Wireless Personal Communications manuscript No.
(will be inserted by the editor)

Overview of LTE for Vehicular Communications

Antonio Cerezo Barranco · José Antonio Yébenes Gálvez · Jesús Aguilar Armijo · Mari Carmen Aguayo-Torres · Juan Carlos Ruiz Sicilia · Gerardo Gómez

the date of receipt and acceptance should be inserted later

Abstract This article provides an overview about vehicle-to-everything communications (V2X) in relation to the latest Long Term Evolution (LTE) standards. We present the main vehicular services and give a brief review of vehicular communication systems over LTE for both infrastructure to vehicle (I2V) communications over the broadcast/multicast LTE service and vehicle-to-vehicle (V2V) communications over the LTE sidelink. Following, it analyzes the performance of vehicular systems using link simulations for several different vehicular channel models implemented over a simulator called WM-SIMA. Finally, we draw out conclusions from the impact of the use of different modulation levels and coding rates, as well as the interference level, in the communication performance.

Keywords Vehicle-to-everything communications (V2X) · LTE-V · broadcast · sidelink

1 Introduction

In the last years there has been a growing interest in vehicular communications. The main reason for it is that the establishment of ad-hoc communications networks between vehicles (and with the infrastructure) would reduce the number of accidents and improve traffic management [8]. The benefits of this new paradigm, called the intelligent transportation systems (ITS), are so direct that research and innovation on this area is being considered as a

---

This work has been supported by the Spanish Government (Ministerio de Economía y Competitividad) and FEDER under grant TEC2016-80090-C2-1-R and by the Universidad de Málaga.

Dpto. Ingeniería de Comunicaciones, Universidad de Málaga, Spain
Tel.: +34 952 13 2759
E-mail: aguayo@ic.uma.es

strategic topic by both the European Union and the authorities of the most developed countries.

The most promising communications technology for ITS, known as cellular vehicle to everything (C-V2X), proposes the use of cellular mobile networks for communication between vehicles and transport infrastructure and a specific link for direct connection between vehicles. The support of the necessary functionalities for C-V2X is among the design requirements of the fifth Generation (5G) systems, although Release 14 of the 3rd Generation Partnership Project (3GPP) standard already incorporates some of these in the Long Term Evolution (LTE) system.

C-V2X channels shows notable differences with conventional cellular channels: much higher Doppler frequencies (because both ends of the communication can be mobile); non-stationary response, with significant correlation between different propagation paths, and considerable influence of the environment on the characteristics of the channel (due to the low height of the antennas involved in direct communication between vehicles).

The particularities of this type of channel and the existence of a direct link between vehicles pose significant problems both in the physical layer and in the radio resources management. For instance, it is important to develop statistical channel models that avoid the problems of the currently proposed geometric-statistical strategies (high computational cost and impossibility of analytical performance evaluation). In addition, new radio resource management algorithms must be designed to adapt the transmission parameters (power, number of retransmissions, coding/modulation) to the vehicular scenario, taking into account the number of vehicles that are accessing the channel.

In this paper, we review the LTE Release 14 standard for vehicular communications. After having a look on the vehicular communication services, we describe the use of the evolved multimedia broadcast multicast service (eMBMS) for communication from infrastructure to vehicles. Later, we overview the use of the variant of LTE for direct vehicle communications over the sidelink.

In order to exemplify the LTE performance, we modified our tool named as WM-SIMA [5] to be able to carry out link simulations over vehicular channels. Some performance results for communication between infrastructure and vehicles as well as direct V2V communications are shown in order to reveal the main issues.

Our work concludes with a summary and some open issues for 5G vehicular communications.

2 Vehicular communications services

The vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications services allow real-time information exchange between vehicles and from infrastructure to vehicles, respectively, with the aim of increasing driver perception and avoiding potentially dangerous situations.

In the United States and the European Union, the deployment of the cooperative intelligent transport systems (C-ITS) have been investigated for more than a decade. In recent years, standardization organizations are playing a fundamental role in the development and testing of message sets and protocols with the aim of accelerating the implementation of the C-ITS. The United States Department of Transportation (US DOT) coordinates with the Society of Automotive Engineers (SAE) and Institute of Electrical and Electronics Engineers (IEEE) the development of standards for dedicated short-range communications (DSRC) in vehicular communications systems. The European Telecommunications Standards Institute (ETSI) and the European Committee for Standardization (CEN) are responsible for creating a set of European standards that ensures interoperability between vehicle-to-everything (V2X) communication systems.

Two modes can be distinguished in vehicular communications: awareness based and event based. In the first mode, each vehicle sends periodically information about its status (speed, acceleration, position, etc.) and the receiver is in charge of extracting event information from the transmitted data. Information frequency can be set between 1 and 10 Hz, depending on the vehicle dynamic. In addition, under the event based mode, the transmitter sends a message when detects an event (emergency braking, for example) while it is expected that the receiver reacts to that event.

Event based	**Awareness based**
Message describes an event	Message describes status of a vehicle
Easy interpretation on receiver side	More complex interpretation on receiver side
One received message is sufficient	Needs to receive more than one message and track value changes
Only known use cases can be described	Data can be used for new uses cases

Table 1 Differences between event based and awareness based communications.

2.1 Message set

Both American and European standards share similarities, but the set of messages are not exactly the same at both sides of the Atlantic Ocean.

In the European standard, cooperative awareness messages (CAMs) [10] are distributed within the ITS network and provide information of presence, positions as well as basic status of the communicating ITS station (ITS-S). All stations shall be able to generate, send and receive CAMs, as long as the participate in V2X networks. By receiving CAMs, an ITS-S is aware of of other stations in its neighbourhood area as well as their positions, movement, basic attributes and basic sensor information. At the receiver side, reasonable efforts can be taken to evaluate the relevance of the messages and the information. This allows ITS stations to get information about its situations and act accordingly.

Decentralized environmental notification messages (DENMs) [11] are triggered by an ITS-S application. A DENM contains information related to a road hazard or an abnormal traffic conditions, including its type and its position. Typically, for road safety ITS applications [14], such as road hazard signalling (RHS), intersection collision risk warning (ICRW), and longitudinal collision risk warning (LCRW), the destination of a DENM transmission are ITS-Ss that are located in a geographic area close to the detected event position. A DENM may also be disseminated over a long distance or to a central ITS-S for vehicle rerouting or road traffic management purposes.

The American standard developed by SAE [21] specifies a message set to be used at the wireless access in vehicular environments (WAVE) system, which is based on the IEEE 802.11p standard over the 5.9 GHz band [15]. However, it can be used by applications deployed over other wireless communications technologies. Specifically, the vehicular messages can be transmitted as any other application message by traditional cellular networks such as LTE over the same usual protocol stack [1]. However, direct links are better suited to the low latency requirements of vehicular communications [19].

The main SAE messages are basic safety messages (BSMs), which are broadcast by stations to the surrounding vehicles and used to assess threat potentials. It is divided in two parts. The first part contains the core data elements (vehicle size, position, speed, heading acceleration, brake system status) and are periodically transmitted. Part II is added to part I depending upon events (e.g., antilock brake system activation) and contains a variable set of data elements drawn from many optional data elements (availability by vehicle model varies). Part I and Part II BSM can be seen as loosely equivalent to the European CAM and DENM messages, respectively.

