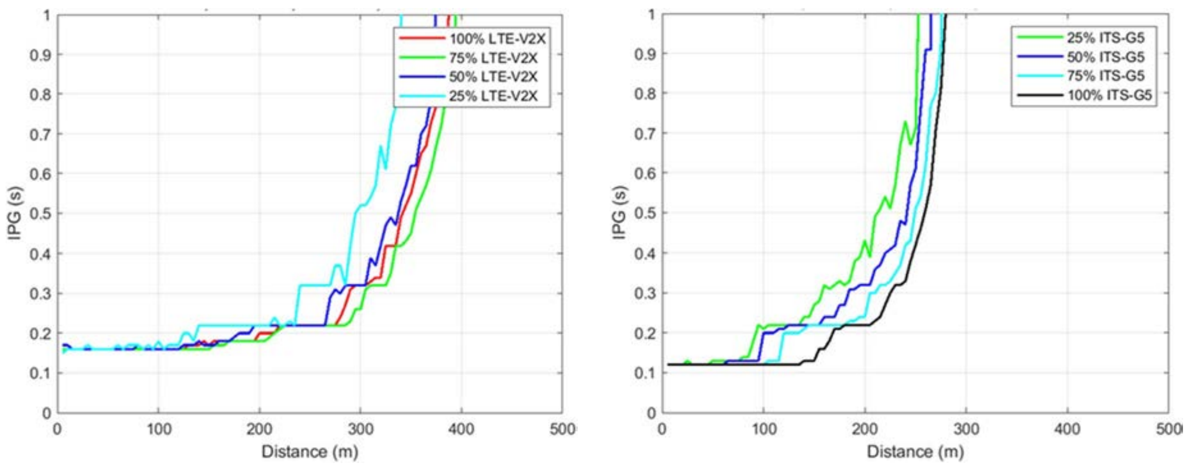
The PRR for a superframe size of 50 ms is depicted in Figure 7.29 for both technologies. The PRR increases for both technologies with a superframe size of 50 ms compared to the 25 ms superframe size.



(a) LTE-V2X (b) ITS-G5

Figure 7.29: PRR for semi-static Method A with superframe size 50 ms (Scenario #2 from Table 7.6)

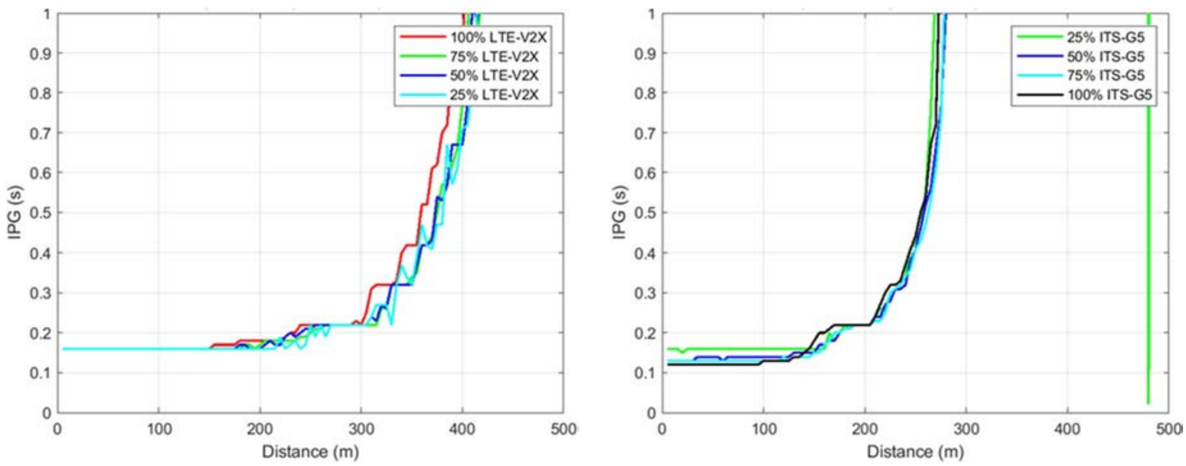
The IPG for a superframe size of 25 ms is depicted in Figure 7.30 for both technologies.



(a) LTE-V2X (b) ITS-G5

Figure 7.30: IPG for semi-static Method A with superframe size 25 ms (Scenario #2 from Table 7.6)

The IPG for a superframe size of 50 ms is depicted in Figure 7.31 for both technologies.



(a) LTE-V2X (b) ITS-G5

Figure 7.31: IPG for semi-static Method A with superframe size 25 ms (Scenario #2 from Table 7.6)

7.3.2.4.4 Wrap up

Introducing a packet delay or increasing the CW size will decrease the number of concurrent transmissions attempts for ITS-G5 stations when operating under a superframe regime, which leads to increased PRR.

The investigated mismatch between time slots of each technology and actual presence of LTE-V2X and ITS-G5 stations, respectively, is not causing any significant decrease in performance.

The superframe size of 50 ms employed with semi-static Method A with the ITS-G5 packet delay enhancement is a better choice for Configuration 2.

7.3.2.5 Method C

7.3.2.5.1 Ideal TDM pattern

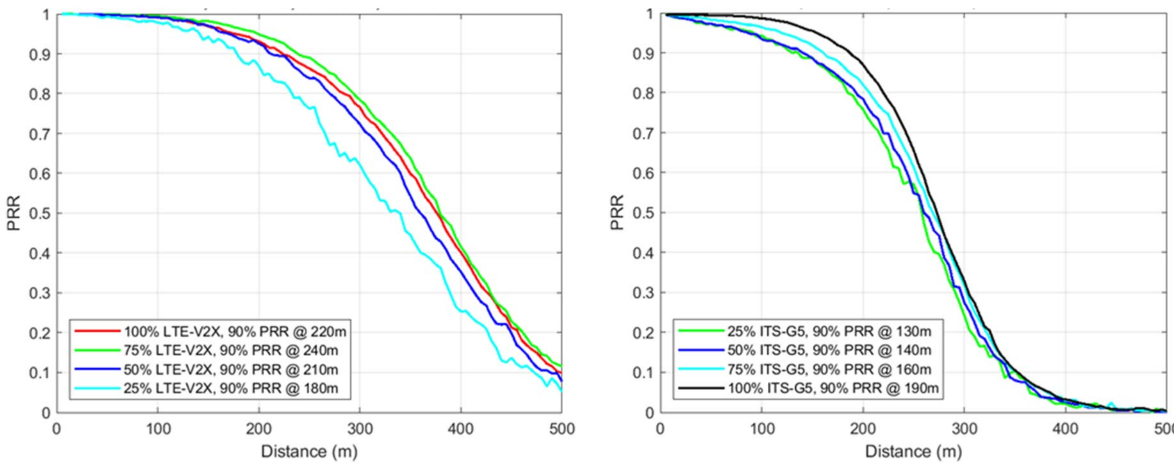
In Method C, LTE-V2X stations transmit ITS-G5 headers to signal about upcoming LTE-V2X transmissions alerting ITS-G5 stations to defer access to the channel, see Clause 6.3.3 for details. ITS-G5 stations are not aware of the superframe and its time slots, only LTE-V2X stations have this information. The simulations conducted in this clause assume that the LTE-V2X stations know the amount of stations pertaining to each technology and select their resources based on this information.

"Configuration 2" from Table 7.9 and Table 7.10 has been used together with the fast highway scenario "Scenario #2" from Table 7.6 containing 123 vehicles generating approximately. 600 packets/s/km. The time slots for each technology together with the technology mixes are tabulated in Table 7.20 and two different superframe sizes have been used, i.e. 25 ms and 50 ms.

Table 7.20: Time slots for different technology mixes

	Technology mix [%]		123 vehicles		Time slots [ms]	
Superframe size	**LTE-V2X**	**ITS-G5**	**LTE-V2X**	**ITS-G5**	**LTE-V2X**	**ITS-G5**
25 ms	0	100	0	123	5	20
	25	75	31	92	6	19
	50	50	62	61	13	12
	75	25	92	31	19	6
	100	0	123	0	20	5
Superframe size	**LTE-V2X**	**ITS-G5**	**LTE-V2X**	**ITS-G5**	**LTE-V2X**	**ITS-G5**
50 ms	0	100	0	123	5	45
	25	75	31	92	13	37
	50	50	62	61	25	25
	75	25	92	31	37	13
	100	0	123	0	45	5

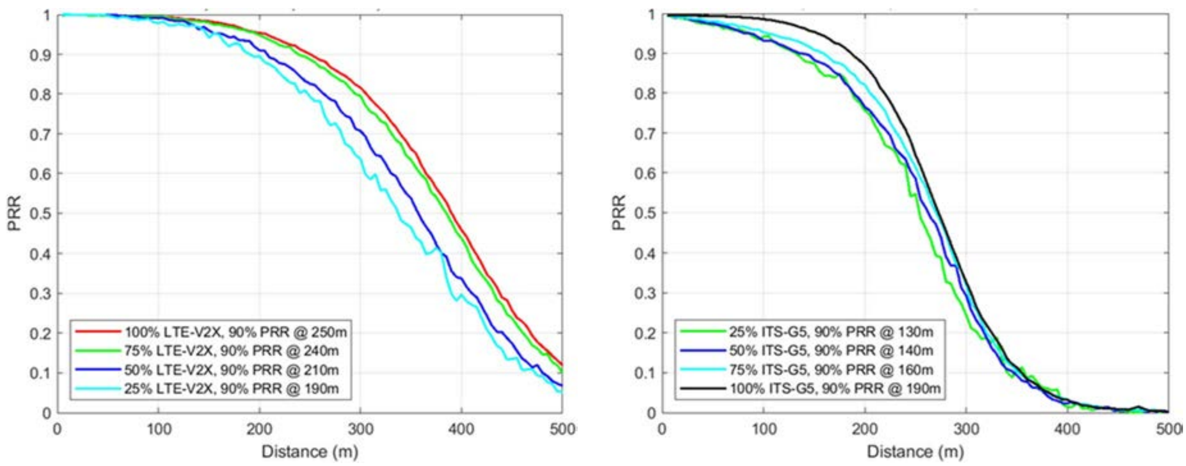
The PRR for a superframe size of 25 ms is depicted in Figure 7.32 for both technologies. When there is 100 % LTE-V2X stations on the channel, LTE-V2X needs to allocate 5 ms to ITS-G5 even if they are not present, which corresponds to 20 % of the channel resources.



(a) LTE-V2X (b) ITS-G5

Figure 7.32: PRR for Method C with superframe size 25 ms (Scenario #2 from Table 7.6)

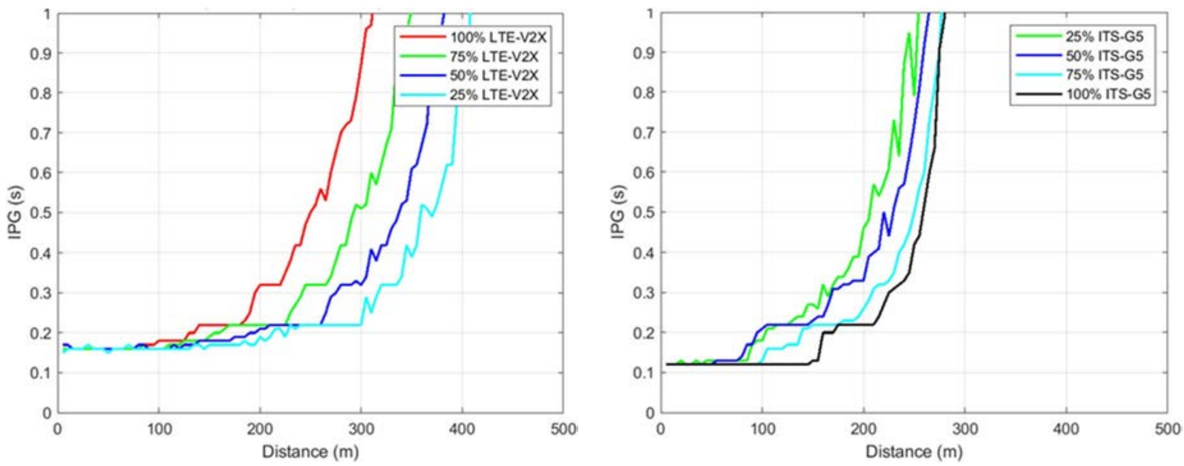
The PRR for a superframe size of 50 ms is depicted in Figure 7.33 for both technologies and the results resemble those with a superframe size of 25 ms in Figure 7.32. When there is 100 % LTE-V2X stations on the channel, LTE-V2X needs to allocate 5 ms to ITS-G5 even if they are not present, which corresponds to 10 % of the channel resources.



(a) LTE-V2X (b) ITS-G5

Figure 7.33: PRR for Method C with superframe size 50 ms (Scenario #2 from Table 7.6)

The IPG for a superframe size of 25 ms is depicted in Figure 7.34 for both technologies.



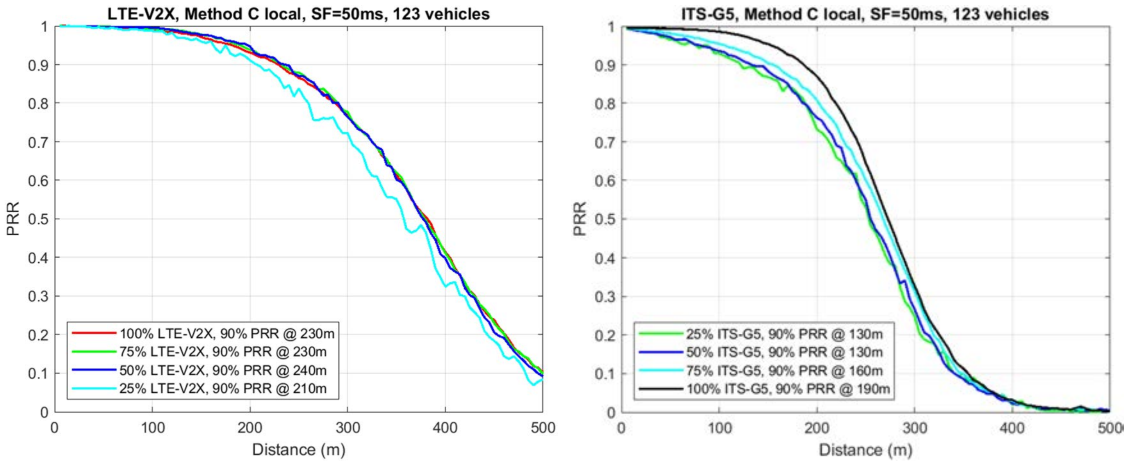
(a) LTE-V2X (b) ITS-G5

Figure 7.34: IPG for Method C with superframe size 25 ms (Scenario #2 from Table 7.6)

7.3.2.5.2 Deriving TDM pattern from local measurements

The results in this clause are using the same simulation set-up as in Clause 7.3.2.5.1 investigating the ideal TDM pattern. The simulations conducted here study the effect of local CBR assessment by LTE-V2X stations for deriving the time slot as outlined in Annex D using Option #1 in Table D.1 (i.e. the native CBR assessment used by LTE-V2X stations, e.g. deploying a decentralized congestion control mechanism). Recall that in Method C, LTE-V2X stations signal to ITS-G5 stations via a header at the beginning of the LTE-V2X transmission that the channel will be used for approximately 1 ms.

