White paper on
Additional Investigation of ITS-G5 and Sidelink LTE-V2X Co-Channel Coexistence Methods

About the C2C-CC

Enhancing road safety and traffic efficiency by means of Cooperative Intelligent Transport Systems and Services (C-ITS) is the dedicated goal of the CAR 2 CAR Communication Consortium. The industrial driven, non-commercial association was founded in 2002 by vehicle manufacturers affiliated with the idea of cooperative road traffic based on Vehicle-to-Vehicle Communications (V2V) and supported by Vehicle-to-Infrastructure Communications (V2I). The Consortium members represent worldwide major vehicle manufactures, equipment suppliers and research organisations.

Over the years, the CAR 2 CAR Communication Consortium has evolved to be one of the key players in preparing the initial deployment of C-ITS in Europe and the subsequent innovation phases. CAR 2 CAR members focus on wireless V2V communication applications based on ITS-G5 and concentrate all efforts on creating standards to ensure the interoperability of cooperative systems, spanning all vehicle classes across borders and brands. As a key contributor, the CAR 2 CAR Communication Consortium and its members work in close cooperation with the European and international standardisation organisations.

Disclaimer

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Abbreviations

AIFS	Arbitration inter-frame space
CBR	Channel busy ratio
C-ITS	Cooperative Intelligent Transport Systems
CEPT	European Conference of Postal and Telecommunications Administrations
CSMA/CA	Carrier sensing multiple access with collision avoidance
CPM	Collective Perception Message
CW	Contention window
DA	Data age
EED	End-to-end delay
ETSI	European Telecommunications Standards Institute
LOS	Line-of-sight
MCM	Manoeuvre Coordination Message
PRR	Packet reception ratio
QPSK	Quadrature phase-shift keying
SB-SPS	Sensing-based semi-persistent scheduling
SC-FDMA	Single-carrier frequency division multiple access
SCI	Sidelink control information
SINR	Signal to noise and interference ratio
V2I	Vehicle-to-infrastructure
V2V	Vehicle-to-vehicle
V2X	Vehicle-to-Everything
WBSP	Wireless blind spot probability

Executive summary

Cooperative Intelligent Transport Systems (C-ITS) are an important pillar to increase road safety through wireless communication that allow vehicles, road users and infrastructure, e.g. to immediately warn each other of dangerous situations such as emergency breaking, end of traffic jams, road works or approaching emergency vehicles. For these road safety applications, there is a frequency designation in the 5.9 GHz band (5.875-5.925 GHz, see ECC Decision (08)01 and Commission Implementing Decision (EU) 2020/1426). This frequency band is shared spectrum, allowing several technologies to access this spectrum. This report gives new insights in so called co-channel coexistence methods, which aim at mitigating interference between different technologies, help to use spectrum efficiently and avoid segregation of spectrum between technologies that serve the same application.

ITS is a key component of the EU Road Safety Policy Framework, which provides recommendations on next steps towards ‘Vision Zero’[1], with a “long-term strategic goal to get close to zero deaths and zero serious injuries on EU roads by 2050”.
The communication technology ETSI ITS-G5 has been designed to serve this goal of safer roads, benefitting all European citizens. ITS-G5 has been fully demonstrated to be a very reliable, low-latency and mature technology. Day-1 cooperative ITS services are standardized by now, and there is a broad basis for deployment. One million ITS-G5 equipped vehicles from different brands rolled-out is forecasted to be reached during the year of 2022[2]. In terms of road infrastructure, C-ROADS, consisting of 18 Member States and several additional associated partners, supported by the European Commission, announced they reached a deployment milestone of 20,000 km equipped with ITS-G5 already in June 2021[3]. These infrastructure deployments contribute to additional use cases, while ITS-G5-equipped vehicles communicate directly in an ad-hoc fashion wherever they are moving and do not require relaying by roadside or base station equipment.
A rich ecosystem is already working on Day-2 services, and advanced applications like Collective Perception Service (CPS), Manoeuvre Coordination Service (MCS) and vehicle platooning. To further foster innovation, to leverage all the investments already made and to build up the communication network of talking vehicles instead of starting from zero vehicles and infrastructure again, backwards compatibility is essential. Finally, interoperability is the key enabler to connect all vehicles, vulnerable road users (VRU) and infrastructure to fully leverage the benefits of an ITS network to ultimately save lives.

The motivation for the work of this document lies in spectrum regulation: In 2017, the European Commission mandated[4] CEPT to work on an extension of the ITS band by 20 MHz, under the condition that the band is not segmented amongst technologies: *“It is important to note that the potential spectrum expansion is not intended to support segmentation and segregation between technologies and applications within the same*

[1] https://www.europarl.europa.eu/doceo/document/A-9-2021-0211_EN.html
[2] source IHS Markit, May 2022. ITS-G5 C-ITS equipped models are e.g. VW Golf 8, VW ID 3, ID 4, VW Multivan, Seat Cupra Born.
[3] https://www.c-roads.eu/fileadmin/user_upload/media/saferoadstoday/20210604_SafeRoadsTODAY_Press_Statement_fin.pdf
[4] European Commission RSCOM17-26 rev.3

band and thus to compensate for any cases of inefficient spectrum use." As an outcome, CEPT Report 71[5] was written and reflected this statement again.
In March 2020 in an updated ECC decision (08)01 on ITS, CEPT asked ETSI to develop a method for co-channel coexistence, as described in the CEPT Report 71: *"CEPT invited ETSI to develop sharing and interference mitigation techniques within 3 years, for ensuring co-channel coexistence in the frequency range 5875-5925 MHz between Road ITS and Urban Rail ITS applications and efficient co-channel sharing between Road ITS radio technologies"* and in ECC DEC (08)01 considering (x) "*that ITS devices should apply spectrum access techniques4 in 5875-5925 MHz to enable sharing of the spectrum and that CEPT invited ETSI to develop sharing and interference mitigation techniques within 3 years, for ensuring co-channel coexistence in the frequency range 5875-5925 MHz between Road ITS".*
ETSI studied coexistence and published the extensive ETSI TR 103 766 [ETSI103766] which investigated co-channel coexistence and included comprehensive technical studies and simulation results, while ETSI TR 103 667 [ETSI103667] listed further ideas of coexistence although by means of technology specific priorities and anchor channels which would lead to band-segmentation and segregation.

ETSI TR 103 766 investigated seven co-channel coexistence methods including time-partitioning of the channel (*Method A*) and a common header (*Method C*) and concluded that *"Method A and Method C are the two most promising approaches for co-channel co-existence between ITS-G5 and LTE-V2X"*.
Based on the technical reports from ETSI, CEPT provided in October 2021 a liaison statement back [CEPTFM21] to ETSI, highlighting that *"the sharing solution that will be selected by ETSI shall not lead to a revision of the current spectrum regulatory framework, nor to a demand for more spectrum, nor to the exclusion of all or part of the spectrum of one radio technology. Similarly, fragmentation or segregation of the band for different radio technologies and generations would not be acceptable. Therefore, it is important that the co-channel coexistence solution (including more detailed technical specifications compared to the current overview description) is fair, non-discriminatory and future-proof."*

The present document provides new technical insights on the topic of co-channel coexistence, as an extension of the work already carried-out in ETSI TR 103 766 [ETSI103766] and in line with the mandate by CEPT. The important contributions of the present document are the following:

1. a new co-channel method called "*header insertion method without superframe*" is investigated, which simplifies the use of a common header to mitigate interference,
2. new simulation configurations were applied to expand the scope of ETSI TR 103 766,
3. and the effect of large packets, representative of Day-2 applications is studied.

Three main methods are investigated in this study.

- ***Method enhanced A*** is based on a time partitioning of the channel (e.g., superframe[6] and time slots) obeyed by both technologies. This method is not

[5] https://docdb.cept.org/download/126
[6] A method based on a superframe structure relies on a concept of an external supervising entity not defined yet.

backwards compatible with existing rolled-out vehicles, and thus disruptive as its implementation would require modifications to already deployed ITS-G5 stations.

- ***Method dynamic C*** is based on the insertion of an IEEE 802.11 (WiFi) header[7] at the beginning of the LTE-V2X time slot, with only the LTE-V2X stations following a time partitioning superframe structure. This method is compatible with the already deployed ITS-G5 stations.
- Additionally, a new method called "***header insertion method without superframe***" was investigated in this report. This new method could also be viewed as *Method dynamic C "light"* as it is also based on insertion of an IEEE 802.11 (WiFi) header[8] at the beginning of the LTE-V2X time slot, but does not require a heavy superframe structure, which arguably makes it easier to be implemented for LTE-V2X stations. This method is also compatible with the already deployed ITS-G5 stations.

Results highlight that large packets (typical of Day-2 applications using e.g. Collective Perception Messages or Manoeuvre Coordination Messages) are much more challenging for co-channel coexistence than smaller packet sizes (typical of Day-1 services, such as CAM). Results clearly point out several strong limitations of *Method enhanced A* which yields poor performance for ITS-G5 packets in congested environments for large packets. In this configuration, ITS-G5 inherits drawbacks of time-synchronous systems.

Key result:
While *Method dynamic C* demonstrates strong versatility and adaptability to a broad range of use cases, the new method "*header insertion method without superframe*" performs even better and is the most promising method to achieve co-channel coexistence.
The present document shows that the method "*header insertion without superframe*" is the most promising method for co-channel coexistence. It is the best all-rounder method. It does not require time-synchronization and is backwards compatible with deployment of ITS-G5. It yields performance improvement compared to no method, and always performs similar or better to the method *dynamic C*. This is a remarkable outcome as *header insertion without superframe* is arguably simpler to implement than method *dynamic C*

[7] As further described in chapter 2.2.2 "header" in this context consists of L-STF, L-LTF, L-SIG. The word "header" and "preamble" had been used interchangeable in this and the previous C2C-CC white paper.
[8] As further described in chapter 2.2.2 "header" in this context consists of L-STF, L-LTF, L-SIG. The word "header" and "preamble" had been used interchangeable in this and the previous C2C-CC white paper.

Observation	Observation description
#1	Without mitigation, co-channel coexistence has a strong negative impact for both technologies and both packet sizes on the PRR (packet reception ratio) performance.
#2	For small packets, the methods *enhanced A*/*semi-static C* based on time division are effective in terms of PRR performance, for both technologies.
#3	For large packets, the methods *enhanced A*/*semi-static C* based on time division perform poorly for high densities for ITS-G5, in terms of PRR.
#4	For aperiodic traffic, the methods *dynamic C* and *header insertion method without superframe* improve the PRR performance of both technologies compared to no method.
#5	Method *header insertion method without superframe* always yields better PRR performance than *dynamic C*.
#6	With periodic traffic, the variation in PRR performance between the methods *enhanced A*/*semi-static C, dynamic C and header insertion method without superframe* is reduced.
#7	Large packets are the worst case for co-channel coexistence.
#8	The EED (end-to-end delay)[9] for ITS-G5 is constant across all methods, traffic types and packets sizes. The EED is in the range of 1-5 ms, except for method *enhanced A*.
#9	The EED for LTE-V2X is constant across all methods, traffic types and packets sizes. The EED is in the range of ~50 ms, including the case where LTE-V2X is the only technology.
#10	The EED for ITS-G5 is degraded by 5x with method *enhanced A* (1-2 ms degraded to 10 ms). This degradation gets worse for large packets and/or higher densities up to 25 ms.
#11	The DA (data age)[10] for ITS-G5 is constant across all methods except method *enhanced A*.
#12	The DA for ITS-G5 is degraded with method *enhanced A*, and this gets worse for large packets and/or higher densities.
#13	In terms of DA, periodic traffic yields better results than aperiodic traffic.
#14	The WBSP (Wireless blind spot probability)[11] for ITS-G5 is close to zero for all methods for small packets, while a wide variation between methods is seen for large packets. Method *enhanced A* yields worst performance for large packets.
#15	For both technologies, periodic traffic compared to aperiodic traffic yields worse results in terms of WBSP.
#16	The WBSP for LTE-V2X is similar for all methods / scenarios.
#17	*Header insertion method without superframe* structure always yields similar or better WBSP performance than all other coexistence methods, for both technologies.

[9] EED is the time difference between the packet generation and the packet reception, considering all the links within a maximum distance; processing time is neglected. see chapter 3.8

[10] DA is the time difference between the instant when the last packet correctly received by a given receiver was generated and the instant a new packet is received by the same receiver from the same transmitter, considering all the links within a maximum distance; the DA includes at the same time the transmission delay and the time difference between consequent correctly decoded packets. See chapter 3.8

[11] WBSP is the probability that no packets are received in an interval of a given duration (wireless blind spot duration) by a given receiver from a given transmitter, considering all the links within a maximum distance; this metric intuitively indicates the probability to have no information update from a neighbour within a given time interval. Lower is better for WBSP.

1 Introduction

1.1 Abstract

Two families of technologies are currently proposed as solutions for direct communications among vehicles and roadside units, also called vehicle-to-everything (V2X) communications, in the intelligent transport system (ITS) band at 5.9 GHz. The first family is represented by ITS-G5 [ETSI302663], which is a solution based on the physical and MAC layers of IEEE 802.11p, which is now part of the main Wireless LAN standard IEEE 802.11-2020. It is already deployed in around one million vehicles (forecasted for 2022) and on 20,000 km or European Roads (according to the C-ROADS platform). This standard is expected to be enhanced soon with the features that are being developed by IEEE under the IEEE 802.11 Task Group “bd”. The second family is today represented by the LTE-V2X standard exploiting the PC5 interface and adopting mode 4, which is also called LTE-V2X sidelink and will be hereafter referred to as simply LTE-V2X [ETSI303613]. Within the same family, the 3GPP is also working on the 5G new radio-V2X (NR-V2X), which is a new technology, not interoperable with LTE-V2X, primarily intended for advanced use cases [ETSI137985].

Given that these wireless technologies are planned to operate in the same channels for road safety, CEPT requested ETSI for the investigation of solutions mitigating the possible reciprocal interference, which resulted in ETSI TR 103 766 [ETSI103766] and ETSI TR 103 667 [ETSI103667]. Specifically, ETSI TR 103 667 focuses on partitioning spectrum, whereas ETSI TR 103 766 focuses on co-channel coexistence, i.e., both technologies use the same frequency channel in the same geographical area.

In ETSI TR 103 766, a number of so-called mitigation methods, or simply *methods*, are proposed and preliminary evaluated to mitigate the inter-technology interference when ITS-G5 and LTE-V2X coexist in the same channel and in the same geographical area. A study was also performed by the CAR 2 CAR Communication Consortium (C2C-CC) and presented in a first white paper [C2CWP1]. The scope of the present document is to deepen the investigation of the main methods individuated in [C2CWP1].

It has been in fact already shown in [ETSI103766] and [C2CWP1] that the co-channel operation of ITS-G5 and LTE-V2X without mitigation implies significant degradation of the performance of both technologies, due to the different mechanisms used for the access to the channel. ITS-G5 inherits the access mechanism from the WiFi standard, which is used in billions of devices operating in shared spectrum today. It is an asynchronous technology based on carrier sensing multiple access with collision avoidance (CSMA/CA), implying a listen-before-talk procedure. LTE-V2X does not use such listen-before-talk, but instead requires synchronization among the stations and is based for resource reservation on a procedure known as sensing-based semi-persistent scheduling (SB-SPS); such procedure exploits the past measurements of channel occupation to infer what is probably happening in the future.

As mentioned, some methods were proposed and investigated in [ETSI103766] and further analysed in our previous white paper [C2CWP1]. Restricting the attention to those that were shown to most limit the performance degradation of co-channel coexistence, here we deepen the study and investigate new configurations. More specifically, the so-called methods *enhanced A* and C (recalled in the further) will be considered, as well as a new solution which is based on the *header insertion* concept

that is also part of *method C* (also detailed in the next sections). Results are shown, assuming a highway scenario with 50%-50% technology distribution, from the point of view of a few different metrics and considering packets of different size and both periodic and aperiodic packet generation patterns. Additionally, their applicability to the evolution of ITS-G5 and to NR-V2X is discussed.

1.2 Outline of the document

The rest of the document is organized as follows. Section 2 recalls the considered methods, including the new proposal compared to existing work in ETSI TR 103 766 [ETSI103766] and the previous C2C-CC white paper [C2CWP1]. Section 3 details the simulation environment and settings of this study. Then, the results are discussed in terms of various metrics from Section 4 to Section 7. The applicability of the investigated methods to the future technologies is discussed in Section 8, before concluding the document with summary considerations in Section 9.

2 Considered mitigation methods

2.1 Introduction

In this section, the considered methods are described and their effectiveness is discussed. More specifically, the so-called *enhanced A*, *semi-static C*, and *dynamic C* methods are recalled, and the new solution called *header insertion method without superframe* is detailed. A preliminary high-level comparison is finally provided.

2.2 Method *enhanced A*

The *enhanced A* is described in [ETSI103766, Clause 6.3.1], based on the principle of time division multiplexing (TDM). It assumes an organization of the time axis in *superframes* of a given duration (e.g., 25 ms), each of them consisting of a portion exclusively dedicated to LTE-V2X, called *LTE-V2X time slot*, and the remaining portion exclusively dedicated to ITS-G5, called *ITS-G5 time slot*. Guard intervals can be used to separate the time slots.

The configuration of the LTE-V2X and ITS-G5 time slots is normally either static, which presumably implies some inefficiencies due to the inability to adapt to variable proportion of ITS-G5 to LTE-V2X equipped stations, or semi-static. A very likely example of possible inefficiency is the case where only one technology is present in a certain communication area, in which case an improperly configured method A may lead to the same resource waste as for technology dedicated channels (band split). If the semi-static configuration is used, a supervising entity must be implemented (which could prove challenging due to the need to aggregate some form of local measurements, and from roads administrated by a variety of different operators), and the stations must be periodically connected to an infrastructure to be reached by such entity. The methodology used by the supervising entity to take the decisions is still an open point. In the case of static and semi-static configuration, the ITS-G5 stations can optionally derive the superframe and time slot boundaries by performing some measurements and detecting ITS-G5 transmissions and non-ITS-G5 transmissions, as better detailed in [ETSI103766, Clause 6.3.3.3]. This feature needs further investigations.

Dynamic configurations are also stated possible in [ETSI103766], although their implementation for this method is not specified and thus appear unclear. In fact, even assuming that the ITS-G5 stations can infer the superframe structure by estimating LTE signals (which might need further investigations), still the LTE-V2X stations must adhere to a common time slot length at least locally, which is thus presumably received again from a supervising entity and thus not different from the semi-static approach.
Note: Methods with superframe structure rely on a supervising entity which is not solved – this would need to be adaptive on local traffic and technology appearance with different technology splits to be spectrum efficient. For this purpose a supervising entity would be required which at the same time would be non-compliant with highest safety requirements for functional safety.

All stations know and adhere to the organization, which also implies that all stations need to be synchronized in time with a certain accuracy, which was shown not to be critical in [C2CWP1]. Each station, equipped with either technology, is allowed to start and complete a transmission only in the correspondent time slot. In the case of LTE-

V2X, this can be implemented by reducing the pool of resources that a station can access, which is a capability foreseen by the specifications. In the case of ITS-G5, new features need to be implemented.

Additionally, in the case of ITS-G5, an artificial delay is added at the generation of each new packet[12] in order to cope with what is hereafter called *channel rush problem*, as better detailed in the further. This feature was added to the originally designed method A and motivated the use of the term *enhanced* for the method.

The channel rush problem in ITS-G5 corresponds to the following effect: if several ITS-G5 stations have packets waiting in the transmission queue at the end of the LTE-V2X time-slot, they sense the channel empty at the same time and they all concurrently start the CSMA/CA backoff mechanism, leading to an increased probability of collisions. To avoid the channel rush problem, the method *enhanced A* assumes that ITS-G5 stations introduce an artificial delay from the instant in which the packet is received at the MAC layer and the instant when the sensing and backoff procedure is started. Such delay is defined to be proportional to the time that remains to the end of the superframe minus the transmission duration and allows to almost distribute the beginning of the sensing and backoff procedure uniformly within the ITS-G5 time slot. More details are provided in ETSI TR 103 766 [ETSI103766] and in the previous C2C-CC white paper [C2CWP1].