2.2 Infrastructure services

SAE J2735 also describes a set of messages specifically designed to be transmitted from infrastructure. The signal phase and timing (SPaT) messages are broadcast by roadside units (RSUs) to provide current status (color) and when the status is expected to change. Moreover, map messages are broadcast to provide geometric layout of an intersection, and are used in conjunction with SPaT messages.

The ETSI infrastructure services [9] supports the management of those messages. In one typical infrastructure application, the message is transmitted by a roadside ITS-S and disseminated to vehicular and personal ITS stations within a target destination area, in which the information included in the message is considered as relevant to traffic participants. Some example of those services are the traffic light maneuver, road and lane topology, traffic light control or infrastructure to vehicle information which supports road signage such as contextual speeds and road works warnings.

Besides communication among roadside, vehicular and personal stations, intelligent transportation systems include V2X application servers which receive information from ITS-Ss regarding the transportation state. Servers are somehow connected to one or more vehicular networks. Traffic and travel related information is carried out using the Transport Protocol Experts Group (TPEG) set of data protocols[1]. TPEG applications include, among others, information on road conditions, weather, fuel prices, parking or delays of public transport. Application servers can communicate with each other for the exchange of V2X messages [6].

3 LTE enhancements for V2X services

One important advantage of cellular networks for vehicular communications is the existence of infrastructure able to connect the vehicles to the vehicular application servers. Certainly, vehicular information might traverse LTE cellular networks. A user equipment (UE) may receive V2X messages via the LTE air interface, LTE-Uu, by usual unicast downlink via a guaranteed bit rate (GBR) bearer as well as a non-GBR bearer. This option was rejected by 3GPP for vehicle to vehicle exchange due to the high delay except for uploading information to the V2X servers via the reverse link of the LTE air interface, as shown in Figure 1. This option might also be acceptable for V2I communications for joint evolved node B (eNB) and RSU deployment.

For V2X information download, the LTE air interface can be used in unicast mode. However, often vehicular services requires disseminating information from infrastructure to a number of vehicles located in an area; then, the preferred option to integrate those services in the cellular networks is broadcasting the information from a base station (BS) to the ITS stations located in the area of interest (as also shown in Figure 1). In LTE, the evolved multimedia broadcast multicast service (eMBMS) can be used for that aim. Section 4 presents an overview of this technology.

There is a second interface for LTE V2X communication: the newly designed sidelink, named as PC5. PC5 permits direct communication between vehicles [19], supports roaming and inter-networks operations and, in the form described later, can be used when the UE providing communications to the ITS station is not served by the LTE network. V2X communications over PC5 reference point is connectionless, i.e., there is no signalling over PC5 control plane for connection establishment. Section 5 outlines V2X services over PC5.

4 LTE broadcast and multicast service for vehicular networks

As previously described, the V2X application server may want to transfer V2X messages to a set of users under LTE coverage. If the UEs provide their geographic location or serving cell information, the V2X Application Server may

---

[1] TPEG is the transportation equivalent to JPEG protocol suite for images.

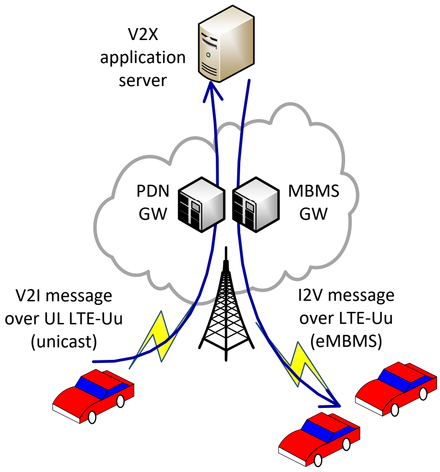


Fig. 1 Transmission of vehicular to/from infrastructure messages over LTE.

use such information to determine the target broadcast area and forward infrastructure to vehicle (I2V) messages to the appropriate multicast/broadcast session. LTE eMBMS delivers content to multiple users simultaneously with a fraction of the resources required by normal data services and greatly reducing transfer delay as compared to unicast transmission.

For the reception, the UE is provided with the V2X user service description (USD) via existing multimedia broadcast multicast service (MBMS) service announcement mechanisms. The exact information in the V2X USD is under the the V2X Application Server, while the V2X message formats are handled by upper layer via Session Description Protocol (SDP). V2X USD at least includes the mobile group identity, the applicable service area and the frequency, besides the IP multicast address and port number. Depending on the V2X application, the V2X message can be carried directly on top of UDP, without any streaming protocols.

4.1 eMBMS architecture

Originally, target applications for eMBMS were mobile TV and radio broadcasting, live streaming video services, as well as file delivery and emergency alerts. The eMBMS requires the following four main network components to provide multimedia services [22] (see Figure 2):

- Broadcast multicast service center (BM-SC): It works as interface between the content provider and the distribution network. Located in the core network, it is responsible for the scheduling and transmission of broadcast/multicast contents, security, billing and content synchronization.
- MBMS gateway (MBMS-GW): Its role is to deliver the traffic to multiple cells in one transmission using IP-Multicast.

- Multi-cell/multicast coordination entity (MCE): It coordinates the admission control as well as the radio resource allocation and scheduling of the eMBMS services in the eNB.
- Mobility management entity (MME): Besides many other functions, it is in charge of the session control signaling and delivering supplementary multicast information to the MCE.

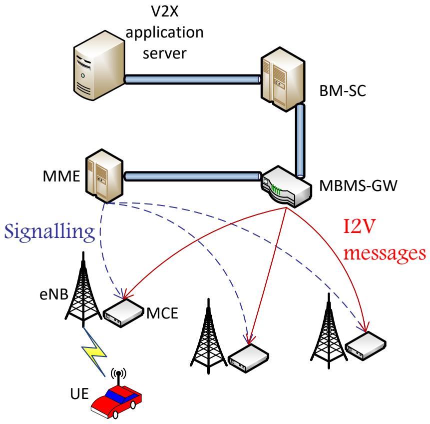


Fig. 2 eMBMS network architecture.

In release 14, some enhancements were introduced in the MBMS system architecture [2]. Two of the most important are the inclusion of free-to-air services, that involved supporting receive-only eMBMS mode with no operator subscription, extending the applicability of mobile broadcast. This might help to solve the problem of coordination among vehicles with subscription to different operators. Moreover, a new interface enables content providers directly to interface with the BM-SC to deliver media content and control information.

4.2 Radio interface

Transmission of a multimedia broadcast multicast service (MBMS) uses either single-cell point to multipoint (SC-PTM) transmission or multicast-broadcast single-frequency network (MBSFN) transmission. The MCE makes the decision on whether to use for each MBMS session.

For SC-PTM, broadcast data is transmitted in the coverage of a single cell. Since the MBMS transmission serves multiple devices, there is no feedback from users. Thus, the physical multicast channel (PMCH) is unacknowledged, hybrid ARQ repetitions are not employed, and multiple input multiple output (MIMO) techniques are not supported. Moreover, it is not possible to estimate the quality of the service using user device metrics. The eMBMS carrier can be dedicated or shared by both unicast and broadcast services.

Multi-cell transmission of multicast/broadcast information is characterized by synchronous transmission from multiple cells within a MBSFN area (Figure 3). All cells in an MBSFN area transmit the same content in reserved finely time-synchronized subframes. The transmission from different cells appears to the receiving UE like multipath from a single cell [22] as long as the OFDM cyclic prefix is long enough to catch all signal replicas. The location of the reference signal is different from unicast services to allow estimation of the combined channel from the set of transmitting eNBs.