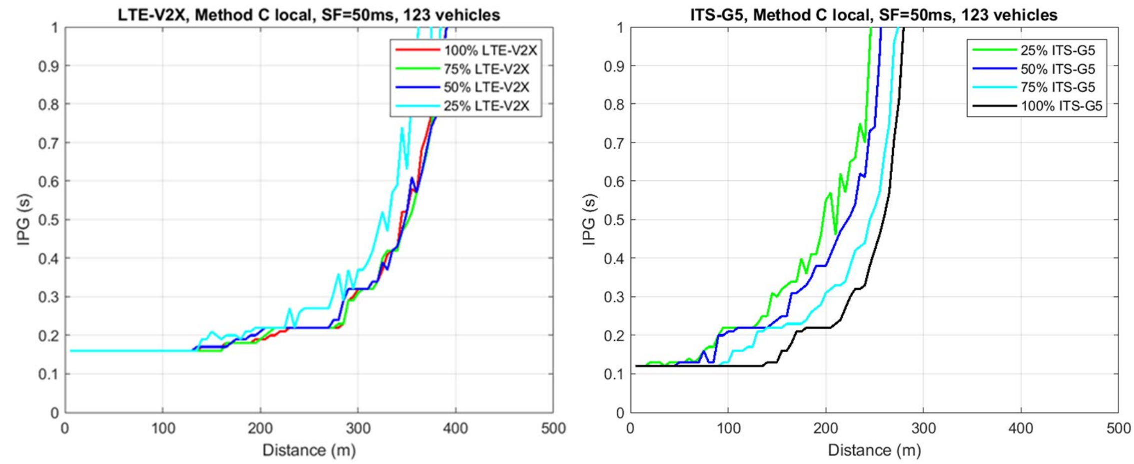
In Figure 7.35, the PRR is shown when the time slot derivation is based on local measurements by LTE-V2X stations. The results for ITS-G5 resembles those found for the ideal TDM pattern in Clause 7.3.2.5.1. For high penetration of LTE-V2X stations (75 % and 100 %) the PRR decreases when using local measurements. When there is 100 % LTE-V2X stations on the channel, LTE-V2X needs to allocate 5 ms to ITS-G5 even if they are not present, which corresponds to 10 % of the channel resources.



(a) LTE-V2X (b) ITS-G5

Figure 7.35: PRR for Method C with local measurements of CBR with superframe size 50 ms (Scenario #2 from Table 7.6)

IPG for this setting is found in Figure 7.36.



(a) LTE-V2X (b) ITS-G5

Figure 7.36: IPG for Method C with local measurements of CBR with superframe size 25 ms (Scenario #2 from Table 7.6)

7.3.2.5.3 Wrap up

ITS-G5 stations are not affected by how LTE-V2X stations derive the TDM pattern since ITS-G5 stations only react to ITS-G5 headers transmitted signalling about an immediate upcoming LTE-V2X transmission. There is a decreased performance in terms of PRR for LTE-V2X stations when deriving the TDM pattern based on local measurements when the number of LTE-V2X stations are high.

7.3.2.6 Comparison several methods

The simulations conducted on comparing several of the proposed methods were using Configuration 1 from Table 7.9 and Table 7.10. Investigated scenarios were #1, #2, #5 and #6, fetched from Table 7.6, shown for clarity also in Table 7.21. They represent four different data traffic scenarios.

Table 7.21: Average number of generated packets every second per kilometre of highway

		Scenario	No of vehicles per kilometre	Maximum speed of vehicles	Average number of generated packets/s/km
Highway	Fast	#1	35	250 km/h	350
		#2	62	140 km/h	620
	Slow	#5	333	50 km/h	1 156
		#6	500	50 km/h	1 736

The superframe size was set to 25 ms and in Table 7.22, the time slots for different technology mixes are found.

Table 7.22: Time slots for different technology mixes with a superframe size of 25 ms

Technology mix [%]		Time slots [ms]	
LTE-V2X	ITS-G5	LTE-V2X	ITS-G5
0	100	5 ms	20 ms
25	75	6 ms	19 ms
50	50	13 ms	12 ms
75	25	19 ms	6 ms
100	0	20 ms	5 ms

In Table 7.23, the number of vehicles pertaining to each technology for different scenarios and technology mixes is tabulated.

Table 7.23: Number of vehicles pertaining to each technology for different scenarios

Ideal mix [%]		Scenario #1		Scenario #2		Scenario #5		Scenario #6	
LTE-V2X	ITS-G5	LTE-V2X	ITS-G5	LTE-V2X	ITS-G5	LTE-V2X	ITS-G5	LTE-V2X	ITS-G5
0	100	0	70	0	123	0	200	0	300
25	75	18	52	31	92	50	150	75	225
50	50	35	35	62	61	100	100	150	150
75	25	52	18	92	31	150	50	225	75
100	0	70	0	123	0	200	0	300	0

Table 7.24 explains the methods simulated and their configurations. The names in Table 7.24 are used when describing the results from the simulations.

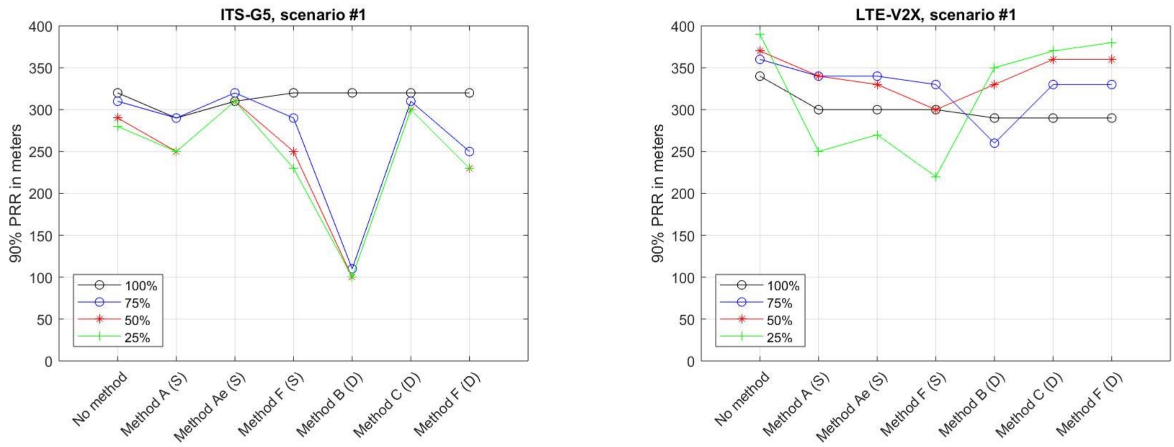
Table 7.24: Description of methods and their configurations

Name	Description
No method	Both technologies are present on the shared communication channel, but no co-existence method is deployed, i.e. LTE-V2X and ITS-G5 schedule transmissions according to their medium access control scheme, respectively.
Method A (S)	Co-channel co-existence method as described in Clause 6.3.1.1 and the time slot for each technology is known a priori to both technologies.
Method Ae (S)	Co-channel co-existence methods as described in Clause 6.3.1.1 and the time slot for each technology is known a priori to both technologies. The enhancement to ITS-G5 as described in Clause 6.3.1.5 is implemented, where ITS-G5 transmissions are artificially delayed.
Method F (S)	Co-channel co-existence method as described in Clause 6.3.6 and the time slot for LTE-V2X is known a priori. ITS-G5 stations are alerted by LTE-V2X stations about upcoming LTE-V2X transmissions through setting the NAV in CTS packets.
Method B (D)	Co-channel co-existence method as described in Clause 6.3.2 and the time slot for LTE-V2X stations is based on local measurements as outlined in Clause 6.2.2. Option #2 in Table D.1 is used for local CBR measurements by LTE-V2X stations. ITS-G5 stations are alerted by LTE-V2X stations about upcoming LTE-V2X transmissions through transmission of energy signals.

Name	Description
Method C (D)	Co-channel co-existence method as described in Clause 6.3.3 implementing Option 1 (Clause 6.3.1.2) and the time slot for LTE-V2X stations is set based on local measurements as outlined in Clause 6.2.2. Option #2 in Table D.1 is used for local CBR measurements by LTE-V2X stations. LTE-V2X stations are indicating the transmission of their packets by means of an ITS-G5 header which acts as an immediate channel reservation for LTE-V2X transmissions.
Method F (D)	Co-channel co-existence method as described in Clause 6.3.6 and the time slot for LTE-V2X stations is set based on local measurements as outlined in Clause 6.2.2. Option #2 in Table D.1 is used for local CBR measurements by LTE-V2X stations. ITS-G5 stations are alerted by LTE-V2X stations about upcoming LTE-V2X transmissions through setting the NAV in CTS packets.
NOTE: (S) behind the method name stands for that the time slot for one or both technologies are known a priori in simulations and (D) stands for that local measurements of technology penetration determine the time slot dynamically. The *a priori* information about time slot is used in simulations for emulating the different ways time slots can be achieved as outlined in Clause 6.2.2.	

Figure 7.37 to Figure 7.40 show the 90 % PRR across the simulated methods for each technology and scenario. The Y axis depicts the distance when 90 % PRR is achieved for transmissions (at shorter distances the PRR increases and at longer distances it decreases). The methods described in Table 7.24 are shown on the X axis and each figure shows ITS-G5 and LTE-V2X, respectively, for each scenario found in Table 7.23.

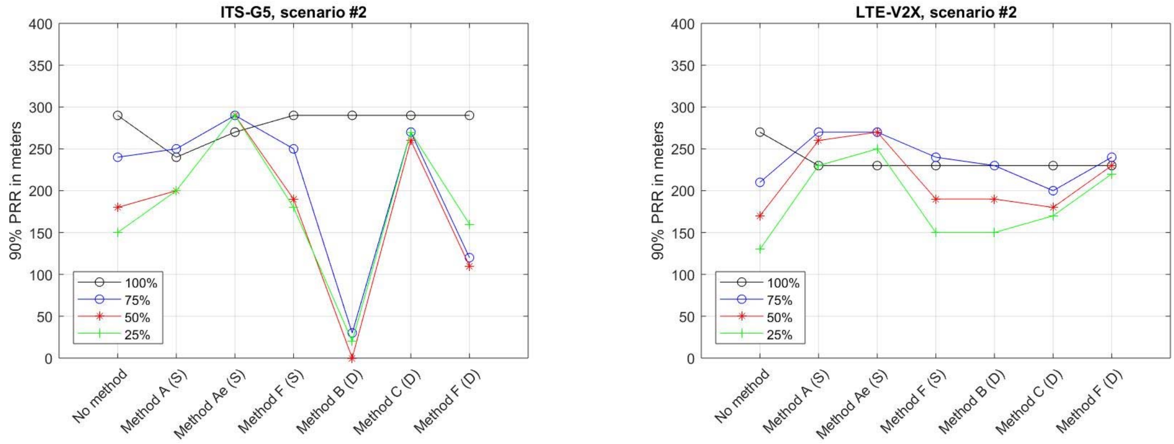
Figure 7.37 shows the 90 % PRR for Scenario #1 with 350 packets generated every second by the vehicles. The black line (100 %) in the figures show when each technology is alone. LTE-V2X stations are always aware of the superframe size and they obey to the time slot limitations, e.g. they need to allocate 5 ms to ITS-G5 out of 25 ms. Therefore, when LTE-V2X is alone on the channel employing a co-channel co-existence method there is a performance degrade due to reserving 20 % of the channel resource to ITS-G5. "Method B (D)" causes many unsuccessful packet receptions for ITS-G5 when LTE-V2X stations are present.



(a) ITS-G5 **(b) LTE-V2X**

Figure 7.37: 90 % PRR for Scenario #1 across all methods

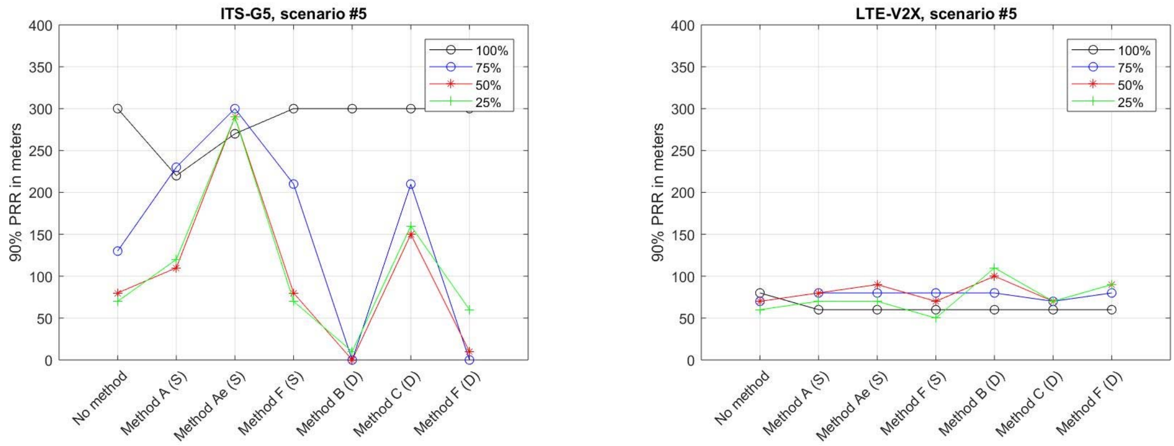
In Scenario #2 shown in Figure 7.38, approximately 600 packets are generated by the vehicles, an increase in number of packets with 75 % compared to in Figure 7.37. "Method B (D)" is an outlier for ITS-G5 causing much decoding problems.



(a) ITS-G5 **(b) LTE-V2X**

Figure 7.38: 90 % PRR for Scenario #1 across all methods

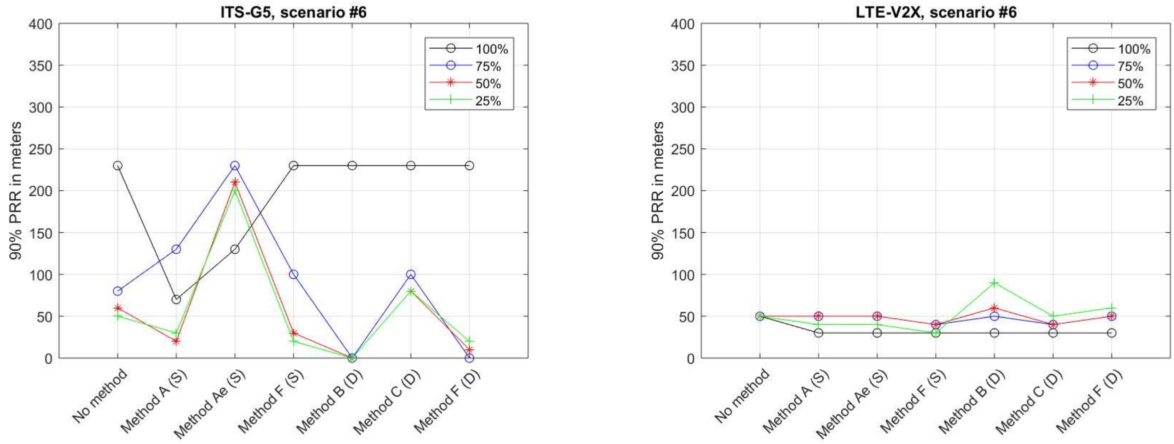
Scenario #5 almost doubles the amount of data traffic compared to Scenario #2 to approximately 1 200 packets/second for every kilometre of highway. In Figure 7.39, it is depicted that "Method Ae (S)" works best for ITS-G5. The packet duration for ITS-G5 is 500 µs and for LTE-V2X it is always 1 ms regardless of packet length in bytes. Configuration 1 of LTE-V2X does not use HARQ for speeds below 250 km/h and it uses 3 out of 5 available subchannels in a subframe of 1 ms. This configuration implies that one LTE-V2X transmission can fit into 1 ms (e.g. if 2 subchannels had been used, then two LTE-V2X transmissions could have been accommodated into 1 ms subframe). This explains the poor performance for LTE-V2X since there are more packets than time slots available in this scenario. Further, in the 100 % case for LTE-V2X, 5 ms need to be always allocated to ITS-G5 corresponding to 20 % of all resources decreasing the number of available subframes, hence, this case performs the worst.



(a) ITS-G5 **(b) LTE-V2X**

Figure 7.39: 90 % PRR for Scenario #5 across all methods

Scenario #6 is even more challenging with its 1 700 packets generated per second per kilometre road. The performance decreases further for both technologies. "Method Ae (S)" is the best option for ITS-G5 whereas none of the methods is beneficial for LTE-V2X.



