5G for V2X Communications

Antonella Molinaro and Claudia Campolo

Abstract Connected and fully automated vehicles are expected to revolutionize transportation systems of the future on a global scale, significantly improving road safety and traffic efficiency, and fostering investments in the automotive market. This new landscape mandates a robust, flexible and business agile communication, networking and computing technology foundation, in which fifth generation (5G) systems and enablers will take the lion's share. By leveraging new-designed efficient air interfaces, a wide range of allocated frequencies, advanced transceivers, multiple radio access technologies, as well as cutting-edge network softwarization principles, 5G intends to guarantee ultra-low latency, ultra-high reliability, and high-data rate vehicle-to-everything (V2X) connectivity. This chapter will describe the *status quo* of V2X communications, by analyzing the main application requirements and the restless activities engaging the R&D community towards 5G-enabled V2X. Research challenges and opportunities, along with perspectives about system design and enablers for 5G-V2X communications will also be part of this chapter.

1 Introduction

The automotive vertical market is undergoing key technological transformations, with the focus of innovation shifting towards connected and fully automated (i.e., autonomous or driverless) vehicles. The potential of such transformation will be

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fully disclosed when independent autonomous vehicles will become connected and cooperate with one another, with roadside infrastructure elements, with pedestrians and other vulnerable road users (VRUs), and with the cloud through vehicle-to-everything (V2X) communications. V2X can create a vehicle's *collective* perception of the surrounding environment and help it making more informed decisions, based on exchanged local views and planned manoeuvres from nearby vehicles, instead of relying on local awareness built upon on-board sensors only (e.g., radar, LIDAR, cameras) like an autonomous vehicle would do.

Connected and fully automated vehicles will combine to bring about safer transportation aiming at zero fatalities on the road, improved traffic flow with the support of the roadside infrastructure, and consequent low environmental impact. However, the complexity of this landscape raises unprecedented challenges. V2X applications such as cooperative sensing and maneuvering, high-density platooning, tele-operated driving show hard-to-meet computing and communication demands, well beyond what the current radio access technologies are able to provide today. Ultra-low latency (below 10 ms), ultra-high reliability (near 100%) and high data rate (in the order of Gbps) communications are demanded by most V2X safety applications. In addition, the inherent dynamics in vehicular environments related to the rapidly changing network topology, the fast-varying wireless channel and possible intermittent connectivity, further increase the system design complexity and overall need an end-to-end comprehensive approach. An optimal end-to-end chain of applications and (edge/cloud) services, radio access and core network functionalities is required to tackle V2X demands and challenges and to maximise the benefits of future investments in the automotive market.

There is a general consensus among the stakeholders, as confirmed by a plenty of initiatives, about the role of 5G as the game changer to realize such a challenging vision. The Third Generation Partnership Project (3GPP), after releasing specifications for cellular V2X (C-V2X) in Release 14 and 15, is currently discussing further enhancements to the 5G architecture in Release 16 [2], in order to meet the most demanding V2X performance requirements. The 5G Automotive Association (5GAA) [5], formed in September 2016 by the major automobile manufacturers and telco players, promotes interoperable end-to-end 5G-based V2X connectivity. A similar intent is shared by the 5G Infrastructure Public Private Partnership (5G-PPP) [26], with projects underway that target such ambitious goals, such as 5GCAR [7] and 5GCARMEN [8]. Also governments around the world are supporting or even advocating connected and automated vehicles [19], [20].

In such a context, this chapter aims to provide an overview of the ongoing efforts in the race towards enabling V2X communications in 5G systems. Solutions for V2X use cases support will be analyzed from an evolutionary point of view, by first scanning early and current enabling technologies, and then investigating future opportunities offered by 5G solutions to the automotive vertical market.

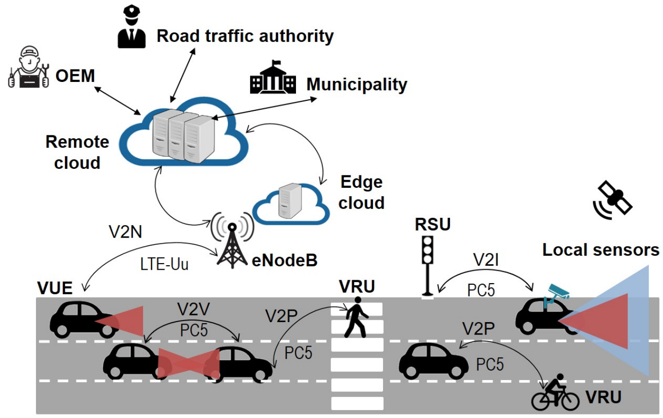

Fig. 1 V2X communication modes, interfaces and entities.

