LTE-V for Sidelink 5G V2X Vehicular Communications

A New 5G Technology for Short-Range Vehicle-to-Everything Communications

Rafael Molina-Masegosa and Javier Gozalvez

This article provides an overview of the long-term evolution-vehicle (LTE-V) standard supporting sidelink or vehicle-to-vehicle (V2V) communications using LTE's direct interface named *PC5* in LTE. We review the physical layer changes introduced under Release 14 for LTE-V, its communication modes 3 and 4, and the LTE-V evolutions under discussion in Release 15 to support fifth-generation (5G) vehicle-to-everything (V2X) communications and autonomous vehicles' applications. Modes 3 and 4 support direct V2V communications but differ on how they allocate the radio resources. Resources are allocated by the cellular network under mode 3. Mode 4 does not require cellular coverage, and vehicles autonomously select their radio resources using a distributed scheduling scheme supported by congestion control

Digital Object Identifier 10.1109/MVT.2017.2752798
Date of publication: 24 October 2017

mechanisms. Mode 4 is considered the baseline mode and represents an alternative to 802.11p or dedicated short-range communications (DSRC). In this context, this article also presents a detailed analysis of the performance of LTE-V sidelink mode 4, and proposes a modification to its distributed scheduling.

V2X Communications Support with LTE-V

V2X communications will enable the exchange of information between vehicles (V2V) and between vehicles and other nodes (infrastructure and pedestrians). This exchange will provide vehicles with a more accurate knowledge of their surrounding environment that can improve traffic safety [1]. Efforts have been made in recent years to develop V2X communications using IEEE 802.11p [18]. However, 802.11p uses a carrier-sense multiple access with collision avoidance medium-access scheme, and can face some challenges when guaranteeing strict reliability levels and ensuring the network's scalability as the load increases [2]. As an alternative, the Third Generation Partnership Project (3GPP) published the first version of Release 14 in September 2016, which includes support for V2X communications [3]. The standard is commonly referred to as LTE-V, LTE-V2X, or cellular V2X. The LTE-V physical layer improves the link budget with regard to 802.11p. In addition, LTE-V can increase the reliability, under certain conditions, by adding a redundant transmission per packet.

The LTE-V standard includes two radio interfaces. The cellular interface (named *Uu*) supports vehicle-to-infrastructure communications, while the PC5 interface supports V2V communications based on direct LTE sidelink. LTE sidelink (or device-to-device communication) was introduced for the first time under Release 12 for public safety, and includes two modes of operation: mode 1 and mode 2. Both modes were designed with the objective of prolonging the battery lifetime of mobile devices at the cost of increasing the latency. Connected vehicles require highly reliable and low-latent V2X communications; therefore, modes 1 and 2 are not suitable for vehicular applications.

Release 14 introduces two new communication modes (modes 3 and 4) specifically designed for V2V communications. In mode 3, the cellular network selects and manages the radio resources used by vehicles for their direct V2V communications. In mode 4, vehicles autonomously select the radio resources for their direct V2V communications. In contrast, mode 4 can operate without cellular coverage, and is therefore considered the baseline V2V mode since safety applications cannot depend on the availability of cellular coverage. Mode 4 includes a distributed scheduling scheme for vehicles to select their radio resources and includes the support for distributed congestion control.

Physical Layer

LTE-V utilizes single-carrier frequency-division multiple access, and supports 10- and 20-MHz channels. Each channel is divided into subframes, resource blocks (RBs), and subchannels. Subframes are 1 ms long [like the transmission time interval (TTI)]. An RB is the smallest unit of frequency resources that can be allocated to a user. It is 180 kHz wide in frequency (12 subcarriers of 15 kHz). LTE-V defines subchannels as a group of RBs in the same subframe, and the number of RBs per subchannel can vary. Subchannels are used to transmit data and control information. The data is transmitted in transport blocks (TBs) over physical sidelink shared channels (PSSCH), and the sidelink control information (SCI) messages are transmitted over physical sidelink control channels (PSCCH) [4]. A TB contains a full packet to be transmitted, e.g., a beacon or cooperative awareness message. A node that wants to transmit a TB must also transmit its associated SCI, which is also referred to as a *scheduling assignment*. The SCI includes information such as the modulation and coding scheme (MCS) used to transmit the TB, the RBs it uses, and the resource reservation interval for semipersistent scheduling (SPS). This information is critical for other nodes to be able to receive and decode the transmitted TB, so the SCI must be correctly received. A TB and its associated SCI must always be transmitted in the same subframe. We refer to the transmission of an SCI and its associated TB in the same subframe as *SCI + TB (or hybrid automatic repeat request transmission in the 3GPP*). LTE-V defines two subchannelization schemes (Figure 1):

- *Adjacent PSCCH + PSSCH*: The SCI and TB are transmitted in adjacent RBs. For each SCI + TB transmission, the SCI occupies the first two RBs of the first subchannel utilized for the transmission. The TB is transmitted in the RBs following the SCI, and can occupy several subchannels (depending on its size). If it does so, it will also occupy the first two RBs of the following subchannels.
- *Nonadjacent PSCCH + PSSCH*: The RBs are divided into pools. One pool is dedicated to transmit only SCIs, and the SCIs occupy two RBs. The second pool is reserved to transmit only TBs and is divided into subchannels.

TBs can be transmitted using quadrature phase shift keying (QPSK) or 16 quadrature amplitude modulation (QAM), whereas the SCIs are always transmitted using QPSK. LTE-V uses turbo coding and normal cyclic prefix. LTE-V subcarriers have a total of 14 symbols per subframe, and four of these symbols are dedicated to the transmission of demodulation reference signals (DMRSs) to combat the Doppler effect at high speeds. DMRSs are transmitted in the third, sixth, ninth, and 12th symbol of each subcarrier per subframe [5]. The maximum transmit power is 23 dBm, and the standard specifies a sensitivity-power-level requirement at the receiver of –90.4 dBm and a maximum input level of –22 dBm [6].

