Supporting Enhanced Vehicle-to-Everything Services by LTE Release 15 Systems

Gábor Fodor, Hieu Do, Shehzad Ali Ashraf, Ricardo Blasco, Wanlu Sun, Marco Belleschi, and Liang Hu

Abstract

Recognizing the increasing demand for intelligent transportation systems, the initial set of the Long Term Evolution (LTE) technical enablers for vehicle-to-everything (V2X) communication services has been substantially enhanced in Release 15 (Rel-15) and will be further developed in Rel-16. These enhancements are driven by the 25 use cases identified for V2X by the Third Generation Partnership Project, which are categorized as vehicle platooning, extended sensors, advanced driving, and remote driving. In this article, we provide an overview of the new V2X features supported by Rel-15 LTE systems, including carrier aggregation, higher-order modulation, low latency support, and new resource management solutions. We also discuss the possible next steps of the 3GPP V2X technology evolution in the upcoming releases.

Introduction

Third Generation Partnership Project (3GPP) specifications have played an important role in the world-wide success of Long Term Evolution (LTE), making it the fastest growing cellular technology in history. Indeed, almost a quarter of all global mobile subscribers currently use LTE, and it is expected that by 2021 this will increase to more than half, accounting for approximately 4.3 billion subscriptions. In certain regions, such as Korea, Japan, China, and the United States, LTE has already reached or exceeded 90 percent penetration [1]. This single technology footprint has led to unprecedented economies of scale, which have resulted in a rapid technology evolution that enables LTE to operate with high spectral and energy efficiency in a great number of spectrum bands.

At the same time, according to the World Health Organization, there were about 1.25 million road traffic fatalities worldwide in 2013, with another 20–50 million people injured and/or disabled through traffic accidents. The overall economic impact of road crashes was estimated to be US$518 billion globally, corresponding to 1–5 percent of the gross domestic product in some countries. Accordingly, there is increasing awareness that, to improve these statistics, advanced sensing, communication, computing, and, in the long term, artificial intelligence technologies should be integrated into the new generation of vehicles. Beyond saving people's lives, these technologies will also enable fully autonomous driving, which will serve as a foundation of the intelligent transportation system (ITS).

Although the benefits of network-assisted device-to-device communications utilizing cellular spectrum have been recognized, 3GPP has been studying technologies for proximity services only since Release 12 (Rel-12) of the LTE specifications [2, 3]. As a result, Rel-12 LTE networks support a special form of physical layer broadcasting-based device-to-device communications over the sidelink (also referred to as the PC5 interface), which can efficiently realize developments such as public safety, critical machine type communications, wearable device applications, coverage extension by relaying, and group communication services within or outside of the coverage area of the cellular infrastructure [2, 4].

To meet the increasing demand for vehicular communications, Rel-14 of LTE specified a first set of technical enablers for vehicle-to-everything (V2X) services [5]. This initial set of technical enablers includes radio interface design, protocols, and management functionalities that together enable vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-network (V2N), and vehicle-to-pedestrian (V2P) communications. V2X communications can be utilized for safety and non-safety (e.g., infotainment) purposes. In particular, the V2X support provided by Rel-14 makes LTE a suitable technology for meeting the requirements of the European Telecommunications Standards Institute (ETSI) for delivering safety messages such as cooperative awareness messages (CAM) and decentralized environmental notification messages (DENM) [6].

Parallel with this development, the research community has been proposing additional technology components that enhance the LTE capabilities and pave the way toward fifth generation (5G) V2X services [7–9]. Due to these research efforts and to expand the LTE platform to meet the evolving requirements of the automotive industry, this initial set of technical enablers provided by Rel-14 has been enhanced in Rel-15. These enhancements are driven by 25 use cases identified for advanced V2X communications — which go beyond the simple delivery of CAM and DENM — by the Services and Architecture working group (SA1) of 3GPP. These advanced use cases are categorized as vehicles platooning, extended sensors, advanced driving, and remote driving [10].

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Category	Use case	Max latency (ms)	Reliability (%)	Data rate (Mb/s)	Positioning accuracy (cm)
Platooning	Support for vehicle platooning, information sharing within platooning.	10	99.99%	65	30
Advanced driving	Cooperative collision avoidance; Information sharing for automated driving; Emergency trajectory alignment; Vulnerable road user detection.	5	99.99%	53	10
Extended sensor	Collective perception of environment; see-through; bird's eye.	10	99.99%	40 Mb/s or several 100 Mb/s (depending on how data is used)	30
Remote driving	Server/operator remotely controls a vehicle.	5	99.999%	Uplink: 25; Downlink: 1	30

Table 1. The new requirements associated with advanced applications

While the 3GPP specifications for V2X communications in Rel-14 and Rel-15 are not frequency-band-specific, the technical solutions are mainly designed to meet the requirements of the European Telecommunications Standards Institute (ETSI) for delivering safety messages and other ITS services. For these services, ETSI has allocated 70 MHz of spectrum in the 5.9 GHz band (Band 47), in which there is no overlap between V2X communications and regular cellular services. However, mobile network operators may also use licensed spectrum resources for delivering V2X communication services, in which case there may be a partial overlap between the spectrum resources used for mobile broadband and V2X services [5].