2 Status quo of V2X communications

2.1 Pre-5G radio access technologies

IEEE 802.11. IEEE 802.11, in particular its amendment *.11p* (ITS-G5 in Europe), has been investigated since nearly two decades as the enabling radio access technology for Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications. Its main attractive feature was the capability of supporting distributed localized interactions among vehicles even in the absence of a roadside infrastructure. Several worldwide field trials have demonstrated the .11p feasibility of supporting cooperative awareness applications (e.g., emergency brake light, stationary vehicle warning), and truck platooning [13]. Although .11p fits the requirements of such applications in low congested scenarios, it suffers from dramatic throughput degradation and poor performance at high density conditions, so it cannot match the very low latency and high-bandwidth requirements of future V2X applications. Such limitations are mainly due to a very basic physical layer and to the lack of a protection mechanism from interference and collisions – which is especially critical for broadcast communications under congestion – as ruled by the distributed Medium Access Control (MAC) operating with the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol [14]. The mandate and rulemaking for 802.11-equipped cars started by US government some years ago has been frozen recently in front of the appearance of the cellular technology as another candidate for V2X support.

3GPP Cellular V2X (C-V2X). The role of 3GPP and cellular networks for V2X has been steadily and rapidly growing, with C-V2X as part of the 3GPP Long Term Evolution (LTE) program, the first stage of specifications for Release 14 completed in June 2017, and a clear roadmap towards further refinements in Release 15 and enhanced capabilities expected for 5G in Release 16. The C-V2X rollout can be facilitated by the ubiquity of the cellular infrastructure, its centralized organization and mature industrial foundation. Furthermore, 3GPP inherits the results of decades of previous standardization works in other organizations that defined vehicular applications and messages [14].

In 3GPP documents, the term V2X collectively refers to communications among different entities, as illustrated in Fig. 1: *(i)* V2V for direct communication between vehicles in close proximity; *(ii)* V2I for communication between vehicles and a roadside unit (RSU) in radio range, which can be implemented either in an eNodeB or in a standalone device (e.g., a traffic light); *(iii)* Vehicle-to-Pedestrian (V2P) between vehicles and vulnerable road users (e.g., pedestrians, bikers); and *(iv)* Vehicle-to-Network (V2N) for communications with remote servers and cloud-based services reachable through the cellular infrastructure.

V2V communications, considered as the highest priority for 3GPP, required modifications in the radio access network [3]. Efforts resulted in the specifications of two communications modes, namely Mode 3 (scheduled) and Mode 4 (autonomous), supporting direct communications over the sidelink (PC5) interface. Communications on the PC5 interface use the 5.9 GHz band, independent or even in the absence of a cellular network, in order to ensure ultra-high availability under all geographies, regardless of the specific Mobile Network Operator (MNO). In Mode 3, operating only in-coverage of an eNodeB conditions, the allocation of radio resources is supervised by the network; whereas in Mode 4 pre-configured resources can be accessed by vehicles in an autonomous manner without the network control, both in- and out-of coverage of an eNodeB (e.g., in urban canyons, tunnels) [21]. Early results have demonstrated the superior performance of C-V2X Mode 4 w.r.t. IEEE 802.11p under many circumstances [21], [23].

V2N communications occur over the cellular LTE-Uu interface operating in the traditional licensed spectrum. Less disruptive although not negligible modifications have been applied to this interface in order to support both unicast and multicast communications.

Architectural enhancements have been also specified to support Vehicular User Equipments (VUEs) and to manage V2X communications [4]. Notably, this entailed adding the *V2X Control Function* module, which provides configuration parameters for VUEs located in and out-of-coverage of an eNodeB, and the *V2X Application Server* (V2X AS), responsible for the control and distribution of traffic, road and service information.