(a) ITS-G5 **(b) LTE-V2X**

Figure 7.40: 90 % PRR for Scenario #6 across all methods

The average IPG across all scenarios is found in Table 7.25. "Method B (D)" causes the largest IPG for ITS-G5 and there is a larger spread among the IPG values for ITS-G5 compared to LTE-V2X.

Table 7.25: Average IPG across all scenarios

	Average IPG [s] probability > 90 %	
Name	**ITS-G5**	**LTE-V2X**
No method	0,31	0,37
Method A (S)	0,29	0,34
Method Ae (S)	0,25	0,34
Method F (S)	0,30	0,37
Method B (D)	0,46	0,34
Method C (D)	0,27	0,35
Method F (D)	0,35	0,34

The average EED across all scenarios is found in Table 7.26. "Method B (D)" causes the largest EED for ITS-G5 and there is a larger spread among the EED values for ITS-G5 compared to LTE-V2X, which is around 90 ms.

Table 7.26: Average EED across all scenarios

	Average EED [s] probability > 90 %	
Name	**ITS-G5**	**LTE-V2X**
No method	0,001	0,089
Method A (S)	0,009	0,090
Method Ae (S)	0,011	0,090
Method F (S)	0,008	0,090
Method B (D)	0,015	0,090
Method C (D)	0,001	0,089
Method F (D)	0,012	0,089

The average DA across all scenarios is found in Table 7.27. "Method B (D)" causes the largest DA for ITS-G5 and there is a larger spread among the DA values for ITS-G5 compared to LTE-V2X, which is around 40 ms.

Table 7.27: Average DA across all scenarios

	Average DA [s] probability > 90 %	
Name	**ITS-G5**	**LTE-V2X**
No method	0,31	0,42
Method A (S)	0,30	0,40
Method A/C (S)	0,26	0,40
Method F (S)	0,30	0,43
Method B (D)	0,47	0,39
Method C (D)	0,27	0,41
Method F (D)	0,36	0,40

It should be noted that IPG and DA have to be put in relation to the current generation rate of packets, whereas EED gives insights to the channel access delay.

"Method B (D)" has a poorer performance then "No method" for ITS-G5, however, when "No method" is employed LTE-V2X suffers from this. The best options for co-channel co-existence are "Method Ae (S)" followed by "Method C (D)", where the former simulation results depend on a supervising entity providing the time slots for each technology and in the latter LTE-V2X stations derives the time slot locally based on measurements. The artificial packet delay for ITS-G5 stations is also crucial to the performance of Method A. Configuration 1 for LTE-V2X, when only one transmission can be fitted into a subframe of 1 ms, is sub-optimal for the high-density vehicle scenarios (i.e. Scenario #5 and Scenario #6) when studying the PRR results.

7.3.2.7 Co-channel co-existence with legacy ITS-G5 stations

The simulations performed herein study the impact of some of the methods when legacy ITS-G5 stations are present that do not implement a co-channel co-existence method per se. Configuration 1 has been used from Table 7.9 and Table 7.10. Investigated scenarios were #1, #2, #5 and #6, fetched from Table 7.6, shown for clarity also in Table 7.28. They represent four different data traffic scenarios.

Table 7.28: Average number of generated packets every second per kilometre of highway

		Scenario	No of vehicles per kilometre	Maximum speed of vehicles	Average number of generated packets/s/km
Highway	**Fast**	#1	35	250 km/h	350
		#2	62	140 km/h	620
	Slow	#5	333	50 km/h	1 156
		#6	500	50 km/h	1 736

The superframe size was set to 25 ms and in Table 7.29, the time slots for different technology mixes are found.

Table 7.29: Time slots for different technology mixes with a superframe size of 25 ms

Technology mix [%]		Time slots [ms]	
LTE-V2X	**ITS-G5**	**LTE-V2X**	**ITS-G5**
0	100	5 ms	20 ms
25	75	6 ms	19 ms
50	50	13 ms	12 ms
75	25	19 ms	6 ms
100	0	20 ms	5 ms

In Table 7.30, the number of vehicles pertaining to each technology for different scenarios and technology mixes is tabulated.

Table 7.30: Number of vehicles pertaining to each technology for different scenarios

Ideal mix [%]		Scenario #1		Scenario #2		Scenario #5		Scenario #6	
LTE-V2X	ITS-G5	LTE-V2X	ITS-G5	LTE-V2X	ITS-G5	LTE-V2X	ITS-G5	LTE-V2X	ITS-G5
0	100	0	70	0	123	0	200	0	300
25	75	18	52	31	92	50	150	75	225
50	50	35	35	62	61	100	100	150	150
75	25	52	18	92	31	150	50	225	75
100	0	70	0	123	0	200	0	300	0

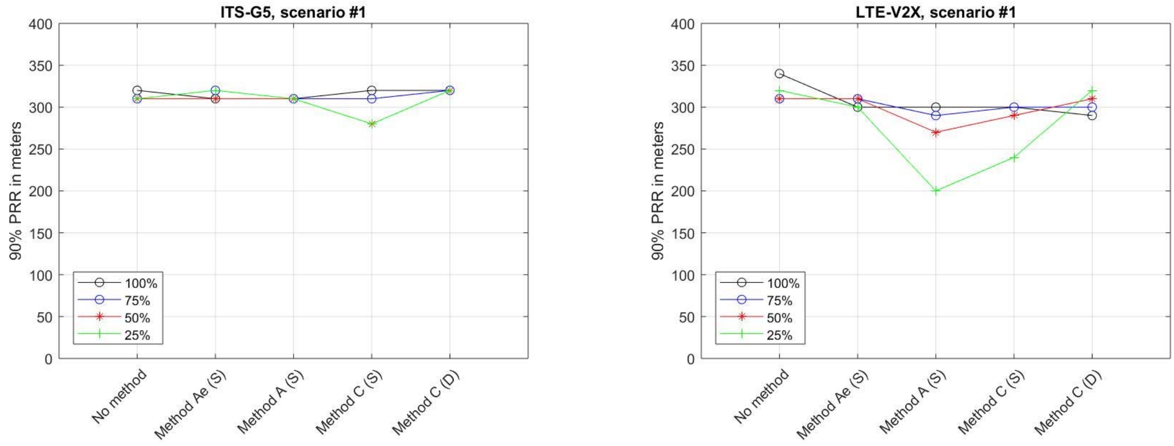
Table 7.31 explains the methods simulated and their configurations. The names in Table 7.31 are used when describing the results from the simulations.

Table 7.31: Description of methods and their configurations

Name	Description
No method	Both technologies are present on the shared communication channel but no co-existence method is deployed, i.e. LTE-V2X and ITS-G5 schedules transmissions according to their medium access control scheme, respectively.
Method Ae (S)	Co-channel co-existence method as described in Clause 6.3.1.1. The time slot for each technology is known a priori to both technologies. The enhancement to ITS-G5 as described in Clause 6.3.1.5 is implemented, where ITS-G5 transmissions are artificially delayed.
Method A (S)	Co-channel co-existence method as described in Clause 6.3.1.1 and the time slot for LTE-V2X is known a priori*. ITS-G5 stations do not employ Method A and they are not aware of superframe or time slots*. As a consequence, LTE-V2X stations will be confined to transmit during their allocated time slot. ITS-G5 stations are allowed to transmit at any time instance, following only their CSMA/CA scheme.
Method C (S)	Co-channel co-existence method as described in Clause 6.3.3 using Option 1 outlined in Clause 6.3.3.2 and the time slot for LTE-V2X is known a priori. ITS-G5 stations do not employ Method C and they are not aware of superframe or time slots. *LTE-V2X stations are indicating the transmission of their packets by means of an ITS-G5 header which acts as an immediate channel reservation.*
Method C (D)	Co-channel co-existence method as described in Clause 6.3.3 using Option 1 outlined in Clause 6.3.3.2 and local measurements by LTE-V2X stations determine the time slot size. Option #2 in Table D.1 is used for local CBR measurements by LTE-V2X stations. ITS-G5 stations do not employ Method C and they are not aware of superframe or time slots. *LTE-V2X stations are indicating the transmission of their packets by means of an ITS-G5 header which acts as an immediate channel reservation.*
NOTE: (S) behind the method name stands for that the time slot for one or both technologies is known a priori in simulations and (D) stands for that local measurements of technology penetration determine the time slot dynamically. The *a priori* information about the time slot is used in simulations for emulating the different ways time slots can be achieved as outlined in Clause 6.2.2.	

Figure 7.41 to Figure 7.44 show the 90 % PRR across the simulated methods for each technology and scenario (the same figure set as in Clause 7.3.2.6). The Y axis depicts the distance when 90 % PRR is achieved for transmissions (at shorter distances the PRR increases and at longer distances it decreases). The methods described in Table 7.31 are shown on the X axis and each figure show ITS-G5 and LTE-V2X, respectively, for each scenario found in Table 7.30.

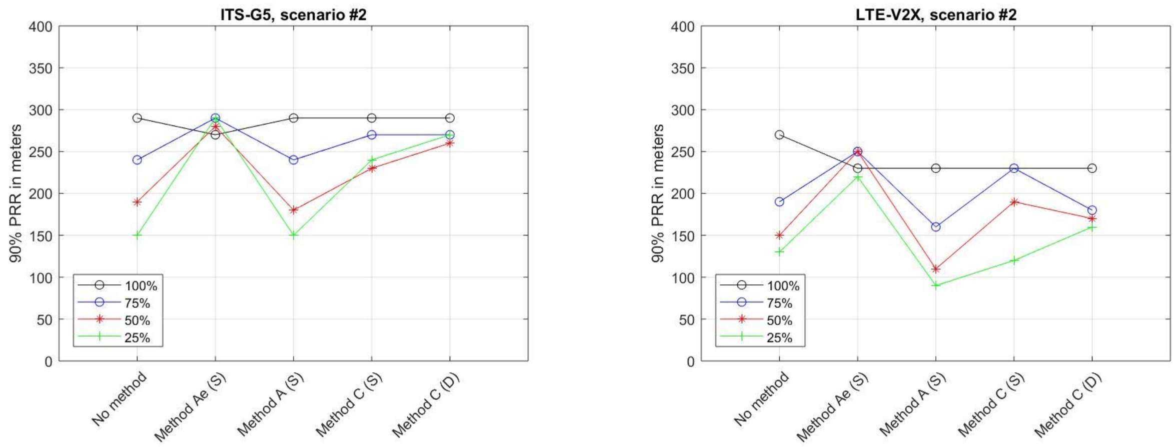
The 90 % PRR in metres for Scenario #1 is depicted in Figure 7.41. This is the scenario which is less congested from a data traffic point of view. The black line (100 %) in the figures show when each technology is alone. In "Method A (S)", when there are few LTE-V2X stations (i.e. 25 %), LTE-V2X suffers from interference created by ITS-G5 stations which are in majority (75 %) since ITS-G5 stations are not aware of the TDM scheme. The two implementations of "Method C (S)/(D)" provide better performance for LTE-V2X compared to "Method A (S)" due to that ITS-G5 stations are alerted about upcoming LTE-V2X transmissions.



(a) ITS-G5 **(b) LTE-V2X**

Figure 7.41: 90 % PRR for Scenario #1 across all methods

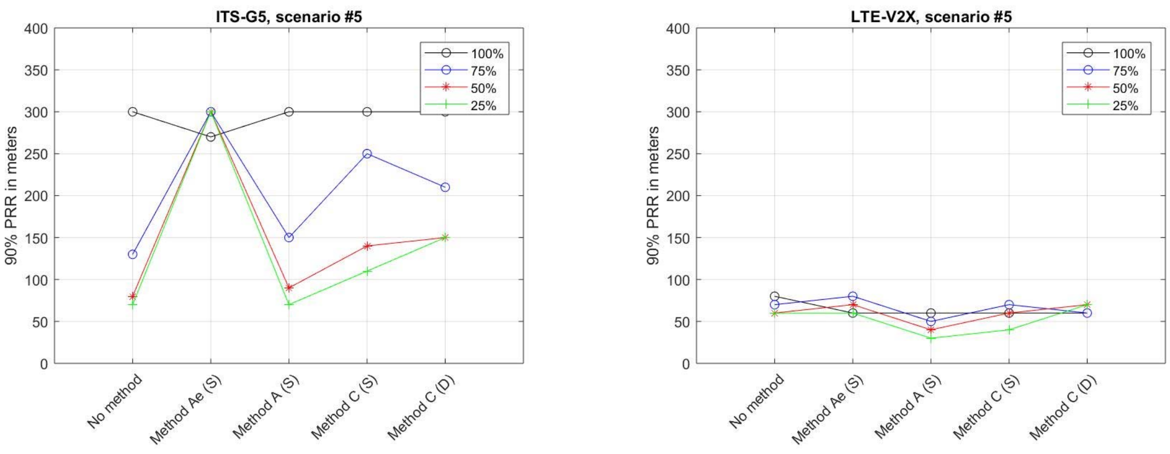
In Scenario #2 shown in Figure 7.42, approximately 600 packets are generated by the vehicles, an increase in number of packets with 75 % compared to in Figure 7.41. In "Method Ae (S)", ITS-G5 stations are aware of superframe and time slots and the PRR for both technologies are close to the performance compared to when a single technology is present on the channel. When looking into "Method A (S)", "Method C (S)", and "Method C (D)", both experience performance degradation when there are few stations of either of the two technologies (green line in both figures).



(a) ITS-G5 **(b) LTE-V2X**

Figure 7.42: 90 % PRR for Scenario #1 across all methods

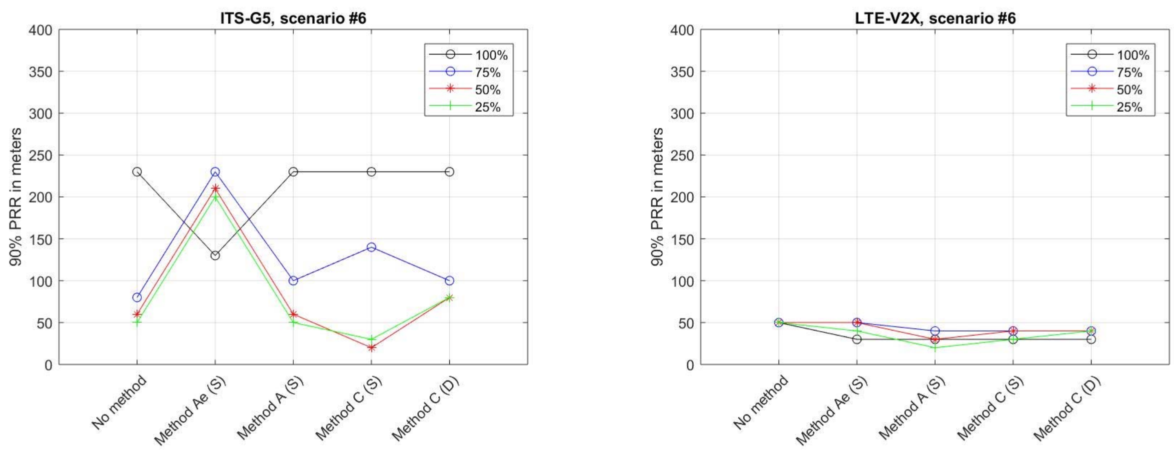
Scenario #5 almost doubles the amount of data traffic compared to Scenario #2 to approximately 1 200 packets/second for every kilometre of highway. In Figure 7.43, it is clearly depicted that "Method A/C (S)" when ITS-G5 stations are aware of time slots have the best performance for ITS-G5. The packet duration for ITS-G5 is 500 µs and for LTE-V2X it is always 1 ms regardless of packet length in bytes. Configuration 1 of LTE-V2X does not use HARQ for speeds below 250 km/h and it uses 3 out of 5 available subchannels in a subframe of 1 ms. This configuration implies that one LTE-V2X transmission can fit into 1 ms (e.g. if 2 subchannels had been used, then two LTE-V2X transmissions could have been accommodated into 1 ms). This explains the poor performance for LTE-V2X since there are more packets than time slots available in this scenario. Further, in the 100 % case for LTE-V2X 5 ms has to be always allocated to ITS-G5 corresponding to 20 % of all resources decreasing the number of available subframes, hence, this case performs the worst.