The MBSFN protocol stack requires an additional SYNC protocol layer to carry information that enable eNBs receive information from the BM-SC on the timing for radio frame transmission and to detect packet losses. MBSFN areas are static, unless changed by operation and maintenance. This limits the freedom of flexibly shifting resources between broadcast and unicast as it needs to be done over the entire single frequency network (SFN) area rather than on a cell by cell basis. On the other hand, MBSFNs widen the coverage area without interference as well as improves reception (mainly for users at the cell edges). Operators have to configure the MBSFN service area parameters, such as the maximum modulation and coding scheme (MCS): lower MCSs achieve higher coverage at the expense of reducing unicast resources.

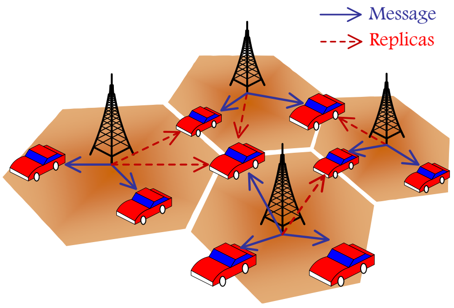


Fig. 3 eMBMS single frequency network.

5 LTE-V overview

LTE PC5 interface inherits from the LTE device to device (D2D) variant added in Release 12 which supports direct communication. However, some features have been modified due to the differences in the transmission channel and the device conditions. The channel is more hostile in the V2X scenario and the priority of devices is also different. Moreover, in D2D communications, the goal is to save battery lifetime; in contrast, in V2X it is to achieve low latency.

Figure 4 shows the architecture for LTE-V network. Usual components of LTE core network are shown: Mobility management entity (MME), Home Subscriber Server (HSS) and Serving Gateway (S-GW). Moreover, a new entity

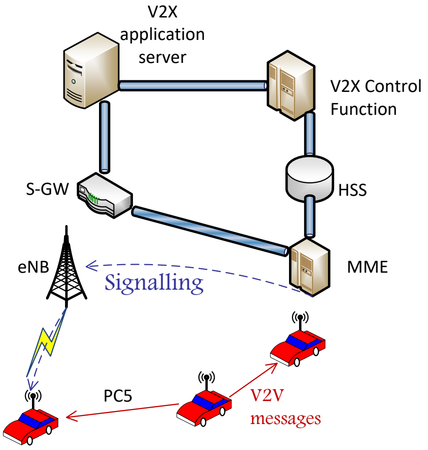


Fig. 4 LTE-V network architecture.

known as V2X control function [12] was added in Release 14 to provision the UE with necessary parameters in order to use V2X communication. Vehicular application servers communicate with it as well as with user equipment, which can discover the V2X control function through interaction with the domain name service function. The operator may pre-configure the UEs with the required provisioning parameters for V2X communication. Also, V2X Control Function may update the parameters with information from the V2X Application Server.

5.1 Physical layer

The new PC5 interface or sidelink has been defined for direct communication in both D2D and LTE-V variants. Sidelink shares similarities with uplink; for example, both use single carrier frequency division multiple access (SC-FDMA). However, the sidelink only supports normal cyclic prefix as it is designed for short-range communications where channels has brief impulsive responses.

In LTE-V, data is transmitted in subchannels. A subchannel consist on a group of physical resource blocks (PRBs) in the same subframe. Two PRBs are used to transmit the sidelink control information (SCI) over the physical sidelink control channel (PSCCH) including, for example, the modulation and coding scheme index. The rest of PRBs are assigned for data transmission over the physical sidelink shared channel (PSSCH). The pair of a PSSCH and its associated PSCCH can be configured to be adjacent or transmitted in two separated pools.

As regards modulation, SCI is always transmitted using QPSK modulation while information data could use also 16QAM. In particular, the MCS index of PSSCH could be any value between 0 and 9.

As LTE-V is designed for short delay communications, it is not possible to wait for an acknowledgement. The only method included in LTE-V to increase the reliability of communication is to transmit twice the same information over subchannels of different subframes.

The lack of an infrastructure managing the network cause the challenge of finding a new synchronization system for the users. In LTE-V, it has been developed as a distributed network in which every user chooses their best source in terms of reliability. Three possible sources are described in the standard. Besides an eNB, the Global Navigation Satellite System (GNSS) can be directly employed. Moreover, if messages from another user are available, that user can be also used as synchronization source.

5.2 Resource scheduling

One of the most critical problems of vehicular communications is the radio resource assignment due to the lack of an element managing the network. In 802.11p, the vehicular variant of WiFi [15], it has been proposed carrier sense multiple access with collision avoidance medium access scheme (CSMA-CA), which causes scalability problems as the number of users increase.

In LTE-V, it has been designed a more complex scheme that improves the system performance. It consists on two modes, Mode 3 and Mode 4, which respectively inherits from Mode 1 and Mode 2 of the D2D variant. Mode 3 depends on cellular coverage, which schedules the users similarly as it is done in cellular access. This mode is only available while in coverage (see Figure 5).

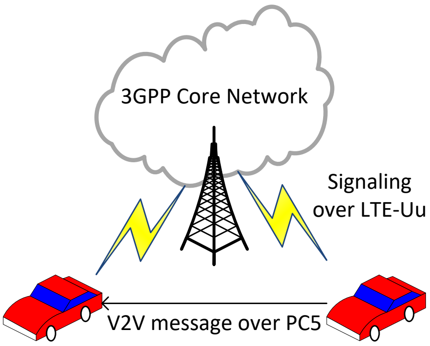


Fig. 5 LTE-V Mode 3: Signaling information is sent to vehicles from the cellular network.

In contrast, Mode 4 (Figure 6) can work out of coverage with a method that tries to avoid the use of busy subchannels by analyzing them in advance. Hybrid coverage is also possible (Figure 7).

In Mode 4, user has the control of a subchannel for a few transmissions by a semipersistent scheduling (SPS). The number of remaining transmission

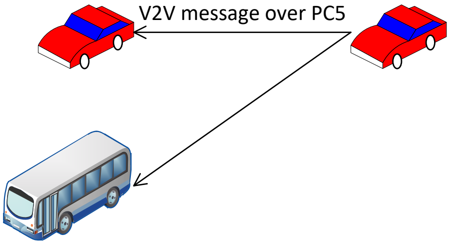


Fig. 6 LTE-V Mode 4: No signaling information from the cellular network available.

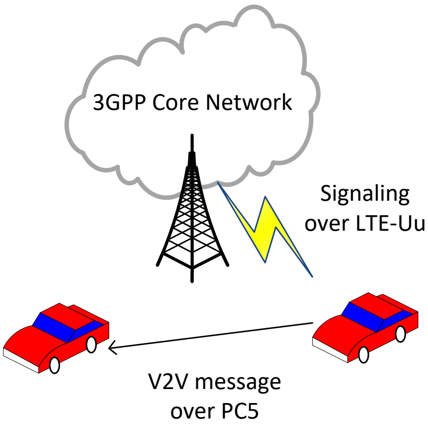


Fig. 7 LTE-V partial coverage.

is placed in the SCI of the subchannel so that the rest of users which are waiting to transmit know when it will be released. In case there is no remaining transmissions, it has been implemented a technique for congestion control in order to reduce situations in which several users are trying to transmit over the same subchannel. The method consist in allowing users to reserve a subchannel following a binomial random variable with probability p. This system parameter takes a value between 0.2 and 1. Higher values of p expedite transmission of the message, reducing delay but increasing collision probability. Lower values are more appropriate for dense traffic areas.