2.2 V2X applications and requirements

V2X applications cover a wide range of use cases, which can be clusterized based on their purpose and requirements [19]. The 5GAA has grouped V2X use cases in four categories: *Safety* aimed at reducing the frequency and severity of vehicle collisions; *Convenience* managing the vehicle health and offering services like diagnostics and software updates; *VRU* targeting safe interactions between vehicles and non-vehicle road users; *Advanced driving assistance* sharing similar objectives with the safety

Table 1 Requirements of V2X autonomous driving use cases [1].

Application	**Main communication mode**	**Payload (bytes)**	**Latency (ms)**	**Reliability (percentage)**	**Data rate (Mbps)**
Vehicles platooning	V2V, V2I	50-6500	10-20	90-99.999	0.012-65
Advanced driving	V2V, V2I	300-12000	3-100	90-99.999	0.096-53
Extended sensors	V2V, V2I, V2P	1600	3-100	90-99.999	10-1000
Remote driving	V2N	-	5	99.999	25 (Uplink); 1 (Downlink)

use cases, but treated separately for their close relationship with (semi-)autonomous vehicle operation. These last use cases exhibit the most demanding performance requirements and have especially catalyzed the interest of 3GPP, which further classified them into four groups, as summarized in Table 1 [1]. *Vehicles platooning* dynamically forming a group of vehicles travelling together at short inter-vehicle distances. *Advanced driving* enabling vehicles to share local sensor data and driving intentions with vehicles in proximity, thus coordinating trajectories and maneuvers. *Extended sensors* for exchanging raw/processed sensor data or live video among VUEs, RSUs, VRUs and V2X ASs. *Remote driving* allowing a remote driver or a cloud application to tele-operate a (private or public) vehicle; this is useful for those passengers who cannot drive themselves (e.g., impaired people) or when the vehicle is located in dangerous or uncomfortable environments (e.g., earthquake-affected regions, road construction work zones, snow ploughing areas).

The demands of such use cases can hardly be supported by current Radio Access Technologies (RATs), neither IEEE 802.11 variants nor LTE and C-V2X Releases 14 and 15. This observation motivated the R&D community to explore more performing solutions, entailing not only improvements of the air interface but a more comprehensive end-to-end approach as provided by 5G.

3 5G for V2X communications

5G systems span communication, networking and computing capabilities, both in the radio access network (RAN) and in the core network (CN) segments. In the following, the major V2X-related 5G areas of research and enhancement will be shortly presented, along with solutions falling in the artificial intelligence and security fields that complete the multidisciplinary 5G-V2X picture.

3.1 Radio access technologies and components

New Radio (NR). Besides further enhancing the PC5 and LTE-Uu interfaces, 3GPP has launched the NR standardization activity for the first phase 5G system in Release

15, and is ready to enhance C-V2X in several ways under the 5G NR Release 16. NR will encompass flexible numerologies and agile frame structure, high frequencies, new multiple access techniques that well answer the quest for high capacity, massive connectivity, ultra-low latency and high reliability of autonomous driving use cases.

- **Millimeter Wave** (mmWave) communications ensure a large bandwidth and high throughput, which can be particularly appealing for: *(i)* V2V communications between very close vehicles, e.g., to support cooperative sensing in a high-density platoon, and *(ii)* V2I communications for bulk data transfer (e.g., for object detection and recognition, real-time high-definition maps) to/from an RSU in a short time frame. The harsh propagation environment may however hamper such benefits. Challenges arise, for example, due to the overhead for the beam training under high mobility and the blockage effect by e.g., pedestrian bodies [15].
- **Non-Orthogonal Multiple Access** (NOMA) allows multiple users to share the same time/frequency resource by either power-domain or code-domain multiplexing. It provides V2X communications with a new dimension, namely interference cancellation, therefore improving spectrum efficiency and reducing latency in dense moving environments (e.g., 2000-4000 vehicles/km^2). Naively applying mature OMA-based resource allocation strategies to NOMA is insufficient, e.g., scheduling, power control, channel state information (CSI) signaling need to be rethought in depth [16].

