# V2X Connectivity: From LTE to Joint Millimeter Wave Vehicular Communications and Radar Sensing

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***Abstract*—To meet the prospective demands of intelligent transportation systems (ITS), the Release 14 (Rel-14) and Rel-15 of the Long Term Evolution (LTE) specifications include solutions for enhanced vehicle-to-everything (V2X) communications. While the technical enablers of Rel-14 are suitable for delivering basic safety messages, Rel-15 supports more demanding ITS services with stringent latency and reliability. Starting in Rel-15 and continuing in Rel-16, the 3GPP was developing a novel radio interface for 5G systems, termed the New Radio (NR), which will enable ultra reliable and low latency communications suitable even for the most demanding ITS applications. In this paper, we overview the new V2X-specific features in Rel-15 and Rel-16. Further, we argue that future V2X and automotive radar systems may reuse common equipment, such as millimeter-wave antenna arrays. We finally discuss the vision of joint vehicular communications and radar sensing as well as characterize unified channel access for millimeter-wave vehicular communications and radar sensing.**

## I. Introduction

Owing to recent advances in wireless communications, positioning, and decision and control systems, the automotive industry is rapidly transforming into intelligent transportation systems (ITSs) that will offer attractive new services. These are expected to become an essential part of smart cities by improving road safety, reducing traffic congestion, and mitigating environmental impact. A key technology component of the emerging ITS applications is cellular vehicle-to-everything (V2X) communications, facilitated by the Third Generation Partnership Project (3GPP) Long Term Evolution (LTE) and New Radio (NR) systems. They enable vehicles to communicate with one another, with the road infrastructure, and with the cellular core network [1].

Recognizing the demand for V2X communications and the projected expansion of the cellular V2X ecosystem, the 3GPP developed a first set of technology enablers for V2X services in Release-14 (Rel-14) of LTE specifications [2]. The physical, medium access control (MAC), and higher layer functionalities designed for LTE in 3GPP Rel-14 enable reliable V2X communications primarily focused on safety-related applications [3]. Specifically, the V2X communications in 3GPP Rel-14 make LTE a viable solution for providing basic safety services by broadcasting cooperative awareness messages and decentralized environmental notification messages (CAM/DENM) [4, 5]. Building on the capabilities of LTE Rel-14 and having the goal of improving the support for ITS services beyond basic safety applications and CAM/DENM delivery, which includes advanced driving, extended sensors, and remote driving applications, the 3GPP in Rel-15 enhanced LTE by targeting advanced automotive use cases [6].

Even though Rel-15 exceeds the capabilities of Rel-14 systems, the Rel-15 enhancements – such as carrier aggregation over the PC5 (sidelink) interface, higher-order modulation, and others – remain limited by the fact that they are based on Rel-14 LTE. Therefore, by taking into account the requirements imposed by future ITSs that support higher degrees of automation – such as driverless parking and driverless urban driving – the 3GPP has specified the requirements for advanced V2X scenarios [7] and designed the NR Rel-16 to satisfy the demands of future V2X scenarios (see Fig. 1 and 2).

To meet the requirements of future ITS services, which demand lower latency and higher reliability – referred to as ultra reliable and low latency communications (URLLC) applications – the 3GPP reduced the latency and enhanced the reliability of the cellular interface in Rel-16. In particular, the Rel-16 URLLC-specific features for the cellular interface enable faster transmission of data and hybrid automatic repeat request (HARQ) acknowledgments in both uplink and downlink, and thereby reduce the latency and increase the reliability on cellular connections. As a result, the NR Rel-16 cellular interface can support advanced V2X use cases, which include advanced driver assistance systems, cooperative adaptive cruise control, platooning and remote driving, etc.

Since some of the V2X services are solely focused on proximity as well as need to remain operational even in the case of a radio link failure and intermittent network coverage [8], in Rel-16, the direct device-to-device (PC5 or sidelink) interface was also enhanced. Specifically, the 3GPP defined a new sidelink interface for NR, which complements the cellular interface and thus makes the NR a highly flexible technology for the emerging ITS services [9].