One of the key requirements on the enhanced technology enablers in Rel-15 was to preserve backward compatibility with Rel-14 V2X for the delivery of CAM/DENM safety messages. This requirement concerns both operating modes of sidelink V2X, namely the network-scheduled mode (Mode 3) and the autonomous mode (Mode 4) [7], detailed later. For the PC5 interface, this requirement implies that the newly developed solutions should coexist in the same resource pool as that used by Rel-14 user equipments (UEs). Consequently, Rel-15 UEs must use the same sidelink scheduling assignment format as used by Rel-14 UEs to avoid degrading the Rel-14 operation [11]. To meet the requirements of advanced V2X services, 3GPP has tasked the radio access network (RAN) working groups with supporting the following features (discussed in the sequel) for the PC5 interface:

- Carrier aggregation of up to 8 PC5 carriers
- Higher-order modulation
- Reducing the maximum time between packet arrival at Layer 1 and selecting resources for packet transmission
- Radio resource pool sharing between UEs using Mode 3 and Mode 4

In addition to these features, the physical layer group of RAN (RAN1) has also studied the feasibility and the achievable performance gains of PC5 operation with transmit diversity and using short transmission time interval for transmissions on the PC5 interface. Furthermore, RAN4 has studied the necessary radio frequency requirements for the specified PC5 functionalities in Band 47 (5.9 GHz). Note that in Rel-15, no new numerology, waveform, or channel coding for PC5 has been considered.

The rest of this article is structured as follows. The next section discusses basic considerations for developing technology enablers for enhanced V2X services. We describe new features of the Rel-15 sidelink, including carrier aggregation and multicarrier diversity, higher-order modulation capability, latency reduction and resource sharing mechanisms, and multi-antenna transmit diversity schemes. Where applicable, we point at Rel-14 to highlight the novel features specified for Rel-15. We offer an outlook for the next steps in the evolution of V2X communications, and discuss the possibilities that open up as 3GPP develops new technology enablers to support communications in higher frequency bands. We then conclude the article.

Basic Considerations for Supporting V2X Services

LTE V2X Connectivity Overview

V2X collectively refers to different types of connectivity (Table 1), including V2V, V2P, V2N, and V2I communication links [12]. The connectivity between the different endpoints — including UEs, infrastructure nodes, and cellular base stations — may be realized by one or more communication interfaces (e.g., cellular or direct device-to-device). Initial support for V2X services was introduced in the 3GPP LTE specifications in Rel-14 to enable safety use cases for meeting the ETSI requirements on delivering CAM and DENM safety messages. For these purposes, the interface for direct communication between UEs (PC5) was redesigned, and two new transmission modes were introduced. Mode 3 enables the cellular base station (eNB) to schedule a sidelink transmission. In contrast, when V2X communication uses Mode 4, vehicles autonomously select resources for their sidelink transmissions from the resource pools that are configured by the network [7]. In addition, in Rel-14 some enhancements were introduced to the existing cellular features.

Backward Compatibility and Coexistence Aspects in the 5.9 GHz Band

In cellular networks the communication between UEs is controlled via infrastructure nodes. This topology simplifies the evolution of the specification without creating compatibility problems between UEs. The infrastructure nodes naturally act as interfaces between UEs using different

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releases of the specifications. Thus, it is sufficient that the infrastructure nodes support the different releases and that some additional measures are taken in the design and configuration of the network. In contrast, the evolution of a network in which UEs communicate directly with each other is much more complicated. In a way, the capabilities of the oldest UEs in the network limit such evolution. This affects almost all physical layer features and also many (but not all) aspects at higher layers. To allow for a purposeful evolution of LTE V2X — especially of the PC5 interface while avoiding incompatibility problems between UEs — it became necessary to consider a different evolution model. In this new model, each set of services is mapped to a single release of the specification. For example, safety services are mapped to Rel-14, whereas advanced driving services are mapped to Rel-15. This ensures that all UEs (present or future) supporting safety services will be compatible with each other. At the same time, the specification may be evolved to ensure that new services can be supported, too. The design of the V2X technical enablers in 3GPP Rel-15 takes into account the following:

- It is not practical to upgrade the hardware of all old vehicles to introduce new services.
- Making the specification backward compatible with the former release (Rel-14) would hinder the development of V2X technology due to the constraints imposed by the former release.