Multi-RATs. 5G will be deployed as a mashup of existing and novel 3GPP (4G LTE, 5G NR) and non-3GPP (e.g., IEEE 802.11) RATs. In the V2X context, the usage of multiple RATs may boost V2I/V2N network throughput and capacity, make more efficient the behaviour of a technology (e.g., mmWave beamforming can be aided by 802.11 messages [15]), or provide redundant connectivity to improve performance of e.g., the remote driving use cases. The design of a 5G multi-RAT framework is still an open issue, which needs proper interfaces towards the application layer and advanced orchestration functionalities for harmonized traffic scheduling and flow management.

802.11 evolution. On a parallel research lane, probably awaken by the rapid C-V2X evolution, recently the IEEE 802.11 has started the Next Generation V2X study group. This group is considering mature physical layer technologies, such as Low Density Parity Check, Space-time block coding, to have an impact on the evolution of 802.11 for higher throughput V2X applications, better reliability/efficiency, and extended range [18].

Transceiver design. Advanced transceivers can be used on board, since vehicles are not limited by small form factors, processing and power consumption issues.

- **Antenna design**. 5G will rely on massive Multiple Input Multiple Output (MIMO), among other techniques, to improve system capacity. The high vehicle speed may however hamper massive MIMO operation due to outdated CSI. Multi-antenna algorithms need to be designed that are robust against imperfect CSI, as well as advanced receivers that take advantage of vehicle characteristics. Even though the form factor of vehicles accommodates a potentially high number of antennas, their integration in practice might entail new approaches for the vehicle architecture [26].

- **In-band Full Duplex (FD)**. It is another disruptive technology that improves the spectral efficiency, theoretically doubling the achievable throughput by simultaneous transmission and reception over the same frequency band. Research in this area has been pushed by recent advancements in self-interference cancellation (SIC) and/or mitigation techniques. The main barriers for the take-off of FD deployment are the harsh and fast time-varying V2X propagation environment that complicates SIC procedures, and the need to entirely revisit the MAC design. The potential of FD techniques has been disclosed for 802.11-based V2X communications in [11], but similar considerations may apply for 5G V2X communications.

Positioning. Satellite-based positioning systems are unable to provide sufficiently accurate position information – especially the relative positioning – to critical V2X applications (e.g., VRU detection, platooning, autonomous driving, self-parking) and in certain challenging but common environments like urban canyons and tunnels. Highly-accurate (sub-meter) positioning can be achieved by combining traditional satellite systems with on-board sensing and infrastructure-based wireless communication technologies (e.g., 802.11, LTE) and 5G radio-assisted techniques [27].

3.2 Network softwarization technologies

Network softwarization technologies have the potential of efficiently handling heterogeneous resources spanning network and cloud domains, and easily and flexibly deploying services, with significant CapEx and OpEx reduction.

Mobile Edge Computing (MEC). The mainstream and short-term impact of softwarization for V2X will be at the network edge, where cloud-like resources (i.e., computing and storage) can be accessed with a low-latency. The edge is close to where data are being generated (by on-board and roadside sensors and cameras), and they are also likely consumed after being processed by the vehicles themselves. The added value of MEC for V2X has been recently recognized by the 5GAA [6] and by the European Telecommunications Standards Institute (ETSI) [17]. MEC is particularly suited for building real-time situational awareness and high-definition local maps, achieved through real-time data analysis and fusion from multiple available sources (e.g., vehicles, RSUs). The V2X AS function can be hosted at the edge, in proximity to vehicles, so that multicast data dissemination as well as mobility management procedures can be orchestrated with a lower latency [12]. Compared to other vertical markets, the automotive domain adds a layer of complexity to the MEC design, in that it entails the migration of services from one edge server to another in response to vehicles' mobility. Vehicles can experience performance degradation and ongoing service interruption during the migration. Seamless service migration between edge servers is further challenged when occurring across different MNOs, e.g., in a case of a country border crossing.