In this paper, we review the V2X features provided by the LTE Rel-15, NR Rel-16, and beyond. We primarily aim to highlight the ongoing evolution of V2X technologies that provides entirely new possibilities as opposed to the backward-constrained LTE. Along with this summary, we describe

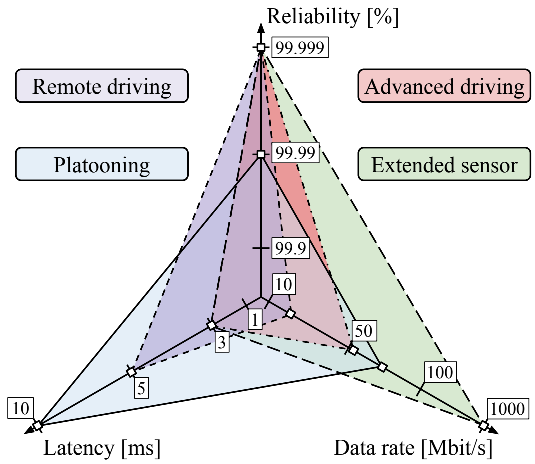


Fig. 1. Requirements of V2X use cases in 3GPP Rel-16.

an approach to harmonizing automotive radar sensing and V2X operating in millimeter-wave (mmWave) frequencies. We believe that the presented discussion facilitates further development of V2X communications and novel V2X services.

## II. Rel-15 V2X Design and Features

While Rel-15 enhances the capabilities of sidelink and thereby facilitates new V2X safety and other services, an important requirement imposed on LTE Rel-15 sidelink features was preserving backward compatibility with the LTE Rel-14 sidelink. This is to ascertain that the Rel-15 user equipments (UEs) can co-exist with the Rel-14 UEs that communicate via the PC5 interface. Specifically, the compatibility requirement ensures that when UEs of Rel-14 and Rel-15 use overlapping resource pools for the sidelink connectivity, all the UEs utilize identical schedule assignment format (particularly, the one from Rel-14) to make certain that the operation of Rel-14 UEs is not degraded by Rel-15 UEs [10].

Accounting for the backward compatibility constraint, and to advance the V2X services offered by LTE Rel-14 systems, several PC5 features were introduced in Rel-15. These include a more aggressive modulation as well as the ability to aggregate up to eight PC5 carriers. Further, the sidelink radio resource pool can be shared between the UEs using Mode 3 (network-scheduled) and Mode 4 (UE autonomous) transmissions. Finally, there are additional mechanisms to shorten the time duration between the moment when a new packet arrives at the physical layer and the moment when the resources are selected for the subsequent transmission.

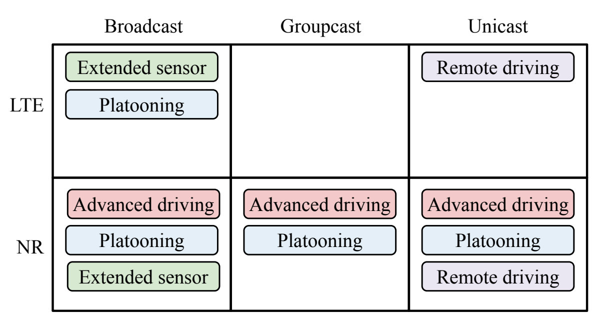


Fig. 2. Technologies and interfaces for 3GPP V2X use cases.

Radio Access Networks physical layer working group (RAN1) has also evaluated the potential performance gains of PC5 operation that employs short transmission intervals and diversity over the PC5 interface. The conclusion was that only the receiver-transparent diversity scheme of small-delay cyclic delay diversity (CDD) can be supported without degrading the performance of the legacy Rel-14 UEs. In general, it has been understood that support for V2X communications in 3GPP has to be designed under the premise that old vehicles are unlikely to be upgraded for new services. Therefore, the backward compatibility of newer specifications became crucial.

Another recommendation was to allocate the same radio resources to the UEs using Rel-15 and Rel-14, even when these UEs are not able to exchange any data. Hence, the principal signaling in V2X communications remains unchanged. Specifically for PC5, the latter leads to introducing the minimal feasible changes to physical sidelink control channel (PSCCH) and demodulation of reference symbols. The above constraints limited the development of Mode 4 in Rel-15, thus resulting in modest enhancements for Rel-15, as described above. To achieve future-proof design of the NR specifications, the 3GPP RAN1 group has designed the subsequent V2X release (i.e., NR Rel-16 V2X) in a more forward-compatible manner.

## III. Further Enhancements of Rel-16 V2X

The 3GPP NR cellular interface (referred to as the Uu interface) is designed to enable both mobile broadband and URLLC services [11]. To ensure that the NR Uu interface supports factory automation, critical machine-type communications, and low latency vehicular communications services, several Uu enhancements were specified in the Rel-16 URLLC work item [12] (see Fig. 3).

These upgrades to the NR Uu interface allow for very low latency transmissions of uplink/downlink data as well as HARQ packets. Therefore, they make the NR Uu interface capable of meeting the stringent requirements collected in Fig. 1. Enabling both mobile broadband and URLLC services over the Uu interface is beneficial for V2X as well as for the factory automation and critical machine-type services [13].