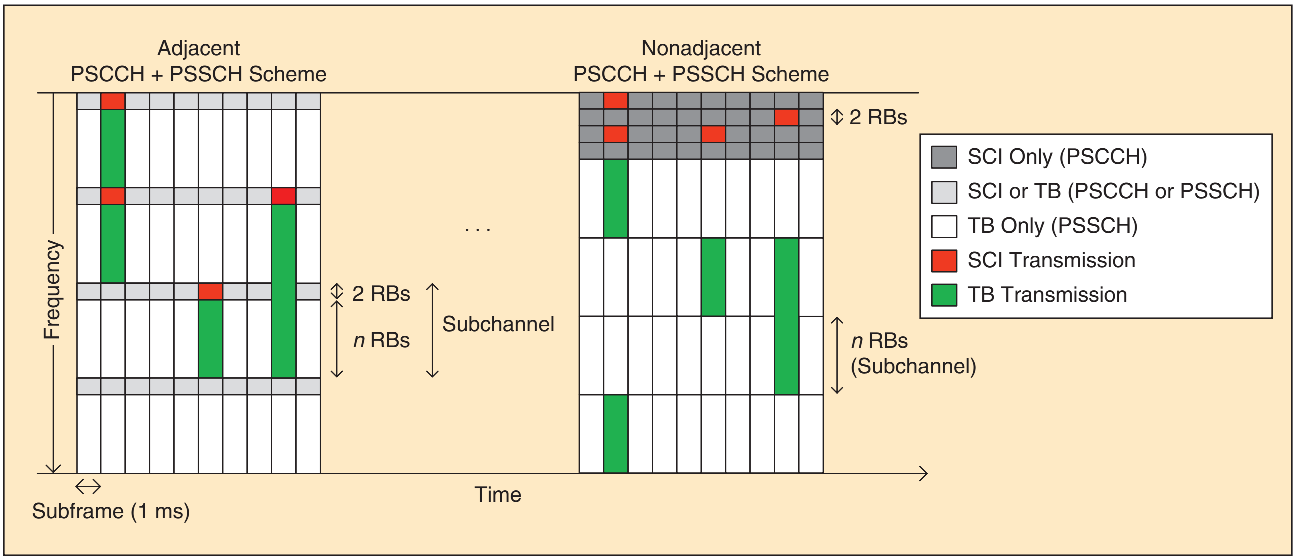

FIGURE 1 LTE-V subchannelization.

Mode 4

Vehicles communicate using sidelink or V2V communications under mode 4 and autonomously select their radio resources independently of whether they are under cellular coverage or not. When the vehicles are under cellular coverage, the network decides how to configure the V2X channel and informs the vehicles through the sidelink V2X configurable parameters [3]. The message includes the carrier frequency of the V2X channel, the V2X resource pool, synchronization references, the subchannelization scheme, the number of subchannels per subframe, and the number of RBs per subchannel, among other things. When the vehicles are not under cellular coverage, they utilize a preconfigured set of parameters to replace the sidelink V2X configurable parameters. However, the standard does not specify a concrete value for each parameter. The V2X resource pool indicates which subframes of a channel are utilized for V2X. The rest of the subframes can be utilized by other services, including cellular communications. The standard includes the option to divide the V2X resource pool based on geographical areas (referred to as *zoning* [3]). In this case, vehicles in an area can only utilize the pool of resources that have been assigned to such areas. In this article, we assume that a channel is completely dedicated to V2X and that zoning is not applied.

Sensing-Based SPS

Vehicles select their subchannels in mode 4 using the sensing-based SPS scheme specified in Release 14 [4], [7]. A vehicle reserves the selected subchannel(s) for a number of consecutive reselection counterpacket transmissions. This counter is randomly set between five and 15, and the vehicle includes its value in the SCI. After each transmission, the reselection counter is decremented by one. When it is equal to zero, new resources must be selected and reserved with probability (1–P). Each vehicle can set up P between zero and 0.8. New resources also need to be reserved if the packet to be transmitted does not fit in the subchannel(s) previously reserved. The reselection counter is randomly chosen every time new resources must be reserved. Packets can be transmitted every 100 subframes [i.e., ten packets per second (10 pps)] or in multiples of 100 subframes (up to a minimum of 1 pps). Each vehicle includes its packet transmission interval in the resource reservation field of its SCI. Thanks to the semipersistent reservation of resources and the inclusion of the reselection counter and packet transmission interval in the SCI, other vehicles can estimate which subchannels are free when making their own reservation, which reduces packet collisions. The process to reserve subchannels is organized in the following three steps:

Step 1: Suppose that a vehicle (V) needs to reserve new subchannels at time (T). It can reserve subchannels between T and the established maximum latency (equal to or less than 100 ms [4]). This time period is referred to as the *selection window*. Within the selection window, the vehicle identifies candidate single-subframe resources (CSRs; also referred to as *candidate resources*) to be reserved by all groups of adjacent subchannels within the same subframe where the SCI + TB to be transmitted will fit.

Step 2: Vehicle V analyzes all the information it has received in the 1,000 subframes before T and creates a list (L_1) of CSRs it could reserve. This list includes all the CSRs in the selection window except those that meet the following two conditions.

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

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

The two conditions must be simultaneously met for V to exclude a CSR. Vehicle V also excludes all CSRs of subframe F in the selection window if V was transmitting during any previous subframe $F - 100*j$ ($j \in \mathrm{N}, 1 \leq j \leq 10$). It should be noted that V is not able to receive the transmissions of other vehicles in the subframe it is transmitting due to half-duplex (HD) transmissions].

After Step 2 is executed, L_1 must include at least 20% of all CSRs in the selection window. If not, Step 2 is iteratively executed until the 20% target is met. The RSRP threshold is increased by 3 dB in each iteration.