As a result, the most viable solution to manage the trade-off between backward compatibility and introducing new features is that each release is aimed at supporting a certain set of services. This design guarantees that all vehicles (present or future) supporting safety services will be compatible with each other. At the same time, the specification may evolve to ensure that new services can be introduced, such that new vehicles can implement both the old and newer releases to support both basic safety and new advanced services. This approach also allows old vehicles to continue to use the basic safety services or, if their hardware can be upgraded to include the new releases, they will be able to use the advanced services. Note that this does not ensure that UEs using different releases of the specification can always communicate with each other. However, it guarantees that UEs using the same service can communicate with each other by using the same set of features.

For efficiency reasons, it is also desirable that UEs using different releases can be deployed in the same radio resources, even if some of them cannot communicate with each other. For LTE V2X, this constraint limits the evolution of the distributed resource allocation mode. In other words, future releases of the LTE V2X specification must ensure that the basic signaling which enables efficient distributed resource allocation remains unchanged.

In practical terms, this implies that:

- The physical sidelink control channel (PSCCH) format and contents must remain unchanged (except for some reserved fields).
- The demodulation reference symbols, which are used for measurements and channel state information acquisition, cannot be modified substantially.

The enhancements and features in Rel-15 have been designed accordingly, taking the above constraints into account.

LTE Rel-15 Features

Carrier Aggregation and Multi-Carrier Diversity

In Rel-14, V2X was designed to target single carrier operation. Nevertheless, basic sidelink multi-carrier support was introduced to allow UEs to participate in multiple ITS (including safety and non-safety related) services, which may be confined to different carriers by ITS spectrum regulatory authorities. The Rel-14 design principle was that a UE should be able to at least monitor the ITS safety carriers and, optionally, to monitor ITS non-safety carriers as well. In other words, the targeted scenario was having different services on different carriers. Note that in 3GPP parlance, the term *carrier* in this context does not refer to a waveform which is modulated, but rather it refers to the main carrier frequency or spectrum resource that is used to deliver a given service. The carrier aggregation feature for the cellular uplink and downlink allows scalable expansion of the effective bandwidth delivered to a UE through concurrent utilization of radio resources across multiple component carriers (see, e.g., [13]). In Rel-15, motivated by the new requirements associated with advanced applications (Table 1 and [10]), 3GPP has enhanced the support for V2X sidelink multi-carrier transmissions. The enhanced set of sidelink features include the following capabilities:

- Packet duplication, allowing for the transmission of multiple copies of the same packet in several carriers in parallel (e.g., to increase reliability).
- Parallel transmission of different packets in several carriers (e.g., to increase throughput).
- Optimization of transmitter and receiver procedures for multi-carrier operation, including carrier selection and synchronization

For Mode 3, the Rel-14 specification already contained most of the elements that were necessary for the eNB to schedule a UE on multiple carriers, and only minor changes have been introduced.

In contrast, multiple enhancements have been introduced for Mode 4. To allow for parallel transmission of packets over multiple carriers, the resource allocation procedure has been enhanced in two ways:

- Avoiding selecting resources in multiple carriers in a way that exceeds the capabilities of the UE (e.g., due to limited number of transmit chains, transmit-receive switching time, radio frequency requirements)
- Enabling the selection of resources on multiple carriers following a decreasing packet priority

Sidelink packet duplication is performed at the Packet Data Convergence Protocol (PDCP) layer, that is, two copies of the same PDCP packet are submitted to two different radio link control entities and then multiplexed onto two different hybrid automatic repeat request (HARQ) entities. This procedure ensures that the two copies are