Network slicing. Network slicing supports vertical markets with diverse requirements on top of the same physical infrastructure, through a flexible usage and configuration of network functions and parameters. This is viable by drawing on Software-defined Networking (SDN) and Network Function Virtualization (NFV). They, respectively, allow to properly steer network traffic with performance guarantees along virtualized network function instances customized for specific use cases. The potential of the network slicing concept for V2X has been early unleashed in [12] and further elaborated by 3GPP [2]. There, the need for a dedicated V2X slice has been argued due to the unique V2X use cases' features, by recognizing the poor fitting of reference slices for other traffic types, such as enhanced Mobile Broadband (eMBB), massive machine type communications (mMTC), ultra-reliable and ultra-low latency communications (URLLC). By flexibly orchestrating multi-access and edge-dominated 5G network infrastructures, dedicated network slices for V2X safety applications can be prioritized over other network traffic. Intra- and inter-MNO mobility entailing, respectively, quick slice resources reconfiguration and inter-operator slice orchestration highly challenge the design of V2X network slicing.

3.3 Data-driven solutions

With high-performance computing and storage facilities and multiple advanced sensors, vehicles as well as roadside infrastructure will produce, exchange, process and consume massive amounts of information-rich data used to make driving safer, more efficient and comfortable. New solutions are needed to facilitate the *analysis* and *distribution* of such data.

Machine learning (ML). As a major branch of artificial intelligence, ML develops efficient methods to analyze huge (big) amount of data by extracting information and knowledge which allow more informed and cognitive decisions. The role of ML in the V2X context will be manifold, with ML methods such as reinforcement learning, deep learning, deep reinforcement learning and unsupervised learning taking the main role. By means of ML vehicles can identify crucial data to be primarily exchanged for cooperative driving purposes with efficient network resources utilization; making ML-assisted decisions also improves radio resource management algorithms [25]. ML techniques can enhance autonomous driving operations in producing accurate models of the surrounding environment from the data generated by cooperative sensing, and in deriving effective manoeuvring strategies accordingly [24]. Applying existing ML methods to V2X raises challenges, which are mainly related to the distributed nature of data produced by multiple sources and the vehicular dynamics hard to be predicted. Theses issues pave the way to distributed learning methods. The decision about where to run ML algorithms (i.e., on board, at the edge, in the cloud) is also another open issue to be addressed.

Information-centric networking (ICN). V2X communications privilege the information content (e.g., accident notification; stationary vehicle warning; road works warning) rather than the identity of the communication endpoints. Notably, such identities are either not known in advance or they may change with time, e.g., the edge server on the other side of a V2N link may change when a vehicle moves. In addition, the same information can be of interest for multiple recipients on the road, so that V2X interactions will be dominated by one-to-many communications, which are notoriously poorly supported by IP-based solutions. ICN natively supports name-based data retrieval and dissemination, and multicast delivery, which perfectly fit the above mentioned V2X characteristics. Furthermore, in-network caching can cope with intermittent connectivity. These features make ICN a candidate solution for V2X data delivery [9]. Despite such potential and the fact that 3GPP is open to networking solutions that may replace and/or work alongside IP, the proper way ICN could be enclosed in the 5G networking still needs to be adequately investigated.

3.4 Security

The 5G-envisioned ubiquitous vehicle connectivity demands strong security and privacy mechanisms to prevent unauthorized access to vehicles and related personal data, and to avoid the malfunctioning of mission-critical applications and future automated driving systems and services [26]. The overhead introduced by the security features (e.g., certificate revocation), typically addressed at the application layer [2], should be reduced, and the timeliness of authentication management should be ensured by accounting for new security implications raising in V2X environments [22]. Recent works have investigated the role that the blockchain (BC) technology could have in a V2X environment. In [10], the decentralized validation architecture of BC, without a trusted third party authority, is used for fast validation of messages exchanged within a platoon by applying a consensus-rule. Last, new security threats could specifically arise with network slicing. V2X network slices with different security assurance requirements may coexist, aiming at ensuring adequate isolation between them and other reference slices [12].

4 Conclusions

In this chapter, we have analysed the technical issues and opportunities related to the V2X support in 5G systems. The analysis clearly shows that the automotive vertical highly challenges 5G entailing the synergies of many stakeholders to meet the stringent needs of V2X use cases. For the full take off of connected and automated vehicles, non-technical barriers must be also removed. They are related to legal and liability issues (who will be liable when a driverless car is involved in a collision? the car's occupants, the auto maker or the software company?); ethics (should an automated car decide for the driver on ethical questions of life and death?); the need to foster end-user acceptance (will we accept it when machines make mistakes, even if they make far fewer mistakes than humans?); and to build solid business models.

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