(a) ITS-G5 (b) LTE-V2X

Figure 7.43: 90 % PRR for Scenario #5 across all methods

Scenario #6 is even more challenging with its 1 700 packets generated per second. The performance decreases further for both technologies.



(a) ITS-G5 (b) LTE-V2X

Figure 7.44: 90 % PRR for Scenario #6 across all methods

The average IPG across all scenarios is found in Table 7.32. There is a slightly larger spread among the IPG values for LTE-V2X compared to ITS-G5.

Table 7.32: Average IPG across all scenarios

	Average IPG [s] probability > 90 %	
Name	**ITS-G5**	**LTE-V2X**
No method	0,34	0,38
Method A/C (S)	0,25	0,34
Method A (S)	0,32	0,46
Method C (S)	0,32	0,36
Method C (D)	0,28	0,34

The average EED across all scenarios is found in Table 7.33. "Method A/B (S)", when ITS-G5 also employs a co-existence method, causes the largest EED for ITS-G5. LTE-V2X has a stable value of 90 ms.

Table 7.33: Average EED across all scenarios

	Average EED [s] probability > 90 %	
Name	**ITS-G5**	**LTE-V2X**
No method	0,001	0,090
Method A/C (S)	0,013	0,090
Method A (S)	0,001	0,090
Method C (S)	0,008	0,090
Method C (D)	0,002	0,090

The average DA across all scenarios is found in Table 7.34.

Table 7.34: Average DA across all scenarios

	Average DA [s] probability > 90 %	
Name	**ITS-G5**	**LTE-V2X**
No method	0,34	0,43
Method A/C (S)	0,25	0,39
Method A (S)	0,33	0,50
Method C (S)	0,32	0,42
Method C (D)	0,28	0,40

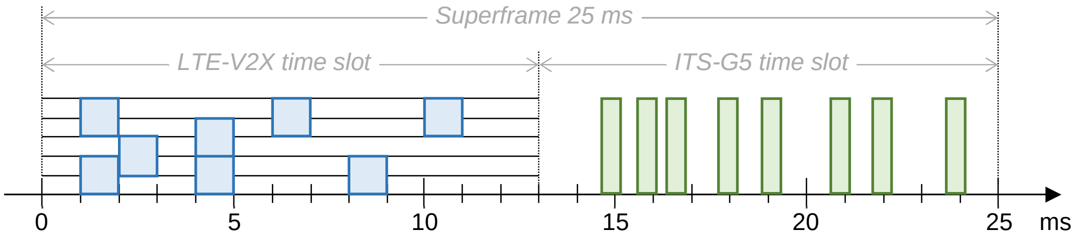
It should be noted that IPG and DA have to be put in relation to the current generation rate of packets, whereas EED gives insights to the channel access delay.

Method C can be deployed together with legacy ITS-G5 inherently but performance increases if ITS-G5 has knowledge about superframe and time slots of course. Dynamic selection of resources in Method C (D) can sometimes be a better choice than static configuration, given that Option #2 from Table D.1 is used (it should be noted that this requires decoding of ITS-G5 headers by LTE-V2X stations).

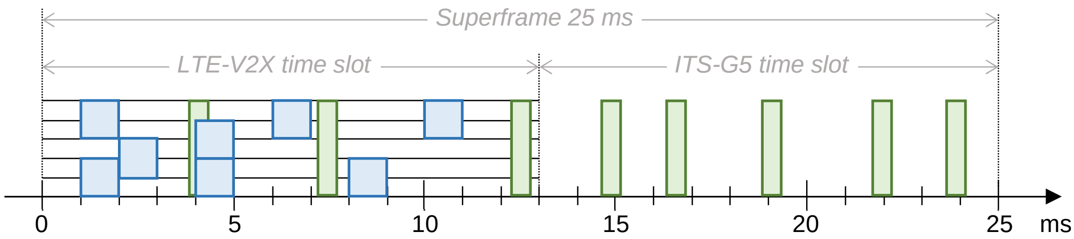
7.3.2.8 Summary simulation results

Focus on simulations have mostly been on Method A and Method C with enhancements and additions. In Method A, LTE-V2X stations and ITS-G5 stations are both aware of the superframe and timeslot for each technology, whereas in Method C only LTE-V2X stations have this knowledge and they signal to ITS-G5 stations about upcoming LTE-V2X transmissions through ITS-G5 header insertion.

Enhancements have been made to Method A to combat that ITS-G5 stations might rush to the channel when it is their timeslot used for transmissions. An artificial packet delay mechanism is introduced to ITS-G5 stations to spread out transmissions over time. Method A has a better performance in terms of PRR than Method C when studying the results in Clause 7.3.2.4 and Clause 7.3.2.5, respectively. These simulations both used Configuration 1 where HARQ is always turned on for LTE-V2X and 2 subchannels out of 5 subchannels are used for transmissions in a subframe. The better performance of Method A is due to that in Method C, ITS-G5 stations are not aware of the LTE-V2X time slot and can start transmissions in unoccupied subframes of the LTE-V2X timeslot when using Method C Option 1 outlined in Clause 6.3.3.2. In Figure 7.45, an illustration of the differences between Method A and Method C Option 1 is depicted. Figure 7.45(a) shows Method A where ITS-G5 stations are aware of their time slot and they are only using this for transmissions. Method C is illustrated in Figure 7.45(b) where ITS-G5 transmissions might occur during the LTE-V2X time slot due to unoccupied subframes.



(a) Method A



(b) Method C Option 1

Figure 7.45: Illustration of packet transmissions for Method A and Method C Option 1 given a superframe of 25 ms with equal time slot distribution

Simulation results for Method C Option 1 comparing the ideal TDM pattern provided a priori with conducting local measurements for deriving the TDM pattern were performed in Clause 7.3.2.5.1 and Clause 7.3.2.5.2, respectively. The performance difference between these two approaches was small. The local measurements performed by LTE-V2X stations was using Option #1 in Table D.1.

Method A and Method C are also performing the best when studying several of the proposed methods in Clause 7.3.2.6. Method B was an outlier for all scenarios simulated for ITS-G5 stations providing poor performance in terms of successful packet reception rate compared to the other methods. Method C was simulated both when the time slot was known a priori to LTE-V2X stations (called Method C (S)) and when it was derived based on local measurements by LTE-V2X stations (called Method C (D)). The local measurements used Option #2 from Table D.1, which requires LTE-V2X stations to also decode parts of the ITS-G5 header to estimate the occurrences of ITS-G5 stations.

Results for when LTE-V2X stations exercise a co-channel co-existence method when there are legacy ITS-G5 stations were presented in Clause 7.3.2.8. For scenarios containing low data traffic volume (i.e. Scenario #1 in Table 7.6), there is hardly any difference between the different methods (this applies also to the results in Clause 7.3.2.6). Method C Option 1 has the best performance in terms of PRR when legacy ITS-G5 stations are present and when the data traffic volume increases.

Method C also comes with Option 2 as outlined in Clause 6.3.3.3, where LTE-V2X stations make reservations through the ITS-G5 header for longer time intervals. This option aims at informing ITS-G5 stations about the start of their time slot to avoid ITS-G5 transmissions in unused subframes of the LTE-V2X time slot (see Figure 7.45(b)). When ITS-G5 stations have the knowledge about the start of their time slot, they can also deploy the possibility of spreading out transmissions over time in their time slot as deployed by Method A and described in Clause 6.3.1.5. Method C Option 2 has not been simulated but the results will be similar of those to Method A enhanced with artificial packet delay for ITS-G5. The implementation of these two approaches are different, where the former requires ITS-G5 to have a priori knowledge about time slot size, while the latter requires LTE-V2X to continuously transmit ITS-G5 headers.

The most influential KPI for evaluating the methods is PRR providing an indication at what distances vehicles will "detect" each other. The 90 percentile EED provides insight to channel access delay and for LTE-V2X this delay is more or less constant throughout all scenarios (around 90 ms) due to the deterministic scheduling of transmissions in the future. For ITS-G5, EED will increase from 1 ms up to 15 ms on average across all scenarios since ITS-G5 is a reactive protocol and searches for resources once a packet is ready for transmission. IPG and DA are similar KPIs capturing lost packets in addition. These needs to be studied in relation to the CAM generation rate (lower rate results in longer IPG and DA by default). IPG measures the time between two successful receptions of packets for a specific TX-RX pair and DA includes also the EED. The IPG and DA results do not differ tremendously between the different methods or scenarios.

8 Conclusions

The present document studies the possibilities for ITS-G5 and LTE-V2X to share a common communication channel in the same geographical area. Typically, co-channel co-existence between different wireless technologies on a shared frequency channel will be less spectral efficient compared to when a single technology is present. The medium access control scheme of wireless technologies is responsible for scheduling transmissions on the shared channel to minimize interference between co-located transmitters of the same technology. Sharing of a common resource can take place in time, frequency, and space domain.

The studied technologies for co-channel co-existence are ITS-G5 based on IEEE 802.11 through the enrolled amendment IEEE 802.11p and LTE-V2X mode 4 developed by 3GPP (introduced in Release 14), both support ad hoc communication in the vehicular domain (V2X communication). These two technologies differ first and foremost on how they access the channel, i.e. medium access control. In ITS-G5, stations listen to the channel for a predetermined listening period before packet transmission to determine if the channel is busy or not. If not busy, the station will transmit directly and if busy, it will defer access for a randomized period of time which is decremented as long as the channel is not busy carrying a transmission. Given a specific coding and modulation scheme, the transmission duration will vary in time depending on packet size. ITS-G5 uses the channel bandwidth for transmissions. LTE-V2X on the other hand, relies on the scheduling of transmissions in a synchronous network, and divides the channel into subframes of 1 ms and within each subframe one or several packets can be transmitted, occupying a subset of the available frequency resources. Varying packet sizes will use more or less frequency resources inside a subframe given a specific modulation and coding scheme. Stations using LTE-V2X will keep track of used subframes, measure the energy of all frequency resources and schedule transmissions into the future based on what has happened in the past. LTE-V2X accesses the channel in the scheduled resources and indicates future reservations in the control information of each transmission. Due to the differences in scheduling packet transmissions, there will be interference between the two technologies when the number of stations and data traffic increases if both are present on the same channel within a certain geographical, i.e. ITS-G5 will cause interference to LTE-V2X and vice versa.

Seven different co-channel co-existence methods are included in the present document and focus on simulations have predominantly been on Method A and Method C. A TDM scheme has been proposed for sharing the channel resources in the time domain since ITS-G5 does not possess the possibility of sharing in the frequency domain. The TDM scheme consists of a superframe containing two time slots, one for each technology. The idea is to vary the duration of time slots inside a fixed-size superframe (e.g. 25 ms, 50 ms) given the current technology penetration. In a real-world deployment, the superframe size will be fixed and the time slot duration for each technology will vary. The retrieval of the time slot division between technologies (e.g. the TDM pattern) can be performed either outside the stations and then signalled to the stations or it can be assessed locally inside the stations. The time slot assessment carried out outside stations have not been investigated but several approaches on how this can be performed is found in Clause 6.2.2. In simulations, the time slot division has been set a priori to the stations for this case and in some simulations a mismatch between the a priori division and the ideal division has been investigated. The local assessment for deciding upon time slot division has been performed in simulations.

It should be noted that the evaluation of methods has been performed using CAM triggered based on vehicle dynamics. DENM and upcoming message types such as collective perception and manoeuvre coordination have not been studied in conjunction with the methods.

In Method A, ITS-G5 stations and LTE-V2X stations are aware of time slot durations for each technology (i.e. stations are instructed from the outside about the division and set a priori in simulations). In this approach, stations are confined to transmit in their time slot belonging to either technology avoiding overlapping transmissions between technologies. There is always 5 ms allocated to each technology in the superframe for guaranteeing that they can enter the channel. For short superframe duration, e.g. 10 ms, this is a waste of resources when only one technology is present on the channel. Longer superframe duration is preferred (e.g. 25 ms, 50 ms) to minimize waste. To avoid ITS-G5 stations rushing to the channel in their time slot, an artificial delay of packets is introduced to increase the performance. Both technologies need to be changed for implementing this approach.

Method C "Option 1" requires LTE-V2X stations to keep track of time slots and ITS-G5 is informed about an immediate LTE-V2X transmission through ITS-G5 header insertion in the beginning of a subframe, but are not aware of the underlying TDM pattern, not even of the fact that the channel is shared with another technology. LTE-V2X stations assess the current penetration of technology locally using CBR and hence determines the time slot locally. It is still possible for ITS-G5 to transmit during unused subframes belonging to the time slot of LTE-V2X. Like in Method A, there is always 5 ms allocated to ITS-G5 in this approach in the superframe even though no ITS-G5 stations are present. This approach requires changes to LTE-V2X while nothing needs to be changed on ITS-G5 side (it can work with already deployed ITS-G5 stations). There is a second option for Method C ("Option 2"), where ITS-G5 stations are aware of the superframe structure but determine their time slot based on information received in the ITS-G5 header relayed by LTE-V2X stations. This requires also that ITS-G5 stations are aware of the superframe size and that LTE-V2X stations are aware of time slot durations for each technology. Hence the LTE-V2X time slot needs to be determined outside of the LTE-V2X stations and signalled to the LTE-V2X stations which, in turn, inform ITS-G5 stations about the current time slot division through ITS-G5 header insertion. Both technologies need to be changed for implementing this option.

Method D and Method E require LTE-V2X stations to be equipped also with ITS-G5 radios to signal the presence of LTE-V2X stations to ITS-G5 stations. This has not been further studied in the present document. Method B and Method F have been simulated but provided a significant performance degradation for ITS-G5 compared to what was achieved with Method A and Method C. Method B, Method D, Method E, Method F and Method G all require changes to LTE-V2X and ITS-G5 to a varying degree.

Method A and Method C are the two most promising approaches for co-channel co-existence between ITS-G5 and LTE-V2X in the same geographical area given the simulation results. The former requires changes to both technologies and that the time slot for each technology is provided from the outside to the stations. The latter requires only changes to LTE-V2X when implementing "Option 1" and the LTE-V2X time slot size is determined locally using CBR assessment. "Option 2" of Method C requires changes to ITS-G5 also and that LTE-V2X stations receive the time slot configuration from outside (not assessed locally). The changes to LTE-V2X required by Method C imply a modification to the physical layer design of LTE-V2X, thus resulting in a broader impact on LTE-V2X compared to Method A. Simulation results for Method A show on average a slight advantage in the packet error rate performance compared to Method C "Option 1" for both technologies. Overall, having two technologies sharing the same channel will always come at the expense of performance.

Co-channel co-existence between LTE-V2X and ITS-G5 requires changes to one or both technologies. The complexity involved in changing technologies boils down to how, e.g. technologies have been implemented in the first place, and it is difficult to estimate the changes required based on simulation results.

Technologies evolve and there are activities in both IEEE as well as in 3GPP for further developing V2X technologies. 5G-NR V2X uses a similar channel access mechanism procedure as LTE-V2X. The same goes for IEEE 802.11bd, the successor to IEEE 802.11p, which uses the same channel access mechanism procedure. To this end, some of the co-channel co-existence mechanisms described in the present document might be valid for these two new technologies. However, further considerations and analysis would be needed to evaluate the effectiveness of those methods in the context of advanced use cases.

Annex A: Detailed description of the ITS-G5 header insertion

A.1 Introduction

There are two ways of introducing the ITS-G5 PHY header and these can be combined. The first option is to insert the PHY header in the last symbol of the previous LTE-V2X subframe by the LTE-V2X stations that wants to send a new packet in a given subframe. This would not need any additional radio resources and would still allow the switching between TX and RX within around 30 µs (instead of the full symbol duration of 71 µs). The purpose of the LTE V2X guard symbol is to accommodate the TX/RX switching and to manage propagation delays, since sidelink packets are not necessarily arriving synchronized. The guard symbol enables ITS-S to receive a subframe/TTI right after transmitting one. Filling this guard symbol partly with another transmission is not foreseen in the current 3GPP Release 14. Therefore, further investigations on the impact of such a design change are necessary.