Similarly to the evolution of LTE, the improvements to the NR cellular technology include support for device-to-device connectivity over the sidelink. Reliance on sidelink communications in NR is useful in the scenarios where the transmitter and the receiver are in mutual proximity, and also in the cases of intermittent network coverage [8]. While support of sidelink was not included in Rel-15 of NR, additional NR sidelink features were developed in NR Rel-16, as detailed in Fig. 3.

By adopting the main principles of the NR Uu interface for the design of the NR sidelink (i.e., including the unicast and QoS-aware capabilities [14]), the NR sidelink complements the Uu-based V2X services in out-of-coverage situations.

The NR sidelink can operate in both lower (up to 7.125 GHz) and higher (up to 52.6 GHz) frequency ranges. Moreover, NR physical layer structures and procedures are, to a

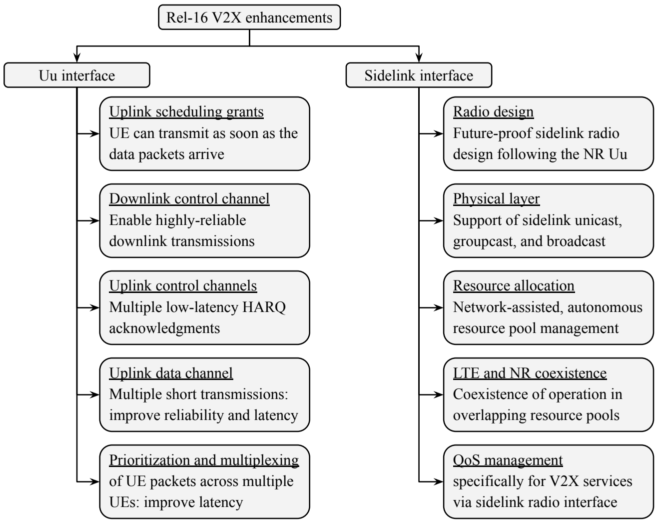
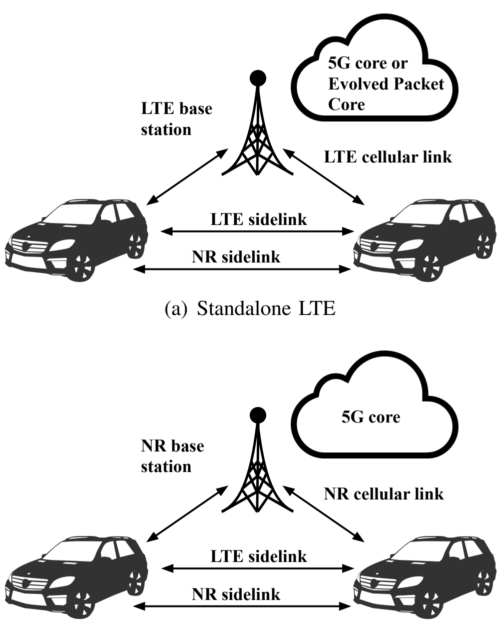



Fig. 3. V2X-related enhancements for interfaces in Rel-16.

large extent, frequency band agnostic. It is expected that the typical NR sidelink-specific scenarios will utilize dedicated frequency bands as well as the frequency bands that are licensed to cellular network operators. Therefore, various NR protocols facilitate coordination and control of sidelink transmissions within the network coverage, which ensures efficient coexistence of sidelink transmissions with cellular data traffic in shared frequency bands.

Further recognizing the fact that the V2X users need to be able to communicate with each other even outside the network coverage, the NR sidelink defines two transmission modes (labeled Mode 1 and Mode 2, respectively) as follows:

- Network-controlled mode. The UE follows the scheduling decisions provided by its serving base station.
- Autonomous mode. The UE makes its own scheduling decisions by relying on the configuration that was previously provided by the network or made available in the subscriber identity module.




(a) Standalone LTE

(b) Standalone NR

Fig. 4. Sidelink-specific scenarios under cellular control.

To fully reap the benefits of centralized scheduling in Mode 1 [15, 16], it is essential for a UE to be capable of transmitting over the sidelink in different deployment scenarios. To this end, the 3GPP Rel-16 includes signaling procedures to coordinate the sidelink transmissions over various cellular technologies. Specifically, the LTE Uu interface can control the NR sidelink transmissions, while the NR Uu interface can manage the LTE sidelink transmissions possibly in addition to NR Uu control as illustrated in Fig. 4.