Step 3: Vehicle V creates a second list (L_2) of CSRs. The total number of CSRs in L_2 must be equal to 20% of all CSRs in the selection window. L_2 includes the CSRs from L_1 (after Step 2) that experienced the lowest average received signal strength indicator (RSSI) over all its RBs. This RSSI value is averaged over all the previous $T_{CSR} - 100*j$ subframes ($j \in \mathrm{N}, 1 \leq j \leq 10$); see Figure 2. Vehicle V randomly chooses one of the CSRs in L_2, and reserves it for the next reselection counterpacket transmissions.

Extensions to Sensing-Based SPS

LTE-V mode 4 provides the option for each packet to be transmitted twice to increase the reliability. In this case, the sensing-based SPS scheme creates a third list (L_3) of CSRs. Suppose that the original SCI + TB transmission took place in a CSR in subframe *SF*; L_3 is made of all CSRs included in L_2 (produced in Step 3) that are in the time interval (*SF*–15 ms; *SF* + 15 ms), with the exception of all the CSRs in *SF*. The sensing-based SPS scheme randomly selects a CSR from L_3 for the redundant transmission of the SCI + TB. The selection for redundant transmissions is maintained semi-persistently for the following reselection counterpackets.

The sensing-based SPS scheme can support higher packet transmission frequencies than 10 pps, specifically 20 pps and 50 pps. In this case, the following changes to the sensing-based SPS scheme are applied:

- The maximum tolerable latency is 50 and 20 ms, respectively, which reduces the selection window.
- The reselection counter can take any value between 10 and 30 for 20 pps, and between 25 and 75 for 50 pps.
- The variable j in Step 3 takes values between 1 and 20 for 20 pps, and between 1 and 50 for 50 pps.

Release 14 includes a variant of the sensing-based SPS scheme for pedestrian-to-vehicle communications, where pedestrians broadcast their presence using mobile devices. The sensing process seriously compromises the battery of these devices, so the standard gives them the option to only sense a percentage of the 1,000 subframes previous to T in Step 2. The mobile devices can only select CSRs in the sensed subframes using the sensing-based SPS scheme.

Mode 3

Vehicles also communicate using sidelink or V2V communications under mode 3. However, the selection of subchannels is managed by the base station or evolved NodeB (eNB), and not by each vehicle as is the case in mode 4. Mode 3 is, hence, only available when vehicles are under cellular coverage. The 3GPP has defined the necessary cellular architecture enhancements to support V2X. One of these enhancements is the V2X control function that is used by the network in mode 3 to manage radio resources and to provide vehicles [or, in general, user equipment (UE)] with the sidelink V2X configurable parameters. Mode 3 utilizes the same subchannel arrangements as defined for mode 4. Vehicles using mode 3 must also transmit an associated SCI/TB, and the transmission of the SCI/TB must take place in the same subframe. As opposed to mode 4, the standards do not specify a resource management algorithm for mode 3. Each operator can implement its own algorithm that should fall under one of these two categories [8]:

- *Dynamic scheduling*: Vehicles request subchannels to the eNB for each packet transmission. This increases the cellular signaling overhead, and delays the packet transmission until vehicles are notified of their assigned subchannels.
- *SPS*: The eNB reserves subchannels for the periodic transmissions of a vehicle like in mode 4. However, in contrast with mode 4, it is up to the eNB to decide how long the reservation should be maintained

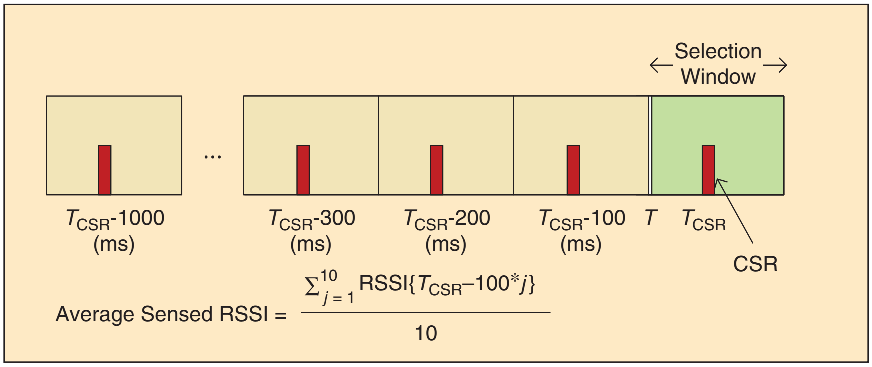

FIGURE 2 Step 3: The average RSSI of a candidate resource.

(i.e. mode 3 does not define a reselection counter). Only the eNB can activate, deactivate, or modify a reservation of subchannels for a vehicle. The vehicle must inform the eNB of the size, priority, and transmission frequency of its packets so that the eNB can semipersistently reserve the appropriate subchannels. This information (referred to as *UE assistance information* [4]) must be provided to the eNB at the start of a transmission, or when any of the traffic characteristics (size, priority, and frequency) change.

Vehicles operating under mode 3 can be supported by different cellular operators or by public land mobile networks (PLMNs). To enable their direct communications, the 3GPP has defined an inter-PLMN architecture [9] that can support the following scenarios:

- Vehicles supported by different PLMNs transmit in different carriers. In this case, vehicles must be able to simultaneously receive in multiple carriers the transmissions of vehicles supported by other PLMNs. To this aim, each PLMN broadcasts in the sidelink V2X configurable parameters the necessary information so that the vehicles it supports can receive the packets transmitted by vehicles supported by other PLMNs.
- Vehicles supported by different PLMNs share the same carrier, but each PLMN is assigned part of the RBs of the carrier. The standard does not specify how the resources should be split among the PLMNs, but introduces a coordination mechanism (through the V2X control function) between PLMNs to avoid packet collisions.