An example is provided in Fig. 2-1, where three ITS-G5 stations introduce an artificial delay before the sensing and backoff procedures; two of them are assumed to generate a new packet within the LTE-V2X time slot, whereas the other one generates the new packet during the ITS-G5 time slot. The artificial delay is added after the generation of each of the three messages, even if generated during the ITS-Gt time slot; the artificial delay is smaller when the packet is generated later within the superframe.

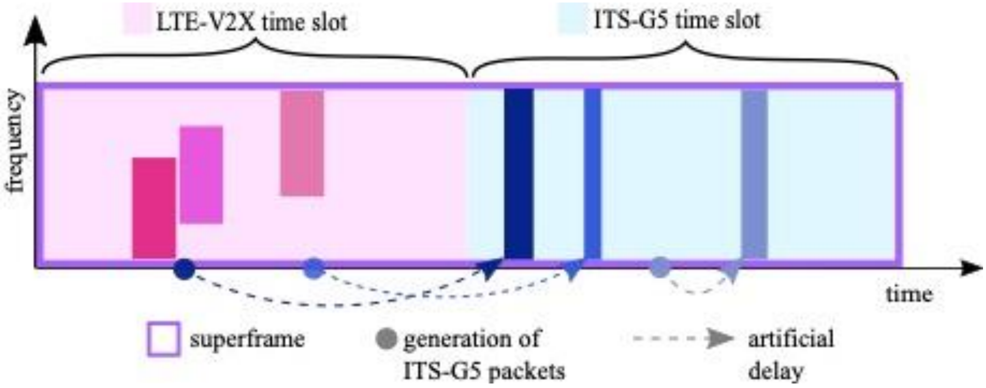


Fig. 2-1 Example illustration of a superframe with three ITS-G5 and three LTE-V2X stations transmitting under enhanced A or semi-static C; in the case of ITS-G5, an artificial delay is added starting from the generation instants.

2.3 Method C

Method C is described in [ETSI103766, Clause 6.3.3], also based on the superframe structure, this time known only by LTE-V2X stations. The idea of *method C* is to

[12] In principle, it would be more appropriate to use the term *message* at the facilities layer, *packet* at networking & transport layer, and *frame* at the access layer. However, given that one message always corresponds to a packet and to a frame, and considering that the term packet is normally used in a broader sense, here the term packet is always used for the sake of simplicity.

introduce at the beginning of each LTE transmission the IEEE 802.11 (WiFi) header, hereafter called *header insertion* for the sake of conciseness, which informs of the duration of the transmission. Without any modification to the ITS-G5 devices, the duration indicated in the IEEE 802.11 signal field of this preamble allows ITS-G5 stations to perceive the channel as busy during the whole LTE-V2X time slot and defer the sensing and backoff process accordingly. Additionally, since the header is recognized by ITS-G5 stations, they will assume the channel as busy when the header is detected, which occurs with received power that depends on the receiver but can be below -85 dBm. If no header is detected, instead, the channel is considered busy only when the signal power is above -65 dBm based on energy detection.

The header insertion requires an extension of the LTE-V2X physical layer, however the header added to the LTE-V2X signal is the same for all transmitters and can be implemented through a fixed sequence of IQ samples (refer to [ETSI103766] for further details). Additionally, the header insertion, lasting 40 µs, can be placed at the beginning of the first LTE-V2X OFDM symbol, which is primarily intended for automatic gain control (AGC) settling, and lasts 71.5 µs. Given that this first LTE-V2X OFDM is not required for proper decoding of the LTE-V2X payload (the performance requirements tests instruct to blank out the first symbol), the header insertion is assumed to have no impact on the decoding performance and data-rate of LTE-V2X. Additionally, since the preamble is strictly the same and because of the properties of OFDM, the signal simultaneously sent from multiple LTE-V2X stations in the same subframe is assumed to not interfere to each other. Instead, from the receiver's perspective, it should appear as just multiple paths of a single signal, similarly to a distributed antennas type of setup.

The header insertion mechanism is exploited in *method C* in two different ways, depending on whether the semi-static or the dynamic configuration is considered. A static configuration is also possible, which has the same characteristics of the semi-static except for a rigid definition of the superframe, and which will not be further considered in this document.

2.3.1 Method C with semi-static configuration

In the semi-static variant, the LTE-V2X nodes indicate in the header the remaining duration of the LTE-V2X time slot, via the IEEE 802.11 signal field, with an upper bound of 10 ms (due to limitations in the header field settings). Please note that, even if the LTE transmission performed in the first subframe can indicate up to 10 ms and might thus not be capable to advertise the entire length of the LTE-V2X time slot, other transmissions are performed by LTE-V2X nodes in the next subframes of the same time slot and will indicate additional intervals. This variant of the Method C is referred to as 'option 2' in [ETSI103766], Clause 6.3.3.

Based on the information derived by the received headers, the ITS-G5 nodes will infer the superframe structure and will access the channel during the ITS-G5 time slot. To avoid the channel rush problem, the same deferring procedure detailed in Section 2.2 is used.

The *semi-static method C* requires that the ITS-G5 nodes are aware of the superframe structure (e.g., a superframe duration of 25 ms) and the overall procedure, even if there is no need for a connection towards the supervising entity for ITS-G5 stations. The impact of possible synchronization inaccuracies was shown not significant in [C2CWP1].

If the estimation of the time slots partitioning by the ITS-G5 stations is effective, the behaviour is the same of *enhanced A*. For this reason, common performance of *enhanced A* and *semi-static C* will be shown in the further.

2.3.2 Method C with dynamic configuration (*dynamic C*)

In the dynamic configuration, the header sent by LTE-V2X stations always indicates 1 ms and has two functions. First, it allows ITS-G5 stations to sense the channel as busy when the preamble is detected, which corresponds to a received power lower than -85 dBm as per the specifications, but even lower than -95 dBm in practical implementations (in contrast, the CCA threshold is defined as -65 dBm); the significance of this effect is further discussed in [Baz22]. Second, it prevents that transmission start during the last OFDM symbol of LTE-V2X, which is left empty to allow (LTE-V2X) transmission-to-reception switch; further discussion of this issue can be found in [ETSI103766, Clause 5.2.1]. This variant of the *Method C* is referred to as ‘option 1’ in [ETSI103766], Clause 6.3.3.

In the case of *dynamic C*, no modification is required on the ITS-G5 side and thus it is fully compatible with ITS-G5 stations already rolled-out. This aspect is particularly relevant, since as per mid-2021, in Europe and based on ITS-G5, already 20’000 km of roads were covered by RSUs and more than 500’000 vehicles were equipped with OBUs that share C-ITS services [CROADS21, NXP21,VW20]. All these RSUs and OBUs are equipped and use ITS-G5 as current defined, therefore the implementation of a co-channel coexistence method that is fully backward compatible increases the effectiveness of the inter-technology interference mitigation (please refer to the Annex D of [C2CWP1] for the definition of backward compatible).

An example of *dynamic C* is provided in Fig. 2-2. In that case, two transmissions from ITS-G5 stations are performed during the LTE-V2X time slot in unused subframes.

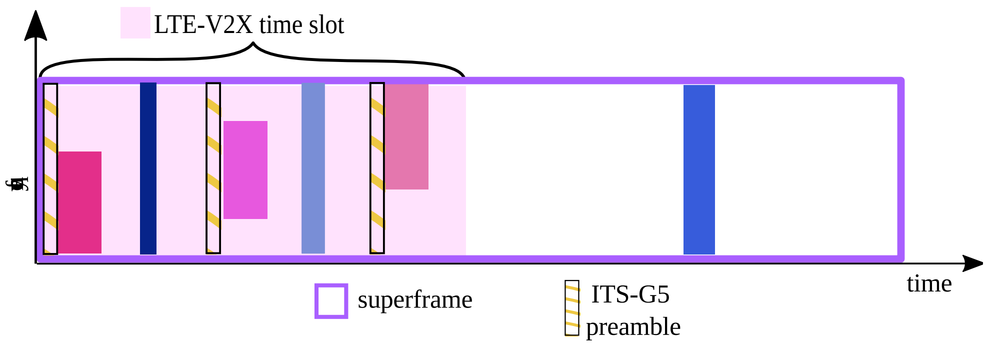


Fig. 2-2 Example illustration of a superframe with three ITS-G5 and three LTE-V2X stations transmitting under dynamic C.

2.3.3 *Header insertion method without superframe* (Method dynamic C “light”)

A new solution, named *header insertion method without superframe* is here also considered. This solution has been proposed in [Baz22] and echoes a proposed

coexistence solution described in a former ETSI LS to CEPT[13]. It assumes an 802.11 (WiFi) header insertion indicating 1 ms reservation, at the beginning of each LTE-V2X transmission, just as for *dynamic C*. However, differently to *dynamic C* option1, no superframe structure is involved from LTE-V2X stations' perspective. Thus, this new method can also be viewed as “Method C option 1 light”, or “Method Dynamic C light”. Alternatively, given the header insertion commonalities, this new solution could also be viewed as a new variant of Method C, possibly called “Method C option 3”, continuing with numbering of the ETSI TR 103 766[ETSI103766].
The LTE-V2X stations reserve their resources in the same way as in the absence of the coexistence method. This means that LTE-V2X stations do not need to perform measurements as in *dynamic C*, arguably leading to less changes required for LTE-V2X implementations. Like with *dynamic C*, this method is fully backward compatible with ITS-G5 stations already rolled-out.

This method is exemplified in Fig. 2-3.

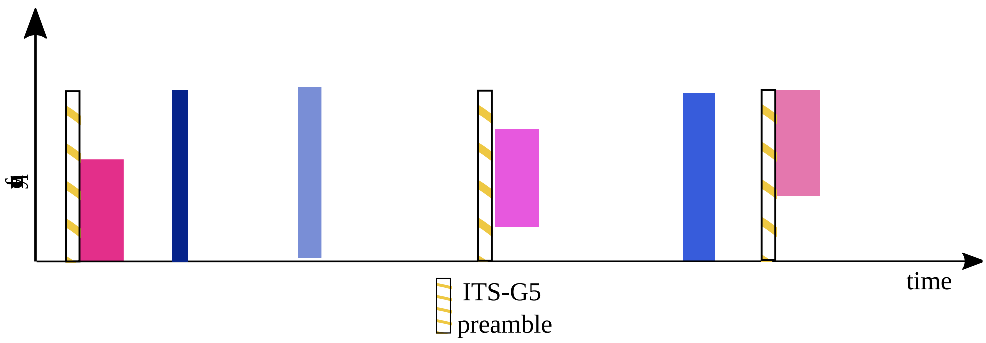


Fig. 2-3 Example illustration with three ITS-G5 and three LTE-V2X stations transmitting under the method with *header insertion without the superframe* structure.

2.4 Summary of the considered methods

The main characteristics of the considered methods are summarized in Table 2-1.

Per each method, the following aspects are considered:

- If the method is based on superframe and time slots.
- If the superframe structure is known by both technologies or just one.
- If semi-static configuration of the superframe is normally used or only possible.
- If dynamic configuration of the superframe is also explicitly possible or its implementation needs clarifications.
- If there is need for a supervising entity, which is not intended in an ad-hoc network.
- If a local distribution of the configuration parameters is required and for which technology.
- The main modifications required by LTE-V2X stations.
- The main modifications required by ITS-G5 stations.
- How variations in the technology proportion are managed.
- The countermeasure introduced to the issue that the last OFDM symbol is left empty in LTE-V2X, called “last symbol gap” issue.

[13] ETSI LS to CEPT FM: Doc. FM(18)135 ”Complementary LS from ETSI to WG FM and WG SE on work progress on the ITS mandate subject", annex to the document, clause 4.2.2.4

- The compatibility with legacy ITS-G5 stations, given that stations and road-side units equipped with this technology are already respectively on the market and deployed in mass market.

Features	*Enhanced A*	*Semi-static C*	*Dynamic C*	*header insertion without superframe*
Superframe and time slots	Yes	Yes	Yes	No
Superframe awareness	Both technologies	LTE-V2X only; inferred in ITS-G5	LTE-V2X only	-
Static/semi-static configuration	Main choice	Yes	No	-
Dynamic configuration	Needs clarifications	No	Yes	-
Supervising entity orchestration	Yes, connected to both technologies[14]	Possibly, LTE-V2X only	Not needed	Not needed
Locally distribution of configuration parameters	Required for both technologies in the semi-static configuration	Required for LTE-V2X	Not needed	Not needed
Main modif. to LTE-V2X	None at the physical layer[15]	Header insertion	Header insertion; measurements performed by the LTE-V2X stations to infer the LTE time slot duration	Header Insertion
Main modif. to ITS-G5	Superframe level time synchronization and superframe management	Superframe level time synchronization	None	None
Management of technology proportion	Fixed and therefore inefficient in static config.; centralized in semi-static config., requiring tuning to avoid unfair allocation	Centralized; needs tuning in LTE-V2X to avoid unfair allocation	Autonomous; requires effective protocols to estimate the technology proportion	Independent on the technology proportion
About LTE “last symbol gap”	Time slots known by ITS-G5	Indication in header	Indication in header	Indication in header
Compliancy with already rolled-out ITS-G5	No[16]	Not completely[17]	Yes	Yes

Table 2-1: Summary comparison of the main characteristics of the methods

[14] Even if method A has been designed for use of supervising entities in both technologies, in [ETSI103766] a solution is proposed to allow implementing the supervising entity only in LTE-V2X.
[15] LTE-V2X already foresees a mechanism to allow restricting the use to some subframes; yet, the upper layer time division structure and the measurements are to be defined.
[16] Legacy ITS-G5 stations are not aware of the superframe structure. They will act as there was no mitigation methods.
[17] Legacy ITS-G5 stations are not able to identify the superframe and synchronize to it. Still, they are able to read the IEEE802.11 (WiFi) header sent by the LTE-V2X stations and defer their access to the channel accordingly.

3 Simulator and Settings

3.1 Introduction

Results in this document have been obtained with the open source WiLabV2Xsim simulator [Tod21], adopting a subversion based on 6.0.[18] WiLabV2Xsim is developed by the National Laboratory of Wireless Communications (WILAB) of CNIT, CNR-IEIIT and University of Bologna.
In this section, the main settings are listed and justified.

3.2 Summary of settings

The main settings adopted in the simulations are summarized in Table 3.1. All numerical values are discussed, with references when applicable, in the following subsections.

Parameter	Setting
Road layout	Highway with 3+3, 4 m width
Road length	8 km
Number of vehicles in the scenario (density)	From 24 to 288 (From 3 to 36 vehicles/km)
Average vehicle speed	120 km/h
Packet size	350 bytes or 1000 bytes
Packet generation interval	Fixed 10 Hz or following CAM rules in [ETSI3026372]
Carrier frequency	5.9 GHz
Bandwidth	10 MHz
Path-loss model	Modified ECC Report 68 rural [ETSI103439]
Shadowing	Log-normal, 3 dB variance, correlated with decorrelation distance 25 m
Transmission power density (before antenna gain)	13 dBm/MHz
Antenna gain (both TX and RX)	3 dBi
Noise figure	6 dB
Synchronization	Ideal
Congestion control	Disabled
Main settings in ITS-G5 (ETSI EN 302 663 V1.3.1, January 2020)	For 350-byte packets: MCS 2 (QPSK, coding rate 0.5); SINR threshold 1.2 dB (see Annex B) For 1000-byte packets: MCS 2 (QPSK, coding rate 0.5); SINR threshold 2.4 dB (see Annex B) Arbitration inter-frame space 110 us Maximum contention window 15 Sensing threshold for unknown signals -65 dBm Received power for preamble detection -98 dBm

[18] This work is based on a subversion of WiLabV2Xsim 6.0 (https://github.com/V2Xgithub/WiLabV2Xsim), which is an update of the LTEV2Vsim 5.4 (https://github.com/alessandrobazzi/LTEV2Vsim) used in [C2CWP1]. The functions related to coexistence used for the white paper are available upon request. Modifications will be included in future releases of the software.

Parameter	Setting
Main settings in LTE-V2X (ETSI EN 303 613 V1.1.1, January 2020)	Subchannel size 10, adjacent configuration For 350-byte packets: MCS 7 (QPSK, coding rate ~0.6); SINR threshold 3.0 dB (see Annex B), 3 subchannels; For 1000-byte packets: MCS 11 (16-QAM, coding rate ~0.5); SINR threshold 5.9 dB (see Annex B), 5 subchannels; Mode 4 with *keep probability* 0.5, minimum power level to sense a resource as busy -110 dBm, selection window between 1 and 100 TTI Minimum (parameter T_1) and maximum (parameter T_2) allocation delay 0 and 100 ms Resource repetition interval 100 ms Blind retransmissions (HARQ) disabled
Output metrics (see section 3.8)	Packet reception ratio (PRR), calculated in steps of 50 m End-to-end delay (EED), calculated within 300 m Data Age (DA), calculated within 500 m Wireless blind spot probability (WBSP), calculated within 300 m
Coexistence configuration, when applicable	In *enhanced A*/*semi-static C* and *dynamic C*, superframe 25 ms In *enhanced A*/*semi-static C*, 13 ms LTE-V2X time slot and 12 ms ITS-G5 time slot

Table 3-1: Main simulation settings

3.3 Scenario

A highway scenario with 3+3 lanes is considered with variable density, from 3 to 36 vehicles/km. For any considered density, the vehicles are driving at average 120 km/h speed, which is compatible with the considered range of densities based on real measurements.

Vehicles are evenly distributed over the lanes, with initial position randomly dropped with uniform distribution over the road length. Wrap-around mobility model is applied, meaning that when a vehicle exits the scenario it enters the same lane from the opposite end of the road segment. Each vehicle moves at a speed which is randomly selected from a Gaussian distribution, with a standard deviation equal to one tenth of the average speed.

With the aim to have an indication of how much the channel is loaded varying the density, in Fig. 3-1, the median CBR is shown varying the density assuming that only one of the two technologies is used, with packets of 350 or 1000 bytes, assuming the CAM generation rules (details in the following Section 3.4). Given that the average speed is constant varying the density, the average number of packets generated by each station is also constant and the CBR linearly increases with the density. In the case of ITS-G5, changing the packet size from 350 bytes to 1000 bytes increases the duration of a transmission almost proportionally, and therefore the CBR increases approximately of a factor three. In the case of LTE-V2X, each transmission always lasts 1 ms, and what changes is the number of used subchannels (from three to five). In principle, with 350 bytes less subchannels are used and therefore the CBR is lower; however, given the contribution of the in-band emission to the measured power, the CBR is only slightly lower when 350 bytes are assumed compared to 1000 bytes.

The considered range of densities allows to perform the performance investigation targeted by this white paper with low to high channel occupation but avoiding reaching very congested conditions, where congestion control mechanisms must intervene. At the occurrence of a congestion under coexistence, in fact, congestion control of one technology necessarily activates first and this alters the overall evaluation. Specific studies on the impact of congestion control are required and adjustments to current algorithms might be needed, but this is beyond the scope of the current document.

Based on these considerations, the congestion control mechanisms are deactivated in all simulations discussed in the present document.