## IV. V2X Developments in Rel-17 and Beyond

Most of the work on Rel-16 is to be concluded in Fall 2019/Spring 2020. Along with these developments, 3GPP is now identifying the possible V2X-specific topics in Rel-17 and beyond. The work on Rel-17 is planned to commence in early 2020. Currently, Rel-17 is expected to be a relatively large effort with over 40 research topics proposed by the member organizations [17].

In terms of V2X support, the following activities are of particular interest to the community:

1) Development of sidelink-related features continues under the “Sidelink enhanced” umbrella.
2) Exploration of the frequency bands above 52.6 GHz for NR becomes in focus.

The latter direction facilitates the use of higher-order modulation and coding schemes (up to QAM-1024) to efficiently utilize wideband mmWave channels above 52.6 GHz. There are also plans to address the use of unlicensed mmWave spectrum, e.g., the 60 GHz sub-band [18]. In parallel, the sensing capabilities of future vehicles will be enhanced with a massive adoption of automotive radars operating in the frequencies of above 30 GHz. Hence, prospective smart vehicles are envisioned to be equipped with both high-rate mmWave connectivity modules and high-resolution mmWave radars. This enables such next-generation vehicles to exchange abundant data with other cars, humans, as well as road infrastructure units [19, 20].

At the same time, the integration of mmWave connectivity and radar sensing systems in consumer vehicles brings additional cost- and space-related challenges. Here, the structure of interference when multiple vehicles engage in mmWave communications and sensing simultaneously is not fully understood as of yet [21]. Consequently, massive deployments of such equipment may challenge the reliability of both communications and sensing components. Motivated by the above, the research community is seeking for feasible solutions to address the said challenges. A promising direction in this regard is to enable joint mmWave communications and radar as we outline further on.

## V. Joint Vehicular Communications and Radar

### A. State-of-the-Art Approaches

The existing solutions for integrating communications and radar functions in vehicular setups typically belong to one of

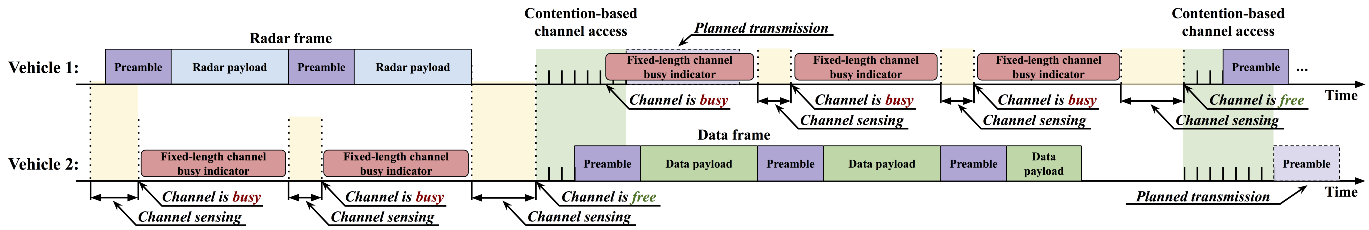



Fig. 5. Unified channel access for joint mmWave automotive radar sensing and communications.

the following:

- *Time-domain duplex (TDD).* TDD suggests uncoordinated operation of radar and telecom subsystems that share common equipment (e.g., a mmWave antenna array) [22]. These systems feature low implementation complexity but lack scalability, since uncoordinated radar and data transmissions from neighboring vehicles may cause interference.
- *Telecom Data over Radar Transmissions (ToR).* ToR systems modulate data signals inside the radar transmissions. This approach demonstrates better scalability than in the TDD cases but can operate only for a limited set of simpler modulation and coding schemes. Hence, spectrum utilization remains low [23].
- *Radar Sensing over Telecom Transmissions (RoT).* With this approach, the existing telecom preamble detection mechanisms are reused for the distance and velocity estimation of the surrounding objects (e.g., nearby vehicles). The RoT option is both flexible and efficient but remains vulnerable to interference and requires all of the vehicles in proximity to use the same type of radar sensing [24].

### B. Unified Automotive Radar Sensing and Communications

Recalling the strengths and the weaknesses of the aforementioned solutions, we further sketch unified channel access for mmWave-based automotive radar sensing and communications. Different from mmWave systems in open space (e.g., for hand-held or wearable devices) – where directional transmissions may lead to deafness – the reflections of the mmWave signal from the vehicle body often permit the cars to detect an active transmission and avoid interfering with it.