Congestion Control

Release 14 supports congestion control in mode 4 [3]. The standard does not specify a particular congestion control algorithm but defines the related metrics and possible mechanisms to reduce the channel congestion. Each time a vehicle has to transmit or retransmit a packet, it estimates the channel busy ratio (CBR) and channel occupancy ratio (CR). If the packet is going to be transmitted at subframe *n*, the measurements are done at subframe *n*–4 [4]. The CBR provides an indication of the level of channel congestion, and is defined as the amount of subchannels in the previous 100 subframes that experience an average RSSI higher than a preconfigured threshold. The standard does not specify this threshold, but the 3GPP working documents usually compute this threshold by adding –107 dBm/RB in the subchannel. The CR quantifies the channel occupancy generated by the transmitting vehicle. It is defined as the amount of subchannels that the transmitting vehicle utilizes during a period of 1,000 subframes. This period can include past and future subframes, and it is up to each vehicle to decide how many past and future subframes it considers when computing the CR with certain restrictions. Future subframes can be considered as each vehicle reserves a number of subchannels using the sensing-based SPS scheme. The CR must be estimated taking into account at least the previous 500 subframes, and only the future subframes that are already reserved by the transmitting vehicle can be considered to compute the CR.

The standard indicates that up to 16 CBR intervals can be defined, and, for each one, a transmitting vehicle cannot overpass a maximum CR_{Limit} that augments as the CBR decreases. The value of CR_{Limit} for each CBR interval varies with the priority of the packet. The standard does not specify the range of each CBR interval and the values of CR_{Limit}. However, Table 1 shows an example from the 3GPP working documents [10] for 10 pps. Higher transmission frequencies augment the CR within a period of 1,000 subframes. In this case, the values of CR_{Limit} for each CBR interval should be revisited.

TABLE 1 ***An example of CBR intervals and CR_{Limit} for congestion control under LTE-V mode 4 [10].***

CBR Measured	*CR_{Limit}*
CBR ≤ 0.65	No limit
0.65 < CBR ≤ 0.675	1.6e-3
0.675 < CBR ≤ 0.7	1.5e-3
0.7 < CBR ≤ 0.725	1.4e-3
0.725 < CBR ≤ 0.75	1.3e-3
0.75 < CBR ≤ 0.775	1.2e-3
0.8 < CBR ≤ 0.825	1.1e-3
0.825 < CBR ≤ 0.85	1.1e-3
0.85 < CBR ≤ 0.875	1.0e-3
0.875 < CBR	0.8e-3

When a vehicle has to transmit a packet (or its redundant version), it measures the CBR and quantifies its CR. If its CR is higher than the value of CR_{Limit} specified for the CBR interval that includes the measured CBR, the vehicle must reduce its CR below CR_{Limit}. To do so, the standard defines several possible mechanisms [7], [8], and it is up to each vehicle to decide which one to utilize:

- *Packet dropping*: The vehicle reduces its CR by not transmitting certain packets generated by the application (but maintains the reserved subchannels).
- *Number of transmissions per packet*: The vehicle can reduce its CR by transmitting each packet only once (i.e., avoiding redundant transmissions).
- *MCS*: The vehicle can reduce the CR by augmenting the MCS. This is possible if the preconfigured subchannelization and the initial MCS results in that the transmission of a packet requires the use of various subchannels. In this case, a packet can be transmitted using a lower number of subchannels by increasing the MCS, which will in turn reduce the CR.
- *Reserved subchannels*: A vehicle can reduce its CR by reducing the number of subchannels it reserves per

transmission. This can be achieved, for example, by augmenting the MCS that reduces the number of RBs necessary to transmit a packet.

- *Transmission power*: Decreasing the transmission power reduces the CBR. If the resulting CBR level falls under a lower CBR interval, CR_{Limit} increases. In this case, a vehicle might be able to satisfy the condition that the CR is below the CR_{Limit} without directly decreasing its CR.

A vehicle can only modify the number of transmissions per packet or the number of reserved subchannels when it has to execute the sensing-based SPS scheme to reserve new subchannels. The other mechanisms can be applied at any point in time, and on a per-packet basis if needed. However, none of the congestion control mechanisms should force a new reservation of subchannels. Forcing a new reservation before the reselection counter is equal to zero can negatively impact other vehicles that reserved their subchannels considering that surrounding vehicles would maintain their reservations. This negative impact is actually also present when implementing packet dropping. However, [11] showed that packet dropping improves the packet delivery ratio (PDR) under congested channels.

Mode 3 does not implement a distributed congestion control process as defined in mode 4. In mode 3, the eNB manages the subchannels and decides how to reduce the channel occupancy. Such decisions can take into account the CBR levels locally measured by vehicles. To this aim, the eNB can request each vehicle periodically (the eNB determines the period) or, on demand, report its measured CBR [8].

Progress of Standardization Activities on 5G V2X

The 3GPP has started the work on new 5G V2X enhancements under Release 15 and has completed the analysis of new use cases and requirements that will be supported by that release [12]. Release 14 supports connected vehicle use cases such as forward collision warning. Release 15 new use cases are more focused on autonomous driving and include platooning, sensor and map sharing, information sharing for partial/conditional and high/full automated driving, and remote driving, among others. These applications can require the transmission of up to 50 pps, a maximum latency between 3 and 10 ms, and up to a 99.99% reliability level (defined in terms of PDR). To support these requirements, some of the LTE-V enhancements (referred to as V2X Phase 2 or eV2X) under discussion in Release 15 include [13]

- *Carrier aggregation*: LTE supports carrier aggregation up to 32 carriers. The 3GPP is considering the aggregation of up to eight carriers for LTE-V sidelink.
- *64-QAM modulation*: Release 14 supports QPSK and 16-QAM. Since 64-QAM increases the data rate and can reduce the channel occupancy, the 3GPP is currently analyzing the need for a new DMRS scheme when introducing 64-QAM.