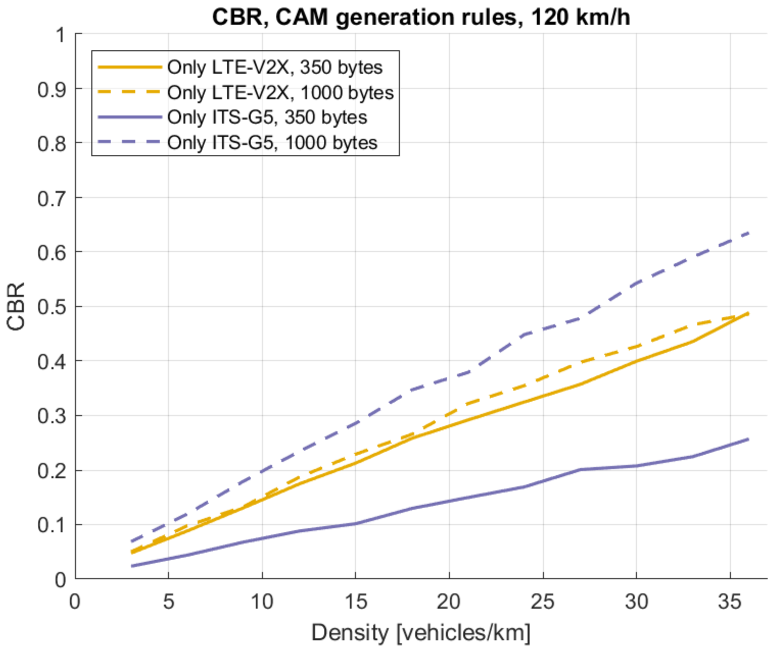


Fig. 3-1 Average CBR vs. density, assuming all C -ITS-S either equipped with ITS-G5 or with LTE-V2X

3.4 Packet size and generation patterns

The simulations reported in this document refer to packets sent continuously by all vehicles in the scenarios. Two sizes are considered to account for current and future services, where the size is indicated referring to the number of bytes of the protocol data unit received at the access layer. The first size is 350 bytes, which is the size of cooperative awareness messages (CAMs) occurring with highest probability in [MarBer18, Mol20]; similar size is also expected for messages related to other services under definition, such as the vulnerable road user awareness messages (VAMs) and those related to platooning [ETSI103439]. The larger size is motivated by the fact that several other services under definition are expected to generate messages of 1000 bytes and even more in some cases. For example, as described in [ETSI103439] and the references therein, the collective perception messages (CPMs) are expected in the range 1000-1900 byes, manoeuvre coordination messages (MCMs) are expected in the range 1000-1300 bytes, and other messages for example related to intersection management or positioning correction are expected of 1000 or more bytes.

Please note that packets are all assumed of the same given size in each simulation. This assumption is in general not expected in real packet generation, as shown for example in [MarBer18] referring to CAMs, and it is used here to simplify the discussion on coexistence. The reason is that, whereas in the case of ITS-G5, packets of variable sizes are easily handled, they can be managed in different ways by LTE-V2X. Indeed, in LTE-V2X, resources of a given size are periodically reserved by SB-SPS and allocating and transmitting consecutive packets of variable size can be handled in different ways. In particular, the main approaches in LTE-V2X are either to waste resources if large resources are reserved and perform a reselection every time a small resource is reserved [Mol20b] or to keep a constant resource size and change the MCS according to the packet size [QLC21, Bar21]. Whereas the former approach causes frequent reselections and unreliable sensing of SB-SPS, the latter implies that the performance of LTE-V2X is limited by the performance of the largest packets (also noting that the largest packets are normally those carrying the certificates and are therefore of primary importance). Assuming packets of the same size allows here to only focus on the impact of coexistence.

Two packet generation patterns are assumed:
1. *Aperiodic generation:* packet generation is based on the rules defined for CAMs in [ETSI3026372].
2. *Periodic generation*: packets are generated periodically, at 10 Hz.

In the case of aperiodic generation, given that the speed of each vehicle is fixed, but different from vehicle to vehicle, packets are generated periodically at the facilities layer of each vehicle, but with a different periodicity from vehicle to vehicle. Even looking at the single vehicle, the periodicity is in general lower than the resource repetition interval adopted in LTE-V2X (which is set to 100 ms) and therefore implies the same effect as aperiodical generations.

The periodic generation case is relevant because the 10 Hz periodicity means 100 ms inter-packet generation, which perfectly matches the resource repetition interval used in LTE-V2X. As a first note, even if this is not the general case based on the specifications, it might occur during some time intervals in particular scenarios, for example due to high speed, where 10 Hz is used as a maximum generation periodicity for CAMs.

More importantly, the implications of the periodic generation, discussed in the further, hold also if the inter-packet generation is not strictly equal to 100 ms, but always a multiple of 100 ms. This case is possible based on the specifications, since the specification on CAM generation [ETSI3026372, Clause 6.1.3] state that the condition for a CAM generation can be checked every 100 ms (it needs to be equal or less than 100 ms). This constraint means that an implementation where the inter-packet generation interval is always a multiple of 100 ms is possible, and indeed this effect is confirmed by the measurements performed on field that are shown in [MarBer18, Section 6.7].

3.5 Access layer configuration

The carrier frequency is 5.9 GHz, and a channel of 10 MHz is assumed. All transceivers are half duplex. All vehicles are assumed to transmit with the same power density of 13 dBm/MHz, and with the same antenna gain, both for transmission and reception, $G_a = 3$ dBi (as an average value of MobileMark [SMW314]). At the receiver, a noise figure $F_n = 6$ dB is assumed (as the NXP SAF5400 [SAF5400]).

As motivated in Section 3.3, congestion control is not performed.

3.5.1 Configuration of ITS-G5

In the numerical simulations, all stations adopt the same modulation and coding scheme (MCS). Following the specifications, MCS 2 (quadrature phase-shift keying, QPSK, with code rate ½) is adopted in ITS-G5 for both packets of 350 and 1000 bytes.

Additionally, for the ITS-G5 stations, the arbitration inter-frame space (AIFS) is set to 110 µs and the maximum contention window (CW) number to 15.

3.5.2 Configuration of LTE-V2X

Also in the case of LTE-V2X, all stations are assumed to adopt the same MCS. Coherently with [C2CWP1], when packets of 350 bytes are considered, MCS 7 is adopted in LTE-V2X, in order to have a similar modulation and coding scheme; in this case, QPSK with code rate approximately 0.6 is used and each packet occupies 3 of the 5 available subchannels that are mandated by the profile specification in one 10 MHz channel [ETSI303613]. As further elaborated in Annex D, differently, for packets of 1000 bytes, a higher MCS is necessarily required for LTE-V2X, since with MCS 7 it is not possible to allocate a packet of 1000 bytes in a single subframe. In this case, MCS 11 is used, which is the most robust MCS able to allocate one packet of 1000 bytes in one subframe. In this case, 16-QAM with code rate approximately 0.5 is used and each packet occupies all the 5 available subchannels. Clearly, adopting a higher MCS comes at the cost of a lower reliability and therefore of less robustness against interference and reduced range.

For LTE-V2X stations, the adjacent configuration is assumed for the transmission of the sidelink control information (SCI). Regarding the resource repetition interval, 100 ms is used for all scenarios. Finally, in the sidelink mode 4 algorithm settings, the power threshold of initial identification of busy resources is set to -110 dBm and the parameter called keep probability is set to 0.5, as intermediate value between 0 and 0.8. To better focus on the coexistence issues, the blind retransmissions (sometimes called HARQ) are disabled for all densities, which is in line with what done for similar speed in [ETSI103766], although not always in line with the ETSI profile. Indeed, it has been shown that they help only in very light traffic scenarios (see, for example, [MarYas18,Nai20]), so that increasing the density the retransmissions are anyway disabled based on the measured CBR. It can be anyway noted that the use of blind retransmissions in LTE-V2X doubles the traffic generated by LTE-V2X stations, and therefore its impact from the perspective of ITS-G5 is approximately the same as with double the LTE-V2X stations.

3.6 Propagation and physical layer modelling

Given the scenarios, the propagation is assumed as always in line-of-sight (LOS) conditions. The propagation is modelled by the path-loss and correlated shadowing. Differently from the previous white paper [C2CWP1], where the propagation was modelled using the path-loss proposed by the WINNER+, scenario B1, in compliance with [ETSI103766], here the modified ECC Report 68 rural model is used as detailed in

[ETSI103439]. More details on these models is are provided in Annex A. It is to note that the results provided with the ECC Report 68 rural model anyway provide an indication of what is achievable assuming the other one, as further discussed in Annex A. Like in [C2CWP1], the shadowing is log-normally distributed with zero mean and a standard deviation of 3 dB, and is correlated with decorrelation distance 25 m. The effect of small-scale variations of the channel is instead modelled through the definition of appropriate requirements in the minimum average signal to interference and noise ratio (SINR) needed to correctly decode the received frame, as summarised hereafter and detailed in Annex B.

During the simulation, the correctness of each reception is determined starting from the calculation of the average SINR, as detailed in Annex B of [C2CWP1]. Given a certain SINR, a packet is assumed as correctly received if the SINR is above a given threshold and lost otherwise. As shown in Annex B, this approach provides results very close to those obtained by probabilistically deriving the packet loss using curves of packet error rate (PER) vs. SINR, as done in [C2CWP1], which require link level simulations also considering the impact of small-scale fading. As motivated in Annex B, the SINR threshold is set for ITS-G5 to 1.2 dB with packets of 350 bytes and to 2.4 dB with packets of 1000 bytes, and for LTE-V2X to 3.0 dB with packets of 350 bytes and to 5.9 dB with packets of 1000 bytes.

3.7 Assumptions related to the methods

In this section, the main assumptions and approximations adopted in the simulation of the mitigation methods are discussed.

In all cases, all nodes are assumed ideally synchronized. Discussing how to obtain synchronization in LTE-V2X or ITS-G5 is outside the scope of the present document. The impact of an error in the synchronization of ITS-G5 nodes was discussed in [C2CWP1].

3.7.1 Assumptions related to *enhanced A*

No relevant assumptions or approximations need to be indicated for method A.

3.7.2 Assumptions related to the methods including the header insertion

In *method C* and in the method adopting *header insertion without the superframe* structure, the following assumptions and approximations apply.

1. The IEEE802.11 (WiFi) header added to the LTE-V2X signal is not explicitly simulated; this implies that the LTE-V2X physical sidelink shared channel (PSSCH) decoding performance is approximated as the same as without the header insertion; the impact of this approximation is expected to be negligible.
2. The IEEE802.11 (WiFi) header sent by LTE-V2X stations is not explicitly simulated; rather, at the beginning of each subframe, per each of the ITS-G5 station which are not yet transmitting or receiving another signal, the power received from all the transmitting LTE-V2X stations is summed (recalling that the header is the same for all LTE-V2X stations and transmissions behave as multiple paths at the receiver) and the header is assumed as detected if the

received power exceeds –98 dBm and the corresponding average SINR is above 0 dB.[19]

3. In the *semi-static configuration of method C*, the ITS-G5 stations procedure to acquire the superframe structure is assumed ideal; therefore, the performance of *semi-static C* is the same as the *enhanced A*.
4. In *dynamic C*, the technology percentage is estimated by LTE-V2X nodes adopting the same solution detailed in [C2CWP1, Annex A].

3.8 Output metrics

Results are obtained in terms of the following output metrics.

- PRR, which is computed as the average ratio between the number of stations correctly decoding a packet at a certain distance from the transmitter and the overall number of stations at the same distance.
- End-to-end delay (EED), which is the time difference between the packet generation and the packet reception, considering all the links within a maximum distance; processing time is neglected.
- Data age (DA), which is the time difference between the instant when the last packet correctly received by a given receiver was generated and the instant a new packet is received by the same receiver from the same transmitter, considering all the links within a maximum distance; the DA includes at the same time the transmission delay and the time difference between consequent correctly decoded packets.
- Wireless Blind Spot Probability (WBSP), which is the probability that no packets are received in an interval of a given duration (wireless blind spot duration) by a given receiver from a given transmitter, considering all the links within a maximum distance [Baz20]; this metric intuitively indicates the probability to have no information update from a neighbour within a given time interval.

Details on the calculations of each figure is provided at the beginning of the sections where it is investigated.

[19] To take into account that the preamble is more protected than the packet, it is assumed correctly decoded when the SINR is above 0 dB, which implies a minimum received power of approximately -98 dBm to successfully decode the preamble in the absence of interference. This value is in good agreement with common IEEE 802.11p receivers.

4 Impact in terms of packet reception ratio

4.1 Definition of packet reception ratio

The PRR is computed as the average ratio between the number of stations correctly decoding a packet at a certain distance from the transmitter and the overall number of stations at the same distance.

The PRR is obtained considering the transmitter-receiver distance with steps of $d_{step} = 10$ m; in other words, the PRR at $d_{step} \cdot \mathrm{K}$ meters (where K is a positive integer) is calculated as the ratio between all correct receptions by stations within $d_{step} \cdot (\mathrm{K}-1)$ and $d_{step} \cdot \mathrm{K}$ meters from the source and all the stations within the same distances from the source. PRR is shown varying the distance.

Differently from [C2CWP1] and [ETSI103766], where the PRR vs. distance was normally provided, here results are shown in terms of maximum distance to have PRR>0.9. This allows to have in a single plot the results varying the vehicle density.

4.2 Results in terms of packet reception ratio

The performance in terms of maximum distance to have PRR>0.9 vs. vehicle density is shown in Fig. 4-1 for aperiodic traffic generation and in Fig. 4-2 for periodic traffic. Please remark that the aperiodic traffic is what normally expected on field, as also observable looking at the measurements discussed in [MarBer18], which were done on the road with real devices, and that the periodic traffic may occur in some particular cases or with specific implementations, as discussed in Section 3.4. The periodic traffic is relevant due to the specific algorithms adopted by LTE-V2X for the mode 4 resource allocation procedure.

Taking as an example Fig. 4-1, four subfigures are shown corresponding to either 350 bytes (Fig. 4-1a and Fig. 4-1b) or 1000 bytes (Fig. 4-1c and Fig. 4-1d), and either the point of view of ITS-G5 (Fig. 4-1a and Fig. 4-1c) or that of LTE-V2X (Fig. 4-1b and Fig. 4-1d). In each subfigure, five curves are shown corresponding to the following cases.

- *Only ITS-G5/only LTE-V2X*: all vehicles mount the same technology, which is either ITS-G5 or LTE-V2X.
- *No method*: 50% vehicles are equipped with ITS-G5 and 50% are equipped with LTE-V2X; no coexistence mitigation method is adopted.
- *Enhanced A/semi-static C*: 50% vehicles are equipped with ITS-G5 and 50% are equipped with LTE-V2X; the *enhanced A* or the *semi-static C* is adopted.
- *Dynamic C*: 50% vehicles are equipped with ITS-G5 and 50% are equipped with LTE-V2X; the *dynamic C* is adopted, with the settings detailed in Section 3.7.2.
- *Header insertion without superframe*: 50% vehicles are equipped with ITS-G5 and 50% are equipped with LTE-V2X; LTE-V2X transmissions include the IEEE802.11 (WiFi) header as in *method C*, but there is no superframe structure.

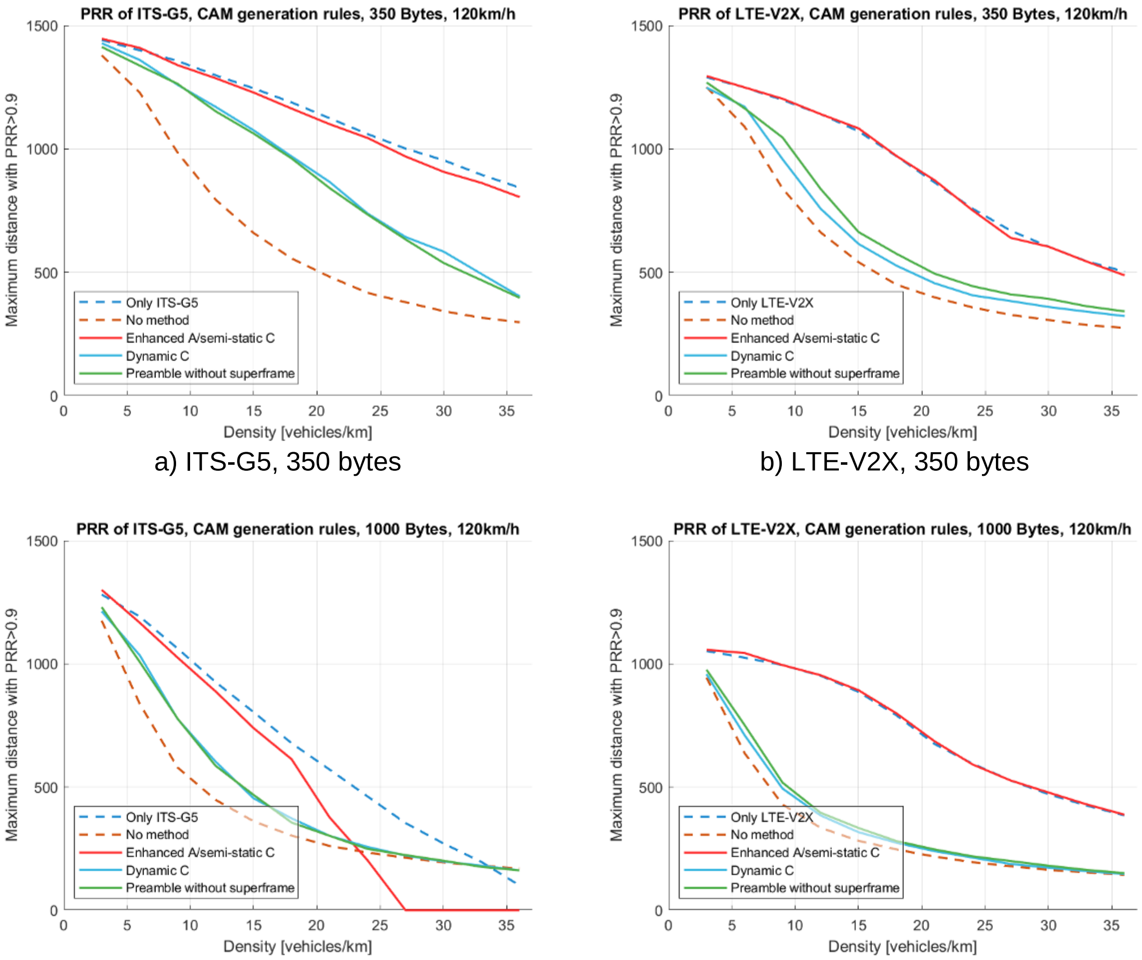
This structure of Fig. 4-1, organized in subfigures each including five curves, is used also in Fig. 4-2 and in the following sections (until Section 7).

Let us first focus on the aperiodic traffic in Fig. 4-1. Looking at the dashed curves, it can be observed that the co-channel coexistence has a strongly negative impact for both technologies and packet sizes. This confirms what already concluded in [C2CWP1] and [ETSI103766] and remarks the necessity of some coexistence mitigation methods in the case both technologies are deployed in the same band.

Looking at the red solid curve corresponding to *enhanced A/semi-static C*, in most of the cases the time-split envisioned by the method is effective in terms of PRR. Please remark that in this study the time slots proportion (12 ms ITS-G5 and 13 ms LTE-V2X) is perfectly aligned with the technology splitting (50% ITS-G5 and 50% LTE-V2X), which is an optimistic scenario. An unfair improvement of the performance of one technology at the expense of the other is expected if other settings are assumed (as already shown in [C2CWP1]). However, even in this optimistic situation, a critical case can be observed from the point of view of ITS-G5 when 1000 bytes is assumed, and the channel load increases. The reason for this behaviour is further discussed in the following section (i.e., Section 4.3).

If we now focus on *dynamic C* (light blue solid curve) and *header insertion without superframe* (green solid curve), it can be observed that these methods allow to improve the performance of both technologies compared to no method. In line with previous results, the improvement is higher for ITS-G5, especially when 350 bytes are assumed. When 1000 bytes are assumed, the ITS-G5 transmission lasts for approximately 1.4 ms (excluding the channel access delay), which is significantly longer than the duration of an LTE-V2X subframe (1 ms). This means that the ITS-G5 transmission spans over at least two subframes; therefore, the generic ITS-G5 station is able to exploit the preamble mechanism to avoid starting its transmission during a subframe that is used by an LTE-V2X station (in the neighbourhood) but cannot do anything if an LTE-V2X station uses the following one, while the ITS-G5 transmission is already ongoing. In all the cases, by nature of its channel access based on reservations, the LTE-V2X station ignores the presence of ongoing ITS-G5 transmissions when sending its packet.