The second option for inserting the ITS-G5 PHY header is in the first symbol of the current LTE-V2X subframe since the first OFDM symbol of an LTE V2X subframe does not carry any data and is only used for the Automatic Gain Control (AGC) calibration process, it could also be used for inserting the ITS-G5 header plus a signal field. Like the guard symbol, this possibility needs to be investigated, and using this first OFDM symbol is not foreseen in the current 3GPP release 14. Indeed, the first symbol can still be used by LTE to carry data, so an impact on capacity should be investigated.

For the reservation of a fixed length time slot (for LTE-V2X e.g. 1 ms subframe), the ITS-G5 PHY header can be "prerecorded" and no additional computational effort is necessary. The ITS-G5 PHY header SIGNAL can be delivered to the upconverter by the same digital to analogue converter as the LTE signal. The use of fixed "prerecorded" ITS-G5 headers has also the advantage that when several LTE V2X users want to use the same subframe (frequency division multiplex) they transmit the same ITS-G5 header information, and therefore do not interfere with each other.

The method does not foresee that the other technology implements a communication stack of ITS-G5. Just the ITS-G5 header signal is transmitted, which can be a prerecorded list of analogue samples. No reception of ITS-G5 signals is foreseen. This implies that the other technology does not necessarily sense when the channel is already used by an ITS-G5 transmitter. In case the other technology is accessing the channel while the channel is used by an ITS-G5 transmitter, interference can occur.

The ITS-G5 header is encoded as per the ETSI specifications ETSI EN 302 663 [i.2]. The ITS-G5 header includes the following components: L-STF (16 µs), L-LTF (16 µs) and L-SIG (8 µs), see Figure 17-5 in IEEE 802.11-2020 [i.3] when using 10 MHz channels.

As shown in Figure 17-5 in IEEE 802.11-2020 [i.3], the signal field symbol (L-SIG) carries 4 bits of information about the modulation coding scheme (referred to as the rate in IEEE terminology) and 12 bits of information about the payload length (which ranges from 0 - 4 095 bytes). There is also 1 reserved bit "R", 1 parity bit "P" and 6 bits for the signal tail. From these 2 fields, the receiving ITS-G5 stations derive the duration of the message. The transmit rate should be one of the mandatory rates supported by ITS-G5 stations. This includes for example "BPSK ½ 3 Mbps" and "QPSK ½ 6 Mbps". Then, the payload size can be set to specific number of bytes to mean a specific duration.

Figure A.1 shows details on the header insertion when sent at the beginning of the LTE-V2X subframe.

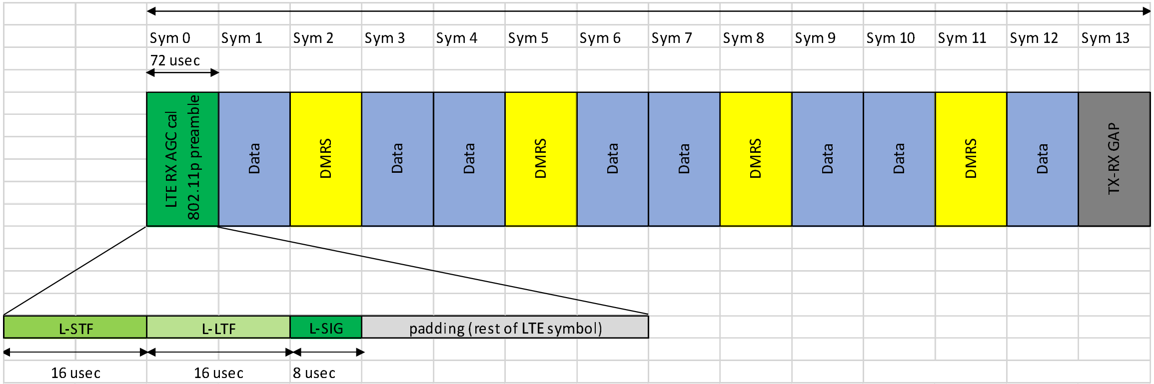


Figure A.1: LTE-V2X data subframe, with 1st symbol used for ITS-G5 header

For use in the context of co-channel co-existence, there are two possible ways to configure the L-SIG information to be transmitted by the LTE-V2X stations.

A.2 Option 1 - configuration of L-SIG information

The first option is to configure the rate and length to indicate a duration of (slightly more than) 1 ms. In this configuration the ITS-G5 header can be viewed as an immediate reservation of 1 ms, solely covering the needs of the present LTE-V2X subframe. This configuration allows ITS-G5 stations to potentially use the empty LTE-V2X subframes (although risking a collision in subsequent LTE-V2X subframes). As described in Clause 6.3.3 Method C, it does not require ITS-G5 stations to be aware of the existence of the superframe and time slot sizes.

This is most likely the natural setting when using "Method C" and "Option 1" described in Clause 6.3.3.2.

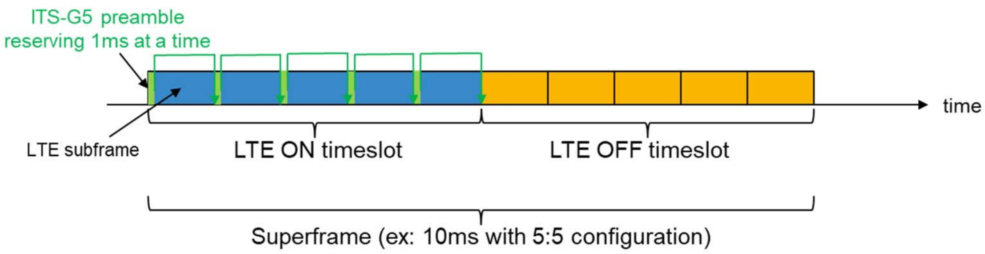


Figure A.2: ITS-G5 header insertion, immediate reservation of 1 ms

In this first configuration, it is proposed that the encoded packet duration is 1,008 ms. The rationale for the additional 8 µs is to have a small additional margin (the minimum granularity is 1 ITS-G5 symbol) to cover for propagation time (the gap might appear slightly larger than 72 µs in case of the first subframe being sent by a LTE-V2X station located closely to the ITS-G5 receiving station while the subsequent LTE-V2X subframe is sent by a LTE-V2X station located far away. In order to code for 1,008 ms, the PSDU DATA field size can be encoded as "720 bytes". The proposed preamble is sampled at 10 MSPS.

Figure A.3 shows the ITS-G5 header (time domain view) sampled at 10 MSPS, for this first configuration.

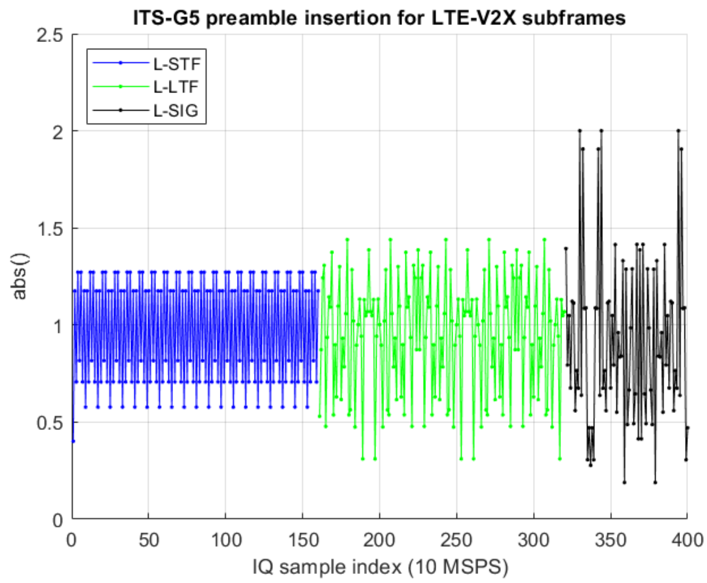


Figure A.3: ITS-G5 header (time domain view) sampled at 10 MSPS

A.3 Option 2 - configuration of L-SIG information

The second option is to configure the rate and length to indicate the time remaining until the end of the current the LTE-V2X time slot. In this configuration the ITS-G5 header can be viewed as a longer reservation covering the needs of the present LTE-V2X subframe, and of the subsequent LTE-V2X subframes within the current LTE-V2X time slot. This configuration forbids ITS-G5 stations to use the empty LTE-V2X. In this configuration, all LTE-V2X stations have to follow the same TDM pattern, in order to ensure that different stations would be sending consistent information via the ITS-G5 header. This configuration can thus only work in a static or semi-static configuration for LTE-V2X and is not compatible with dynamically changing of the TDM partitions based on local measurements as outlined in Clause 6.3.2.2 and in Clause A.2.

This configuration is used with Option 2 of Method C outlined in Clause 6.3.3.3. It should be noted that within a given subframe, all LTE-V2X stations will issue the same ITS-G5 header content.

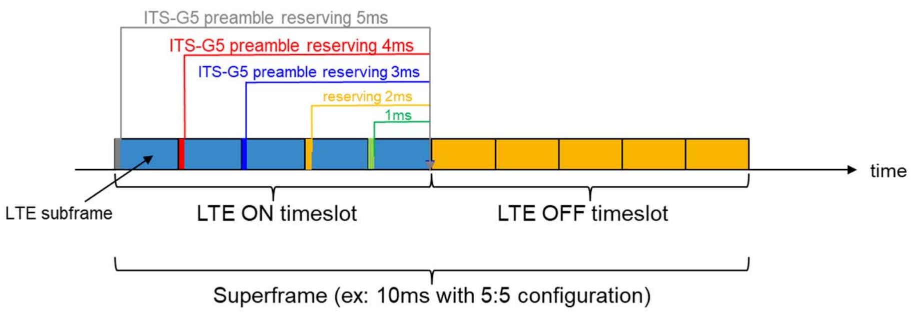


Figure A.4: ITS-G5 header insertion: reservation until the end of current LTE-V2X time slot

The maximum packet duration which can be instructed by (rate, length) is 10,98 ms with (BPSK ½, 4 095 bytes), thus having all the required granularity for superframes of 11 ms or less, since durations of 1, 2, 3,…, 10 ms can be accommodated.

It should be noted that ETSI EN 302 571 [i.34] limits the duration of "real" ITS-G5 packets to 4 ms, but most likely this limitation does not apply here.

For superframes ≥ 11 ms, such as 20 ms, a slightly different scheme is defined, considering a maximum duration of 10 ms that can be instructed by the ITS-G5 header. The packet duration indicating the time remaining until the end of the current the LTE-V2X time slot is upper-bounded to 10 ms. Figure A.5 shows an example with a superframe of 20 ms, in a 15:5 configuration. The first 6 LTE-V2X subframes contain a header indicating a duration of 10 ms, while for the subsequent LTE-V2X subframes the duration is decreasing towards 1 ms (9, 8, … 1 ms).

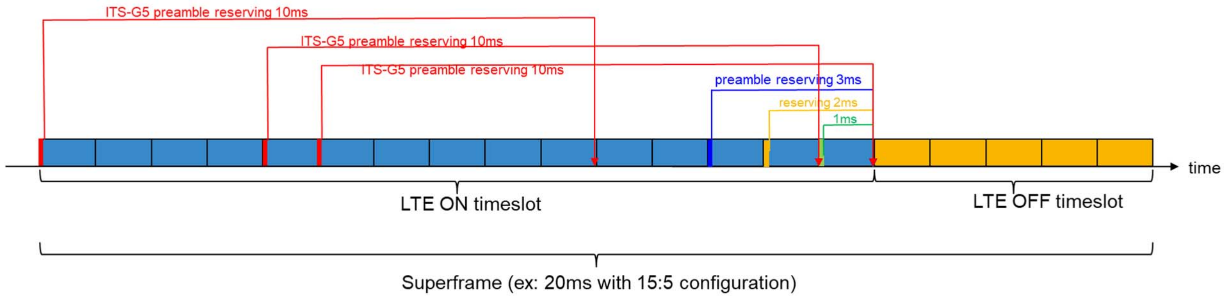


Figure A.5: ITS-G5 header insertion: reservations until the end of current LTE-V2X time slot, superframe ≥ 20 ms

In this configuration, LTE-V2X stations have to be able to send different versions of the preamble coding for different durations. If one preamble is stored in a LUT as 16-bits I + 16-bits Q, it occupies 2,4 kB of data (15,36e6 × 40e-6 × 4/1 024 = 2,4). When more preambles need to be stored, only the IQ samples corresponding to different L-SIG (+ resampling filters delays) would be needed in addition (since the L-STF and L-LTF are identical for all ITS-G5 headers). This approximately leads to 0,48 kB of data (15,36e6 × 8e-6 × 4/1 024 = 0,48) per additional preamble. Thus, as an example, for 4 preambles the amount of LUT memory needed is 3 84 kB (2,4 + 0,48 × 3), and for 10 preambles the amount of LUT memory needed is 6,72 kB (2,4 + 0,48 × 9).

A.4 Resampling of ITS-G5 header to LTE native rate

When sent by ITS-G5 stations, ITS-G5 packets are sent at the IEEE 802.11p native rate of 10 MSPS, while LTE-V2X packets are sent at 15,36 MSPS, typically. Therefore, the precomputed ITS-G5 header sequence is initially generated at 10 MSPS, then most likely rate-converted to 15,36 MSPS. How the sequence is resampled to LTE-compatible rate is up to each implementation, although a straight rate conversion by 192/125 is recommended. Typical quality metrics of transmit signal should be applicable (for example in terms of EVM) to ensure integrity of the transmitted signal, and correct decoding of the preamble by ITS-G5 stations.

A.5 Transmit power for the ITS-G5 header

The ITS-G5 header transmitted within an LTE-V2X subframe should be transmitted with the same transmit power as the rest of the subframe, regardless of the number of subchannels used by the LTE-V2X message. This is to ensure identical power-level in time domain throughout the subframe.

A.6 Multiple LTE-V2X stations transmitting ITS-G5 headers in the same subframe

The ITS-G5 headers span the full ITS-G5 frequency bandwidth (8,125 MHz), which will be different from the bandwidth of the allocated LTE-V2X RB. Such headers can be transmitted by multiple LTE-V2X stations simultaneously. This clause provides details on how to model the case when multiple identical ITS-G5 headers are transmitted by different LTE-V2X stations in the same subframe.

Since LTE-V2X transmissions are fully synchronized in subframes occurring every 1 ms, all LTE-V2X stations that transmit in one subframe will also send the ITS-G5 header at the same time within the first OFDM symbol of the subframe. Since the header transmitted by each station is identical, ITS-G5 stations will receive the header from multiple LTE-V2X stations with different receive power (depending on the propagation loss). To simplify the simulations of this method, the energy received by all LTE-V2X stations transmitting at the same time is summed up. This assumption is expected to represent the upper bound for the detection performance, since depending on the channel impulse responses and Doppler shifts, only some transmissions will add up fully constructively, but others might only partially add up or might add up destructively leading to a lower detection performance. Therefore, the results for Method C can be understood as an upper bound for the achievable performance, i.e. performance with ideal header detection.

The term 'header detection' denotes the combination of the 'acquisition' of the packet (typically based on correlations of the L-STF sequences) and the decoding of the SIGNAL field:

- For the successful acquisition (if implemented explicitly) of the ITS-G5 header, the (cumulated) received signal needs to exceed -94 dBm (which is arguably a lower bound as some ITS-G5 devices have a better preamble sensitivity)
- For the decoding of the SIGNAL field, a link level PER vs SINR mapping curve (or a 90 % PRR threshold) may be used to determine if the SIGNAL field is successfully decoded

The detailed (idealized) simulation assumptions for overlapping ITS-G5 header transmissions by LTE-V2X stations are:

- The received power of all header transmissions can be summed up $RSRP_{sum\ header}$
- For the header acquisition (if implemented explicitly), the sum of the received power of all headers is used to compare with the detection trigger value of -94 dBm
- For the decoding of the Signal Field, the SINR is computed as:

$$SINR = RSRP_{sum\ header}/(RSSI - RSRP_{sum\ header})$$

For ITS-G5 stations the "capture effect" is considered.