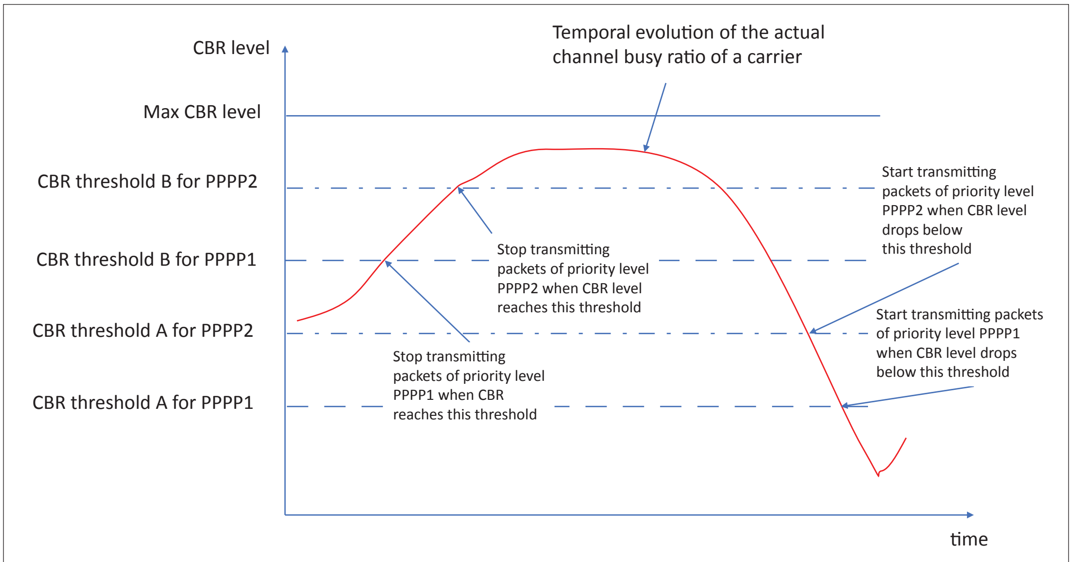

Figure 1. Illustration of how the channel busy ratio (CBR) and its associated thresholds determine the transmission of packets that belong to different proximity services' per-packet priority (PPPP) classes. Transmissions of packets belonging to a specific PPPP class are not allowed when the congestion level of the carrier exceeds threshold B of that class and are allowed when the congestion level of the carrier drops below threshold A of that class.

For correct multi-carrier operation outside network and global navigation satellite system coverage, the distributed synchronization protocol from Rel-14 has been extended to include the possibility of defining synchronization carriers that act as synchronization anchors.

always transmitted on different carriers. Besides the increased transmission diversity, the redundant transmission of the same packet in different carriers is also beneficial for UEs which have limited receiver capabilities that cannot monitor multiple sidelink carriers simultaneously.

To restrict the use of duplication to those packets that require high reliability, 3GPP has introduced a new packet reliability tag, called proximity services per-packet reliability on top of the legacy proximity services per packet priority (PPPP) which only depends on the packet latency requirement. Depending on the per-packet reliability associated with a given packet and network configuration, the UE can determine whether to perform PDCP packet duplication over the sidelink or not.

The work by 3GPP has considered the issue of fair utilization of carriers as well as the existence of UEs with limited receiver capabilities that have no or limited carrier selection possibilities. To this end, the specification allows for configuring different thresholds allowing/barring the use of specific carriers based on the level of congestion measured in terms of the channel busy ratio (CBR) and the priority level of the packet indicated by the PPPP. Specifically, for a given sidelink carrier and PPPP, it is possible to configure a lower threshold on the carrier CBR so that the UE is allowed to select such a carrier for the transmission of a packet with that priority level if the congestion is below the threshold. Once a carrier is selected, the UE shall keep using this selected carrier for the transmission of a packet with that priority level until the congestion exceeds a higher threshold.

For example, a possible configuration could be one in which the lower CBR threshold A is lower for higher-priority packets (i.e., PPPP1 in Fig. 1 and higher for lower-priority packets (i.e., PPPP2 in Fig. 1). Setting the lower CBR threshold levels this way ensures that a UE can use a sidelink carrier for transmitting a high-priority packet, while for transmitting a low-priority packet the CBR requirements can be more relaxed. With the same reasoning, the higher CBR threshold B can be lower for higher-priority packets and higher for lower-priority packets in order to ensure high reliability to higher priority packets.

In the example illustrated in Fig. 1, there are two threshold levels (A and B) associated with each of the two PPPP classes (PPPP1 and PPPP2, respectively). These in total four threshold levels determine when the transmitter should stop transmitting packets and start transmitting packets that belong to a specific priority class (i.e., PPPP1 or PPPP2). Specifically, the transmissions of packets belonging to a specific PPPP class are not allowed when the congestion level exceeds threshold B of that class and are allowed when the congestion level of the CBR drops below threshold A of that class.

An important aspect of multi-carrier communication is the synchronization of the different carriers. Multi-carrier operation in Rel-15 is restricted to component carriers that are synchronized in time at the frame and subframe levels. For correct multi-carrier operation outside network and global navigation satellite system coverage, the distributed synchronization protocol from Rel-14 has been extended to include the possibility of defining synchronization carriers that act as synchronization anchors.