In order to further reduce the number of collisions, UE provisioning supports geolocation (GLOC). This option divides the V2X resource pool based on geographical areas, thus requiring access to the user location (see Figure 8). Areas are provided to the user as polygons through a specific management object while it is still in coverage. Different resources are to be used by users transmitting at each area, reducing the interference and the collision probability.

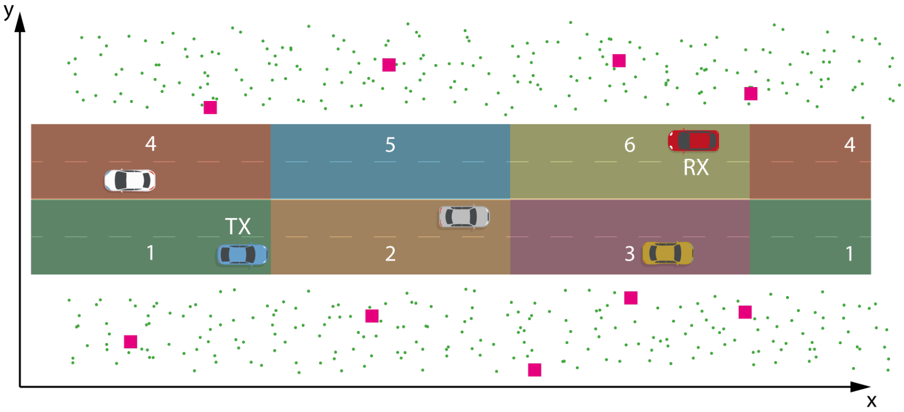


Fig. 8 Sketch of GLOC based access with different resources per direction. Different colors are associated to different access resources.

6 Simulation setup

In order to exemplify the performance of LTE for vehicular communications, I2V and V2V simulations have been carried out using the Wireless Mobile Simulator- Advanced (WM-SIMA) tool [5]. Periodic CAM messages are transmitted in order to obtain statistics that characterize vehicular communications.

For broadcast tests, we use the multicast mode of the WM-SIMA simulator. This mode enables to configure the resource allocation, allowing to choose the number of PRBs for both unicast and multicast from the pool of the LTE bandwidth. The infrastructure to vehicle communications make use of the multicast resources while unicast transmissions are simultaneously carried out over the rest of resources.

For vehicular to vehicular communications, the single-link mode of the tool was used, including the other vehicles as interferers in the form we describe below.

6.1 V2V scenario

Regarding V2V communications, GLOC based multiple access in combination with a distributed medium access control (MAC) scheme is used as resource partition scheme. Road is divided in segments called single orthogonal access resources (ARs) with certain reuse along the road. Within single-lane partition (SLP), division is done along the road as a whole. If geolocation is accurate enough, lanes can be distinguished and divided in segments [18], i.e. multi-lane partition (MLP).

We considered a straight road, split in n_{AR} zones, half for each direction. As an example, a road with six zones in total, three per direction, is shown in Figure 8. Each color represents different orthogonal resources (frequency bands) allocated to each zone. The length of the segments is fixed to the safety distance, which depends on the speed of the vehicles. Furthermore, the simulations are carried out with both transmitter and receiver following the directions of movement shown in Figure 8, that is, they approach each other from opposite directions.

In addition, the number of interfering vehicles is randomly obtained so that certain density of vehicles per meter which depends on the scenario is maintained. A realization is also shown in Figure 8. The lane of the road where the intended vehicle is located is modeled by a uniform discrete probability function and the position over it is modeled by a uniform distribution over the length of the road strip. Each interfering vehicle is assigned a constant velocity along the road given by a truncated Gaussian distribution. During the simulation, all vehicles move along their corresponding direction changing AR. We assumed that there are more density of cars in a urban avenue than in a rural highway as well as they are moving slower.

6.1.1 V2V interference

The impact of the interference of the other vehicles on the receiving vehicle is of utmost importance in the reception quality. In the geolocation based multiple access previously described, vehicles moving in the same direction than that transmitter under evaluation and transmitting simultaneously in the same access resources can possibly interfere (Figure 8). The instantaneous interference power can be evaluated as

$$I(t) = \sum_{i \in S_I(t)} P^i_{Tx} \cdot \frac{1}{L_i(t)} \cdot p^i_{rI} \tag{1}$$

where $S_I(t)$ is the set of vehicles which at instant t are located in the same zone than the evaluated vehicle (changing in time due to mobility), P^i_{Tx} is the transmission power of the i-th interfering vehicle, and $L_i(t)$ is the path loss between the i-th interfering vehicle and the receiving one, which depends among others on the distance between them and, thus, on each zone length. p^i_{rI} is the probability of the i-th vehicle interfering to the receiver, which can be evaluated as:

$$p^i_{rI} = p^{Tx}_{rT} \cdot p^i_{rT} \tag{2}$$

being p^{Tx}_{rT} the transmission probability of the evaluated transmitter and p^i_{rT} the transmission probability of the i-th interfering vehicle.

In our simulations, we assumed it is not needed any reservation nor information exchange to access the resources, that is, vehicles estimate their position and transmit in the AR corresponding to their zone as soon as they have data to transmit [18]. Therefore, transmission probabilities for both transmitting p^{Tx}_{rT} and interfering vehicles p^i_{rT} have the same value given by

$$p_{rT} = \left\lceil \frac{N_{ST}}{N_{SA}} \right\rceil = \left\lceil \frac{\frac{N_p}{N_b}}{N_{SA}} \right\rceil \tag{3}$$

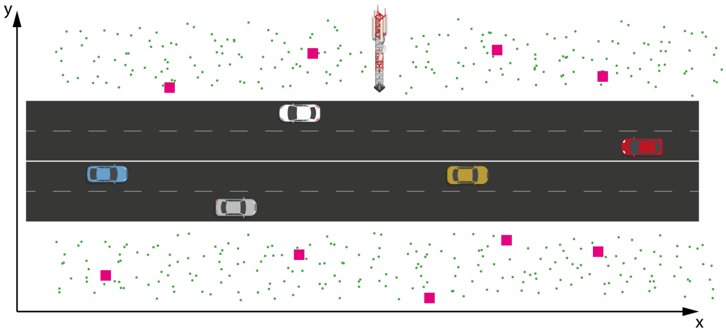


Fig. 9 I2V scenario

where N_{ST} is the number of LTE subframes used to transmit a CAM packet, and N_{SA} is the number of LTE subframes between consecutive packets. N_{ST} can be evaluated from the ratio between the number of bits in a CAM packet, N_p, and the number of data bits in an LTE subframe N_b, which depends of the MCS being employed for transmission. $\lceil \cdot \rceil$ represents rounding up to the nearest whole number, as usual. Note that, in general, transmission using a lower MCS will be more robust for the same interference power. On the other hand, the transmission itself will last for longer, thus increasing the collision probability and the interference power.