A.7 Options of Method C

A.7.1 Option 1

Method C "Option 1" is described in Clause 6.3.3.2 and it is linked to how the immediate reservation of the channel is performed by LTE-V2X as detailed in Clause A.2.This option is applicable only in conjunction with "Dynamical local configuration of time slot sizes" as outlined in Clause 6.2.2. It assumes ITS-G5 header reservations of 1,008 ms. This method assumes ITS-G5 stations with time-synchronization capabilities (as described in Annex F) and hence the capability for ITS-G5 stations to avoid sending messages that may overlap with the next superframe.

A.7.2 Option 2

This option is applicable only in conjunction with static or semi-static configuration as outlined in Clause 6.2.1. It assumes ITS-G5 header reservations pointing to the end of the current LTE-V2X time slot (or upper bounded to 10 ms). This method assumes ITS-G5 stations with time-synchronization capabilities (as described in Annex F) and hence the capability for ITS-G5 stations to avoid sending messages that may overlap with the next superframe, as well as the capability for ITS-G5 to derive the starting time of the ITS-G5 time slot and thus to apply the artificial packet delay described for in Clause 6.3.1.5 (in which ITS-G5 transmissions are spread over time in an attempt to avoid concurrent transmissions).

In this option, the TDM instructions are given only to LTE-V2X stations. The TDM instructions are forwarded by LTE-V2X stations to the ITS-G5 stations by means of the ITS-G5 header. ITS-G5 stations have to know the superframe size and the time slot size is provided by the LTE-V2X stations. To derive the starting time of the ITS-G5 time slot. It is further required that ITS-G5 stations establish the following:

- A mechanism to identify if a given ITS-G5 header originates from an ITS-G5 station or a LTE-V2X station. This classification can be based on the fact that LTE-V2X stations can only send a limited set of duration indications (e.g. 5, 6, 7, 8, 9, 10 ms). Assuming that the minimum duration of LTE-V2X time slot is 5 ms, and that for 'normal' ITS-G5 messages sent by ITS-G5 stations the duration will be at most 4 ms, it should be reasonably easy to distinguish between the 2 possible origins.

- A continuously updated table, which collects the time when the latest ITS-G5 header indicating a given LTE-V2X time slot duration was received from the LTE-V2X stations. Table A.1 shows an example of such concept.

Table A.1: Example of a table collecting latest valid ITS-G5 header indications from LTE-V2X stations

LTE-V2X time slot duration	5 ms	6 ms	…	10 ms	…	(superframe size -5) ms
Latest received message	2020/2/11/09:59	2020/2/11/09:55	…	2020/2/11/09:50	…	[N/A]

- Upon reception of a LTE-V2X originating header, update the corresponding entry of Table A.1.

- For each entry of Table A.1, implement a time-out mechanism which may reset the content of the cell to "N/A", if no valid LTE-V2X ITS-G5 header has been sent within a predefined time (e.g. several hours).

At any point in time, the LTE-V2X time slot duration is derived as being the highest valid entry of Table A.1 (not "N/A"), and ≥ 5 ms

It is expected that this configuration will have similar performance as "Method A enhanced" , i.e. Method A with the artificial packet delay as described in Clause 6.3.1.5.

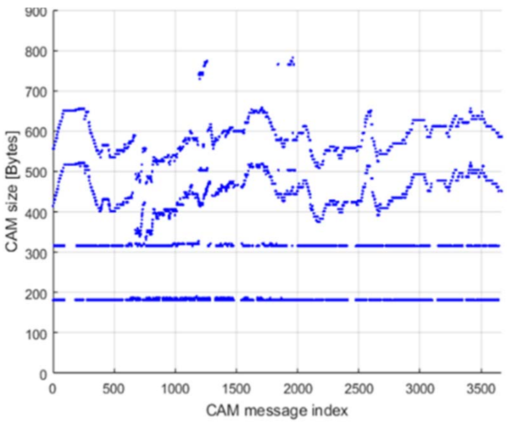
Annex B: Collected statistics for CAMs

Statistics on CAM message distribution during real test drives have been collected. The collection of messages has been performed using vehicles driving around in different traffic situations named "urban", "suburban" and "highway". Table B.1 outlines the driving scenarios and Figure B.1 shows maps over the driving scenarios. Results from these test drives were presented at the ETSI ITS workshop 2019 [i.14] and the full study is available at the C2C-CC's website [i.15].

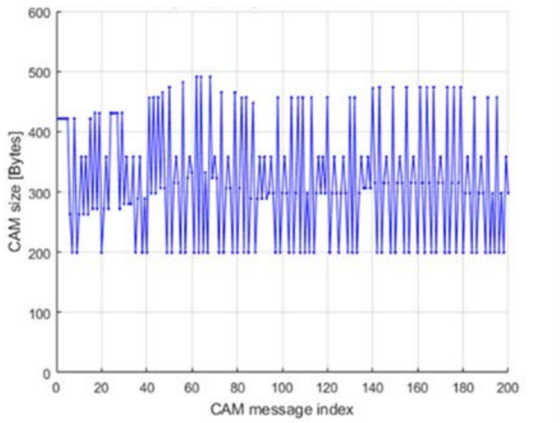
Table B.1: Outlines the driving scenarios

City	Scenario	Standard	Facilities layer profile
(I) Gifhorn, Germany	Urban	ETSI ITS-G5	C2C-CC profile 1.3
	Suburban		
	Highway (slow)		
(II) Vienna, Austria	Urban	ETSI ITS-G5	SCOOP 1.2, 2.4.1
	Suburban		
	Highway		

It has been observed from the traces collected that the CAM size changes from one message to the other, for all the test drives. This variability is caused by, e.g. the security certificate handling and the 'optional' low frequency container containing the path history. Figure B.1 shows examples of traces.



(a) Urban environment



(b) Highway scenario

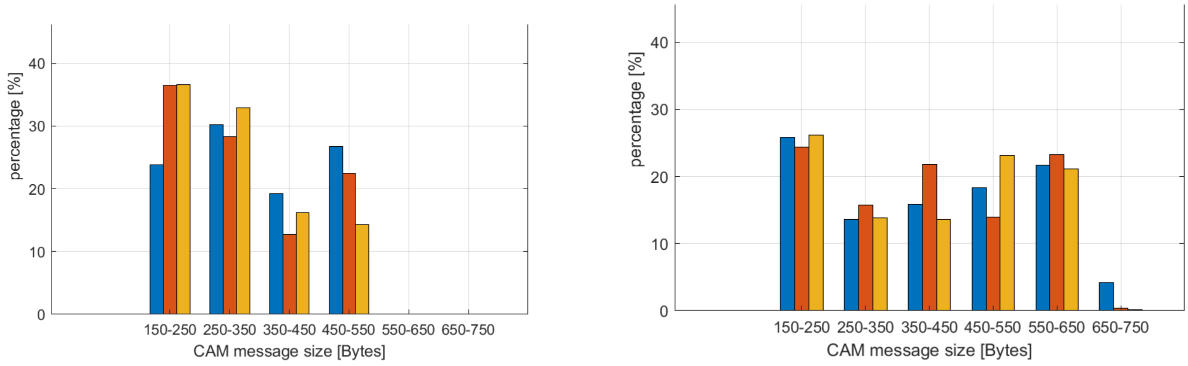
Figure B.1: Shows traces for CAM sizes

The average CAM size is typically around 350 bytes. However, significant differences in the upper part of the CAM distribution were found during the test drives. Table B.2 outlines the minimum and maximum sizes of CAMs together with mean.

Table B.2: Minimum, mean, and maximum CAM sizes for all scenarios

Trace	CAM sizes, mean value	CAM sizes, min value	CAM sizes, max value
urban (I)	339 bytes	199 bytes	526 bytes
suburban (I)	308 bytes	199 bytes	504 bytes
highway (I)	297 bytes	199 bytes	500 bytes
urban (II)	406 bytes	182 bytes	782 bytes
suburban (II)	396 bytes	182 bytes	765 bytes
highway (II)	399 bytes	182 bytes	807 bytes
Overall average	**357 Bytes**		

Figure B.2 shows the distribution of CAM sizes with a granularity of 100 bytes bins (150 - 250 bytes, 250 - 350 bytes, etc.) for the two cities and the three different scenarios, blue bar is urban, red bar is suburban and yellow bar is highway.



(a) Gifhorn **(b) Vienna**

Figure B.2: Histograms of CAM sizes

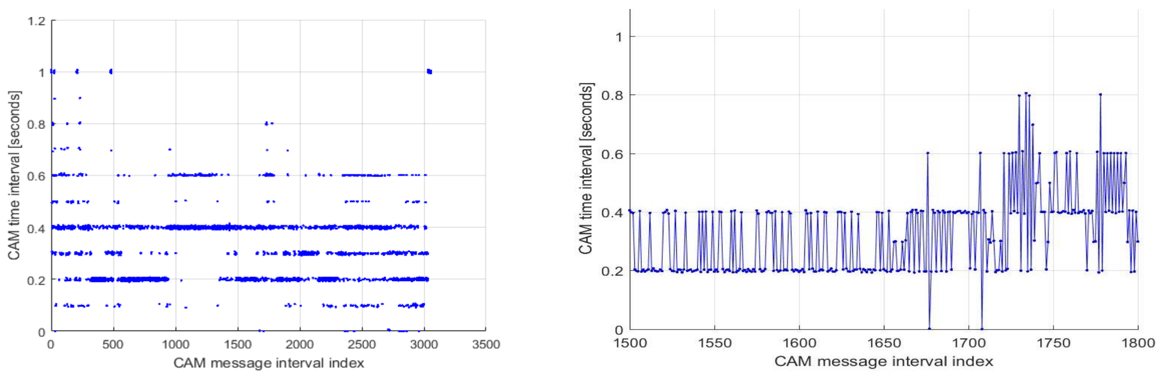
Table B.3 tabulates the percentage of the total number of messages transmitted in each scenario for the different "bins".

Table B.3: Percentage of messages ending up in different bins for a specific scenario

Trace	150 - 250 bytes	250 - 350 bytes	350 - 450 bytes	450 - 550 bytes	550 - 650 bytes	650 - 750 bytes
urban (I)	24 %	30 %	19 %	27 %		
suburban (I)	37 %	28 %	13 %	22 %		
highway (I)	37 %	33 %	16 %	14 %		
urban (II)	26 %	14 %	16 %	18 %	22 %	4 %
suburban (II)	24 %	16 %	22 %	14 %	23 %	
highway (II)	26 %	14 %	14 %	23 %	21 %	
Overall average	29 %	22 %	17 %	20 %	11 %	1 %

CAMs are triggered based on vehicle dynamics such as speed, change of speed and direction (heading), with 1 Hz - 10 Hz. For details around the CAM triggering procedure look in Clause 6.1.3 of ETSI EN 302 637-2 [i.17]. DENMs are event-triggered messages and they are transmitted as long as there is an impending danger with a frequency between 1 Hz - 20 Hz, which is determined by the event causing the DENM dissemination. The triggering of DENMs is asynchronous and cannot be predicted.

The time between two consecutive CAMs triggered from the same vehicle is varying between 100 ms - 1 000 ms and Figure B.3 shows this for the slow highway scenario in Gifhorn, Germany. The average time between two consecutive messages is approximately 330 ms for this scenario.



(a) 3 000 messages **(b) zoomed in on messages between 1 500 - 1 800**

Figure B.3: The time between consecutive CAMs in a highway scenario

The time interval between CAMs depends on the driving scenario but the average values varies between 0,33 s - 0,47 s. Figure B.4 outlines the histograms for all driving scenarios.

(a) (b) (c)

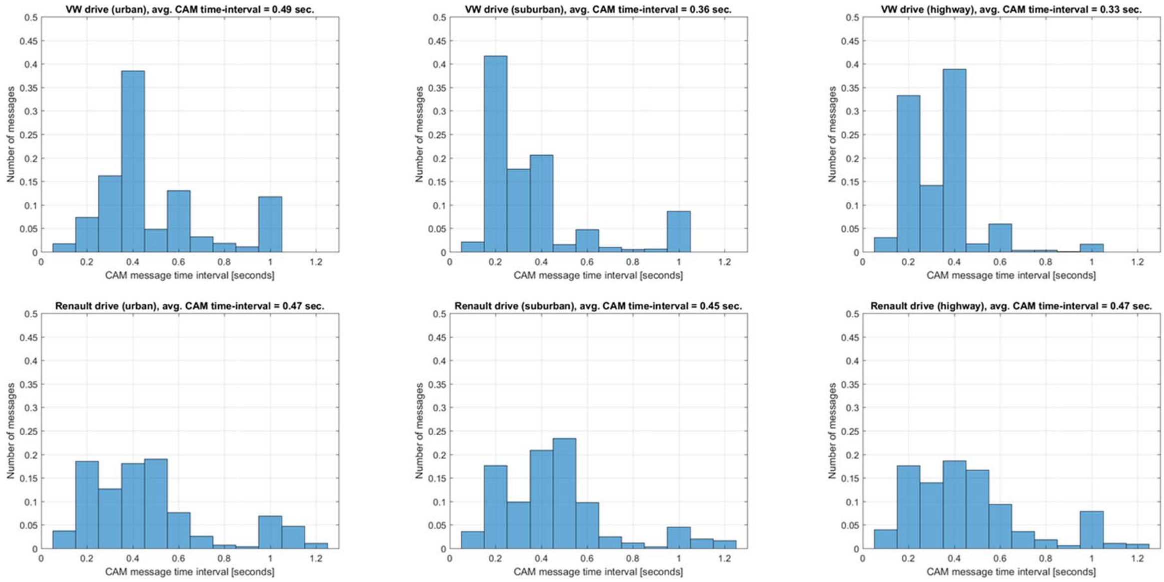


Figure B.4: Histograms for time intervals for all driving scenarios; (a) urban (Gifhorn), (b) suburban (Gifhorn), (c) slow highway (Gifhorn), (d) urban (Vienna), (e) suburban (Vienna), and (f) highway (Vienna)

Annex C: Eclipse Sumo™ generated mobility traces

Eclipse Sumo™ is an open-source mobility simulator that can model road traffic and produces as an output a trace of the vehicles coordinates throughout the simulation. Usage of Eclipse Sumo™ and of these Eclipse Sumo™ traces is not mandatory for the simulations. A collection of traces generated with Eclipse Sumo™ is available in tr_103766v010101p0.zip file which accompanies the present document. An overview of the available traces is found in Table C.1.

Table C.1: Overview of available Eclipse Sumo™ traces

Map	Max speed	Number of vehicles	Folder name
Fast highway (3 km)	50 km/h	10	3km_highway_50kmph_10vh
Fast highway (3 km)	70 km/h	10	3km_highway_70kmph_10vh
Fast highway (3 km)	70 km/h	245	3km_highway_70kmph_245vh
Fast highway (3 km)	140 km/h	10	3km_highway_140kmph_10vh
Fast highway (3 km)	140 km/h	123	3km_highway_140kmph_123vh
Fast highway (3 km)	250 km/h	10	3km_highway_250kmph_10vh
Fast highway (3 km)	250 km/h	70	3km_highway_250kmph_70vh
Slow Highway (600 m)	50 km/h	10	600m_highway_50kmph_10vh
Slow Highway (600 m)	50 km/h	100	600m_highway_50kmph_100vh
Slow Highway (600 m)	50 km/h	200	600m_highway_50kmph_200vh
Slow Highway (600 m)	50 km/h	300	600m_highway_50kmph_300vh
Urban	15 km/h	10	urban_15kmph_10vh
Urban	15 km/h	100	urban_15kmph_100vh
Urban	15 km/h	200	urban_15kmph_200vh
Urban	15 km/h	300	urban_15kmph_300vh

Annex D: Technology detection

D.1 Introduction

The present annex describes how the technologies can detect each other.