A VEHICLE CAN ONLY MODIFY THE NUMBER OF TRANSMISSIONS PER PACKET OR THE NUMBER OF RESERVED SUBCHANNELS WHEN IT HAS TO EXECUTE THE SENSING-BASED SPS SCHEME TO RESERVE NEW SUBCHANNELS.

- *Reduction of the maximum time between arrival and start*: Release 15 seeks to reduce this maximum time from 20 ms (Release 14) to less than 10 ms.
- *Shared resources between modes 3 and 4*: Both modes could independently operate using a different pool of RBs. However, Release 15 is analyzing the possibility for both modes to coexist to optimize the usage of resources. Such coexistence might require changes for both modes. To date, only minor changes have been discussed, e.g., giving higher priority to mode 3 reservations (indicated through the SCI), or including the resource reservation field in the SCI of mode 3 transmissions so that mode 4 can take them into account [14].
- *Transmit diversity*: Release 15 is looking into the feasibility and gains that can be achieved in LTE-V using transmit diversity schemes (e.g. space time and frequency block coding, and small delay cyclic delay diversity).
- *TTI*: Release 15 is analyzing the possibility of reducing the TTI for LTE-V from 1 ms to 0.5 ms or two symbols. The analysis must take into account that vehicles with different TTI values (Releases 14 and 15) will need to coexist in the same pool of RBs. Release 14 vehicles will not be able to overhear Release 15 vehicles using lower TTIs. However, their transmissions should not interfere with those from Release 14.

Performance of LTE-V Mode 4

This section presents a comprehensive analysis of the performance of LTE-V mode 4 under the Highway Fast (60 vehicles/km at 140 km/h) and Highway Slow (120 vehicles/km at 70 km/h) scenarios defined in [15]. Vehicles transmit packets of 190 B, except one of every five packets that has a size of 300 B [15]. Packets are periodically transmitted every 100, 50, or 20 ms (10, 20, or 50 pps, respectively). We assume that a 10-MHz channel at 5.9 GHz is completely dedicated to mode 4 using adjacent PSCCH + PSSCH subchannelization. Four subchannels of 12 RBs each are defined per subframe. The 300-B packets occupy two subchannels, and the 190-B packets occupy one. QPSK and a code rate of 0.5 is used for the TBs corresponding to the 300-B packets (TBs occupy 20 RBs), whereas the 190-B packets are transmitted with QPSK and a code rate of 0.7 (TBs occupy 10 RBs). $P = 0$. The propagation is modeled using the WINNER + B1 pathloss model and a log-normal shadowing with spatial correlation. Radio transmission

MANY AUTONOMOUS DRIVING APPLICATIONS REQUIRE VEHICLES TO TRANSMIT A HIGH NUMBER OF PPS.

errors are modeled using look-up tables from [16] that map the signal-to-interference noise ratio (SINR) to the block error rate (BLER). We assume perfect synchronization, and all vehicles transmit at 23 dBm. The noise figure is set to 9 dB, and the RSRP threshold for the sensing-based SPS scheme is initially set to –110 dBm.

Figure 3 compares the PDR of 802.11p and LTE-V as a function of the distance between the transmitter and receiver. LTE-V is configured without redundant transmissions, and vehicles transmit 10 pps or 50 pps. The figure shows that LTE-V outperforms 802.11p when 802.11p is configured with the default 6 Mb/s data rate. However, 802.11p can improve its performance when configured with an 18-Mb/s data rate [17] and even outperform LTE-V. We will later show that LTE-V can also increase its performance under highly loaded scenarios by augmenting the MCS.

Figure 3 shows that when vehicles transmit 10 pps, 802.11p can achieve a performance close to LTE-V (with the configuration under analysis) up to a distance of 160 m if the 802.11p data rate is increased to 18 Mb/s. From this distance, 802.11p achieves a smaller PDR than LTE-V due to the physical layer performance and the dominant effect of propagation. When the channel load increases (vehicles transmit 50 pps), packet collisions become the dominant source of errors. In this case, 802.11p can outperform LTE-V (with the configuration under analysis) if the 802.11p data rate is increased to 18 Mb/s. As demonstrated in [17], augmenting the data rate reduces the channel load and packet collisions. The reduction of packet collisions under highly loaded scenarios (like when vehicles transmit 50 pps) compensates the negative physical layer effects of increasing the data rate and using a less robust modulation and coding rate.

Figure 3 shows that, just like 802.11p, the performance of LTE-V is significantly degraded when vehicles transmit more pps and the load increases. Many autonomous driving applications require vehicles to transmit a high number of pps. In this case, it is important to analyze the effectiveness of some of the congestion control mechanisms. Figure 4 shows the effect of transmitting each SCI + TB packet once (no redundancy) or twice. Figure 4 shows that redundant transmissions improve the PDR under low loads (10 pps). However, redundant transmissions increase the load, and therefore the packet collisions as illustrated in Table 2. This results in that redundant transmissions decrease the PDR from a certain distance when the load augments (Figure 4). However, redundant transmissions always improve the PDR at short distances between the transmitter and receiver due to the impact of HD errors. These errors occur when a vehicle is transmitting in a subframe and cannot receive the packets of other vehicles transmitting in the same subframe.