Assuming that all vehicles transmit the same power P_{Tx} and Gaussian interference, the next expression for instantaneous interference power is obtained:

$$I = P_{Tx} \cdot p_{rT}^2 \cdot \text{mean}\left(\sum_{i \in S_I(t)} \frac{1}{L_i(t)}\right). \tag{4}$$

6.2 I2V scenario

An SC-PTM transmission has been analyzed for infrastructure to vehicle communication. Base stations have been settled following a hexagonal deployment. The same set of resources are set up for broadcasting at all cells. No frequency reuse is considered, thus all surrounding BSs interfere at the reception.

A vehicle moving along a road is receiving data broadcast by its serving eNB. We considered also users following straight line trajectories (Figure 9). This scenario permits to analyze how the error rate increases with distance for a certain MCS. Conversely, coverage for a given MCS can be studied.

6.3 Vehicular channel models

WM-SIMA tool allows the inclusion of channel realizations which are the result of different modelling techniques. These can be used in time or frequency domain. To appreciate the effect of Doppler spread over the vehicular communications [7], more realistic time domain simulations are carried out in this paper. This subsection gives a glimpse of those channel models and the scenarios where they are useful.

Channel modeling techniques can be classified in three wide groups depending on how their parameters are calculated [7]:

- Geometry-based deterministic model (GBDM): It sets a model based on channel measurement campaigns for different typical scenarios, drawing deterministic representations for different kind of channels. It uses ray-tracing strategies to obtain the frequency selective channel response. As elements in the scenario moves, time variable conditions are created.
- Geometry-based stochastic model (GBSM): It defines some scenarios (e.g. "rural", "urban" or "highways") where typical assumptions are made to simplify the elements of the geometry description. Scatterers, blockers or reflectors are placed based on statistical processes. It shares with GBDM the use of ray-tracing. A main drawback of both geometric models is their high computational cost.
- Non geometry-based stochastic model (NGBSM): This technique, such as the tapped-delay line (TDL) model, represents channel by means of echoes whose average power and delay are known and described by the power delay profile (PDP). Different power profiles characterize distinct scenarios. Each echo is considered a Gaussian process, likely time-correlated by certain Doppler spread function. NGBSMs are quite simple and computationally lighter.

Sidelink V2V channel modeling is challenging due to the changing environment, very high relative vehicle speed (double than towards infrastructure) and low antenna height at both sides of communication. On the one hand, the assumption of wide-sense stationarity (WSS) is not possible in general because of the very high variable characteristics of the environments. On the other hand, characteristics of the different multi-path components between transmitter and receiver presents strong correlation, thus the assumption of uncorrelated scatterers is not applicable. In summary, radio-propagation channels in vehicular communications present harsh features that make questionable that wide-sense stationary uncorrelated scatterers (WSSUS) channel models can be employed [7].

Each modeling type is useful for certain communication scenarios. Both geometrical models are intrinsically non-stationary as the mobility of transmitter, receiver and others elements is considered. We have used them to model channel in V2V communications. However, I2V links are similar to that of conventional cellular communications, making possible to use NGBSMs. Next, a brief description of the channel models employed in this paper is presented.

6.3.1 TDL model

WM-SIMA simulator allows entering any PDP based model by defining each echo delay and power value. There exists a set of standardized PDP for certain scenarios such as urban, rural, etc. [3]. The channel small scale effects are simulated as a FIR filter whose coefficients result from applying a Rayleigh or Ricean (line-of-sight case) distribution at each echo.

The relative speed of the transmitter and receiver as well as the carrier frequency of the communication are also selected, which results in certain maximum Doppler frequency [16]. Time correlation is simulated by filtering the Rayleigh/Rice echoes through an appropriate spreading filter [16] or by using the sum-of-sinusoids (SoS) method [20].

6.3.2 Cluster delay line model

The cluster delay line (CDL) model corresponds to that proposed by 3GPP for channel modeling at frequencies from 0.5 to 100 GHz [3]. Several rays with common spatial and temporal characteristics are joined in groups of rays called clusters.

This channel model belongs the GBSM type. A PDP is obtained at each simulation following a ray-tracing process where the geometric description only covers the arrival angles from the last scatterers and the departure angles to the first scatterers from the transmitting side. However, propagation between the first and the last interaction is not defined geometrically but given as statistical distributions for delays and power values in [3]. Thus, this model presents two statistic levels in different phases of the modeling; first, in the calculation of the PDP and, second, applying the temporary dependency in each cluster of rays to generate the slow fading.

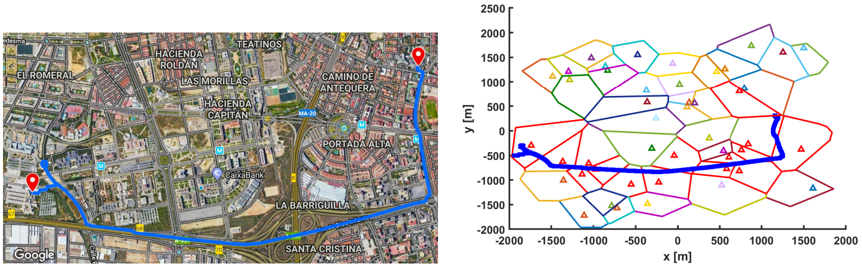
CDL model allows selecting different environments such as rural macrocell (RMa), urban macrocell (UMa), urban microcell (UMi) or indoor scenarios. Also, the antenna heights, the carrier frequency and the speeds of the link ends are configurable. In addition, it is worth to mention that the 3GPP CDL model can be used to simulate other common situations in vehicular communications such as penetration of the signal through walls or cars. Real mobility trajectories and eNB positions such as that shown in Figure 10 can also be simulated in WM-SIMA[2]. CDL propagation channel model might be employed for both V2V and I2V simulations with transmission ends modified accordingly.

6.3.3 Vehicular GBSM

This channel employ results of a tool presented in [17] based on a measurement campaign of V2V channels, using a GBSM model. The basic idea is to place an ensemble of point scatterers according to a statistical distribution, assign them different properties, determine their respective signal contribution and finally sum up the total contribution at the receiver. There are three different types of scatterers: mobile scatterers, that simulate vehicles traveling the scenario;

---

[2] WM-SIMA simulator allows including any eNB position. Those shown here are only for the sake of exemplification and do not represent a real deployment.



(a) (b)

Fig. 10 **(a)** Example of a real trajectory in Málaga city (Spain). **(b)** Simulated trajectory over a cellular map in WM-SIMA. Positions of the eNB are marked by triangles and the irregular coverage area borders plotted in colors.

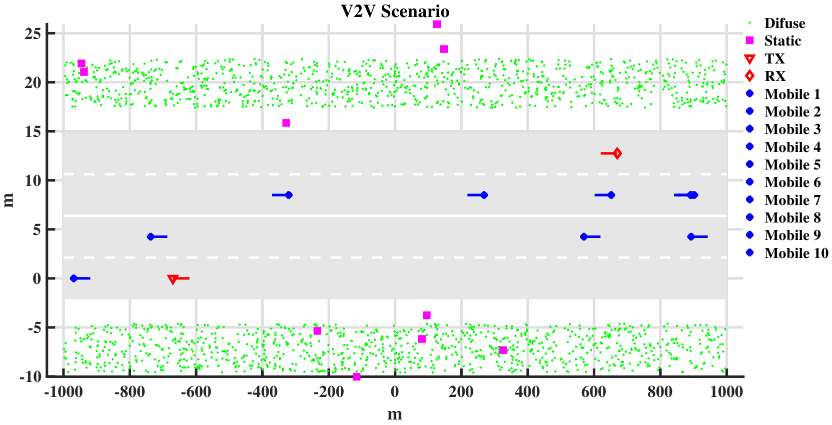


Fig. 11 A randomly generated scenario for a V2V channel. In addition to the transmitter (red triangle) and the receiver (red rhombus), three different types of reflectors can be observed: mobile scatterers (blue asterisks), static scatterers (pink squares), and diffuse scatterers (green points). The line indicates the direction of movement of the elements.

static scatterers, that that simulate traffic signs and other statics elements; and diffuse scatterers, that simulate all the reflections with the objects that surround the roads. Figure 11 shows an initial location for a V2V scenario used to generate a channel realization. From this scenario, positions of the elements are updated at each time instant and the resulting channel is obtained by ray tracing.