D.2 ITS-G5 detecting LTE-V2X

D.2.1 Cyclic prefix

This option requires no changes to LTE-V2X but depending on the ITS-G5 receiver implementation, this option might require changes to ITS-G5.

With the Cyclic Prefix (CP) option, the first 144 samples (duration of 4,7 μs for a sampling rate of LTE-V2X 30,72 MHz) of an OFDM symbol (2 192 samples and duration of 71,3 μs) are the same as the last 144 samples. This repetition characteristic can be used by an ITS-G5 receiver to detect the LTE-V2X signal by delay correlation. The sampling frequency of a ITS-G5 receiver is usually 10 MHz, which is different from that of an LTE-V2X receiver. It is assumed that there is not any sampling rate conversion before delay correlation in an ITS-G5 receiver. Therefore, the delay value in the detection process is set as 667 samples (i.e. (2 192 - 144) / 30,72 MHz × 10 MHz).

The impact of the detection process on an ITS-G5 receiver depends on the implementation of the ITS-G5 System-on-Chip (SoC). If the ITS-G5 SoC is based on hard logic, the detection logic is used to detect ITS-G5 signals. Thus, the delay value is fixed to 16 samples and changing the delay value may require re-designing of the ITS-G5 SoC. On the other hand, if the ITS-G5 SoC is based on Software Defined Radio (SDR), it may be possible to change the delay value from 16 samples to 667 samples to detect the CP pattern of an LTE-V2X signal. This approach would require to change the delay value of ITS-G5 from 16 samples to 667 samples and that the LTE-V2X transmission occupies that whole bandwidth (no division of transmissions in the frequency domain).

D.2.2 Change CCA threshold

This option does not require changes to LTE-V2X but it requires changing the CCA threshold for ITS-G5.

For ITS-G5 to detect LTE-V2X signals energy detection could be used, which is already part of the ITS-G5 standard. ITS-G5 stations need to consider the channel busy if the received power is stronger than -65 dBm for any technology and the channel is considered busy if the received power is stronger than -85 dBm for ITS-G5 transmissions. Changing the CCA threshold for ITS-G5 would imply that an ITS station would defer its channel transmission as long as the signal is stronger than -85 dBm regardless of technology.

D.2.3 LTE-V2X transmits energy signals

This option requires changes to LTE-V2X and it requires changing the CCA threshold to ITS-G5.

LTE-V2X can transmit energy signals to reserve channel resources and the CCA threshold needs to be altered on ITS-G5 as described in Clause 6.3.2, to make this option viable.

D.2.4 LTE-V2X transmits ITS-G5 PHY header

This option requires changes to LTE-V2X but no changes are required to ITS-G5.

LTE-V2X can transmit the ITS-G5 PHY header to reserve channel resources and ITS-G5 would defer access.

D.3 LTE-V2X CBR assessment

The metric technology ratio percentage, $Tech_{percentage}$, is introduced to provide an indication of the actual percentage of users belonging to LTE-V2X and to ITS-G5 technologies, respectively, in a given geographical area at a given time. The $Tech_{percentage}$ is computed by LTE-V2X stations (only), see Equation (D.1).

$$Tech_{percentage} = \frac{CBR_{LTE}}{CBR_{LTE+ITSG5}}. \qquad \text{(D.1)}$$

The objective is essentially for LTE-V2X stations to distinguish between the messages pertaining to their technology from the messages pertaining to ITS-G5, in a given frequency channel. This capability is sometimes also referred to as self-detection. There are two ways of assessing CBR_{LTE} outlined in Equation (D.2) and Equation (D.3), respectively. The $CBR_{LTE+ITSG5}$ assessment is further described in Table D.1.

The CBR_{LTE} assessment according to Equation (D.2) is described as, the total number of subchannels occupied by the data associated with correctly received PSCCH SCIs (having a CRC pass) in a given interval is normalized by the number of subframes in the same interval and the number of non-overlapping subchannels.

$$CBR_{LTE} = \frac{\sum_{j=1}^{N_{PSCCH_{CRCPASS}}} \mathrm{UsedNumSubchannel}_j}{\mathrm{numSubchannel} \times numSubframes_{Tech_{percentage}}} \qquad \text{(D.2)}$$

where $N_{PSCCH_{CRCPASS}}$ is the number of LTE-V2X PSCCH decoded successfully (having a CRC pass), and$\mathrm{UsedNumSubchannel}_j$ is the number of subchannels occupied by the data associated with the jth correctly decoded PSCCH SCI (and thus populated accordingly by the associated PSSCH data). The rational for not taking into account the PSCCH pertaining to HARQ retransmission is to avoid double counting these packets (since ITS-G5 does not do repetitions). The $\mathrm{numSubchannel}$ is the number of subchannels as defined in Table B.2 of ETSI TS 103 613, that is 5 subchannels and $\mathrm{numSubframes}_{Tech_{percentage}}$ is the integration time of the measurement, set to 100 ms.

When there are multiple LTE-V2X stations causing interferences to each other, many of their PSCCH reception may be failed. It can lead to an underestimation of the CBR_{LTE}. Therefore, an alternative method for CBR_{LTE} assessment is defined in Equation (D.3). Then the total number of PSCCH SCIs of which its reference signal received power (RSRP) is higher than a threshold received power in a given interval is normalized by the number of subframes in the same interval and the number of subchannels.

$$CBR_{LTE} = \frac{N_{PSCCH_{RSRP \geq Threshold}}}{\mathrm{numSubchannel} \times numSubframes_{Tech_{percentage}}} \qquad \text{(D.3)}$$

where $N_{PSCCH_{RSRP \geq Threshold}}$ is the number of LTE-V2X PSCCH of which its RSRP is higher than a defined threshold received power. The $\mathrm{numSubchannel}$ is the number of subchannels as defined in Table B.2 of ETSI TS 103 613 [i.35], that is 5 subchannels and $\mathrm{numSubframes}_{Tech_{percentage}}$ is the integration time of the measurement, set to 100 ms.

Two options for measuring the aggregated traffic in the channel and assessing $CBR_{LTE+ITSG5}$ (data traffic originating from LTE-V2X as well as ITS-G5 stations) are outlined in Table D.1.

Table D.1: Options for the $CBR_{LTE+ITSG5}$ found in Equation (1)

Option	Description
#1	$CBR_{LTE+ITSG5}$ is exactly the native channel busy ratio (CBR) as defined by LTE-V2X. (See note).
#2	$CBR_{LTE+ITSG5}$ is defined as CBR_{LTE} + CBR_{ITSG5}, where CBR_{ITSG5} measures the occupancy of the channel originating from ITS-G5 specifically. In order to perform this measurement, LTE-V2X stations are required to detect ITS-G5 preambles (based on STF) and/or decode SIG field (based on LTF and SIG), and distinguish ITS-G5 headers transmitted by LTE-V2X stations from those transmitted by ITS-G5 stations.
NOTE: Option #1 is an attempt to minimize deviation from LTE-V2X release 14 standard. It relies upon the existing LTE-V2X CBR measurement to capture the overall traffic in the channel. The LTE-V2X CBR is defined in specification ETSI TS 136 213 [i.8], and is used in the resource selection procedure [i.8] and the CRlimit computation in ETSI TS 103 574 [i.25].	

Option #2 in Table D.1 requires changes to legacy LTE-V2X stations whereas Option #1 does not require any modifications. For simulations of Option #2 in the present document, the following assumptions are made:

- The CBR_{LTE} measurement accuracy of an LTE-V2X station is assumed to be identical to that of an ITS-G5 station, i.e. assuming ITS-G5 headers are decoded
- LTE-V2X stations disregard all ITS-G5 headers transmitted by LTE-V2X stations, i.e. they have perfect knowledge about the ITS-G5 headers transmitted by other LTE-V2X stations

The assumptions provide an upper bound on the achievable performance with this approach of the LTE-V2X CBR assessment.

Annex E: Details about the LOS channel models

The LOS pathloss models depend on the following parameters:

- distance between transmitter and receiver d in metres
- carrier frequency f_c in Hertz
- speed of light $c = 299792458\,\frac{m}{s}$
- wavelength $\lambda = \frac{c}{f_c}$ in metres
- height of the transmitter h_t in metres
- height of the receiver h_r in metres

The free space pathloss is defined as:

$$PL_{FS} = 20 \cdot \log_{10}\left(4\pi \cdot d \cdot \frac{f_c}{c}\right). \tag{E.1}$$

The two-ray ground reflection model [i.21] pathloss is defined as

$$PL_{TR-G,1} = 20 \cdot \log_{10}\left(4\pi \cdot d \cdot \frac{f_c}{c}\left|1 + \Gamma_{\perp} e^{i\varphi}\right|^{-1}\right), \tag{E.2}$$

with

$$\varphi = \frac{2\pi\left(\sqrt{d^2 + (h_t - h_r)^2} - \sqrt{d^2 + (h_t + h_r)^2}\right)}{\lambda}, \tag{E.3}$$

$$\Gamma_{\perp} = \frac{\frac{h_t + h_r}{\sqrt{d^2 + (h_t + h_r)^2}} - \sqrt{\varepsilon_r - \frac{d^2}{d^2 + (h_t + h_r)^2}}}{\frac{h_t + h_r}{\sqrt{d^2 + (h_t + h_r)^2}} + \sqrt{\varepsilon_r - \frac{d^2}{d^2 + (h_t + h_r)^2}}}, \tag{E.4}$$

and the relative permittivity ε_r.

As an alternative, when assuming perfect horizontal E-field polarization and ground reflection ($\Gamma_{\perp} = -1$), the two-ray ground reflection model [i.20] is defined as:

$$PL_{TR-G,2} = 20 \cdot \log_{10}\left(4\pi \cdot d \cdot \frac{f_c}{c} \cdot 2 \cdot \left|\sin\left(-\frac{\varphi}{2}\right)\right|^{-1}\right). \tag{E.5}$$

The log-distance two-ray ground pathloss [i.21] is defined as:

$$PL_{LDTR-G} = \begin{cases} PL_{FS} & \text{if } d \le d_c \\ 20 \cdot \log_{10}\left(\frac{d^2}{h_t h_r}\right) & \text{if } d > d_c \end{cases}, \tag{E.6}$$

with the cross-over distance:

$$d_c = \frac{4\pi(h_t h_r)}{\lambda}. \tag{E.7}$$

Equation (6) in Recommendation ITU-R P.1411-10 [i.22] pathloss is defined as:

$$PL_{P1411(6)} = L_{bp} + 6 + \begin{cases} 20 \cdot \log_{10}\left(\frac{d}{R_{bp}}\right) & \text{if } d \leq R_{bp} \\ 40 \cdot \log_{10}\left(\frac{d}{R_{bp}}\right) & \text{if } d > R_{bp} \end{cases}, \tag{E.8}$$

with the break point distance:

$$R_{bp} \approx \frac{4h_t h_r}{\lambda}, \tag{E.9}$$

and the basic transmission loss at the break point:

$$L_{bp} = \left| 20 \cdot \log_{10}\left(\frac{\lambda^2}{8\pi h_t h_r}\right) \right|. \tag{E.10}$$

and $R_S = 20$ m.

The WINNER+ B1 LOS model pathloss is defined as:

$$PL_{WINNER+} = \begin{cases} 22{,}7 \cdot \log_{10}(d) + 41 + 20 \cdot \log_{10}\left(\frac{f_c}{5 \cdot 10^9}\right) & \text{if } 10\text{m} < d \leq d'_{BP} \\ 40 \cdot \log_{10}(d) + 9{,}45 - 34{,}6 \log_{10}(h_e) + 2{,}7 \cdot \log_{10}\left(\frac{f_c}{5 \cdot 10^9}\right) & \text{if } d'_{BP} < d < 5\text{km} \end{cases}, \tag{E.11}$$

with the break point distance:

$$d'_{BP} = 4 \cdot h_t h_r f_c / c, \tag{E.12}$$

and the effective antenna height h_e.

The three slope propagation model from ECC Report 68 [i.23] pathloss is defined as:

$$PL_{TS} = \begin{cases} -20 \cdot \log_{10}\left(\frac{\lambda}{4\pi d}\right) & \text{if } d \leq d_0 \\ -20 \cdot \log_{10}\left(\frac{\lambda}{4\pi d_0}\right) + 10n_0 \cdot \log_{10}\left(\frac{d}{d_0}\right) & \text{if } d_0 < d \leq d_1, \\ -20 \cdot \log_{10}\left(\frac{\lambda}{4\pi d_0}\right) + 10n_0 \cdot \log_{10}\left(\frac{d_1}{d_0}\right) + 10n_1 \cdot \log_{10}\left(\frac{d}{d_1}\right) & \text{if } d > d_1 \end{cases} \tag{E.13}$$

with the parameter sets for different environment conditions as defined in Table E.1.

Table E.1: Parameters for the three slope propagation model from ECC Report 68 [i.23]

Parameter	Urban	Suburban	Rural
Breakpoint distance d_0 (m)	64	128	256
Pathloss factor n_0 beyond the first break point	3,8	3,3	2,8
Breakpoint distance d_1 (m)	128	256	1 024
Pathloss factor n_1 beyond the second breakpoint	4,3	3,8	3,3

Annex F:
ITS-G5 stations with time synchronization

This annex describes enhancements that can be applied to some methods (e.g. A, C, etc.) when ITS-G5 stations have time synchronization capabilities. One motivation for this add-on is to avoid potential overlap between ITS-G5 messages which transmissions starting near the end of the ITS-G5 time slot, and LTE-V2X messages sent at the beginning of the LTE-V2X time slot coinciding with the beginning of a new superframe. Figure F.1 illustrates this situation and T0 is when the new superframe starts.

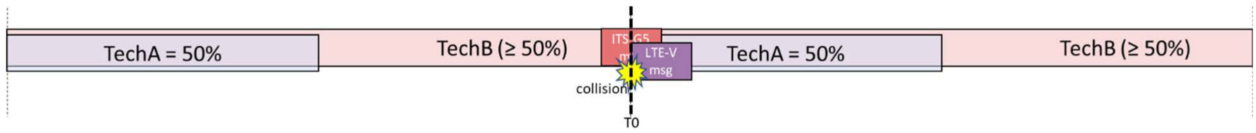


Figure F.1: Possible collision near the turn-around time

It is assumed that ITS-G5 stations are aware of the repeating superframe structure and its duration (e.g. 10 or 20 ms), and that time synchronization capabilities provide the knowledge of absolute timing, as shown in Figure F.2.

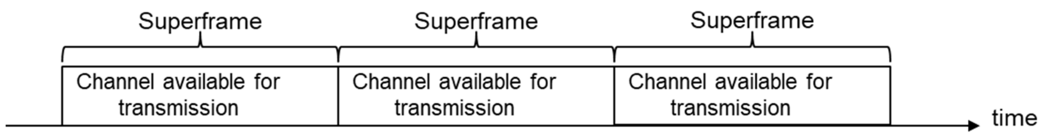


Figure F.2: Perception of the superframe structure by ITS-G5 stations

ITS-G5 stations are not allowed to transmit messages that would overlap with the next superframe. By knowing their own time synchronization accuracy and tolerance, and the duration of the packet to be transmitted, the period of time at the end of the ITS-G5 time slot during which the transmission cannot be initiated might differ for each station and for each packet size.

Figure F.3 shows an example where one station with varying packet lengths of 0,5, 1,0 and 0,3 ms respectively obtained from the upper layers at the same pace of the superframe.