Directly comparing *dynamic C* with *header insertion without superframe*, it can be noted that in all the cases the latter one provides similar or better performance than the former one, yet without the complication of the technology proportion estimation and superframe structure required at the LTE-V2X stations. In *dynamic C*, in fact, even if the LTE-V2X stations can use only a portion of the superframe and leave the rest free to be used by ITS-G5 stations, the average number of LTE-V2X transmissions per subframe in a given area will correspondingly increase looking at those subframes that are part of the LTE-V2X time slot; as a consequence, the interference generated by the LTE-V2X transmissions to ITS-G5 in that part of the superframe increases and the overall performance of ITS-G5 does not improve. Just as a note, these results are obtained assuming for *dynamic C* the same settings as in [C2CWP1], which were shown to overestimate the proportion of LTE-V2X nodes; however, if a different algorithm was adopted for the estimation of the technology distribution, this would unavoidably improve the performance of either technology at the expense of the worsening of the performance of the other.



a) ITS-G5, 350 bytes

b) LTE-V2X, 350 bytes

c) ITS-G5, 1000 bytes

d) LTE-V2X, 1000 bytes

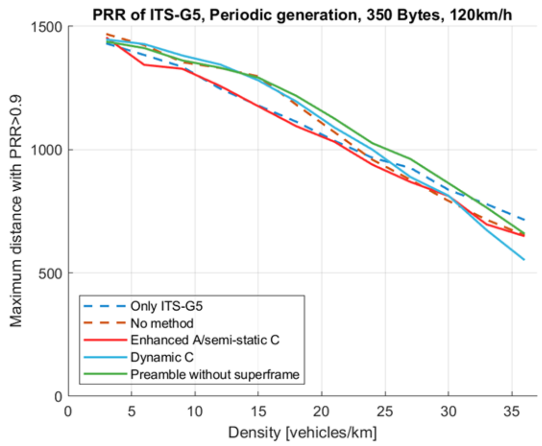
Fig. 4-1 Maximum distance with PRR>0.9 vs. density. Aperiodic traffic.

Let us now move to the case with periodic traffic, addressed in Fig. 4-2. As already discussed, although this is not the common operational condition, the generation of packets every 100 ms is possible in some cases.

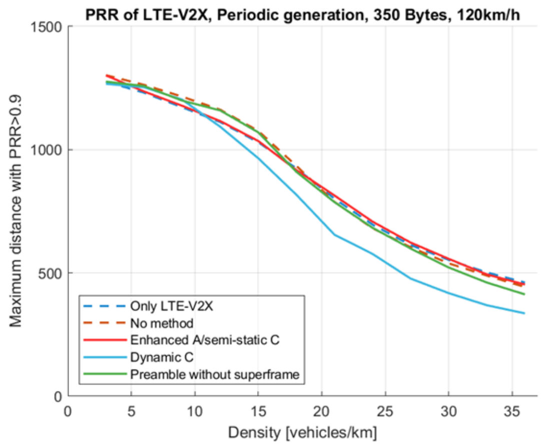
In the case of periodical traffic, with periodicity exactly equal to the allocation period of LTE-V2X, LTE-V2X can exploit the energy detected from the past ITS-G5 transmissions to infer the interference expected in the future by the available time-frequency resources. The generic LTE-V2X station will use with low probability a resource in a subframe that will probably be occupied by an ITS-G5 transmission.

The consequence of this behaviour is observable in Fig. 4-2 already when comparing the dashed curves. In this specific scenario, with packets of 350 bytes the performance of both technologies does not reduce (and even slightly improves) in the case of no method compared to the technology alone. With packets of 1000 bytes, each ITS-G5 transmission covers more than one subframe and this causes the LTE-V2X stations to concentrate in some subframes with higher probability. This in turn causes a reduction of the PRR for LTE-V2X and an improvement of the PRR for ITS-G5. It is however to note that the improvement in terms of PRR observable in some cases implies a worsening in terms of other metrics, such as the WBSP analysed in Section 6.

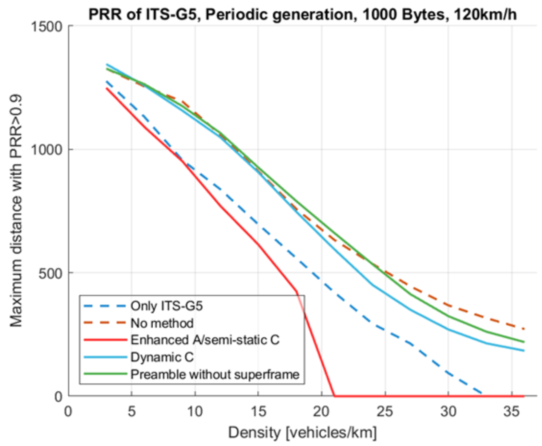
Looking at the curves corresponding to the investigated methods, the conclusions that can be inferred are in line to what already discussed: (i) *enhanced A*/*semi-static C* provides performance similar to the single technology, except for large packets in ITS-G5; (ii) the use of the header insertion allows in most of the cases similar or slightly better performance than no method; and (iii) the *dynamic C* is never preferable than the *header insertion without superframe*, and it rather causes a small performance degradation of LTE-V2X.



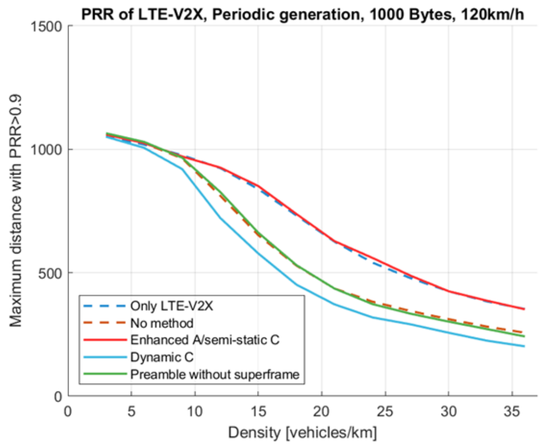
a) ITS-G5, 350 bytes



b) LTE-V2X, 350 bytes



c) ITS-G5, 1000 bytes



d) LTE-V2X, 1000 bytes

Fig. 4-2 Maximum distance with PRR>0.9 vs. density. Periodic traffic.

4.3 On the performance of ITS-G5 with *enhanced A*/*semi-static C* and large packets

It was shown in [C2CWP1] and [ETSI103766], and confirmed by Fig. 4-1a, that *enhanced A* and *semi-static C* are effective from the point of view of ITS-G5 when the time splitting is optimal and when the duration of the transmissions is short compared to the duration of the ITS-G5 time slot.

However, even maintaining the optimal time splitting (i.e., 50%-50% technology proportion and similar time slots in the superframe), the performance of ITS-G5 is significantly reduced when the duration of the transmissions is not small compared to the duration of the ITS-G5 time slot. This is clearly visible from the solid red curve of Fig. 4-1c.

The reason for this behaviour is as follows. Let us assume that a single ITS-G5 station generates and transmits continuously, one packet after the other, with packets of 1000 bytes. One packet of 1000 bytes encoded using the MCS 2 (QPSK, coding rate 1/2) lasts approximately 1500 µs if we include the AIFS of 110 µs but neglect the backoff time. This corresponds to approximately 670 packets per second.

If we now assume the superframe structure with 12 ms over 25 ms dedicated to the ITS-G5 time slot, and removing the last portion of the time slot, which cannot be used to start a new transmission, we have that no more than 7 transmissions can be transmitted in the remaining 10.6 ms. This means no more than 280 messages per second, which is less than 42% what can be transmitted when only ITS-G5 uses the channel for all the time. This 42% is significantly lower than the 50% expected by the superframe organization.

These considerations show possible performance degradation in ITS-G5 with *enhanced A* or *semi-static C* in the presence of large packets, or, changing the perspective, a reduction of the capacity for ITS-G5 which is not proportional to the time slot dedicated to that technology. This is due in minor part to (i) the fact that the ITS-G5 slot is 0.5 ms less than half the superframe (since 25 ms implies an odd number of intervals of 1 ms) and (ii) there is a gap at the end of the ITS-G5 slot which reduces the portion of time that can be used to start a transmission, but more importantly that (iii) a transmission not starting within one slot is necessarily delayed to the following superframe.

Please note that the problem is even worse for larger messages (CPMs up to 1900 bytes and MCMs up to 1300 bytes are for example envisioned in [ETSI103439]), and that there is no simple solution, since increasing the superframe duration might improve the PRR but implies a worsening of the other metrics that can be inacceptable.

4.4 Main observations

As a recap, looking at the performance from the perspective of PRR, the main observations regarding the investigated methods are as follows.

- *Enhanced A* and *semi-static C* with optimal time slots partitioning of the superframe allow LTE-V2X to perceive similar performance as in the case of only LTE-V2X.
- *Enhanced A* and *semi-static C* with optimal time slots partitioning of the superframe allow ITS-G5 to perceive similar performance as in the case of only ITS-G5 if the transmissions are short compared to the ITS-G5 time slot, i.e., for small to medium packets.
- In the case of *enhanced A* and *semi-static C*, even assuming optimal time slots partitioning of the superframe, if the ITS-G5 transmissions are long compared to the ITS-G5 time slot duration, i.e., for large packets. then a degradation of the performance is observed in ITS-G5.
- *Dynamic C* allows small performance improvement in LTE-V2X compared to “no method” if the traffic is aperiodic (smaller if packets are large) and causes a small loss if the traffic is periodic.

- *Dynamic C* allows some performance improvement in ITS-G5 compared to "no method" if the traffic is aperiodic (smaller if packets are large) and implies similar performance than "no method" if the traffic is periodic.
- The *header insertion without the superframe* structure allows small performance improvement in LTE-V2X compared to "no method" if the traffic is aperiodic (smaller if packets are large) and implies similar performance if the traffic is periodic.
- The *header insertion without the superframe* structure allows some performance improvement in ITS-G5 compared to "no method" if the traffic is aperiodic (smaller if packets are large) and implies similar performance if the traffic is periodic.
- The *header insertion without the superframe* structure provides always similar or better performance than *Dynamic C*.

5 Impact in terms of delay and data age

5.1 Introduction

In this section, the performance is investigated from the point of view of two metrics related to latency, EED and DA. As hereafter detailed, EED describes the delay from the generation of a packet to its reception, whereas the DA gives information about the correlation among errors.
In this work we do not show results in terms of inter-packet gap (IPG) [C2CWP1], which is another metric often used in these kind of studies, because it would not provide additional information to EED and DA.

5.2 Definition of end-to-end delay

In this section, the EED is investigated, defined as the delay from the packet generation to the correct packet decoding, as exemplified in Fig. 5-1. The delay internal to the stations to go from the generation to the access layer at the transmitter and reversely at the receiver are neglected. If a packet is not received, it does not impact on the delay and thus only correct receptions impact on this metric.
Only transmissions within 300 m are considered, assuming that the delay is more relevant
in the short communication range.

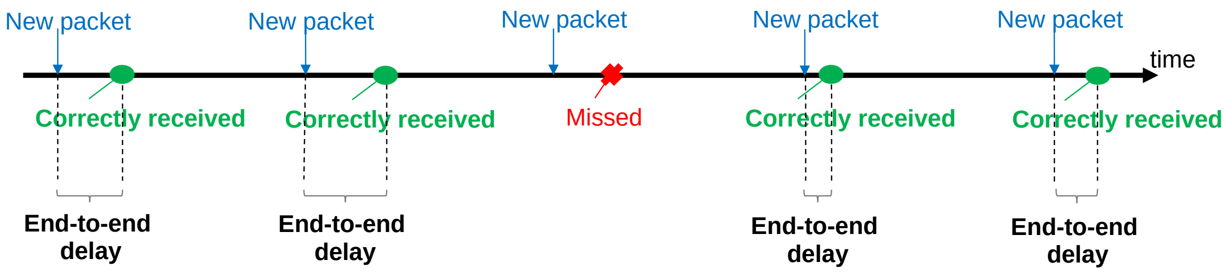


Fig. 5-1 End-to-end (EED) exemplification.

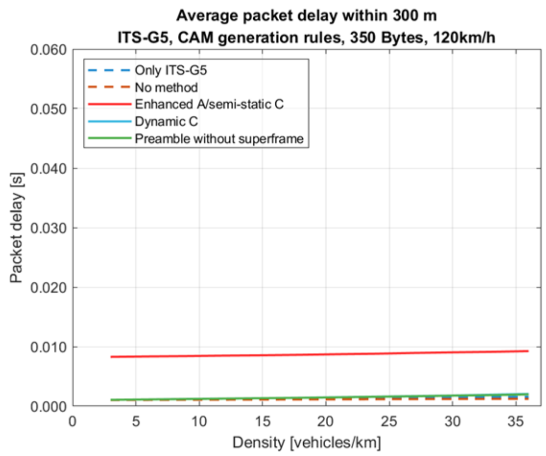
5.3 Results in terms of end-to-end delay

Results in terms of average EED varying the vehicle density are provided in Fig. 5-2 for the aperiodic traffic, which is the normal operating conditions, and in Fig. 5-3 for the periodic traffic, which is possible in some specific cases. From the perspective of the average EED, the packet generation pattern has negligible impact and the curves shown in Fig. 5-2 and Fig. 5-3 have a similar trend.

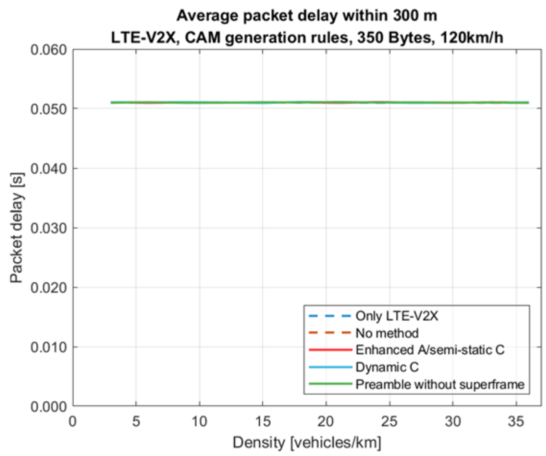
As expected, in LTE-V2X the average EED is always the same and it corresponds to the average between the minimum and the maximum allowed delay, a.k.a. T_1 and T_2, respectively. In fact, in LTE-V2X the resource used for a transmission is selected within a delay budget defined by T_1 and T_2 based on information related to sensing, which is on average homogeneous over all resources. This observation, which is by design valid because and until the superframe is smaller than T_2, does not change in the presence of coexistence with ITS-G5.

Looking at ITS-G5, it can be noted that the average EED is in general much lower than that of LTE-V2X but slightly increases with the density. The average EED is anyway well below 10 ms except when looking at coexistence with *enhanced A* or *semi-static C*, due to the nature of the superframe. A slow increase is visible when the channel load increases.

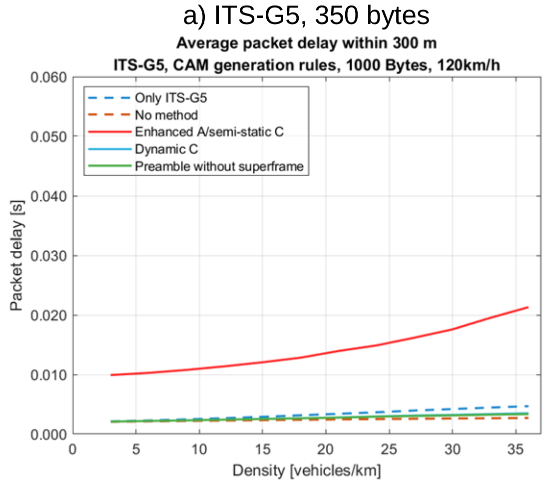
In the case of ITS-G5 under the *enhanced A* or *semi-static C*, the superframe structure and the artificial delay designed to avoid the rush to the channel add a certain average delay. This delay corresponds to the average between no delay and a delay equal to the LTE time slot plus the guard interval at the end of the ITS-G5 time slot. This additional delay is proportional to the time remaining until the guard interval at the end of the ITS-G5 time slot. At one (positive) extreme, the packet is generated just before the beginning of the guard interval and therefore no additional delay is added. At the other (negative) extreme, the packet is generated at the beginning of the guard interval and needs to be delayed by the duration of the time interval and the entire LTE time slot. In our simulations, recalling that the LTE time slot is 13 ms, the additional delay is therefore on average around 7 ms, and the full 13 ms plus the guard interval in the worst case (meaning approximately 13.5 ms with 350 byte packets and 14.5 ms with 1000 byte packets). Note that the worst case is particularly relevant for functional safety considerations. The discussion on the increase of the ITS-G5 EED remarks that trying to reduce the impact on PRR by increasing the duration of the superframe would proportionally increase the delay.



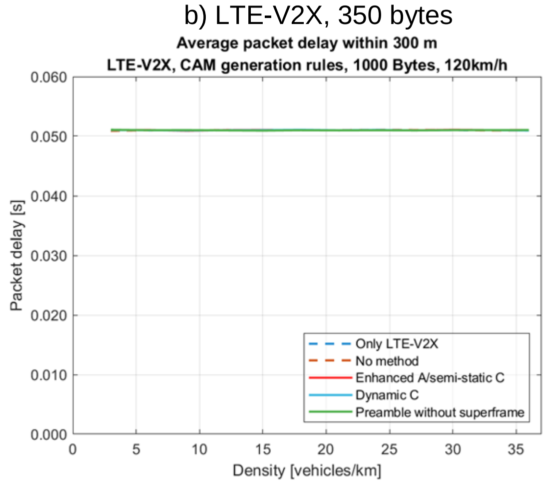
a) ITS-G5, 350 bytes



b) LTE-V2X, 350 bytes

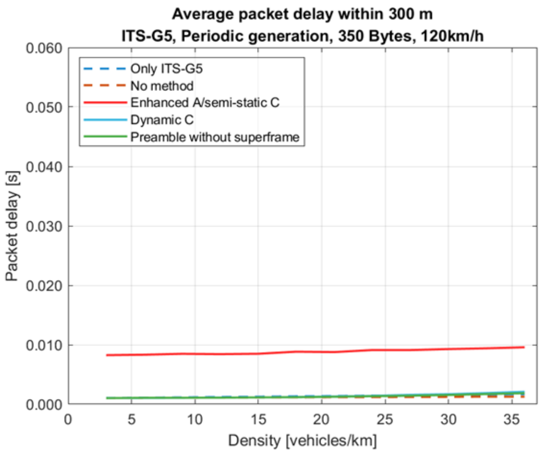


c) ITS-G5, 1000 bytes

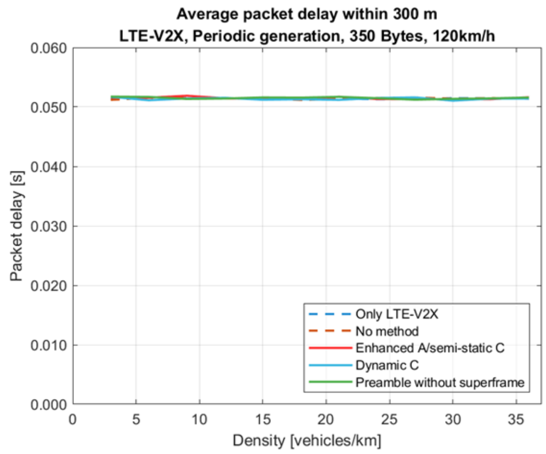


d) LTE-V2X, 1000 bytes

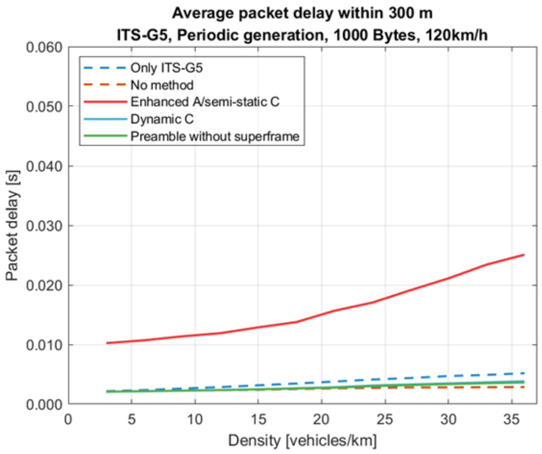
Fig. 5-2 Average EED for correct receptions within 300 m vs. density. Aperiodic traffic.