Finally, in terms of spectrum requirements, the Rel-15 specification supports intra-band aggregation of carriers from band 47 (5855–5925 MHz), including the combination of 10+10 MHz (already supported in Rel-14), 10+20 MHz, and 10+10+10 MHz.

Higher Order Modulation

The Rel-14 PC5 supported the use of quadrature phase shift keying (QPSK) and 16-quadrature amplitude modulation (QAM) to enable basic V2X safety applications. The Rel-15 PC5 aims to

In Rel-15 V2X systems, scenarios requiring higher bit rates and tolerating somewhat reduced sidelink coverage can benefit from the usage of 64-QAM.

Scaling Factor	Peak spectral efficiency without retransmission	Peak spectral efficiency with retransmission
1	2.4 b/s/Hz	2.04 b/s/Hz
0.8 (without additional TBS values)	3.3 b/s/Hz	1.6 b/s/Hz
0.8 (with additional TBS values)	3.4 b/s/Hz	2.7 b/s/Hz

Table 2. Peak spectral efficiency for Rel-14 and Rel-15.

attain higher spectral efficiency, especially in situations with good channel quality, by supporting the use of higher order modulation, including 64-QAM. Therefore, in Rel-15 V2X systems, scenarios requiring higher bit rates and tolerating somewhat reduced sidelink coverage can benefit from the usage of 64-QAM.

The LTE sidelink design can advantageously be built on concepts and some physical layer structures used for the LTE cellular uplink. Therefore, when designing modulation and coding schemes (MCSs) for the Rel-15 sidelink, a natural starting point for the design was the LTE cellular uplink MCSs and cellular uplink transport block configurations. Thus, the possible transport block sizes (TBSs) for Rel-14 PC5 transmissions are based on that of the LTE uplink. However, the subframe structure used for Rel-15 V2X transmissions includes important changes as compared with the LTE uplink subframe structure due to the need for automatic gain control, tighter demodulation reference symbol placements, and the guard period. Specifically, these changes include:

- The first orthogonal frequency-division multiplexing (OFDM) symbol of the subframe is used to settle the automatic gain control.
- The number of OFDM symbols used for demodulation reference signals is higher (i.e., 4 symbols in comparison to 2 symbols in uplink), which helps to acquire high-quality channel state information in high-mobility scenarios.
- The last OFDM symbol is not transmitted due to the presence of the guard period.

Due to these differences between the Rel-15 sidelink structure and the Rel-15 cellular uplink structure, and as a consequence of the additional overhead associated with sidelink transmissions, some of the MCS/TBS configurations specified for Rel-14 cellular uplink transmissions would lead to code rates above 0.93 or even 1 for Rel-15 sidelink communication. In particular, the following configurations are problematic for Rel-15 sidelink if the Rel-14 uplink MCS/TBS table was used "as is" for sidelink transmissions:

- For modulation and coding scheme index $I_{MCS} = 10$ (QPSK configuration with the highest coding rate) and some bandwidth allocations, decoding leads to errors with single transmission.
- For $I_{MCS} = 18–20$ (16-QAM configurations with highest coding rates), most bandwidth allocations lead to decoding errors with single transmission.
- Some high I_{MCS} (e.g., $I_{MCS} > 23$) with 64-QAM lead to decoding errors with single transmission.

To resolve the problematic MCSs, TBS values are scaled with a certain scaling factor. This scaling factor should be decided such that at least the transport block at least up to MCS value 28 is decodable based on single transmission. This is due to the fact that it is not common for the LTE specification to provide TBS values which cannot be decoded based on a single transmission. Also, note that for safety related V2X applications, it is necessary that the packets are transmitted reliably and within the latency budget. That is, relying on multiple transmissions for decoding a single transport block is not reasonable for sidelink V2X, which is inherently less reliable than traditional uplink/downlink transmissions. Therefore, designing a system that allows for decoding based on a single decodable transmission is important for the LTE sidelink. To ensure that the coding rate values are below 0.932 at least up to MCS values of 28, the scaling factor is chosen to be 0.8 given that only 9 symbols out of 14 are usable for data transmission. Furthermore, by using a scaling factor lower than 1 (i.e., 0.8), the peak spectral efficiency is reduced as compared to that of Rel-14 when retransmissions are necessary.

To compensate for the loss in peak spectral efficiency, some additional TBS values are introduced corresponding to $I_{MCS} > 28$. Table 2 shows the peak spectral efficiency achieved in the case of single transmission and in the case of retransmissions, with and without applying the scaling factor. Note that 10 MHz sidelink channel bandwidth is assumed to be available in the 5.9 GHz ITS spectrum. It can be seen that peak spectral efficiency of Rel-15 PC5 transmission (i.e., scaling factor of 0.8 with additional TBS values) is the highest due to the introduction of 64-QAM.