Within this model, by keeping the position of the transmitter fixed, it would be also possible to simulate transmission from/to infrastructure.

7 Simulation results

7.1 V2V results

This section shows the results of a set of simulations carried out over the channel models described in subsections 6.3.2 and 6.3.3. It is assumed a line-of-sight (LOS) in the link between transmitter and receiver as it is a common situation in straight trajectories. As previously stated, two different propagation scenarios are used, one of them corresponding to an avenue of a city and the other one to a highway in a rural environment.

In both scenarios, a four line road, two per direction, is considered (Figure 8). A hybrid GLOC scheme is simulated: the same resources are chosen for all lines at each direction (SLP scheme per direction) but different resources are assigned to both directions (MLP between directions). Thus, a split of the road in a three segments reuse results in six ARs in total ($n_{AR} = 6$), as shown in Figure 8. The length of the segments is fixed to the safety distance, which depends of the speed the vehicles. Furthermore, the simulations are carried out with transmitter and receiver following opposite directions as shown in Figure 8.

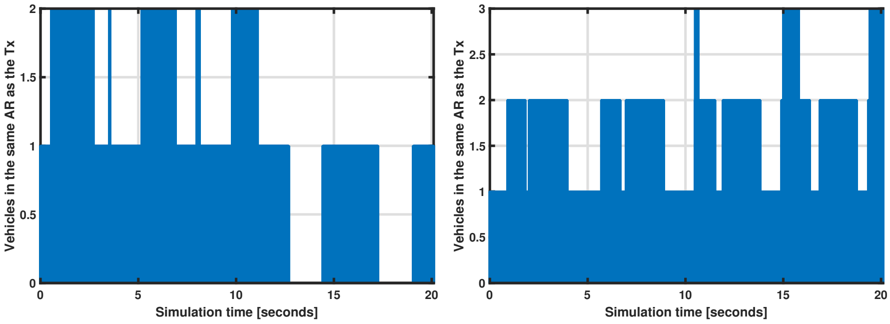
Regarding the general parameters for all V2V simulations carried out, 8 PRBs are available for each AR, selected from 9 MHz bandwidth available in total. The carrier frequency used is 5.88 GHz, the height of the antennas is 1.5 m and the transmission power is 23 dBm. Also, CAM type messages are used: 400 bytes of size and 100 ms between consecutive packets. The duration of the simulations is fixed to 20 seconds. A summary of main parameters is provided in Table 2. Moreover, the specific parameters for each scenario are collected in this table, too.

In terms of interference, $S_I(t)$ is obtained from a particular scenario realization. The number of users located at the same zone than the transmitter as employed in simulations is given in Figure 12. The initial positions of the set of interfering vehicles ($t = 0s$) is obtained at the beginning of the simulation from a realization of a Pearson distribution [17] with average density as shown in Table 2; later, these interferers move in their corresponding directions, changing their AR and so the number of interferers to the intended receiver.

Several simulations have been carried out for rural and urban scenarios. Next sections present the results and give insight in them.

7.1.1 V2V results using CDL channel model

In order to compare them in terms of packet error rate (PER) and delay, four MCSs are drawn out: MCS 0, MCS 6, MCS 11 and MCS 18 [13]. As mentioned in Section 6.3.2, the CDL model has two statistic levels. A limited set of only ten PDP realizations have been averaged at each distance between transmitter and receiver, each 20 seconds long. Results are analyzed to evaluate impact of



(a) (b)

Fig. 12 Instant number of interfering vehicles: **(a)** Rural highway; **(b)** Urban avenue.

Parameter type	Name	Description	Value	Units
General	P_{Tx}	Transmission power	23	dBm
	f_c	Carrier frequency	5.88	GHz
	h_{ant}	Antenna height	1.5	m
	$linkVS$	Link vision status	LOS	
	$nPRB$	Total number of PRB	50	PRB
	nAR	Number of orthogonal AR	6	AR
	$nPRB_{AR}$	Number of PRB per AR	8	PRB/AR
	$pSize$	Packet size	400	bytes
	$pTime$	Time between packet transmissions	100	ms
	t_{sim}	Duration of the simulation	20	s
Rural highway	v	Vehicle speeds	120	km/h
	d_{safe}	Safe distance	140	m
	$model$	Environment type for the channel model	Rural	
	χ_{MD}	Average density of vehicles	0.005	vehicle/meter
Urban avenue	v	Vehicle speeds	30	km/h
	d_{safe}	Safe distance	40	m
	$model$	Environment type for the channel model	Urban	
	χ_{MD}	Average density of vehicles	0.01	vehicle/meter

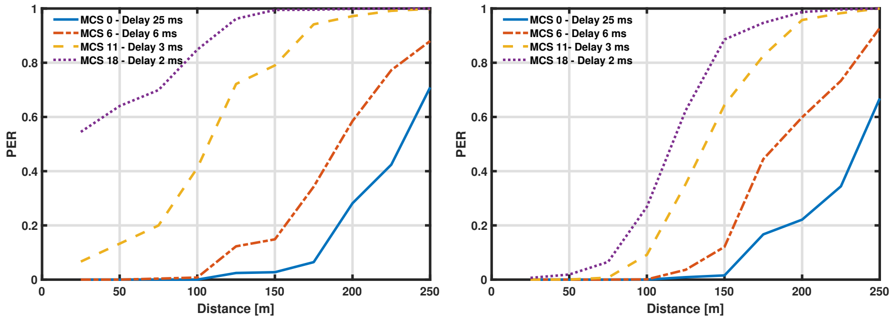
Table 2 Summary of main V2V simulation parameters

the Doppler effect and of the interference.

Impact of the Doppler effect

For this analysis, ten power delay profile realizations have been carried out and the results have been collected in the Figure 13 for both environments (rural highway and city avenue) and. Distance between transmitter and receiver changes from 25 meters to 250 meters along simulation. In order to fix the influence of interference on the results per MCS, the probability p_{rT} has been matched to 0.1 in eq. (4), in such a manner that it is easier to appreciate the Doppler effect in the PER.

Regarding the results, as it is well known, in general urban environments have worse propagation condition than rural scenarios, since the number of scatterers and blockers is higher. For this reason, path loss is higher. However, as in the rural highway the vehicle speed is four times that at urban avenues, the impact of intercarrier interference (ICI) due to Doppler spread over the LTE orthogonal frequency division multiplexing (OFDM) transmission is more relevant than the different path losses. Moreover, obstacles such as mountains in the rural scenario are farther than in urban scenarios, where the main obstacles such as buildings are a few meters away; thus, delays of the multipath components in rural scenarios are longer. In consequence, the intersymbol interference (ISI) is not always avoided by the OFDM cyclic prefix. As expected, results show that using a lower MCS is more robust against errors. (Note that the interference probability is fixed for this set of simulations.)