The probability of HD errors is independent of the distance and nonnegligible when each SCI + TB packet is transmitted only once and vehicles transmit a high number of pps (e.g., it is equal to 2.5% for 50 pps). Redundant

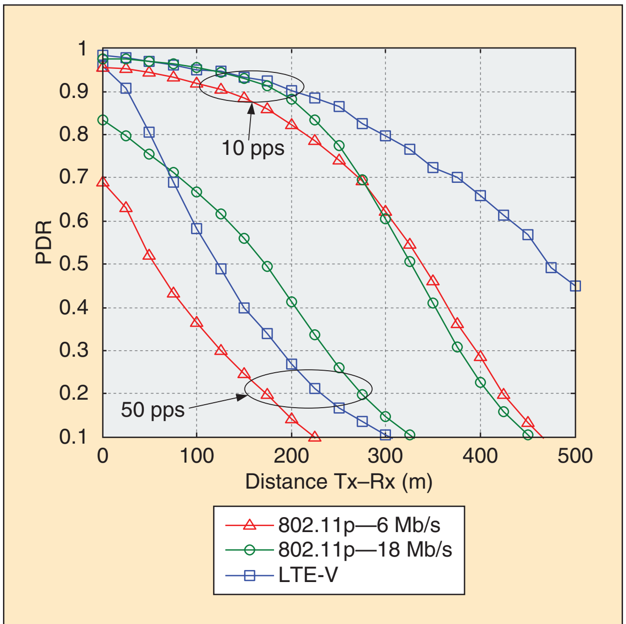

FIGURE 3 A comparison of LTE-V and 802.11p in Highway Slow. Tx: Transmitter; Rx: Receiver.

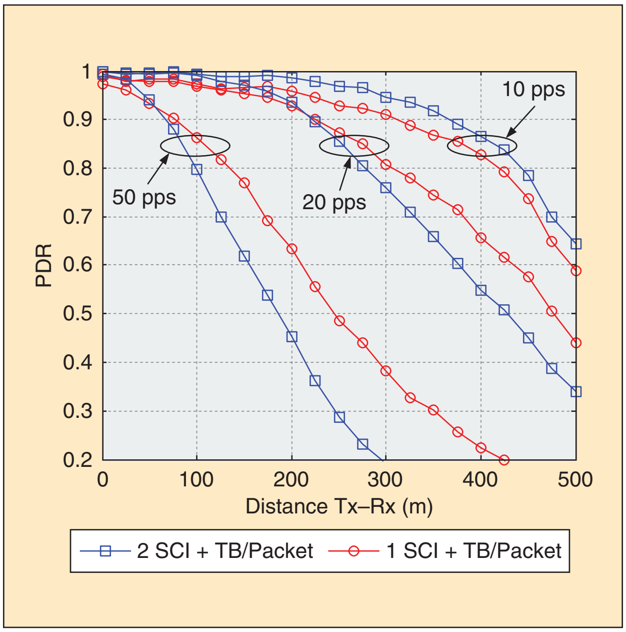

FIGURE 4 The effect of the number of transmissions per packet under the Highway Fast scenario.

TABLE 2 *The impact of redundant transmissions and the number of packets transmitted per second on packet collisions.*

Scenario	*pps*	*Redundant Transmission*	*Occupied Subchannels (%)*	*Subchannels with Packet Collisions (%)*
Highway Fast	10	No	17.08	0.78
		Yes	31.72	3.21
	20	No	32.22	2.76
		Yes	55.03	14.37
	50	No	62.08	23.33
		Yes	80.39	56.83
Highway Slow	10	No	32.46	3.38
		Yes	55.23	14.13
	20	No	55.05	14.53
		Yes	76.09	44.47
	50	No	80.91	56.64
		Yes	91.35	79.05

transmissions eliminate HD errors since the probability that two vehicles transmit their two SCI + TB packets in the same subframe is negligible.

Sepulcre et al. [17] showed that increasing the data rate can improve the performance of 802.11p, especially when channels are congested. Figure 5 analyzes the effect of the data rate on the LTE-V performance, considering that all packets have a size of 190 B and that each packet is transmitted twice. The figure depicts the PDR for QPSK and a code rate of 0.5 (QPSK-r0.5), QPSK and a code rate of 0.7 (QPSK-r0.7), and 16-QAM and a code rate of 0.5 (16-QAM-r0.5). Each packet occupies 16, 12, and 8 RBs with QPSK-r0.5, QPSK-r0.7, and 16-QAM-r0.5, and each subframe includes three, four, and six subchannels, respectively. Increasing the data rate decreases the error protection, but also the number of packet collisions (Table 3). The lower number of collisions explains why increasing the data rate always improves the PDR under the Highway Slow scenario (Figure 5). This effect is not always observed in Highway Fast, where vehicles move at faster speeds (140 km/h). In this case, the Doppler effect has a significant impact on the link level performance of 16-QAM-r0.5 that exhibits an error floor [16] (cannot reduce the BLER below 8% even for high SINRs). The lower packet collisions obtained with 16-QAM-r0.5 does not compensate this error floor when vehicles transmit 20 pps [Figure 5(a)]. However, when the load increases (50 pps), 16-QAM-r0.5 significantly reduces the packet collisions (Table 3), and achieves the best PDR despite its error floor [Figure 5(b)].