Furthermore, to allow efficient coexistence of Rel-14 and Rel-15 UEs, differentiating the use of Rel-14 and Rel-15 transmissions is necessary. This implies that the receiving UE must know if the received transmissions are according to the Rel-14 or Rel-15 format. To facilitate format differentiation, in Rel-15 an indicator in the sidelink control information (SCI) is used. For instance, one of the reserved bits in the SCI used in Rel-14 can be set to 1 when the Rel-15 transmission formats are used.

Transmission Format Selection

Obviously, sidelink transmissions performed with Rel-15 transmission formats cannot be decoded by Rel-14 UEs. In particular, Rel-14 UEs cannot decode packets if the transmitter applies TBS-scaling or 64-QAM. Therefore, it is important that the selection of the Rel-15 transmission formats take into account the specific V2X service for which the packet transmission takes place. For V2X safety transmissions, for example, transmission formats that are specific to Rel-15 are not desirable, since safety related critical information should be decodable by both Rel-15 and Rel-14 UEs. Therefore, the selection of the transmission formats for the transmission of a certain packet must not depend only on radio layer information such as the prevailing channel conditions. To this end, it is indicated by the V2X application server to the radio layer procedures whether a certain V2X service should be transmitted using Rel-14 or Rel-15 transmission formats. That is, the mobile network operator or traffic authority provides the UE with the release format to be used for the transmission of a packet associated with a specific V2X service. On the other hand, the radio layers — upon selecting the release format as indicated by the upper layers — are in charge of selecting the most appropriate MCS depending on the channel conditions.

Latency Reduction

In Rel-14 of the LTE V2V specifications, the radio-layer latency (i.e., the time between the arrival of a packet to the PDCP layer and the end of the last (re)transmission associated with that packet) for Mode 4, where the UE autonomously selects the resources for transmission is limited by the duration of the selection window. (Note that the notion of the selection window is different from the concept of the contention window. The selection window is a set of subframes, from among which the UE selects resources for its subsequent transmission.) More specifically, a UE performing resource selection during the transmission time interval n could select resources anywhere in the selection window $[n + T_1, n + T_2]$, where T_1 and T_2 define the maximum processing time for the packet (e.g., for encoding and modulating) and the maximum latency, respectively. The actual selection of resource is determined by a procedure that combines sensing-based resource exclusion and randomization. In this way, the size of the selection window controls a trade-off between latency and collision probability. For example, increasing T_2 reduces the probability that two UEs with correlated channel observations randomly select the same resource at the expense of increasing the radio-layer latency and vice versa. In Rel-14 it was agreed, based on numerical evaluations, to use T_1 = 4 ms and T_2 = 20 ms as values defining the smallest possible selection window. Consequently, the minimum guaranteed radio-layer latency in Rel-14 is 20 ms.

To reduce the radio-layer latency, in Rel-15 it has been agreed to support lower values of T_2, down to a minimum of $T_{2,\min}$ = 10 ms. The actual allowed value(s) may be (pre)configured independently for each PPPP value, meaning that packets with different priorities may be guaranteed different latency values. This allows for controlling the increase in collision probability, ensuring that only high-priority packets have quicker access to the channel.

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Resource Sharing between Mode 3 and Mode 4 UEs

As introduced earlier, Rel-14 specifies two modes of sidelink transmissions for V2X, known as Mode 3 and Mode 4. In Mode 3 the eNB schedules a sidelink transmission by sending a scheduling assignment to the UE via a downlink control information format 5A. The UE incorporates the scheduling assignment into its SCI format 1, and transmits the SCI in the sidelink to notify potential receivers about the associated data transmission. In contrast, in Mode 4 each UE autonomously learns and predicts the behavior of other UEs to find the best resources for its transmissions. This is called resource selection based on sensing.

The existence of two transmission modes leads to two options for resource pool allocation for V2X. The first option consists of configuring disjoint resource pools for Modes 3 and 4, while the second option consists of letting the resource pools of the two modes at least partially overlap. The first option avoids collisions between Mode 3 and Mode 4 transmissions, but typically leads to inefficient use of the system resources. In particular, if the size of each pool is fixed, a pool can be underutilized or overutilized, depending on the traffic conditions in the network. Dynamic (re) configuration of resource pools can improve the resource utilization, but is not advisable since it consumes signaling resources, and potentially has large impact on the system's stability, including the disruption of ongoing communication processes. Rel-14, however, lacks effective mechanisms to support the second option, that is, mechanisms for the efficient coexistence of Mode 3 and Mode 4 transmissions in the same set of resources. Rel-15 resolves the problem via two solutions.