(a) (b)

Fig. 13 Average PER and delay for CDL channel model and fixed interference: **(a)** Rural highway **(b)** Urban avenue.

In relation to those delay results shown next to the legend in Figure 13, the main factor affecting them is the packet segmentation on the allocated resources and, to a lesser extent, other network factors such as the cyclic redundancy check (CRC), propagation delays, etc. So, these values are higher than the time needed to transmit a complete packet over the allocated resources to the transmitter using certain MCS. MCS 0 has the lowest spectral efficiency, hence, more LTE subframes are needed to transmit each packet.

Impact of the interference

Urban avenue environment is used to illustrate the impact of the interference in the PER since the number of interfering vehicles is higher than that in rural highways. The number of vehicles possibly interfering transmission is that shown in Figure 12 and the collision probability evaluated accordingly. In this case, the results are shown in Figure 14.

Figure 14 reveals counterintuitive results; for example, the transmission using theoretically a less robust MCS 6 have fewer errors than that MCS 0, with lower coding rate and modulation level. The reason is that MCS 0 has more interference level than MCS 6 as a single packet transmission occupies the channel for longer, the number of collisions increases and the signal to noise and interference ratio (SINR) is worse than with higher MCSs. Moreover, delay reduces as MCS is higher and the interference decreases. There exists a kind of tradeoff between robustness and reduced interference-delay that changes depending on the specific scenario.

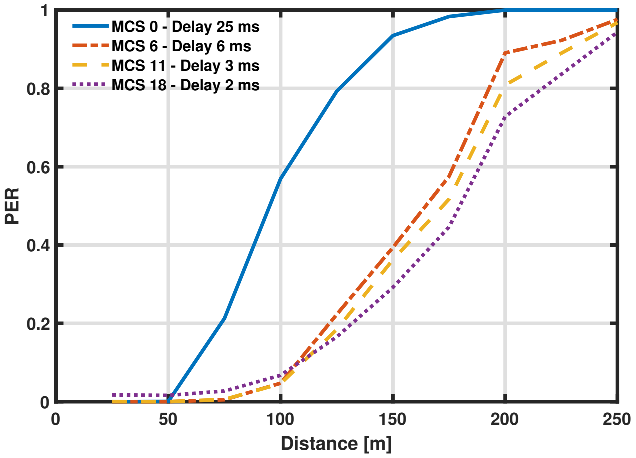


Fig. 14 Average PER and delay for CDL channel model. Urban avenue scenario with interfering vehicles and six zone GLOC.

7.1.2 V2V results using Vehicular GBSM

In the simulations with the Vehicular GBSM channel model, two different scenarios are generated, one for urban environment and one for rural highway. As explained in Section 6.3.3, different traffic densities and speeds are used. In this way, scenarios similar to Figure 11 are obtained, where the transmitting and receiving vehicles are located in such a way that the simulation ends just at the crossing point. Each simulation is only one realization of each environment and the PDP only correspond to that simulation. For these reasons, the PER values that are obtained from the complete simulations are particular values resulting from the geometry of the simulated scenario, avoiding the WSSUS assumption.

Figure 15 show the PER and the delay for several possible MCS. According to the analysis results done in Section 7.1.1, results show that the high speed of the rural highway most penalizes the PER.

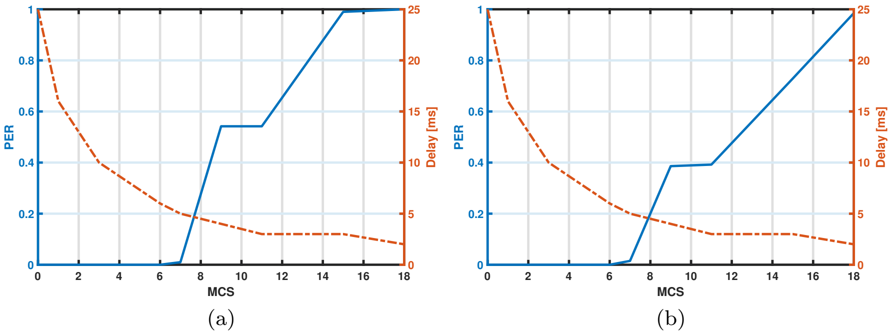


Fig. 15 PER and delay with Vehicular GBSM channel model: **(a)** Rural highway **(b)** Urban avenue.

7.2 I2V results

Main simulation parameters for infrastructure to vehicle transmission are summarized in Table 3. Two different propagation environments are used, an avenue in a city and a highway in a rural setting. For both, macrocells have been considered, i.e., RMa and UMa scenarios in [3] have been simulated. Path losses as a function of distance has been included using the method described by [3], this is a dual slope model based on measurement campaigns. In this case, no line of sight has been considered. The existence of a line of sight would improve the performance as Doppler spread is more easily sorted out.

Channel has been simulated as a TDL, with power delay profile and delay spread scaling factor as given in [3] (363 ns for UMa and 37 ns for RMa at 6 GHz, the closer value to 5.9 GHz). The Doppler spectrum for each tap is characterized by the classical (Jakes) spectrum shape and a maximum Doppler shift $f_D = \frac{v}{\lambda}$, where v is the vehicle speed and λ the wavelenght at 5.9 GHz. For urban areas, speed has been taken as 30 km/h while for the rural scenario the speed is 120 km/h.

Regarding the LTE setting, 10 PRBs have been reserved for multicast transmission. Four MCSs (MCS 0, MCS 6, MCS 11 and MCS 21 [13]) have been simulated. Comparison is done in terms of packet error rate and transmission delay.

Results for both rural and urban scenarios are shown in Figure 16. Each curve represents PER as a function of distance from the vehicle to the broadcasting base station. Next to each plot, packet delay is given considering a source producing a 400 byte packet every 100 ms.

In both scenarios, there is no ISI as the most delayed echo is still within the OFDM cyclic prefix. The main source of packet errors is Doppler spread. Channel estimation has been taken as ideal, but ICI appears due to the loss of orthogonality among subcarriers in the OFDM transmission [7]. The effect is more noticeable for higher vehicle speeds. The product of f_D for the symbol period T is about 0.04 for the rural scenario, what represents a signal to

Parameter type	Name	Description	Value	Units
Generals	P_{Tx}	Transmission power	18.22	dBm
	f_c	Carrier frequency	5.9	GHz
	h_{BS}	Antenna heigh of the Base Station	10	m
	h_{UE}	Antenna heigh of the User Equipment	1.5	m
	$linkVS$	Link state of vision	NLOS	
	$nPRB$	Total number of PRB used in multicast transmission	10	PRB
	$pSize$	Packet size	400	bytes
	$pTime$	Time between packet transmissions	100	ms
	t_{sim}	Duration of the simulation	20	s
Rural scenario	v	Vehicle speed	120	km/h
	$model$	Environment type for the channel model	Rural	
Urban scenario	v	Vehicle speed	30	km/h
	$model$	Environment type for the channel model	Urban	

Table 3 Summary of main parameters for I2V simulations

intercarrier interference of about 25 dB, while it is increased to nearly 40 dB for the 30 km/h scenario [7].