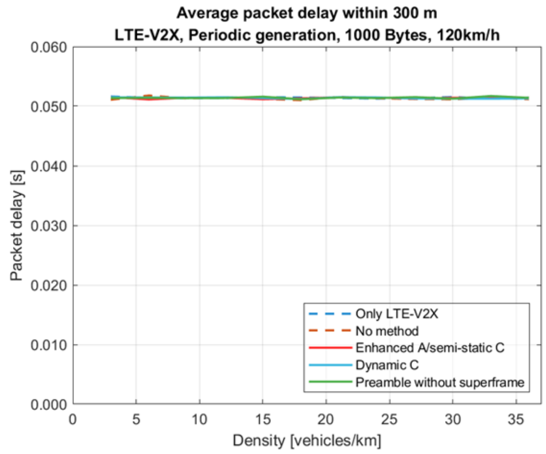
a) ITS-G5, 350 bytes



b) LTE-V2X, 350 bytes



c) ITS-G5, 1000 bytes



d) LTE-V2X, 1000 bytes

Fig. 5-3 Average EED for correct receptions within 300 m vs. density. Periodic traffic.

5.4 Definition of data age

In this section, results are shown in terms of DA, defined as the time elapsed from the generation of a correctly received packet and the next correctly decoded one by the same receiver from the same transmitter. DA, which is exemplified in Fig. 5-4, implicitly accounts for the allocation delay, which is already shown as part of the EED, and the correlation among errors, which is instead not addressed by the EED.
DA is evaluated for all transmissions within 500 m, assuming that this metric is relevant on a larger range compared to the delay.

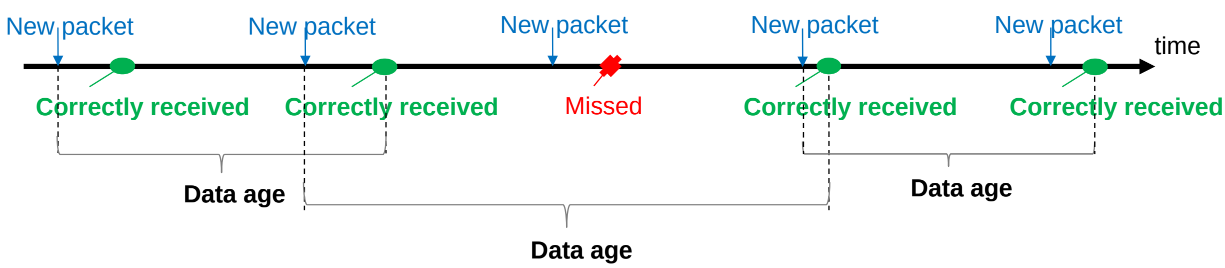


Fig. 5-4 Data age (DA) exemplification.

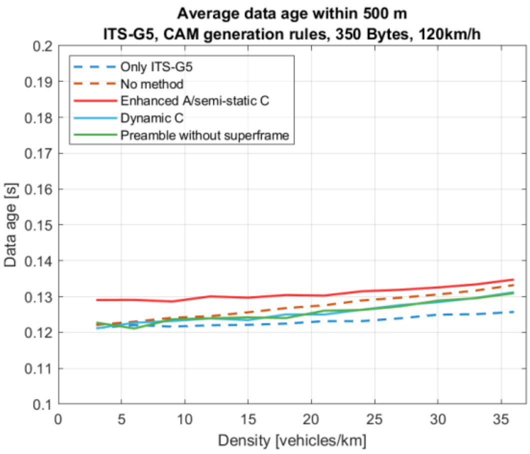
5.5 Results in terms of data age

Results in terms of average DA varying the vehicle density are provided in Fig. 5-5 for the aperiodic traffic, which is the normal operating conditions, and in Fig. 5-6 for the periodic traffic, which is possible in some specific cases.

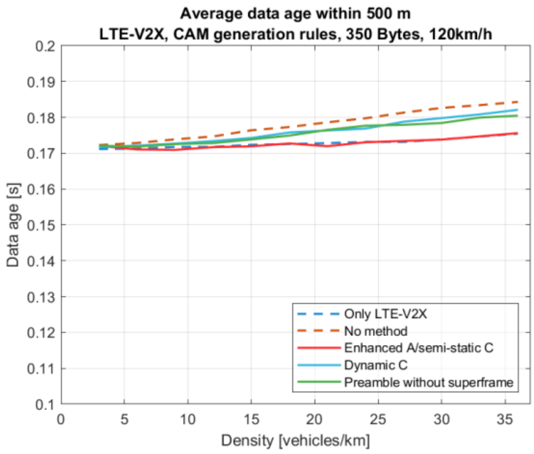
From the perspective of the average DA, the aperiodic generation pattern (Fig. 5-5) causes on average an increment of 20 ms compared to the periodic traffic (Fig. 5-6) in both technologies and for all considered cases. This effect is due to the fact that following the ETSI rules, the average interval between the generation of two consecutive CAMs at 120 km/h is 120 ms, compared to the 100 ms used in the periodic case.

Looking at Fig. 5-5 and Fig. 5-6 and focusing on ITS-G5, it can be observed that the DA is similar in all the cases except for *enhanced A/semi-static C*. The increase of DA in that case is related to the added delay already discussed in Section 5.3. The increase is worse with packets of 1000 bytes due to the higher PRR observed in Section 4.2. A slightly increased DA can also be observed in ITS-G5 under periodic traffic with high density, when ITS-G5 alone is compared to the case of coexistence without methods; this effect is due to the fact that with packets of 1000 bytes, the ITS-G5 transmissions have a longer duration than those in LTE-V2X, and therefore the channel is on average less busy in the case of coexistence.

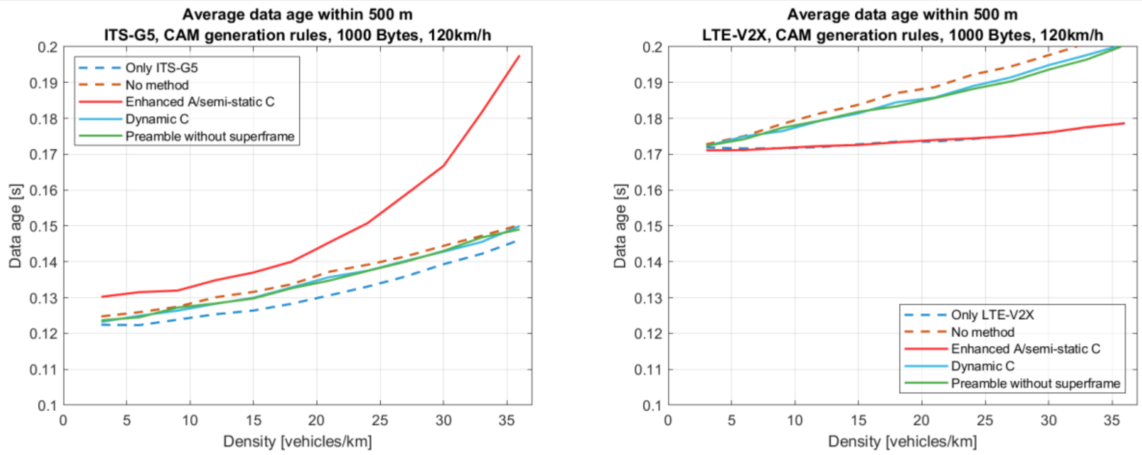
From the perspective of LTE-V2X, the DA remains similar in all the cases except for a small increase with large density, aperiodic traffic, 1000 bytes, in the case of no methods or coexistence methods based on the header insertion. The cause of this small increase is that the SB-SPS mechanism of LTE-V2X is less effective and is compliant with the results shown in Section 4.2.



a) ITS-G5, 350 bytes

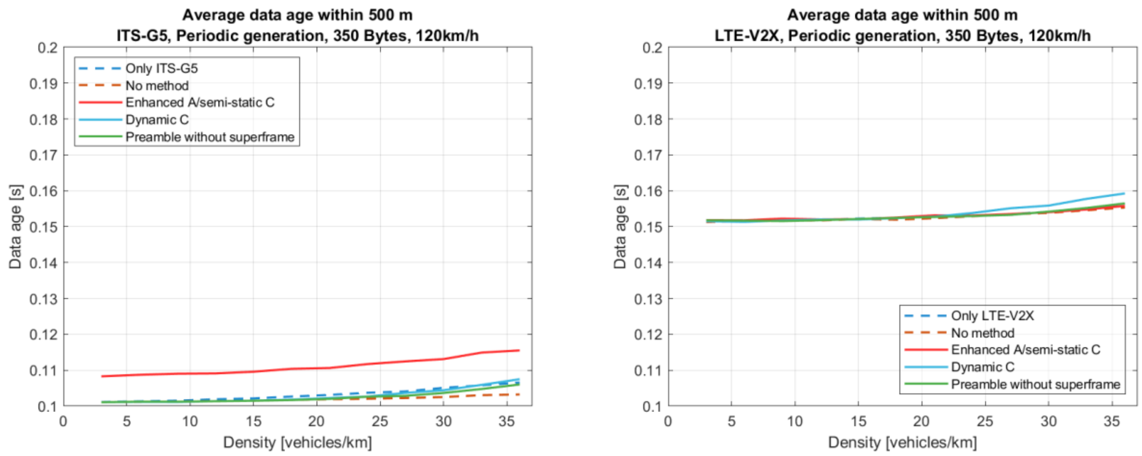


b) LTE-V2X, 350 bytes

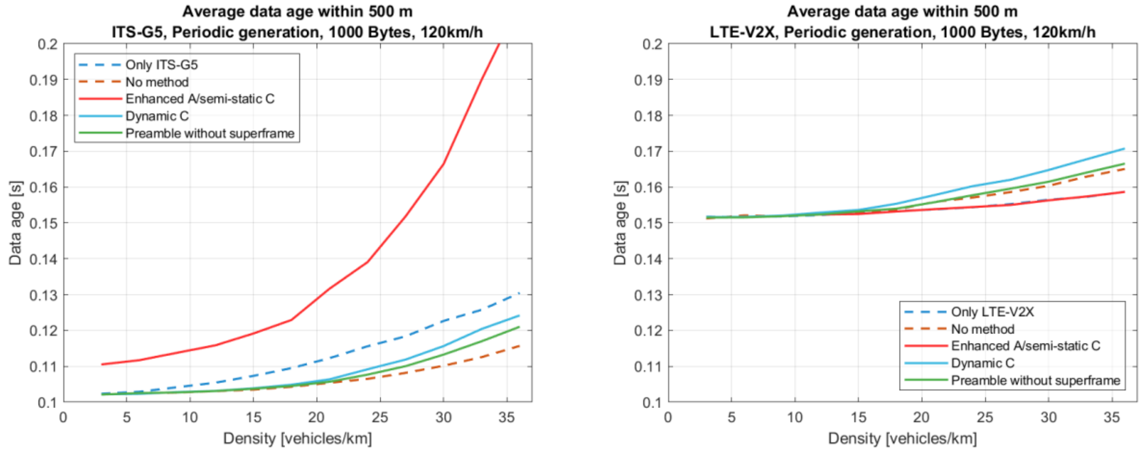


c) ITS-G5, 1000 bytes d) LTE-V2X, 1000 bytes

Fig. 5-5 Average DA for correct receptions within 500 m vs. density. Aperiodic traffic.



a) ITS-G5, 350 bytes b) LTE-V2X, 350 bytes



c) ITS-G5, 1000 bytes d) LTE-V2X, 1000 bytes

Fig. 5-6 Average DA for correct receptions within 500 m vs. density. Periodic traffic.

5.6 Main observations

As a recap, looking at the performance from the perspective of the delay, the main observations regarding the investigated methods are as follows.

- Compared to the single technology, all the methods always imply a similar EED in LTE-V2X; to be noted that this is by design of the LTE-V2X protocol and that it assumes that the superframe is smaller than the delay budget used for the resource allocation.

- Compared to the single technology, the EED remains always similar in ITS-G5 with the exception of *enhanced A*/*semi-static C*, where it increases on average by at least half of the LTE-V2X time slot duration, and in the worst case by the duration of the LTE time slot and an additional guard interval at the end of the ITS-G5 time slot; this means, as a worst case under the superframe structure here considered, approximately 13.5 ms with 350 byte packets and 14.5 ms with 1000 byte packets.
- Compared to the single technology, *enhanced A* and *semi-static C* always imply a similar DA in LTE-V2X.
- The methods based on the header insertion always provide similar DA in LTE-V2X to the case with coexistence without methods, which is also similar to the single technology in most cases but slightly higher under high density, large packets, aperiodic traffic generation.
- *Enhanced A* and *semi-static C* imply for ITS-G5 an increased DA compared to the single technology, especially for large packets and high vehicle density; with the settings assumed here and looking at the highest density case, the increase is of approximately 50% and 100% percent compared to the single technology when assuming aperiodic and periodic traffic, respectively.
- Compared to the single technology, the DA remains similar in ITS-G5 with methods based on the header insertion.

6 Impact in terms of wireless blind spot probability

6.1 Introduction

In this section, the performance is investigated from the point of view of the WBSP.

6.2 Definition of wireless blind spot probability

The WBSP, exemplified in Fig. 6-1, represents the probability that one station does not receive any packets in a given time interval from one station that is within a given distance. Hereafter, the interval is set to 500 ms and the distance is set to 300 m.

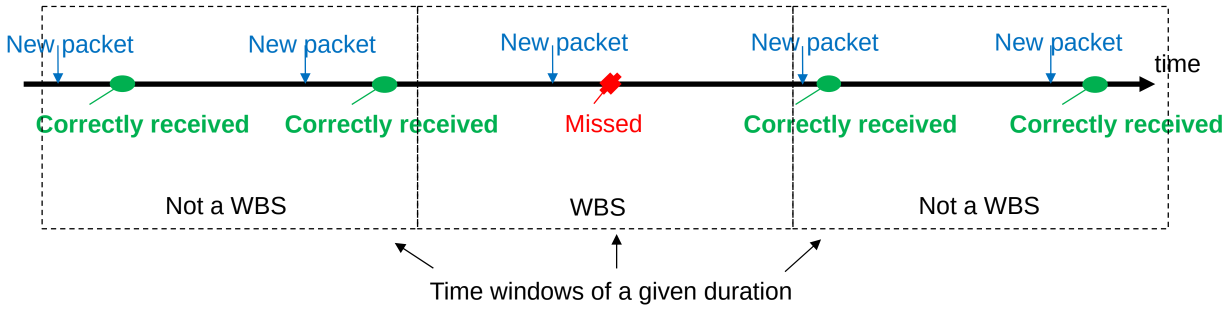


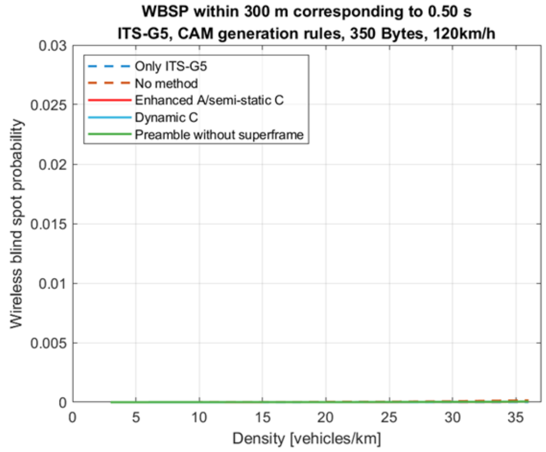
Fig. 6-1 Wireless blind spot probability (WBSP) exemplification.

6.3 Results in terms of wireless blind spot probability

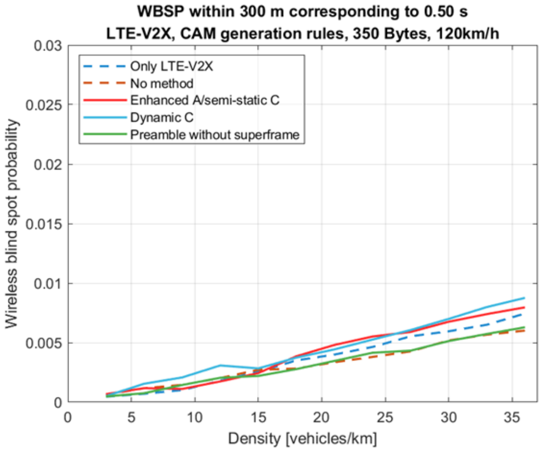
Results in terms of WBSP are shown in Fig. 6-2 (aperiodic traffic) and Fig. 6-3 (periodic traffic).

The results in terms of WBSP clearly show the drawback due to periodic packet generation, which may have appeared preferable when looking only at the PRR in Section 4. Comparing Fig. 6-2 (aperiodic) with Fig. 6-3 (periodic), it can be in fact observed that the WBSP increases in all the cases and for both technologies. The increase of WBSP is due to a significantly higher correlation between consecutive errors, which cannot be captured looking at the PRR and which was not visible looking at the delay metrics. It is also to note that this is observed despite the increased in the aperiodic case of the average generation time between consecutive packets.

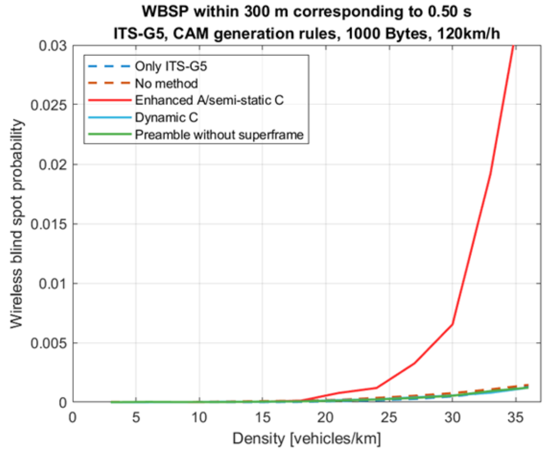
Comparing the various curves, all methods appear to behave similarly, and the only remarkable exception is looking at ITS-G5 with 1000 bytes, high density, when *enhanced A*/*semi-static C* is used. This is a direct consequence of the increased PRR discussed in Section 0.