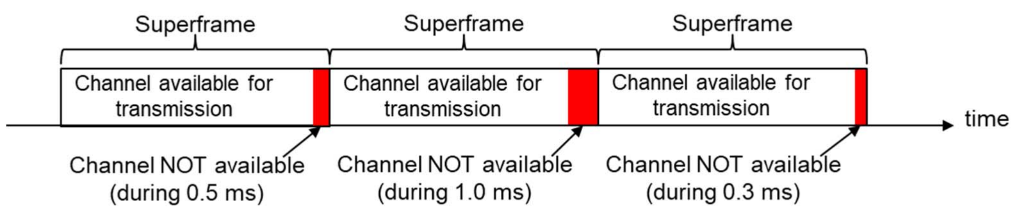


Figure F.3: Perception of the superframe structure by ITS-G5 stations, not allowing messages overlapping with next superframe start

For simulation purposes in the present document, it is assumed that ITS-G5 stations have a time synchronization accuracy of 0,1 ms.

Annex G: Derivation of the traffic mix mismatch for numerical simulations

For a realistic assessment of the performance of the co-existence methods considered in the present document, numerical simulations need to be conducted with the targeted vehicles traffic mix as well as including an offset on the targeted vehicles traffic mix. To enable a realistic investigation of the latter, it is proposed to keep the TDM pattern unchanged and adapt the distribution of the cars in the simulation. When changing the TDM pattern, only large offsets can be configured, e.g. for a superframe duration of 10 ms a change of 1 ms causes already an extreme mismatch between technology distribution and TDM pattern. However, when decreasing the number of vehicles of one technology and to the same extend increasing the number of the other technology's vehicles, the overall number of vehicles is unchanged; in this case the fixed global TDM pattern and the technology distribution will also exhibit a mismatch. This mismatch can be changed in a much finer granularity and enables a more realistic simulation. It is proposed to adapt the technology distribution in such a way that at least 50 % of the vehicles observe ±5,55 % of the theoretical vehicle distribution centred around the ideal technology distribution. This corresponds to the optimal TDM pattern when, e.g. adopting a superframe duration of 10 ms and a time slot granularity of 1 ms for an ideal technology distribution of 50 %/50 %.

In the following, $n = vehicles_{Tech_A} + vehicles_{Tech_B}$ denotes the number of vehicles in the simulation, where $vehicles_{Tech_A}$ and $vehicles_{Tech_B}$ correspond to the number of vehicles using technology A and technology B, respectively. Furthermore, $p = \frac{vehicles_{Tech_A}}{n}$ describes the ratio of vehicles of technology A vehicles in the simulation. When placing vehicles of technology A with a probability p and vehicles of technology B with a probability $(1 - p)$ into an area, the distribution of the vehicles can be described by a binomial distribution. With the approximation of the binomial distribution according to the law of large numbers as a normal distribution, a normal distribution with standard deviation $\sigma = \sqrt{n \cdot p \cdot (1 - p)}$ and mean $\mu = n \cdot p$ is obtained. The cumulative distribution function (CDF) of the normal distribution is denoted by $F(x; \mu, \sigma)$, where x denotes the point where the CDF is evaluated. The parameters μ and σ of $F(x; \mu, \sigma)$ define the mean and the standard deviation of the normal distribution and are computed as described above.

For a superframe duration of 10 ms and a slot granularity of 1 ms, evaluating $F(x; \mu, \sigma)$ for each of the start and end values of the nine discrete bins $\bar{R} = \lceil p \cdot 9 \rfloor$, the result in Figure G.1 for $p = 0{,}5$, i.e. a 50 %/50 % technology distribution between technology A and B, is obtained.

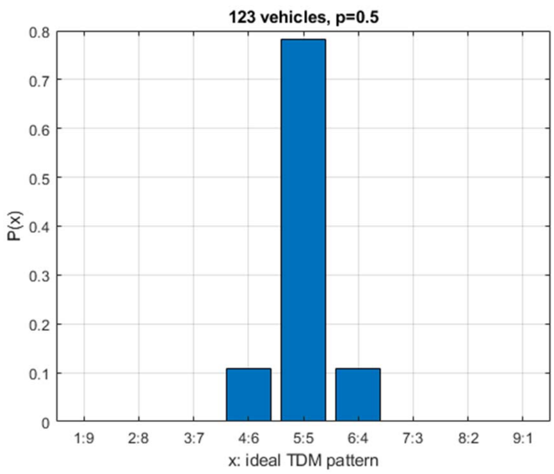


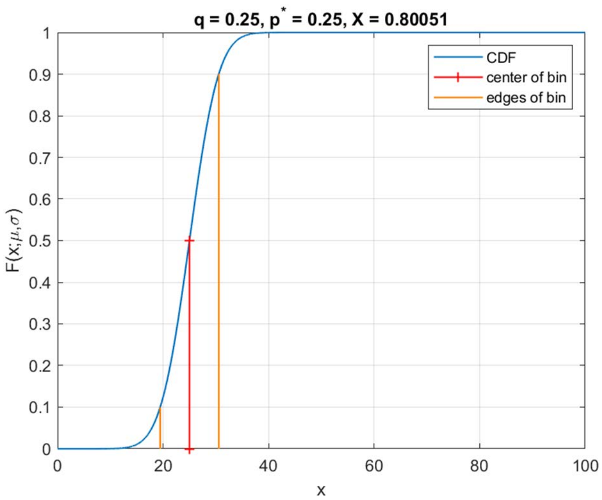
Figure G.1: Probability distribution for p = 0,5, with bins from 1:9 to 9:1, using a normal distribution

Let introduce a mismatch between the theoretical technology distribution ($vehicles_{Tech_A}$ and $vehicles_{Tech_B}$) and the simulated technology distribution. The mismatched number of vehicles used in the simulations is indicated by a superscript "*", i.e. $vehicles^*_{Tech_A}$ and $vehicles^*_{Tech_B}$. Furthermore, the centre of the bin of interest is defined by $q = \max\left(\frac{vehicles_{Tech_A}}{vehicles_{Tech_B}}, \frac{1}{18}\right)$ for $q \leq 1$, where for $q > 1$, technology A and technology B will be exchanged to calculate the result. The max operation is needed to investigate technology ratios smaller than $\frac{1}{18}$. Since the CDF is only defined for positive values, in those cases the bin is placed starting from 0. The centre of the bin of interest q will always correspond to the theoretical traffic mix.

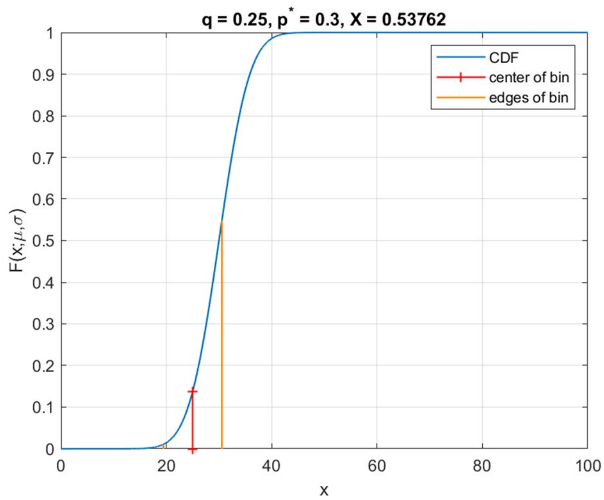
Using the definitions above, the ratio of vehicles in the desired bin of with $\frac{n}{9}$ is computed by:

$$X = F\left(n \cdot \left(q + \frac{1}{18}\right); \mu, \sigma\right) - F\left(n \cdot \left(q - \frac{1}{18}\right); \mu, \sigma\right) \qquad \text{(G.1)}$$

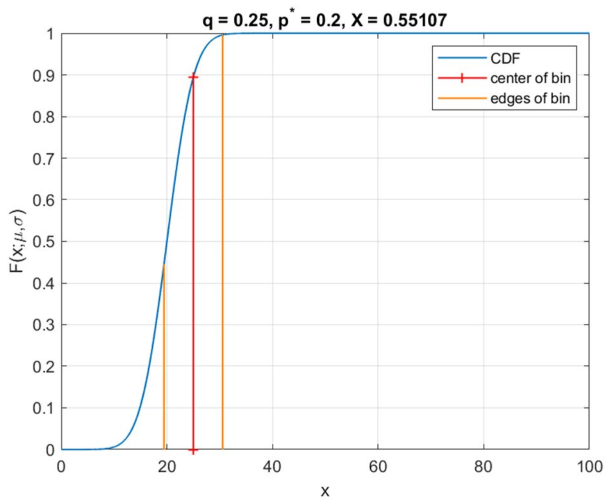
Note that the mean and the standard deviation of the normal distribution are computed with $p^* = \frac{vehicles^*_{Tech_A}}{n}$ instead of p. To obtain the mismatched technology distribution w.r.t. the lower end of the CDF, the value $vehicles^*_{Tech_A}$ is chosen for the simulations, where $X > 50\ \%$ and $X < 50\ \%$ for $(vehicles^*_{Tech_A} + 1)$. Furthermore, the mismatched technology distribution w.r.t. the upper end of the CDF, here $vehicles^*_{Tech_A}$ is chosen in such a way that $X > 50\ \%$ and $X < 50\ \%$ for $(vehicles^*_{Tech_A} - 1)$.



a) $q = 0{,}25$, $p^* = 0{,}25$



b) $q = 0{,}25$, $p^* = 0{,}3$



c) $q = 0{,}25$, $p^* = 0{,}2$

Figure G.2: Example of proposed approach for technology distribution 25 %/75 % and 100 vehicles

Figure G.2 shows as the proposed approach for an example with 100 cars. Starting with $p^* = q = 0{,}25$ in subfigure a), more than 80 % of the vehicles are in the bin of with $n/9$ centred at $n \cdot q = 25$. While keeping the bin unchanged, the technology mix p^* is increased, and therefore also the CDF changes until the situation in subfigure b) is reached. Here, with $p^* = 0{,}30$, the number of vehicles within the bin (X) is approximately 53,8 %. For $p^* = 0{,}31$, X would be 45,6 %. Therefore, 30 and 70 vehicles of technology A and technology B, respectively, are chosen for the simulation of 100 vehicles for the lower end of the CDF. The situation for decreasing the technology mix p^* is depicted in subfigure c). Here, with $p^* = 0{,}20$, the number of vehicles within the bin (X) is approximately 55,1 %.

For $p^* = 0{,}19$, X would be 45,3 %. Therefore, 20 and 80 vehicles of technology A and technology B, respectively, are chosen for the simulation of 100 vehicles for the upper end of the CDF.

Using the methodology described above, the resulting vehicle traffic mix for the different number of users considered in the TR as well as different theoretical technology distributions is summarized in Table G.1. For the theoretical technology distribution 0 %/100 %, as described above, the bin is centred at $q = 1/18$ to enable an evaluation of the CDF. Therefore, an evaluation is only possible at the lower edge of the CDF. Similarly, for the theoretical technology distribution 50 %/50 %, the lower and upper CDF will be identical to exchanging technology A with technology B due to the symmetry of the CDF for $q = 0{,}5$.

Table G.1: Vehicle traffic mix as number of vehicles for simulations with a mismatch between TDM pattern and technology distribution

Theoretical technology distribution	**0 %/100 %**		**25 %/75 %**		**50 %/50 %**	
# of users	lower	upper	lower	upper	lower	upper
70	7/63	N/A	21/49	14/56	38/32	32/38
100	11/89	N/A	30/70	20/80	55/45	45/55
123	13/110	N/A	37/86	24/99	68/55	55/68
200	22/178	N/A	61/139	39/161	111/89	89/111
245	27/218	N/A	74/171	48/197	136/109	109/136
300	33/267	N/A	91/209	59/241	166/134	134/166

The traffic mix in Table G.1 will be evaluated once for LTE-V2X and ITS-G5 as technology A and technology B, respectively, as well as for ITS-G5 and LTE-V2X as technology A and technology B, respectively.

As an example, the results for 123 vehicles and $p = 0{,}44715 = 55/123$, as given by Table G.1 for a 50 %/50 % theoretical technology distribution, is depicted in Figure G.3. Here, it is observed that approximately 50 % of the vehicles observe the optimal TDM pattern.

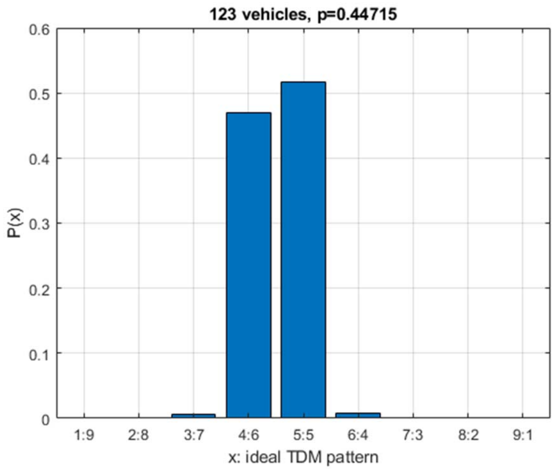


Figure G.3: Probability distribution for p = 0,44715, with bins from 1:9 to 9:1, using a normal distribution

Annex H: Time slot durations

This annex tabulates all possible time slot durations, assuming 5 ms minimum time slot duration for each technology, given the two superframe sizes 25 ms and 50 ms as the $Tech_{percentage}$ changes, see Tables H.1 and H.2.

Table H.1: Time slot duration for each technology for a superframe of 25 ms

Superframe of 25 ms		
$Tech_{percentage}$	**LTE-V2X**	**ITS-G5**
[0:22[%	5 ms	20 ms
[22:26[%	6 ms	19 ms
[26:30[%	7 ms	18 ms
[30:34[%	8 ms	17 ms
[34:38[%	9 ms	16 ms
[38:42[%	10 ms	15 ms
[42:46[%	11 ms	14 ms
[46:50[%	12 ms	13 ms
[50:54[%	13 ms	12 ms
[54:58[%	14 ms	11 ms
[58:62[%	15 ms	10 ms
[62:66[%	16 ms	9 ms
[66:70[%	17 ms	8 ms
[70:74[%	18 ms	7 ms
[74:78[%	19 ms	6 ms
[78-100] %	20 ms	5 ms

Table H.2: Time slot duration for each technology for a superframe of 50 ms

Superframe of 50 ms		
$Tech_{percentage}$	**LTE-V2X**	**ITS-G5**
[0:11[%	5 ms	45 ms
[11:13[%	6 ms	44 ms
[13:15[%	7 ms	43 ms
[15:17[%	8 ms	42 ms
[17:19[%	9 ms	41 ms
[19:21[%	10 ms	40 ms
[21:23[%	11 ms	39 ms
[23:25[%	12 ms	38 ms
[25:27[%	13 ms	37 ms
[27:29[%	14 ms	36 ms
[29:31[%	15 ms	35 ms
[31:33[%	16 ms	34 ms
[33:35[%	17 ms	33 ms
[35:37[%	18 ms	32 ms
[37:39[%	19 ms	31 ms
[39:41[%	20 ms	30 ms
[41:43[%	21 ms	29 ms
[43:45[%	22 ms	28 ms
[45:47[%	23 ms	27 ms
[47:49[%	24 ms	26 ms
[49:51[%	25 ms	25 ms
[51:53[%	26 ms	24 ms
[53:55[%	27 ms	23 ms
[55:57[%	28 ms	22 ms
[57:59[%	29 ms	21 ms
[59:61[%	30 ms	20 ms
[61:63[%	31 ms	19 ms
[63:65[%	32 ms	18 ms
[65:67[%	33 ms	17 ms
[67:69[%	34 ms	16 ms

Superframe of 50 ms		
$Tech_{percentage}$	**LTE-V2X**	**ITS-G5**
[69:71[%	35 ms	15 ms
[71:73[%	36 ms	14 ms
[73:75[%	37 ms	13 ms
[75:77[%	38 ms	12 ms
[77:79[%	39 ms	11 ms
[79:81[%	40 ms	10 ms
[81:83[%	41 ms	9 ms
[83:85[%	42 ms	8 ms
[85:87[%	43 ms	7 ms
[87:89[%	44 ms	6 ms
[89-100] %	45 ms	5 ms

History

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