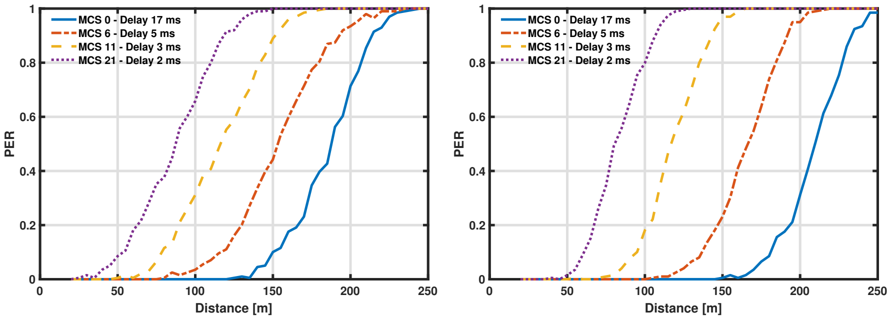
As expected, lower MCSs improves the reception probability at a certain distance (PER is lower) whereas delay is higher as the packet is transmitted with a lower spectral efficiency and the number of resources devoted to eMBMS is fixed. For the usual LTE 10% target, distances higher than 60m are hardly allowable for MCS 21. That amount increases to 150m and longer for MCS 0 but a 17 ms delay should be allowable. Those values would allow cooperative awareness, vulnerable user protection, and traffic efficiency but are far from delay and reliability values needed for cooperative maneuvers or teleoperated driving [4].

8 Conclusion

In this paper, we have reviewed the LTE standard for vehicular communications. Both multicast infrastructure to vehicles communications and direct vehicle communications over the sidelink are summarized as well as the application layer over it.

In order to exemplify the LTE performance, we have carried out link simulations over vehicular channels using our WM-SIMA tool. Results show a tradeoff to select the appropriate MCS for communications. For I2V communications, a lower MCS increases coverage at the expense of higher transmission delay. Transmitting simultaneously from a set of neighbour base stations would improve coverage but it requires accurate synchronization among BSs.

The selection of the appropriate MCS for direct communications between vehicles has to take into account that lower MCSs has also higher interference



(a) (b)

Fig. 16 Packet error rate for I2V transmission as a function of distance between the receiving vehicle and the BS: **(a)** Rural scenario, 120 km/h; **(b)** Urban scenario, 30 km/h.

power as duration of each packet transmission is longer. Depending on the scenario, that can modify expected relative robustness of MCSs.

As for the next generation wireless communications, more degrees of freedom regarding 5G new radio (NR) numerology are available. For example, the subcarrier spacing greatly influences the effect of Doppler spread. New techniques for parameter selection in vehicular communications are still to be designed.

References

1. 3rd Generation Partnership Project (3GPP): Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); LTE physical layer; General description. 3GPP TS 36.201 **Release 14** (2017)
2. 3rd Generation Partnership Project (3GPP): Enhanced television services over 3GPP eMBMS (2017, last access July 23rd, 2019). URL https://www.3gpp.org/images/PDF/EnTV_article_for_3GPP_Web_site_v8.pdf
3. 3rd Generation Partnership Project (3GPP): Study on channel model for frequencies from 0.5 to 100 GHz. 3GPP TR 38.901 **Release 15** (2018)
4. Boban, M., Kousaridas, A., Manolakis, K., Eichinger, J., Xu, W.: Connected roads of the future: Use cases, requirements, and design considerations for vehicle-to-everything communications. IEEE Vehicular Technology Magazine **13**(3), 110–123 (2018)
5. Carreras, A., Delgado-Luque, I.M., Martín-Vega, F.J., Gómez, G., Aguayo-Torres, M.C., Entrambasaguas, J.T.: A system-level simulator for the downlink of LTE-A: Case of study—cell-offloading in HetNets. Wireless Personal Communications **100**(1), 177–191 (2018)
6. CEN Technical Committee 278: Traffic and travel data exchange (2018)
7. Cortés, J.A., Aguayo-Torres, M.C., Cañete, F.J., Gómez, G., Martos-Naya, E., Entrambasaguas, J.T.: Vehicular channels: Characteristics, models and implications on communication systems design. Wireless Personal Communications **106**(1), 237–260 (2019)
8. European Commission: Directive 2010/40/EU of the European Parliament and of the Council of 7 July 2010 on the framework for the deployment of intelligent transport systems in the field of road transport and for interfaces with other modes of transport (2010)

9. European Telecommunications Standards Institute: Intelligent Transport System (ITS); Vehicular communications; Basic set of applications; Facilities layer protocols and communication requirements for infrastructure services. ETSI TS 103.301 (2016)
10. European Telecommunications Standards Institute: Intelligent Transport System (ITS); Vehicular communications; Basic set of applications; Part 2: Specification of cooperative awareness basic service. ETSI EN 102.637 -2 (2019)
11. European Telecommunications Standards Institute: Intelligent Transport System (ITS); Vehicular communications; Basic set of applications; Part 3: Specifications of decentralized environmental notification basic service. ETSI EN 102.637-3 (2019)
12. 3rd Generation Partnership Project (3GPP):
13. 3rd Generation Partnership Project (3GPP): Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures. 3GPP TS 36.213 **Release 15** (2019)
14. Institute, E.T.S.: Intelligent transport system (ITS); v2x applications; part 1 to 3. ETSI TS 101 539 (2013)
15. Institute of Electrical and Electronics Engineers (IEEE): IEEE standard for information technology–telecommunications and information exchange between systems local and metropolitan area networks–specific requirements part 11: Wireless LAN medium access control (MAC) and physical layer (PHY) specifications. IEEE Std 802.11-2012 (Revision of IEEE Std 802.11-2007) (2012)
16. Jakes, W.: Microwave Mobile Communications. John Wiley & Sons, New York (1974)
17. Karedal, J., Tufvesson, F., Czink, N., Paier, A., Dumard, C., Zemen, T., Mecklenbrauker, C.F., Molisch, A.F.: A geometry-based stochastic MIMO model for vehicle-to-vehicle communications. IEEE Transactions on Wireless Communications **8**(7), 3646–3657 (2009). DOI 10.1109/TWC.2009.080753
18. Martín-Vega, F.J., Soret, B., Aguayo-Torres, M.C., Kovács, I.Z., Gómez, G.: Geolocation-based access for vehicular communications: Analysis and optimization via stochastic geometry. IEEE Transactions on Vehicular Technology **67**(4), 3069–3084 (2018). DOI 10.1109/TVT.2017.2775249
19. Molina-Masegosa, R., Gozalvez, J.: LTE-V for sidelink 5G V2X vehicular communications: A new 5G technology for short-range vehicle-to-everything communications. IEEE Vehicular Technology Magazine **12**(4), 30–39 (2017)
20. Pop, M.F., Beaulieu, N.C.: Limitations of sum-of-sinusoids fading channel simulators. IEEE Transactions on Communications **49**(4), 699–708 (2001)
21. Society of Automotive Engineers: Dedicated short range communications (DSRC) message set dictionary. SAE J2735 (2009)
22. Viavi Solutions: LTE evolved multimedia broadcast multicast services (eMBMS) https://www.viavisolutions.com/de-de/literature/lte-evolved-multimedia-broadcast-multicast-services-embms-white-paper-en.pdf (last access 23 july 2019) (2015)