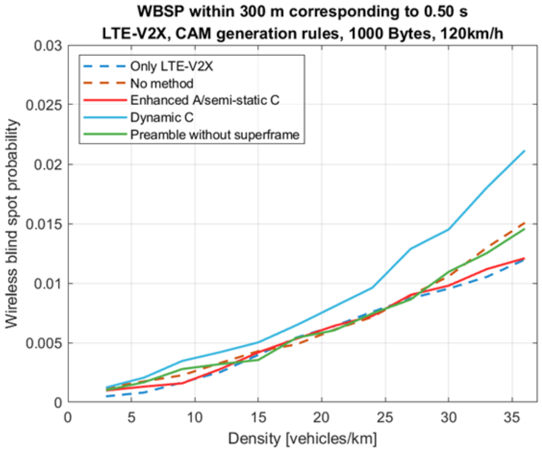
a) ITS-G5, 350 bytes



b) LTE-V2X, 350 bytes

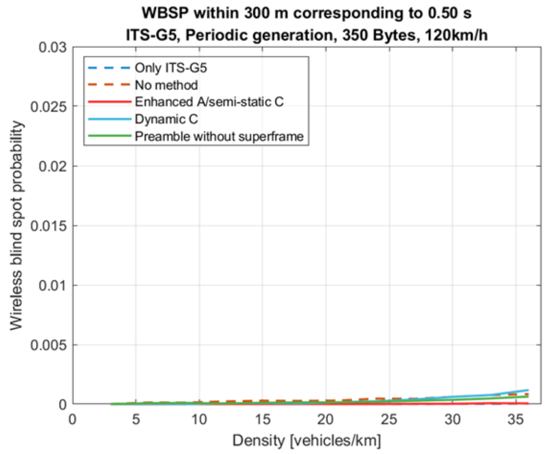


c) ITS-G5, 1000 bytes

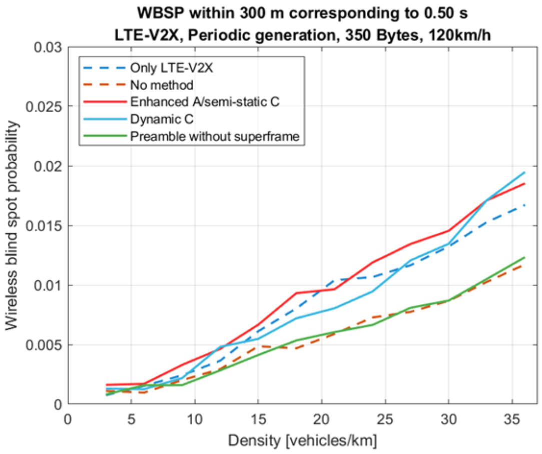


d) LTE-V2X, 1000 bytes

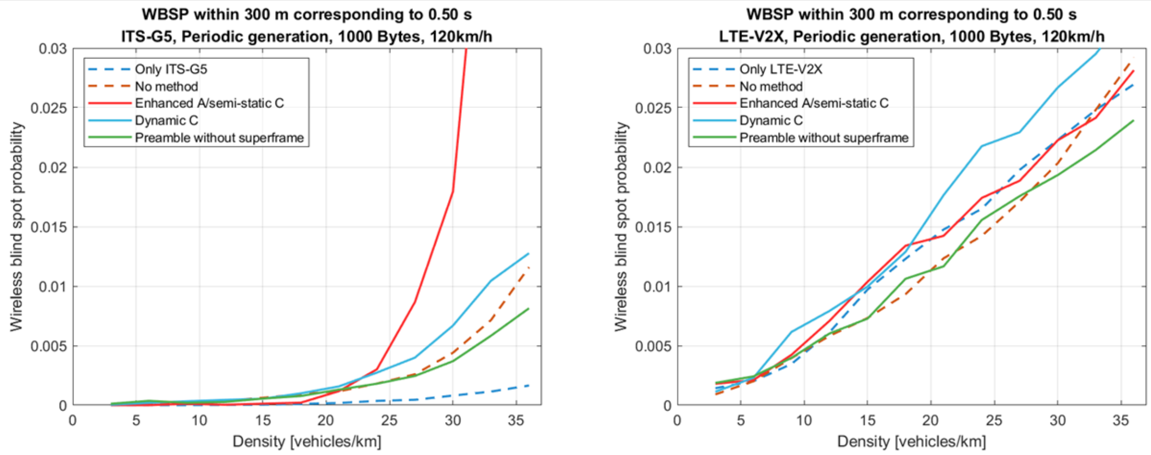
Fig. 6-2 WBSP within 500 ms from receivers within 300 m vs. density. Aperiodic traffic.



a) ITS-G5, 350 bytes



b) LTE-V2X, 350 bytes



c) ITS-G5, 1000 bytes

d) LTE-V2X, 1000 bytes

Fig. 6-3 WBSP within 500 ms from receivers within 300 m vs. density. Periodic traffic.

6.4 Main observations

As a recap, looking at the performance from the perspective of the WBSP, the main observation is that it increases in all the cases and for both technologies when a periodic packet generation is adopted.

Regarding the investigated methods, the following considerations can also be added.

- The *enhanced A and semi-static C* imply an WBSP similar to the single technology in LTE-V2X.
- The *enhanced A and semi-static C* cause a significant increase of the WBSP in ITS-G5 with large packets; with the settings assumed here and looking at the highest density case, the increase compared to the single technology is from less than 2 ms to more than 30 ms with both periodic and aperiodic traffic.
- *Dynamic C* implies in LTE-V2X similar or worse performance than the coexistence without any methods, and the difference is more relevant with high density and periodic traffic.
- *Dynamic C* causes in ITS-G5 similar performance than the coexistence without any methods, which is in turn similar or worse than the case with ITS-G5 alone.
- The use of the *header insertion without the superfame* structure is always similar or preferable in terms of WBSP than all the other cases with coexistence, for both technologies.

7 Impact on the channel busy ratio

7.1 Introduction

In this section, the impact on the CBR is analysed. Looking at the CBR allows to understand the impact of coexistence on the way the channel is used and observed in the two technologies and can be used to drive possible studies on congestion control mechanisms in the case of co-channel coexistence.

7.2 Channel busy ratio in ITS-G5

The evaluation of the CBR in ITS-G5 is here shortly recalled and exemplified in Fig. 7-1. In ITS-G5, each station measures the sensed power during intervals of 100 ms (T_{CBR} in Fig. 7-1) and calculates the CBR as the portion of time when a transmission is detected, the station itself is transmitting, or the received power exceeded a threshold set to -85 dBm.

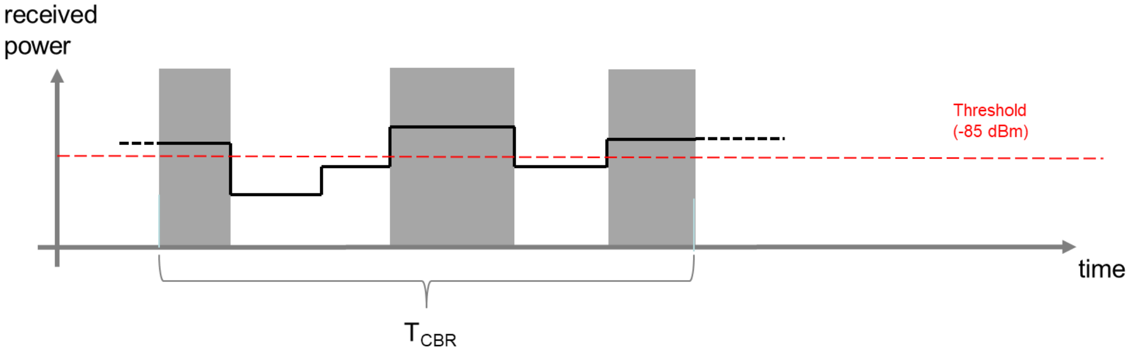


Fig. 7-1 Exemplification of the CBR calculation in ITS-G5.

7.3 Channel busy ratio in LTE-V2X

The evaluation of the CBR in LTE-V2X is here shortly recalled and exemplified in Fig. 7-2.
In LTE-V2X, each station measures the sensed power in each subframe and subchannel during intervals of 100 ms (T_{CBR} in Fig. 7-2) and calculates the CBR as the portion of subchannels where a transmission is detected, the station itself is transmitting, or the average received power exceeded a threshold set to -94 dBm. Recalling that the subchannel occupies only 1/5 of the channel, this threshold is consistent with the value adopted in ITS-G5 (where the power is measured over the full channel).

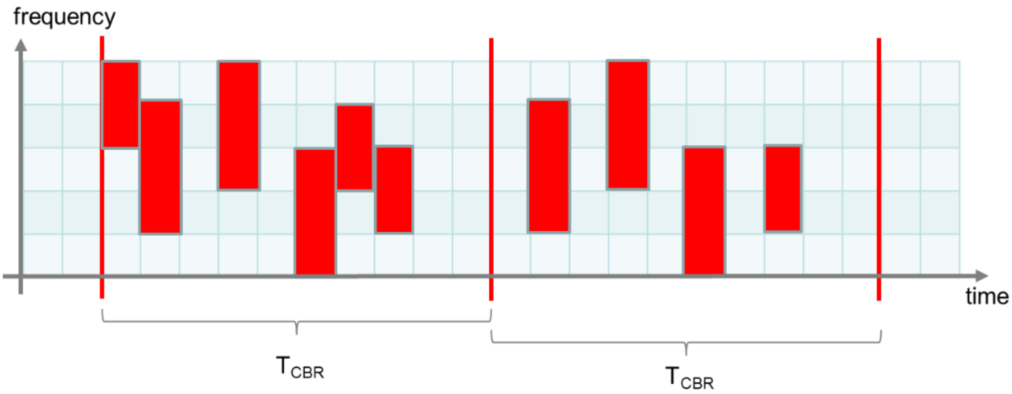


Fig. 7-2 Exemplification of the CBR calculation in LTE-V2X.

7.4 Results in terms of channel busy ratio

The average CBR calculated by the ITS-G5 and LTE-V2X stations in the considered scenarios is shown in Fig. 7-3 and Fig. 7-4. From the perspective of CBR, the curves are similar comparing the aperiodic traffic (Fig. 7-3) with the periodic traffic (Fig. 7-4). Those related to the aperiodic traffic are only slightly lower, due to the fact that less than 10 packets per second are on average generated by vehicles moving at an average speed of 120 km/h, following the CAM generation rules.

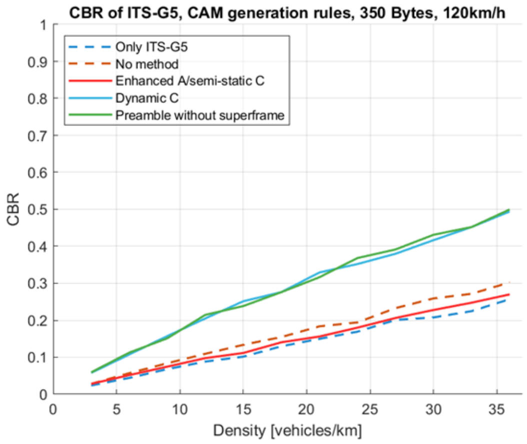
In the case of *enhanced A* or *semi-static C*, the CBR is calculated by the ITS-G5 and LTE-V2X stations only with reference to the respective time slots. In this case and for both technologies, the measured CBR is therefore similar to that measured with the technology alone.

Comparing the average CBR of ITS-G5 with the *enhanced A* or *semi-static C* to that of “no method”, similar values can be noted if the packets are of 350 bytes, whereas an increase is observed if the packets are of 1000 bytes. In the latter case, in fact, the transmissions from LTE-V2X stations are shorter than those from ITS-G5 ones, and, as a consequence, the CBR calculated with the *enhanced A* or *semi-static C* in the ITS-G5 time slot is higher compared to that calculated in the case of ITS-G5 coexisting without any methods.

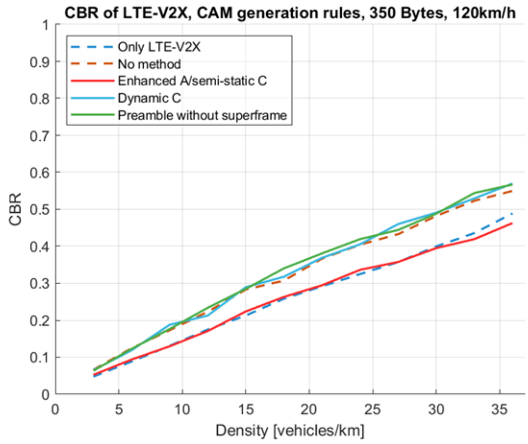
Looking at ITS-G5 with the methods adopting the header insertion, it can be noted that they cause an increase of the CBR compared to the case of coexistence without any methods. This is due to the fact that the header insertion allows the ITS-G5 station to detect a transmission from an LTE-V2X station even if the received power is below -85 dBm. This effect, which protects the ITS-G5 stations from transmitting in the presence of a source of interference, is further investigated in [Baz22].

Focusing on LTE-V2X with the methods adopting the header insertion, the CBR measured is always similar to the one measured with coexistence but without any methods. The CBR is also always larger than the case with LTE-V2X alone and the difference increases with packets of 1000 bytes. The reason for the larger CBR is that all ITS-G5 transmissions always occupy the entire channel (thus all the five LTE-V2X subchannels) and that the packets of 1000 bytes imply transmissions that span over two consecutive subframes. This effect may cause LTE-V2X stations to activate the congestion control mechanisms earlier compared to what happens if the same average number of stations were all equipped with LTE-V2X.

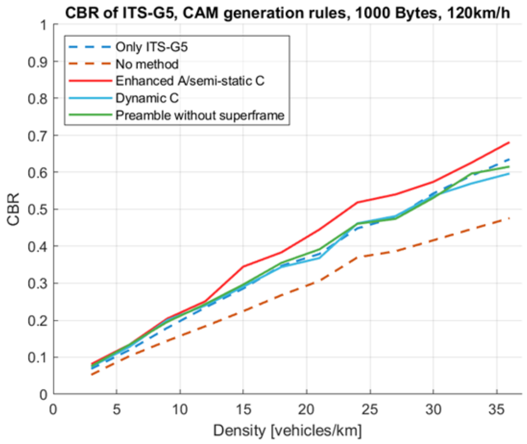
It can be also observed that comparing the methods with header insertion to the case without mitigation methods, the CBR of ITS-G5 increases, whereas the LTE-V2X remains similar. This effect, which is due to the ability of ITS-G5 stations to detect the LTE-V2X transmissions with higher probability, may have as a side effect to imply that congestion control mechanisms are activated earlier in ITS-G5.



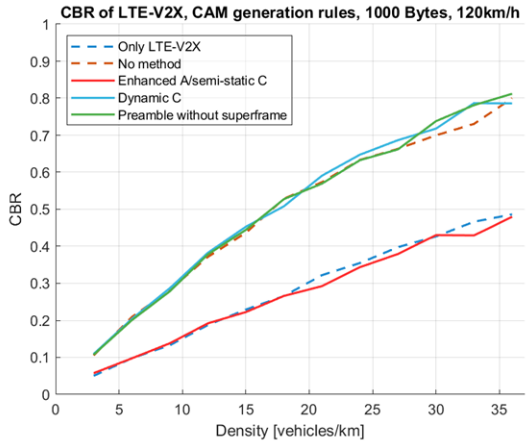
a) ITS-G5, 350 bytes



b) LTE-V2X, 350 bytes

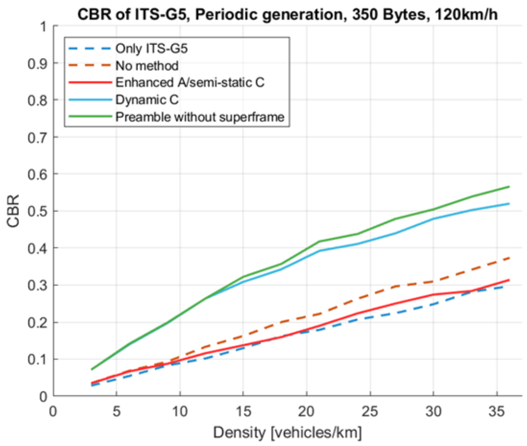


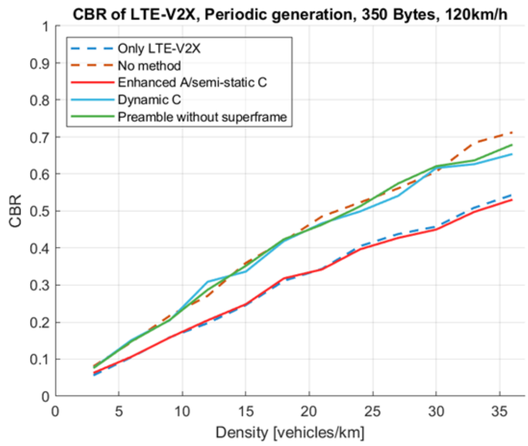
c) ITS-G5, 1000 bytes



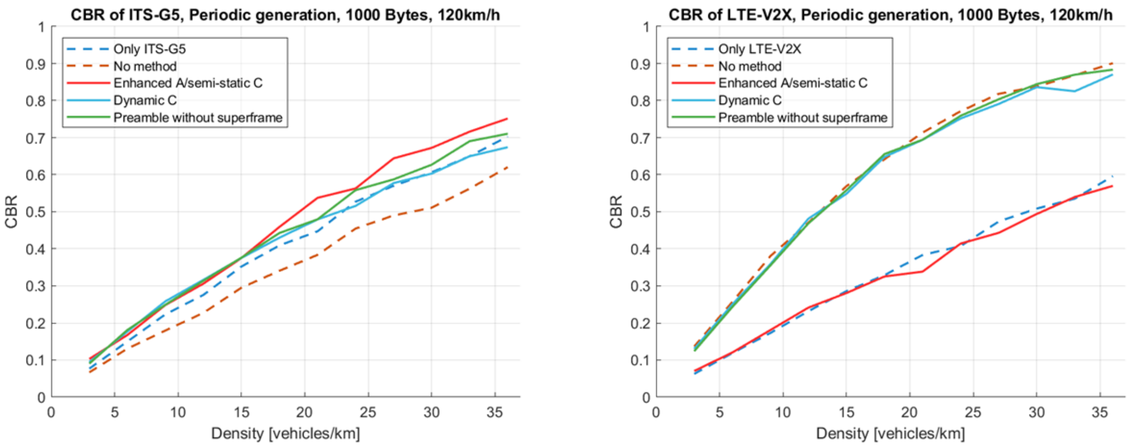
d) LTE-V2X, 1000 bytes

Fig. 7-3 Average CBR vs. density. Aperiodic traffic.





a) ITS-G5, 350 bytes   b) LTE-V2X, 350 bytes



c) ITS-G5, 1000 bytes   d) LTE-V2X, 1000 bytes

Fig. 7-4 Average CBR vs. density. Periodic traffic.

7.5 Main observations

Focusing on the CBR, the following observations can be summarised.

- The *enhanced A* and *semi-static C* imply a similar CBR in each technology compared to the case of the same technology alone; it is to note that this is true based on a calculation of the CBR scaled to the corresponding time slot and under the assumption of a perfect match between the time slot proportion and the technology percentage (here both set to 50%-50%).
- With the methods assuming the header insertion, the CBR calculated by ITS-G5 stations increases compared to the technology alone with small packets and is similar with large packets.
- With the methods assuming the header insertion, the CBR calculated by LTE-V2X stations increases compared to the same technology alone; it nearly doubles with long transmissions in ITS-G5.

These results remark that further studies on the appropriateness of current congestion control mechanisms is required in the case of coexistence.

8 Discussion on the applicability to NR-V2X sidelink and IEEE 802.11bd

8.1 Introduction

In this section, the applicability of the considered coexistence methods is discussed with reference to NR-V2X sidelink (in part already standardized by the 3GPP) and to ITS-G5 enhanced with the features of IEEE 802.11bd (expected to be published by IEEE at the end of 2022).

8.2 Applicability of the coexistence methods to NR-V2X sidelink

The main part of NR-V2X sidelink was standardised in 2020 as part of Release 16 of 5G, and additional features are being completed this year in Release 17. The autonomous mode for resource allocation in NR-V2X is called mode 2. Even if NR-V2X has similarities with LTE-V2X and they overall share the same approach (e.g., synchronous transmissions, resources organized in subchannels and TTIs, SB-SPS mechanism for periodic traffic), they are different technologies and they are not interoperable. Indeed, a specific document of 3GPP is devoted to the co-channel coexistence of LTE-V2X with NR-V2X.

The main differences between NR-V2X and LTE-V2X that are relevant for the discussed co-channel coexistence methods are:

- *Numerology*: in NR-V2X sub-6 GHz the transmission time interval (TTI), which is the granularity in the time domain for allocation and transmission, can be 0.25 ms, 0.5 ms, or 1 ms; the last one corresponds to what used in LTE-V2X.
- *Revision of the SB-SPS procedure*: in NR-V2X, the sensing of past transmissions is relevant only if associated with the corresponding SCI; if no SCI is received, the measured power is irrelevant.

More details on NR-V2X can be found for example in [Tod21,Gar21].

Both aspects are not significant when looking at the *enhanced A*. In that case, in fact, there is a time-split avoiding concurrent transmissions from the two technologies.