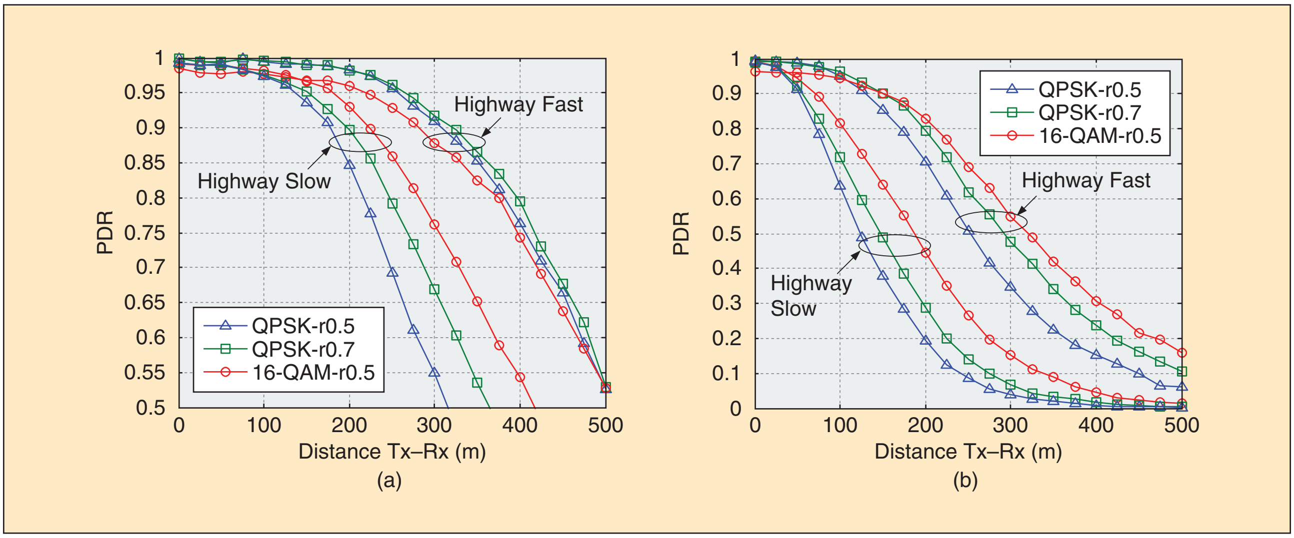

FIGURE 5 The effect of the MCS (a) 20 pps and (b) 50 pps.

TABLE 3 ***The impact of the MCS on channel occupancy and packet collisions.***

Scenario	*pps*	*MCS*	*Occupied Subchannels (%)*	*Subchannels with Packet Collisions (%)*
Highway Fast	20	QPSK-r0.5	66.43	12.53
		QPSK-r0.7	51.93	7.12
		16-QAM-r0.5	36.88	2.54
	50	QPSK-r0.5	97.19	71.85
		QPSK-r0.7	90.41	49.23
		16-QAM-r0.5	78.57	20.56
Highway Slow	20	QPSK-r0.5	91.82	51.82
		QPSK-r0.7	82.28	29.82
		16-QAM-r0.5	64.49	12.59
	50	QPSK-r0.5	99.82	97.05
		QPSK-r0.7	99.13	90.22
		16-QAM-r0.5	95.49	67.26

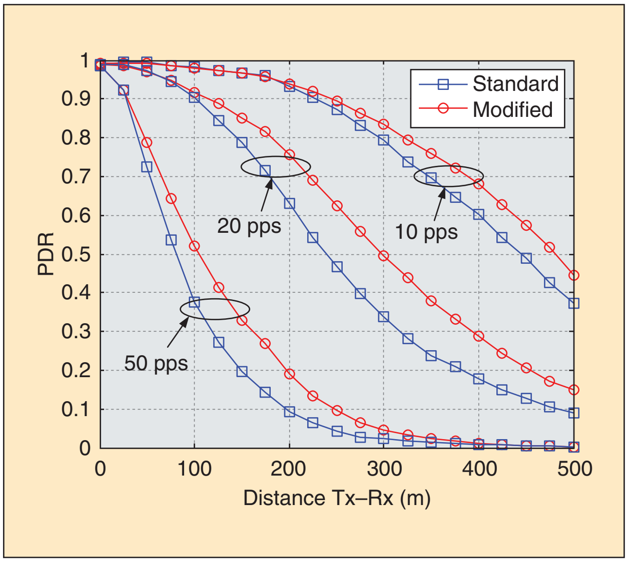

FIGURE 6 A comparison of the standard and modified sensing-based SPS (Highway Slow and redundant transmissions).

Modified Sensing-Based SPS

The sensing-based SPS scheme can present certain inefficiencies when packets have different sizes and need a different number of subchannels. This is the case with the traffic model in [15]. The baseline configuration utilized in the previous section results in that 300-B packets require two subchannels, and 190-B packets require only one. A reservation done for a 190-B packet will not be maintained for the following reselection counter transmissions since a 300-B packet will be generated before the counter is equal to zero. A new reservation will then be required for the 300-B packet, and the two reserved subchannels will be maintained for reselection counter transmissions. This is highly inefficient since the following four transmissions correspond to 190-B packets, and they only need one subchannel. Thus, the sensing-based SPS scheme excludes more resources in Step 2 that are really being utilized, and more vehicles will compete for the nonexcluded resources. To overcome this inefficiency, this article proposes a modification to the sensing-based SPS scheme when the packets to be transmitted have different sizes and the larger packets are less frequent than the smaller ones (a likely scenario in vehicular communications). We propose that no subchannels are reserved when transmitting the larger packets (300 B in this study). The sensing-based SPS scheme is used to select the subchannels necessary to transmit this packet. However, the selected subchannels will not be reserved for the following reselection counter transmissions. Instead, the sensing-based SPS scheme will be again applied to select the subchannel used to transmit the next 190-B packet. This subchannel will be the one reserved for the following reselection counter transmissions.

Figure 6 shows that the modified scheme improves the PDR compared to when applying the standard one defined in Release 14. The gains achieved are particularly relevant for medium to large distances and when vehicles transmit more pps. The gains achieved result from a more efficient utilization of subchannels. Table 4 shows that vehicles utilize all the subchannels they reserve with the modified scheme. On the other hand, the standard scheme results in a large percentage of reserved subchannels not being utilized by the vehicles that reserved them. These unused subchannels cannot be occupied by other vehicles, and the standard scheme occupies a lower percentage of subchannels than our proposal. This has a negative effect on the PDR of the standard scheme since vehicles compete for a smaller number of subchannels, and therefore experience more packet collisions.