The first solution involves Mode 3 UEs informig Mode 4 UEs of their transmission intention. Note that the sensing procedure performed at a Mode 4 UE consists of reading scheduling assignments contained in the SCI sent by other UEs and measuring signal strength in the pertinent resource elements. To facilitate the prediction of resource uses, the resource reservation field in the SCI is used by the transmitting UE to inform other UEs about its intention to transmit in the future using the same radio resources. The reservation is particularly suitable for periodic-like traffic such as the CAM. However, for Mode 3 transmissions the field is set to zero in Rel-14. As a result, Mode 4 UEs cannot predict transmission behavior of Mode 3 UEs even when the latter ones have semi-persistent scheduling grants for PC5 transmissions. This leads to collisions and degraded performance of both Mode 3 and Mode 4 UEs if they share the same set of resources. The problem is solved in Rel-15 by setting the resource reservation field in the SCI format 1 of Mode 3 UEs to the corresponding semi-persistent scheduling period.

According to the second solution, Mode 3 UEs also perform sensing and reporting certain metrics of the sensed resources to the eNB. Mode 3 UEs, for example, may report a map of free resource elements according to their sensing results. By sensing and reporting, Mode 3 UEs help the eNB to become aware of the impact of Mode 4 transmissions on the shared resource pool, and thereby to determine the best resources for each Mode 3 transmission.

Transmit Diversity

To support advanced V2X services with high reliability requirements, as identified in SA1, the RAN1 working group has decided to study the feasibility of transmit diversity supported by multi-antenna transmissions over the PC5 interface. It was recognized that the transmit diversity feature will have to coexist with functionalities implemented by Rel-14-compliant UEs.

To satisfy the backward compatibility requirements discussed earlier, it is natural to distinguish two types of transmissions for Rel-15 UEs:

To maintain backward compatibility, the sidelink scheduling assignment transmissions on PSCCH must be decodable by Rel-14 UEs. Therefore, the processing of the scheduling assignments must remain transparent to a receiver in the sense that the receiver does not need to know whether a multi-antenna scheme is used by the transmitter or which one.

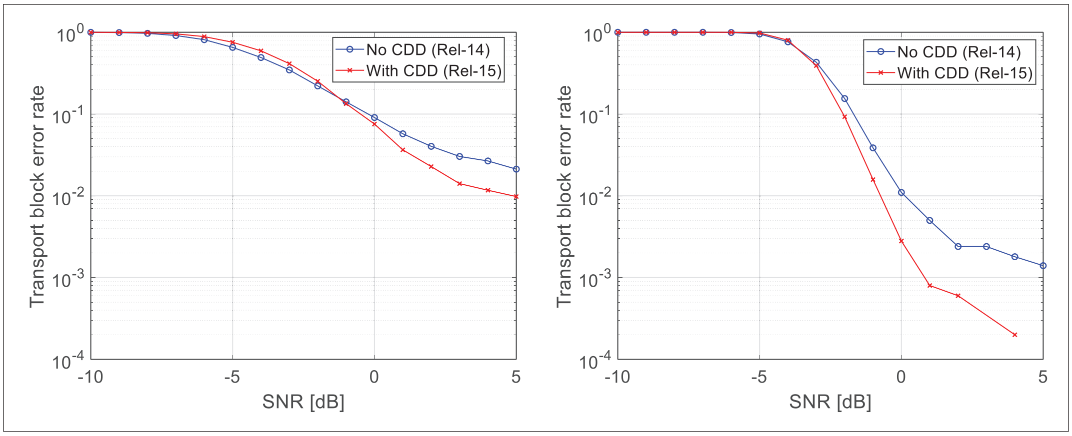

FIGURE 2. Comparison between the small delay CDD scheme (Rel-15) and the single-antenna scheme (Rel-14) for two channels: PSCCH (left figure) and PSSCH (right figure), at 140 km/h using QPSK. Packet transmission on PSCCH does not use retransmission, whereas PSSCH uses one retransmission, which leads to lower transport block error rates.

- Transmissions of sidelink scheduling assignments on the PSCCH
- Transmissions of data payload on the physical sidelink shared channel (PSSCH), where payload is defined as information carried by symbols that are not used as reference symbols

We discuss these two types of transmissions below.

To maintain backward compatibility, the sidelink scheduling assignment transmissions on PSCCH must be decodable by Rel-14 UEs. Therefore, the processing of the scheduling assignments must remain transparent to a receiver in the sense that the receiver does not need to know whether a multi-antenna scheme is used by the transmitter or which one. Among the options of transparent multi-antenna transmission schemes supporting transmit diversity, small delay cyclic delay diversity (CDD) is a promising candidate for PSCCH transmissions. The CDD scheme transforms spatial diversity into frequency diversity by multiplying the frequency domain data symbols with a linear increasing phase factor that depends on the cyclic delay. Thus, the diversity gain can be exploited to improve reliability.