When looking at the numerology with the header insertion, nothing changes if the TTI of 1 ms is adopted. If the TTI is equal to 0.5 ms, then the OFDM symbol duration of the NR-V2X signal is approximately 35 µs, which is smaller than the 40 µs; however, the header can be still inserted without introducing other modifications by using the first symbol, still used in NR-V2X for AGC, and the last part of the inter-subframe gap (which is of the same duration as an OFDM symbol). Changes to the NR-V2X impacting on the transmitted data are only required if the TTI equal to 0.25 ms is adopted, because in that case the AGC symbol and the gap are not sufficient.

Focusing on the modifications to the SB-SPS with the methods including the header insertion, the difference is that periodical traffic from ITS-G5 stations will not allow the NR-V2X stations to estimate that some resources are being used, as shown for LTE-V2X in the previous sections. Indeed, no SCI is associated to the ITS-G5 signal, and any power measured by the NR-V2X stations is therefore simply ignored. The result is that the periodical traffic is expected to impact similarly than aperiodical traffic from the perspective of PRR (i.e., similar average packet loss), with the addition of a worsening in terms of WBSP (i.e., higher probability of bursts of errors looking at the generic transmitter towards the same receiver).

8.3 Applicability of the coexistence methods to IEEE 802.11bd

IEEE 802.11bd is a new amendment to the IEEE 802.11 Wi-Fi standard series, under development by the IEEE bd Task Group. Final public version (D4.0) is expected to be published towards the end of 2022. IEEE 802.11bd is designed to coexist and be backwards-compatible with what was designed as IEEE 802.11p (now part of IEEE 802.11-2020). IEEE 802.11bd is expected to be included in an enhanced version of ITS-G5, and a station equipped with such an advanced version will be able to communicate with another station equipped with the legacy ITS-G5.

In IEEE 802.11bd, the only difference which is relevant for co-channel coexistence is the optional introduction of packet repetitions. Packet repetitions allow time diversity and maximal ratio combining at the receiver, which are useful in low traffic scenarios to improve the reliability and range.

To guarantee coexistence with current version of IEEE 802.11p, the IEEE 802.11bd packets starts with the same header. Therefore, all the methods based on the header insertion are inherently applicable to the new IEEE 802.11bd technology.

In principle, also the *enhanced A*, which implements a time-splitting, can be extended to IEEE 802.11bd in the same way as for ITS-G5. However, one aspect to be remarked in this case is that the superframe structure introduces constrains to the duration of a transmission that may have a similar impact as what observed in Section 4.3 for large packets.

9 Conclusion

In this white paper we have deepened the performance of the main solutions individuated for the improvement of co-channel coexistence of ITS-G5 and LTE-V2X. We have used a highway scenario and varied the traffic density without reaching the congestion levels where congestion control mechanisms have to be applied. Results have been provided with either medium-sized and large packets, and with either aperiodic generation pattern, which is today the normal condition of operation looking at CAMs, or periodic generation pattern, which can occur in some situations. In the shown simulations, either all stations are equipped with the same technology, or 50% adopt ITS-G5 and the other 50% adopt LTE-V2X.

We have considered the methods denoted in [ETSI103766] as *enhanced A*, *semi-static C*, and *dynamic C*, since they were shown to be the preferable solutions. Additionally, we have considered a method that applies the header insertion inside the LTE-V2X signal like in *method C*, but without any superframe structure. The main conclusions deriving from our study are as follows.

9.1 Summary of the impact of the methods on the various metrics

Looking at the performance of methods *enhanced A or semi-static C*, which are methods based on the concept of time-splitting through the use of static superframes and (slowly) modifiable time slots, assuming here an idealistically optimal time-splitting (50%-50% splitting and average 50%-50% technology distribution), the following comments can be provided.

- The packet reception ratio (PRR) of ITS-G5 is similar to the case of all nodes equipped with ITS-G5 as long as the duration of a transmission is sufficiently smaller than the ITS-G5 time slot (i.e., with small to medium sized packets).
- The PRR of ITS-G5 reduces if the duration of a transmission is large compared to the ITS-G5 time slot, as observed for packets of 1000 bytes (i.e., for large packets).
- The PRR of LTE-V2X is similar to the case of all nodes equipped with LTE-V2X (for any packet size).
- In ITS-G5, higher end-to-end delay (EED) and data age (DA) are observed compared to all the other cases; the increase is mainly due to the artificial delay used to avoid the channel rush problem, which is on average equal to half the duration of the LTE-V2X time slot; the DA increases significantly in the case of large packets and high vehicle density as a consequence of the higher PRR.
- Given a delay budget larger than the superframe, the EED and DA in LTE-V2X is not affected by the method.

For small packets, Method *enhanced A* with ideal superframe organization is the best method in terms of PRR, but the worst in terms of delays (this outcome is well aligned with results of ETSI TR 103 766 [ETSI103766]). For small packets, Method *enhanced A* performs poorly (for all metrics) for large packets & large densities for ITS-G5, due to the additional delay mechanism which reduces the ITS-G5 capacity. These results indicate that the superframe concept may in fact introduce more challenges than it solves problems. Although reasonably well suited for LTE-V2X by essence, performance impact on ITS-G5 is significant.

Note: Methods with superframe structure rely on a supervising entity which is not solved – this would need to be adaptive on local traffic and technology appearance with different technology splits to be spectrum efficient. For this purpose, a supervising entity would be required which at the same time would be non-compliant with highest safety requirements for functional safety.

Looking at the performance of the other methods, based on IEEE 802.11p header insertion in the LTE-V2X signals (i.e., *dynamic C* and *header insertion without the superframe* structure), the following comments can be provided.

- The use of the superframe (i.e., dynamic C) shows always similar or worse performance than without it (i.e., *header insertion without the superframe* structure).
- The PRR of ITS-G5 is improved compared to the case of coexistence without any method; the improvement is higher with smaller packets than with larger packets.
- The PRR of LTE-V2X with aperiodic traffic is in general improved compared to the case of coexistence without any method, especially with smaller packets; the improvement is limited if larger packets cause long transmissions by ITS-G5 stations.
- Looking at the PRR of LTE-V2X with periodic traffic, compared to the case of coexistence without any method, a slight loss is observed with *dynamic C*, whereas the *header insertion without superframe* gives similar PRR.
- The EED and DA in ITS-G5 is similar to both the case with ITS-G5 alone and the case of coexistence without any method.
- The EED in LTE-V2X is always similar to all the other cases by design (due to the delay budget set at the scheduler).
- The DA in LTE-V2X is similar to the case with coexistence without methods, which is also similar to the single technology in most cases but slightly higher under high density, large packets, aperiodic traffic generation.

Both *header insertion method without superframe* and *dynamic C* proved beneficial and provided performance improvement for all metrics compared to the starting point situation without any method. Furthermore, the new method *header insertion method without superframe* yielded a better performance than method *dynamic C*, without the need to have the superframe structure. This means that the need to realize the local measurements, or to communicate with a supervising entity, is lifted. In fact, this method appears to be the easier one to setup: it requires no changes for ITS-G5 stations (thus being compatible with already deployed stations), and for LTE-V2X stations it only requires transmission of the IEEE802.11 (WiFi) header at the beginning of the packets.

Finally, looking at the way the methods impact on the channel busy ratio (CBR), the following comments can be provided.

- With *enhanced A or semi-static C*, in ITS-G5 the CBR is similar to what observed for the single technology if it is calculated only inside the ITS-G5 time slot; a small increase is observed with large packets.
- With *enhanced A or semi-static C*, in LTE-V2X the CBR is similar to the case with LTE-V2X alone if it is calculated only in the LTE-V2X time slot.
- With the other methods, based on header insertion in the LTE-V2X signals, the CBR in ITS-G5 is larger than the case of ITS-G5 alone with small packets, whereas it is similar with large packets. With LTE-V2X packets including

IEEE802.11 (WiFi) header, the ITS-G5 CBR metric appears more meaningful, in a sense that it enables the ITS-G5 to process and categorize such LTE-V2X packets as ‘regular’ ITS-G5 packets, leading to a functioning that is better aligned with the situation of having ITS-G5 stations alone.

- With the other methods, based on IEEE802.11 (WiFi) header insertion in the LTE-V2X signals, the CBR in LTE-V2X is larger than the case with LTE-V2X alone, especially with long transmissions in ITS-G5.

Based on the simulation results, it comes clear that large packets are more challenging than small packets. Large packets can be considered as the worst case for co-channel coexistence.

Key results: The present document shows that the method “*header insertion without superframe*” is the most promising method for co-channel coexistence. It is the best all-rounder method. It yields performance improvement compared to no method, and always performs similar or better to the method *dynamic C*. This is a remarkable outcome as *header insertion without superframe* is arguably simpler to implement than method *dynamic C*

9.2 Concluding remarks

Based on the results, the time division methods, i.e., *enhanced A and semi-static Method C*, imply for ITS-G5 (i) an increase in the average delay and (ii) a reduction of the average number of successful transmissions per area and per time unit for large packets. This holds even when the time slot partition is consistent with the technology proportion, which is clearly an optimistic assumption expected to be rarely respected in practice. The delay increase is apparent in the results for ITS-G5 because it normally uses a fast access when the channel is idle, but is delayed during the non-accessible time slot of the time division methods. These drawbacks are in addition to the fact that these methods do not apply to the legacy ITS-G5 stations that have been already rolled out.

Note: Methods with superframe structure rely on a supervising entity which is not solved – this would need to be adaptive on local traffic and technology appearance with different technology splits to be spectrum efficient. For this purpose, a supervising entity would be required which at the same time would be non-compliant with highest safety requirements for functional safety.

Based on the results, the use of the IEEE 802.11(WiFi) header insertion at the beginning of the LTE-V2X signal allows to reduce the inter-technology interference caused by co-channel coexistence, improving the performance of both technologies compared to the case without any methods. The use of the superframe structure, which is proposed in *method C* and which implies that the LTE-V2X stations know the start and end of the LTE-V2X time slot, either because instructed or autonomously determined (which are both solutions that require further studies) appear not required. Additional studies appear necessary regarding the congestion control mechanisms of the two technologies to avoid an unfair access to the channel under high channel load.

When looking at the results with large packets, it can be noted that they are indeed more challenging from the perspective of co-channel coexistence. When looking at *enhanced A* and *semi-static C*, there is a reduction for ITS-G5 of the successful transmissions per area and per time unit. When looking at the *methods with the header insertion*, the main problem is that the ITS-G5 transmissions last for longer than a single LTE-V2X subframe. In all the cases, additional mechanisms or variants to the methods may help that specifically address the larger packets.

When focusing on different generation patterns, it is noted that the performance changes if aperiodic or periodic generation of packets is considered. It is observed that a periodic generation in ITS-G5 apparently implies a higher average packet reception probability for both technologies in case of coexistence as an indirect effect of the semi-persistent scheduling procedure of LTE-V2X, but the drawback is that it increases the probability of bursts of errors. This aspect is common to any mitigation method, but especially relevant when the methods with header insertion are considered.

Annex A – Path-loss models

In this white paper, we adopt a different model than the one adopted in [TR103766] and [C2CWP1]. In those documents, the WINNER+, scenario B1 (urban microcell) is used as suggested by 3GPP for the investigation of LTE-V2X sidelink. Hereafter, we will use *WINNER+, B1* for conciseness.
The point is that the WINNER+, B1 model has been defined for urban dense scenarios and has a path-loss exponent equal to 4 beyond few tens of meters, which brings to a power reduction with the distance that is not in agreement with many observations done on field in the highway scenarios.
For this reason, in this document we use a modified version of the model defined in the ECC Report 68 for the rural area [ETSI103439], hereafter denoted as *ECC Report 68 rural*.

The two models bring to different results if we look at the performance at a given density. However, the overall conclusions that stem from simulations performed with these two models are similar. Indeed, as shown in this Annex, if a proper scaling of the vehicle density and of the transmitter-receiver distance is performed, the curves appear very similar.

The pathloss in the case of WINNER+ scenarios B1 (urban microcell), LOS, is as follows:

$$PL_{dB}(d) = \begin{cases} 42.42 + 22.7\log_{10}(d) & if\ d \leq d_{T0} \\ 20.05 + 40.0\log_{10}(d) & otherwise \end{cases}$$

where $d_{T0} = 19.67$m is the breakpoint distance.

The modified ECC 68 path-loss model considered in this work is calculated as follows[20]:

$$PL_{dB}(d) = \begin{cases} 20\log_{10}\left(\frac{\lambda}{4\mu d}\right) & if\ d \leq d_{T0} \\ 20\log_{10}\left(\frac{\lambda}{4\mu d_{T0}}\right) - 10n_0\log_{10}\left(\frac{d}{d_{T0}}\right) & if\ d_{T0} < d \leq d_{T1} \\ 20\log_{10}\left(\frac{\lambda}{4\mu d_{T0}}\right) - 10n_0\log_{10}\left(\frac{d_{T1}}{d_{T0}}\right) - 10n_1\log_{10}\left(\frac{d}{d_{T1}}\right) & otherwise \end{cases}$$

where d_{T0} is the first breakpoint distance, n_0 is the path loss factor beyond the first breakpoint distance, d_{T1} is the second breakpoint distance, n_1 is the path loss factor beyond the second breakpoint distance.
Given that a highway scenario is investigated, a rural channel model is considered, with $d_{T0} = 128$m, $n_0 = 2.8$, $d_{T1} = 512$m, and $n_1 = 3.3$.
The comparison of the path loss models as functions of the transmitter-receiver distance is shown in Figure A-1.

[20] The considered channel model is a modified versions of that detailed in the ECC REPORT 68 [ECC68]. The modification, compared to the original ECC Report 68, is in smaller values for the breakpoint distances. The rational is that the original models in ECC Report 68 have been developed for the link between a device, with height 1.5m, and an access point, with height 10m to 25m (the addressed technologies were broadband wireless access systems, such as WiMax).

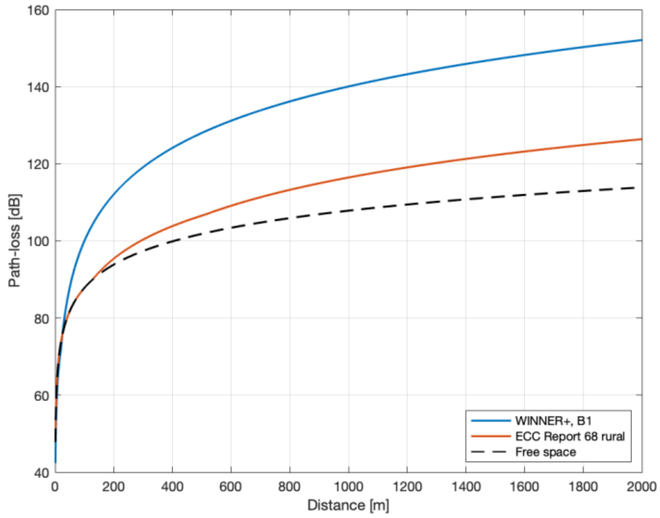


Figure A-1 Comparison between the path-loss deriving from the WINNER+, B1, ECC Report 68 rural, and free-space models as function of the transmitter-receiver distance.

Figure A-2 shows the power received as the distance varies. The received power is then compared with the sensitivity threshold at -85 dBm. The figure shows how the distance at which the received power crosses the sensitivity threshold is 800 meters with the ECC Report 68 rural, and around 200 meters with the WINNER+, B1, i.e. about 4 times greater when considering the ECC Rural 68 model than when considering the WINNER+, B1 model.

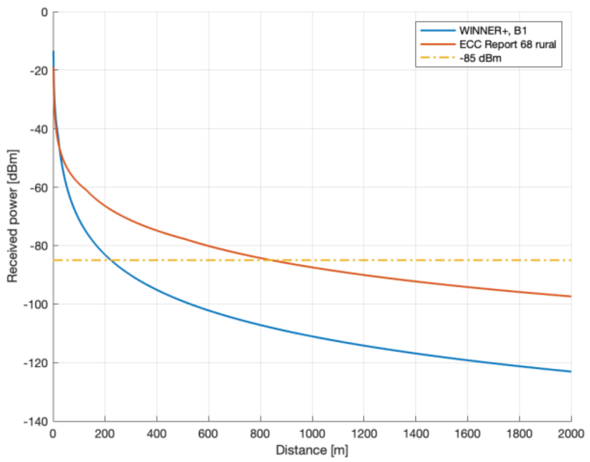
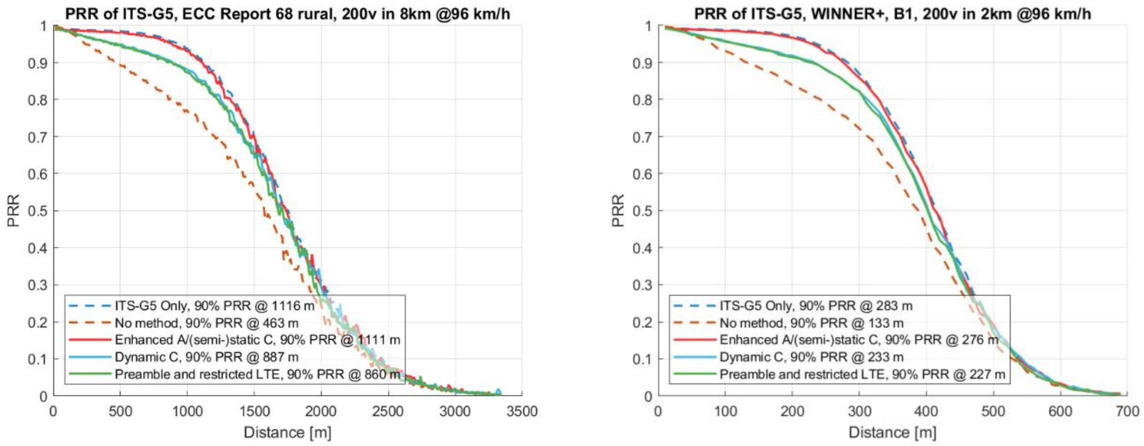


Figure A-2 Received power, with transmission power 23 dBm and antenna gain 3 dBi both at the transmitter and the receiver.

The impact of the channel model on the PRR has been evaluated by simulating a coexistence configuration between ITS-G5 and LTE-V2X. Specifically, the vehicle density is scaled so that the vehicle density set when the WINNER+, B1 model is used is equal to four times the vehicle density that is set when the ECC Report 68 rural is adopted. The packet size is equal to 350 bytes, the MCS is 2 for ITS-G5 and 7 for LTE-V2X. A scenario with 50% of traffic ITS-G5 and 50% LTE-V2X is simulated. *Enhanced A*/*semi-static C*, *dynamic C* and *no method* are simulated and compared with the case without coexistence (single technology).