Table 4 *The utilization of subchannels by the standard and modified sensing-based SPS schemes (Highway Slow scenario and redundant transmissions).*

Scheme	*pps*	*Occupied Subchannels (%)*	*Reserved Subchannels Utilized (%)*
Standard	10	55.97	68.12
	20	77.07	64.79
	50	92.04	62.32
Modified	10	56.79	100
	20	85.01	100
	50	99.03	100

Conclusions

This article has presented a comprehensive overview of the LTE-V standard for sidelink or V2V communications based on the PC5 interface. The article also includes a detailed analysis of LTE-V mode 4. This mode is considered the baseline scheme, as it does not require any cellular infrastructure support. The conducted study has shown that LTE-V can represent an alternative to 802.11p or DSRC due to its improved link budget, the support for redundant transmissions per packet, different subchannelization schemes, and the infrastructure assistance under mode 3. However, the distributed scheduling designed for LTE-V mode 4 is not collision-free, and requires a careful configuration of the transmission parameters, in particular for autonomous applications that require vehicles to transmit more pps. In this case, congestion control mechanisms and more efficient distributed scheduling schemes are necessary.

Acknowledgments

This work is supported in part by the Spanish Ministerio de Economía y Competitividad and FEDER funds under the project TEC2014-5716-R and research grant PEJ-2014-A-33622.

Author Information

Rafael Molina-Masegosa (rafael.molinam@umh.es) received his telecommunications engineering degree from the University of Granada (UGR), Spain. During his final degree project, he worked on brain image processing, directed by researchers from the Signal Processing and Biomedical Applications group at UGR. In December 2015, he joined the Ubiquitous Wireless Communications Research Laboratory at the Universidad Miguel Hernández de Elche, Spain, where he is currently working toward his Ph.D. degree and is studying fifth-generation wireless vehicular networks.

Javier Gozalvez (j.gozalvez@umh.es) received his electronics engineering degree from the engineering school at École Nationale Supérieure d'Électronique, Informatique et Radiocommunications de Bordeaux, France, and his Ph.D. degree in mobile communications from the University of Strathclyde, Glasgow, United Kingdom. Since October 2002, he has been with the Universidad Miguel Hernández de Elche, Spain, where he is currently an associate professor and director of the UWICORE laboratory. At UWICORE, he leads research activities in the areas of vehicular networks, fifth-generation device-centric networks, and wireless industrial networks. He has published more than 135 papers in international conference proceedings and journals, and has served as principal investigator for 30 research projects and contracts. He has received several awards at international and national conferences, the Best Research Paper Award from the *Journal of Network and Computer Applications* (Elsevier) in 2014, and the Runner-Up prize for the "Juan López de Peñalver" award of the Royal Academy of Engineering in Spain that recognizes the most notable Spanish engineers under 40 years of age. He is an expert evaluator for the European Commission and research agencies across Europe.

References

[1] M. Eiza, T. Owens, Q. Ni, and Q. Shi, "Situation-aware QoS routing algorithm for vehicular ad hoc networks," *IEEE Trans. Veh. Technol.*, vol. 64, no. 12, pp. 5520–5535, Dec. 2015.
[2] G. Araniti, C. Campolo, M. Condoluci, A. Iera, and A. Molinaro, "LTE for vehicular networking: a survey," *IEEE Commun. Mag.*, vol. 51, no. 5, pp. 148–157, May 2013.
[3] 3GPP, "Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; Stage 2 (v14.3.0, Release 14)," 3GPP, Tech. Rep. 36.300, June 2017.
[4] 3GPP, "Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures (v14.3.0, Release 14)," 3GPP, Tech. Rep. 36.213, June 2017.
[5] 3GPP, "Evolved Universal Terrestrial Radio Access (E-UTRA); Physical channels and modulation (v14.3.0, Release 14)," 3GPP, Tech. Rep. 36.211, June 2017.
[6] 3GPP, "Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio transmission and reception (v14.4.0, Release 14)," 3GPP, Tech. Rep. 36.101, July 2017.
[7] 3GPP, "Evolved Universal Terrestrial Radio Access (E-UTRA); Medium Access Control (MAC) protocol specification (v14.3.0, Release 14)," 3GPP, Tech. Rep. 36.321, June 2017.
[8] 3GPP, "Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Resource Control (RRC); Protocol specification (v14.3.0, Release 14)," 3GPP, Tech. Rep. 36.331, July 2017.
[9] 3GPP, "Architecture enhancements for V2X services (v14.3.0, Release 14)," 3GPP, Tech. Rep. 23.285, June 2017.
[10] Qualcomm Incorporated, "R1-1611594. Congestion control for V2V," presented at 3GPP TSG RAN WG1 Meeting #87, Reno, NV, Nov. 2016.
[11] Intel Corporation, "R1-1702143. Evaluation of congestion control schemes for V2V communication," presented at 3GPP TSG RAN WG1 Meeting #88, Athens, Greece, Feb. 2017.
[12] 3GPP, "Study on enhancement of 3GPP support for 5G V2X services (v15.0.0, Release 15)," 3GPP, Tech. Rep. 22.886, Mar. 2017.
[13] 3GPP MCC Support. "Draft Report of 3GPP TSG RAN WG1 #89 v0.2.0," presented at 3GPP TSG RAN WG1 Meeting #89, Hangzhou, China, May 2017.
[14] Ericsson. "R1-1708942. Radio resource pool sharing between mode 3 and mode 4 UEs," presented at 3GPP TSG RAN WG1 Meeting #89, Hangzhou, China, May 2017.
[15] 3GPP, "Study on LTE-based V2X services (v14.0.0, Release 14)," Tech. Rep. 36.885, July 2016.
[16] Huawei, HSilicon, "R1-160284. DMRS enhancement of V2V," presented at 3GPP TSG RAN WG1 Meeting #84, St. Julian's, Malta, Feb. 2016.
[17] M. Sepulcre, J. Gozalvez, and B. Coll-Perales. (2017, Apr.). Why 6Mbps is not (always) the optimum data rate for beaconing in vehicular networks. *IEEE Trans. Mobile Comput.* [Online]. Available: http://ieeexplore.ieee.org/document/7906621/
[18] IEEE 802.11p-2010—Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 6: Wireless Access in Vehicular Environments IEEE, 2010.

VT