A possible approach is for the vehicle's radar sensing to receive assistance from the telecom module that performs contention-based access [25]. Here, one can follow the radar-aware carrier sense multiple access (RA-CSMA) scheme outlined in Fig. 5:

1) The telecom module reserves the channel by transmitting a preamble.
2) The subject vehicle may perform the actual sensing during the time that the channel has been reserved for.
3) When the channel reservation is over, the vehicle either continues occupying the channel by transmitting another preamble or releases it to other vehicles.

To implement this form of a carrier sense multiple access (CSMA)-based access procedure, additional preambles need

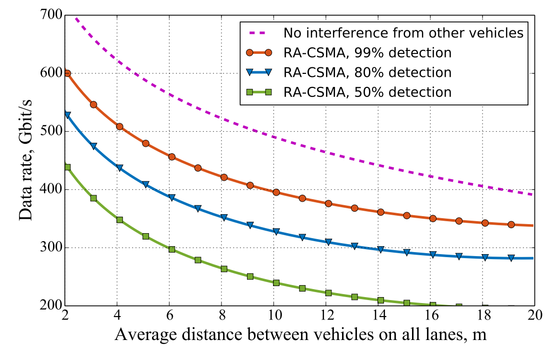



Fig. 6. Data rate with RA-CSMA.

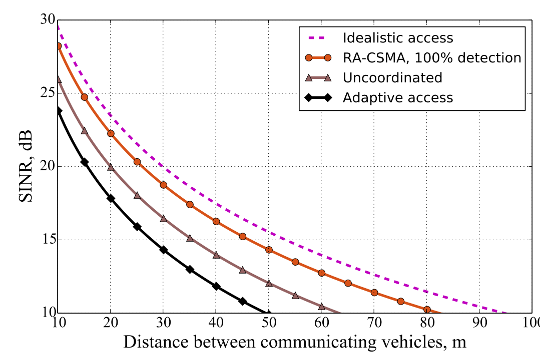



Fig. 7. Gains in average SINR with proposed solution.

to be introduced into the communications signaling. Hence, the neighboring vehicles are made able to continuously detect an active transmission (either data or radar) and postpone their transmissions until when the current transmission is over. These extra preambles add to the overhead and thus challenge the performance of the presented solution. To evaluate the latter in a typical setup (highway scenario with three lanes in each direction), we apply a combination of practical measurements, ray-based simulations, and mathematical modeling, as in [25].

We begin with Fig. 6 that studies the effects of preamble detection probability on the data rate of our system. The channel of 275–325 GHz with 50 GHz of bandwidth is considered. As observed in the figure, if the chances of detecting a preamble are high enough, the proposed solution allows for a notable increase in the average data rate. However, the performance of the system at hand degrades substantially if the preambles cannot be detected reliably.

We proceed with Fig. 7 that contrasts the described RA-CSMA approach (by assuming always reliable preamble detection) with alternative solutions, namely:

- *Idealistic access.* Perfect time synchronization and ideal time-division multiple access (TDMA). This scheme is an upper bound with no inter-vehicle interference.
- *Uncoordinated access.* ALOHA-based operation.
- *Adaptive access.* Random access without coordination between the vehicles. Each of them employs adaptive binary exponential backoff.

Fig. 7 assesses the average signal-to-interference-plus-noise ratio (SINR) for different separation distances between the communicating cars. We observe that the proposed approach offers substantial gains in the achievable SINR and the communications range (SINR $> 10\,\text{dB}$) as contrasted to the state-of-the-art solutions. Summarizing, the presented results imply that unified channel access for vehicular communications and radar sensing is a promising enabler for reliable and high-rate V2X systems.

## VI. Conclusions

Emerging V2X communications require tight integration into the cellular network architecture. Specifically, LTE and NR systems that support URLLC connectivity may assist and control high-rate vehicular communications more efficiently as compared to decentralized solutions. In this paper, we reviewed the evolution of cellular V2X communications starting from LTE Rel-14 to NR Rel-16 and beyond. We particularly highlighted that the work on V2X communications can be divided into two major clusters.

The first one relates to the support of basic V2X-specific features while maintaining the backward compatibility with past solutions, such as LTE Rel-14. The second cluster of work addresses the design of novel V2X connectivity mechanisms for future smart vehicles in Rel-16, Rel-17, and beyond. These solutions prepare to employ the full potential of sidelink features, mmWave band capacity, and direct vehicular interactions, but will not remain backward compatible with previous technology.

Recognizing common enablers between mmWave-based automotive radar sensing and vehicular communications, we further outline an approach for joint V2X communications and radar sensing. According to the respective RA-CSMA scheme, harmonized operation of the communications and radar subsystems reduces the chances of interference between the radar sensing and the V2X communications functions. We believe that this study facilitates the prospective utilization of intelligent connected vehicles.

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