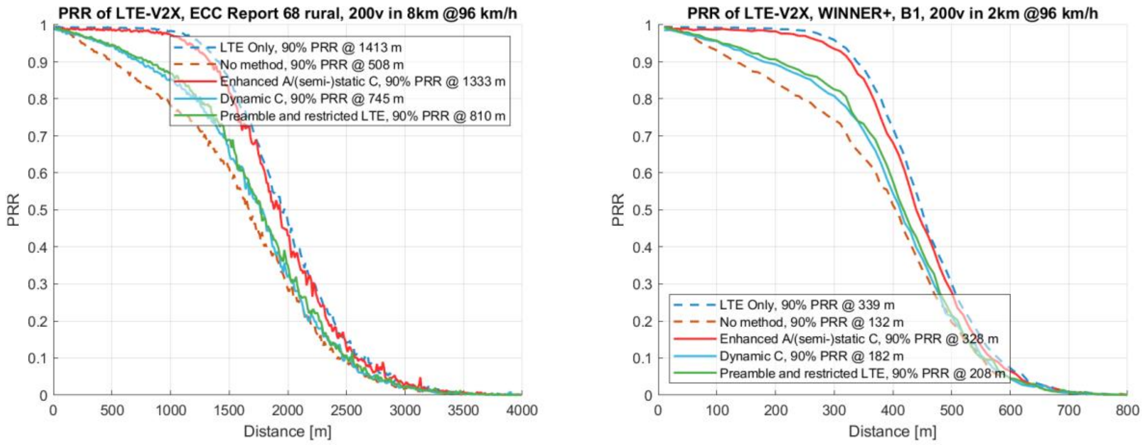
Figure A-3 shows the PRR using the ECC Report 68 rural (left) and the WINNER+, B1 (right) channel models, respectively, for the ITS-G5 technology. a) LTE-V2X, 350 bytes, ECC Report 68 rural b) LTE-V2X, 350 bytes, WINNER+, B1

Figure A-4 shows the PRR using the ECC Report 68 rural (left) and the WINNER+, B1 (right) channel models, respectively, for the LTE-V2X technology. It can be noted that the curves corresponding to the same setting have the same trends with the two models if the x-axis is scaled so that the same traffic is present within the same range (i.e., by compensating the scaled density).



a) ITS-G5, 350 bytes, ECC Report 68 rural b) ITS-G5, 350 bytes, WINNER+, B1

Figure A-3 PRR as a function of the distance for the ITS-G5 single technology, compared with *Enhanced A*, *dynamic C*, and *header insertion without superframe (preamble)*. Results are obtained with the ECC Report 68 rural model (left) and WINNER+, B1, model (right).



a) LTE-V2X, 350 bytes, ECC Report 68 rural b) LTE-V2X, 350 bytes, WINNER+, B1

Figure A-4 PRR as a function of the distance for the LTE-V2X single technology, compared with A, *dynamic C*, and *header insertion without superframe (preamble)*. Results are obtained with the ECC Report 68 rural model (left) and WINNER+, B1, model (right).

These results demonstrate that by using appropriately scaled vehicle density and distance, the conclusions are the same. When referring to the WINNER+, B1 and the ECC Report 68 rural models, there is a factor approximately equal to four (four times less density and four times larger range in the ECC Report 68 rural model). Therefore, in this document results are provided using the ECC Report 68 rural model, but they allow to infer what would be obtained adopting the WINNER+, B1 model.

Annex B – Physical layer abstraction

In this Annex, we propose the mathematical model for the PHY abstraction of V2X communications. Specifically, we present the methodology used to derive a parametric model, with a single parameter that depends on the operating scenario.

When experimental measurements are available under specific parameter settings, the empirical SINR vs. PER curve can be extracted from the measured data. Normally, the measured data is obtained in the absence of interference and it is assumed that the interference has the same properties of noise, i.e., it is white, Gaussian, with zero mean. Nonetheless, such curve is not general and cannot be used for other parameter settings, and it is difficult to obtain measurements for any possible configuration (such as MCS and packet size). Even relying on access layer simulations, obtaining a curve for each possible configuration is complicated.

The approach here proposed starts from a limited number of curves that relate PER and SINR in some configurations, to obtain a PHY layer abstraction which is valid also under other settings for which there are no results available. The method is detailed in [Bar22].

In Figure B-1, the PER as a function of the signal to noise ratio is shown under some MCSs and packet sizes for both the ITS-G5 and LTE-V2X technologies.

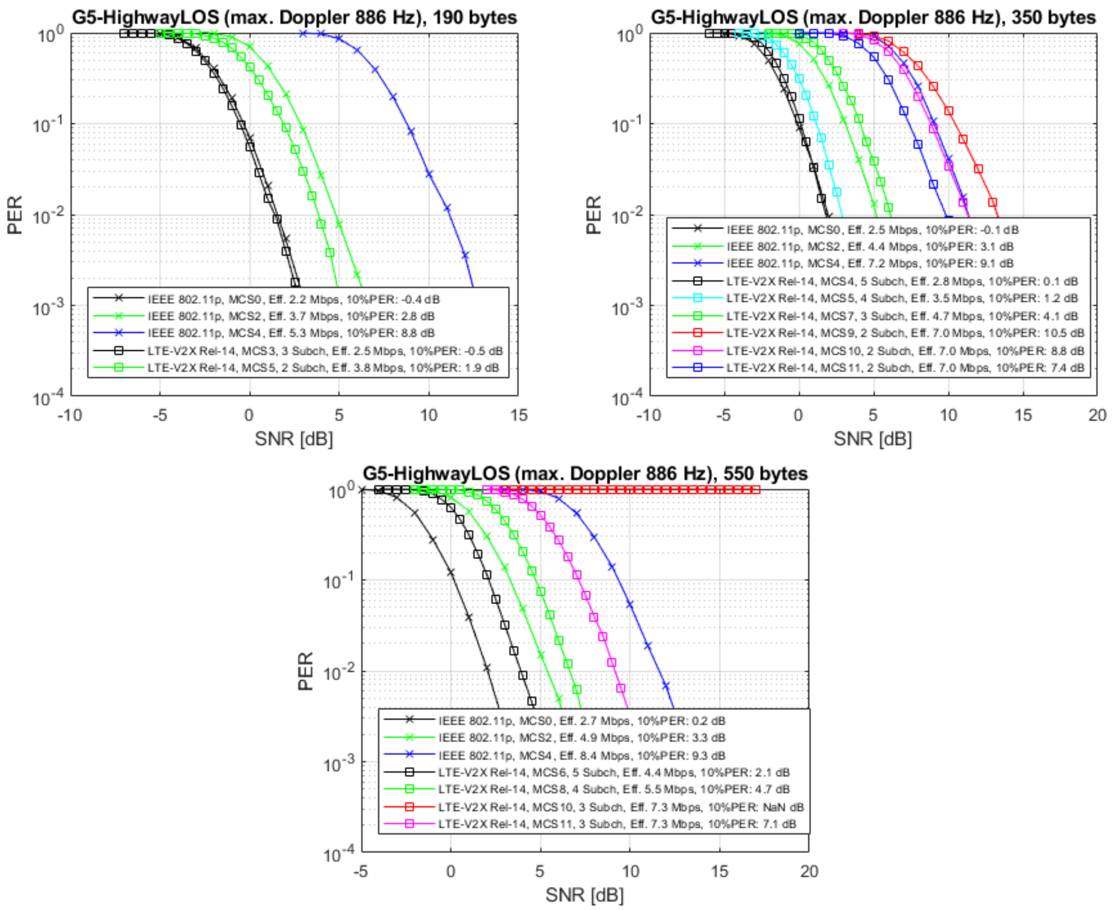


Figure B-1 PER for 802.11p and LTE-V2X under different MCS conditions as a function of the signal to noise ratio, in the highway LOS scenario with packets of 190, 350, and 550 bytes.

B.1 Approximation of the SINR vs. PER curve with a step function

The abstraction relies on a step function that approximates the PER vs. SINR curve, i.e. a packet is defined as correctly received if the SINR is above the threshold $\gamma_{\text{th}}(\boldsymbol{\theta})$, where $\boldsymbol{\theta}$ represents a vector with the parameters of the specific configuration. In the cases where the curves are available, using the SINR value corresponding to a PER equal to 0.5 was found to provide an accurate approximation for network-level simulations, as shown in [Bar22].

B.1 Setting of the SINR threshold

Based on values known for some configurations, an approach is then provided to set the value of $\gamma_{\text{th}}(\boldsymbol{\theta})$ for a broader range of configurations, based on the concept of effective throughput and a parameter, hereafter denoted as α, which indicates the loss compared to the capacity of an ideal additive white Gaussian noise (AWGN) channel with the given effective throughput.

As a preliminary step, the time necessary for a packet transmission for ITS-G5 and LTE-V2X is calculated.

ITS-G5: The time required to transmit a packet, for a given payload P_b, can be calculated as

$$T_{\text{tx}}^{(ITS-G5)} = T_{\text{AIFS}} + T_{\text{pre}} + T_{\text{sym}} \times n_{\text{sym}}$$

where T_{AIFS} is the duration of the AIFS (110 µs), T_{pre} is the preamble duration (40 µs), T_{sym} is the OFDM symbol duration, $n_{\text{sym}} = \lceil 8P_{\text{b}}/n_{\text{bpS}} \rceil$ denotes the number of OFDM symbols required to transmit a certain payload (including MAC header, service, and tails bits), and n_{bpS} is the number of data bits per OFDM symbol.

LTE-V2X: In LTE-V2X, a packet is normally transmitted on one or more subchannels within one TTI, which lasts 1 ms. In general, the transmission can be split over more than one TTI if the packet size and adopted MCS require more physical resource blocks (PRBs) than those that are available. The time necessary for a packet transmission is therefore

$$T_{\text{tx}}^{(\text{LTE-V2X})} = T_{\text{TTI}} \left\lceil \frac{n_{\text{PRB-pck}}}{n_{\text{PRB-TTI}}} \right\rceil = T_{\text{TTI}} \cdot n_{\text{TTI}}$$

where T_{TTI} is the TTI duration, $n_{\text{PRB-pck}}$ is the number of PRBs necessary for one packet transmission (which depends on P_{b} and the adopted MCS), $n_{\text{PRB-TTI}}$ is the number of PRBs in a TTI, and $n_{\text{TTI}} = \left\lceil \frac{n_{\text{PRB-pck}}}{n_{\text{PRB-TTI}}} \right\rceil$ is the number of TTIs needed for transmitting the packet. In most of the cases, such as in this white paper, the transmission lasts one TTI, thus $n_{\text{TTI}} = 1$ and $T_{\text{tx}}^{(\text{LTE-V2X})} = T_{\text{TTI}}$ (i.e., 1 ms in LTE-V2X).

Based on the duration of a transmission and the carried data, the effective throughput is calculated, which corresponds to the maximum net throughput for the given configuration.

In particular, given the packet size P_b and the MCS, the effective throughput is calculated as the ratio of the number of data bits and the transmission time previously discussed, as

$$\Psi_\mathrm{e}^{(ITS-G5)}(\theta) = \frac{8P_\mathrm{b}}{T_\mathrm{tx}^{(ITS-G5)}}$$

$$\Psi_\mathrm{e}^{(\text{LTE-V2X})}(\theta) = \frac{8P_\mathrm{b}}{T_\mathrm{tx}^{(\text{LTE-V2X})}} \cdot \frac{m_\text{subch} \cdot n_\text{PRB-subch} \cdot n_\text{TTI}}{n_\text{PRB-pck}}$$

where $\boldsymbol{\theta}$ represents the generic parameter vector, i.e. $\boldsymbol{\theta}$ = [T_pre, T_AIFS, T_sym, n_sym] for ITS-G5 and $\boldsymbol{\theta}$ = [$n_\text{PRB-subch}$, $n_\text{PRB-pck}$, m_subch] for LTE-V2X, with m_subch being the number of subchannels and $n_\text{PRB-subch}$ the subchannel size, expressed as number of PRBs. Please note that the number of PRBs in a TTI can be written as a function of the subchannels and PRBs per subchannels as $n_\text{PRB-TTI} = m_\text{subch} \cdot n_\text{PRB-subch}$.

To relate the effective throughput with the PHY settings, SINR and the channel conditions, we consider the channel capacity as defined by the Shannon-Hartley theorem, i.e. the maximum theoretical throughput that can be achieved over an AWGN channel for a given SINR

$$\Psi_\mathrm{s}(\gamma) = B\log_2(1+\gamma)$$

where B is the bandwidth of the channel and γ is the SINR.

Then, we assume that for each parameter setting there exists an attenuation factor α such that the relationship between SINR and the effective throughput can be approximated as an attenuated and truncated form of the Shannon bound

$$\Psi_\mathrm{e}(\theta) \simeq \alpha\Psi_\mathrm{s}\big(\gamma_\mathrm{th}(\theta)\big).$$

If α is known, the corresponding SINR threshold is obtained by inverting (6) as

$$\gamma_\mathrm{th}(\theta) = 2^{\frac{\Psi_\mathrm{e}(\theta)}{\alpha}} - 1$$

Then, a packet is defined as correctly received if the SINR is above the threshold $\gamma_\mathrm{th}(\boldsymbol{\theta})$.

In the general case, the attenuation factor α is unknown. We consider that a number N of PER vs. SINR curves are available for the operation environment of interest. Each curve corresponds to a specific parameter setting, i.e. $\{\boldsymbol{\theta_1}, \boldsymbol{\theta_2}, \ldots, \boldsymbol{\theta_N}\}$, where $\boldsymbol{\theta_i}$ represents a vector that includes the PHY and MAC parameters for the i^th setting. A threshold $\hat{\gamma}_{th}(\theta_i)$ is associated to each curve. In order to estimate the parameter α, a least-square approach is considered over the set of available curves, i.e.

$$\hat{\alpha} = \arg\min_{\alpha} \sum_{i=1}^{N} \left[\Psi_\mathrm{e}(\theta_i) - \alpha\Psi_\mathrm{s}\big(\hat{\gamma}_{th}(\theta_i)\big)\right]^2 .$$

Note that, once the α is estimated as $\hat{\alpha}$, the model can be used also for any parameter setting θ beyond those for which a curve is available, e.g. for any MCS and for any packet size.

In the particular case of Highway LOS conditions, the approach proposed leads with the use of the curves shown in Figure B-1 to an estimated $\hat{\alpha}$ equal to 0.37, as better detailed in [Bar22]. The relationship between the SINR threshold and the effective throughput that derives from this optimization, together with the values that are available as an input, is shown in Figure B-2.

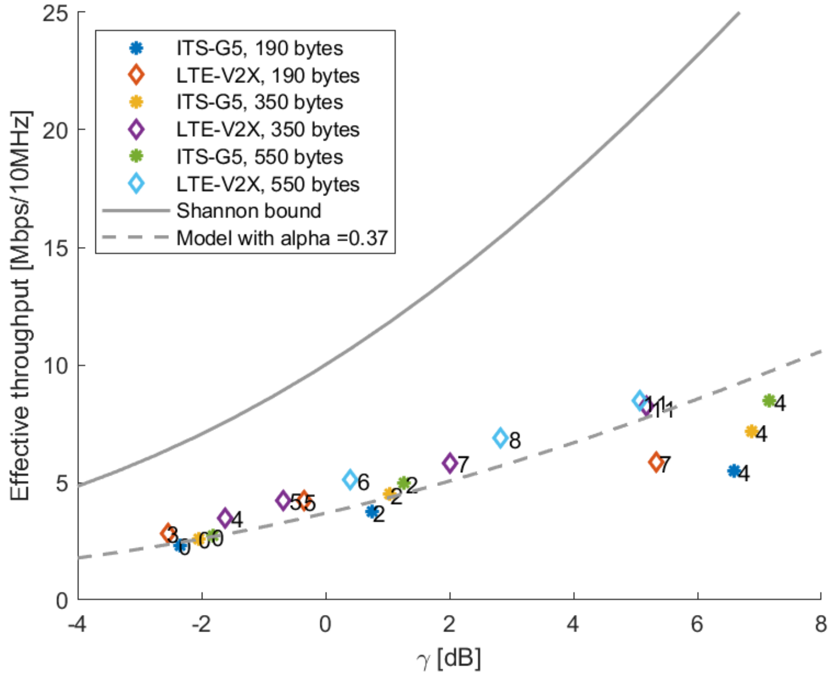


Figure B-2 Effective throughput as a function of the SINR threshold. The symbols correspond to values from link-level simulations; the dashed curve represents the fitting curve deriving from the proposed model and the best-fit *α*.

In [Bar22], results from network simulations performed using the WiLabSim simulator are shown with reference to both technologies. The results show that the proposed model leads to curves that are very close to those obtained considering the corresponding empirical PER vs. SINR curve, both looking at the error rate and the correlation among consecutive errors.

In the case of this work, the use of the curve was in principle possible for the configurations with packets of 350 bytes, but were not possible for those with packets of 1000 bytes. For the sake of consistency, the detailed PHY abstraction has been anyway used in all the cases.

Annex C – LTE-V2X mapping of messages

The present document assumes an LTE-V2X profile as defined by ETSI EN 303 613[ETSI303613], which specifies the common parameters for the LTE-V2X stations.

It defines that the subframe is organized with 5 subchannels of 10 RB each, as illustrated by Figure C-1, leading to five possible PSSCH sizes: 8, 18, 27, 36 or 48 RB.

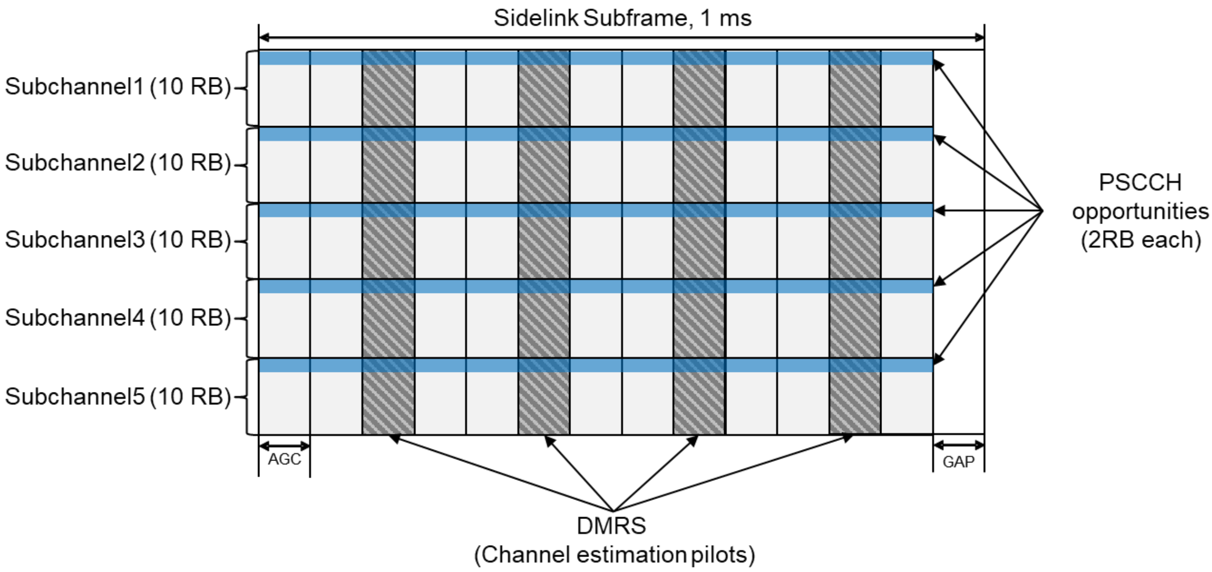


Figure C-1: LTE-V2X subframe structure

This profile also defines the MCS ranges, for instance I_MCS 3 to 11 for OBU with speeds ≤ 160 km/h.

Table C-1 shows the transport block size (TBS) in bytes, from a given combination of I_MCS and number of subchannels. It also highlights the possible parameterization to support 350 and 1000 bytes. It can be remarked that for 1000 bytes one has to use 5 subchannels and a high MCS.

Table C-2: TBS as a function of I_MCS and number of subchannels for LTE-V2X

350 bytes — Scheduling options: 2 Sbch MCS 9/10/11 ; 3 Sbch MCS 7 ; 4 Sbch MCS 5 ; 4 Sbch MCS 4

1000 bytes — Scheduling options: 5 Sbch MCS 10/11

TBS in [bytes]

I_MCS	Qm	I_TBS	Number of subchannels				
			1	2	3	4	5
			8 PRB	18 PRB	27 PRB	36 PRB	48 PRB
0	2	0	26	MCS < 3 not available for > 1 subchannel			
1	2	1	32				
2	2	2	41				
3	2	3	55	129	193	261	349
4	2	4	69	161	241	325	437
5	2	5	85	193	293	389	533
6	2	6	101	233	349	469	621
7	2	7	121	277	421	549	749
8	2	8	137	317	469	621	839
9	2	9	157	357	533		935
10	2	10	173	389	597	775	1063
11	4	10	173	389	597	775	1063

MCS > 11 available only for RSU (up to MCS 17)

EN 303 613, Annex C: List of MCS-RB problematic cases to be excluded

Configuration allowed but higher MCS performing better

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