In contrast to the backward compatibility requirements on PSCCH transmissions, the data payload transmissions on the PSSCH do not need to be decodable by Rel-14 UEs. Therefore, the RAN1 working group has carefully considered both transparent and non-transparent diversity schemes for PSSCH transmissions. Although some non-transparent schemes, including the Alamouti space-frequency block coding scheme, can provide diversity gains for Rel-15 transmissions, they may degrade the performance of Rel-14 UE receivers that use interference rejection combining. More specifically, when Rel-15 UEs equipped with two transmit antennas employ a non-transparent diversity scheme, the two-port Rel-15 interferer may degrade the performance of Rel-14 receptions compared to a situation in which only one-port Rel-14 interferers operate. This performance degradation is due to the limited degree of freedom at the Rel-14 receivers. (Note that two Rx antennas are assumed in both Rel-14 and Rel-15.) By comparing the potential gains for Rel-15 transmissions and the potential degradations to Rel-14 transmissions, it was finally concluded that the transparent diversity scheme should also be applied to the Rel-15 PSSCH transmissions.

Link-level simulations are presented in Fig. 2 to compare the block error rate (BLER) performance of transmissions without and with small delay CDD on the physical channels PSCCH (left) and PSSCH (right). As clearly shown in the figure, small delay CDD outperforms single-antenna transmission schemes by exploiting the diversity gain, especially at higher (practically relevant) signal-to-noise ratio (SNR) levels.

OUTLOOK: V2X SERVICES IN 3GPP NEW RADIO

The establishment of the new radio interface termed New Radio (NR) in Rel-15 has laid a solid technical foundation for supporting V2X services beyond the currently supported Rel-14 and Rel-15 LTE-based V2X services. In order to realize the full potential of NR for V2X, 3GPP is preparing for the development of the NR V2X specifications in parallel with the enhancements of the LTE-based V2X services. After completing this preparation phase in the study item on evaluation methodology for new V2X use cases [14], the 3GPP RAN plenary approved a new study item on NR V2X [15] in June 2018. This study item aims to identify technical solutions for the NR sidelink design to meet the requirements of advanced V2X services summarized in [10]. Indeed, while some of the services described in [10] can already be supported by the LTE Rel-15 standards suite, the full support of all advanced services can only be achieved through NR V2X. To this end, NR V2X will contain a number of new features of both the sidelink (PC5 interface) and the cellular uplink/downlink. One of these new features is expected to be support for sidelink unicast and groupcast transmissions, as opposed to the physical layer broadcast-based LTE sidelink design. Another feature can be sophisticated quality of service management for V2X operations at the radio interface. We expect that advanced mechanisms will be developed for managing the coexistence of NR and LTE V2X services. Together with the inherent advantages of 3GPP NR — due to the support of higher frequency bands, advanced multi-antenna and beamforming, lean design, and multiple numerologies — the targeted new features of NR V2X will facilitate high V2X performance such as high data rate, low latency, and high reliability. As a result, the NR V2X will be able to realize the use cases identified in [10] that map to the high stages of V2X evolution [1].

Conclusions

Vehicular communications and a range of advanced safety and non-safety related services built around communications between vehicles, pedestrians, and infrastructure nodes can make transportation systems safe and energy-efficient. To meet the increasing demand for vehicular communications, Rel-14 and Rel-15 of the 3GPP LTE specifications include physical and medium access control layer support and protocols for a wide range of intelligent transportation system services. As the evolution of the 3GPP protocol family continues with the development of NR, and the demand for vehicles platooning, extended sensors, advanced driving, and remote driving increases, we expect that Rel-16 will include a number of new technology enablers. In particular, we expect that the sidelink of 3GPP NR will extend the capabilities of the sidelink of Rel-14 and Rel-15. These new technology enablers will affect the capabilities of the physical and medium access control layers and are likely to take advantage of the advanced new features of NR — such as mmWave communications, multi-antenna solutions, and solutions for low latency and high reliability — for both the cellular and the sidelink interfaces. As the work in 3GPP toward including new features in Rel-16 progresses, it is becoming clear that designing physical-layer structures and physical and medium access control procedures to support unicast, groupcast, and broadcast sessions, managing radio bearers and quality of service over the sidelink and supporting channel-state-information-dependent solutions will pose new challenges as compared to those addressed in Rel-15.

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