IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received July 12, 2021, accepted July 23, 2021, date of publication July 26, 2021, date of current version August 9, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3100472

On 5G-V2X Use Cases and Enabling Technologies: A Comprehensive Survey

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This work was supported in part by the National Program for the Urgent Aid and Reception of Scientists in Exile (PAUSE Program) through the Collège de France.

ABSTRACT 5G technologies promise faster connections, lower latency, higher reliability, more capacity and wider coverage. We are looking to rely on these technologies to achieve Vehicle-to-Everything (V2X) communications, which increase the safety and autonomy of vehicles in addition to road safety, saving energy and costs. The integration of vehicular communication systems and 5G is the subject of many research. Nowadays, researchers address challenges such as automated and intelligent networks, cloud and edge data processing, network management, virtualization, security, privacy and finally interoperability. This paper provides a survey of the latest V2X use cases including requirements, and various 5G enabling technologies under consideration for vehicular communications. Subsequently, we first provide an interesting mapping between the three 5G pillars and V2X use case groups. Then, we present a summary of potential applications of enabling technologies for V2X use case groups. Finally, the open directions of research are discussed, and the challenges that await to be met are pointed out.

INDEX TERMS 5G, V2X, 3GPP, use cases, resource management, NR SL, NFV, SDN, network slicing, C-RAN, NOMA, mmWave, full-duplex.

LIST OF ABBREVIATIONS

The next list describes several abbreviations that will be later used in the survey.

C-RAN	Cloud/Centralized Radio Access Network
CAM	Cooperative Awareness Message
CAPEX	CAPital EXpenses
CEPT	European Conference of Postal and Telecommunications Administrations
CLC	Cooperative Lane Change
CoCA	Cooperative Collision Avoidance
DENM	Decentralized Environmental Notification Message
ECU	Electronic Control Unit
eMBB	enhanced Mobile Broadband
EtrA	Emergency Trajectory Alignment
ETSI	European Telecommunications Standards Institute
FD	Full-Duplex
ITS	Intelligent Transport Systems
IVC	Inter-Vehicle Communications
KPI	Key Performance Indicator
LDM	Local Dynamic Map
LoA	Level of Automation
MANET	Mobile Ad Hoc Network
MEC	Mobile (or Multi-access) Edge Computing
mMTC	massive Machine Type Communications
mmWave	Millimeter Wave
MNO	Mobile Network Operator
MR-DC	Multi-Radio Dual Connectivity
NFV	Network Function Virtualization
NOMA	Non-Orthogonal Multiple Access
NR	New Radio, 5G radio access technology
OPEX	OPErating EXpenses

The associate editor coordinating the review of this manuscript and approving it for publication was Kashif Sharif.

PLMN	Public Land Mobile Network
SDN	Software Defined Networking
TTA	Telecommunications Technology Association
UE	User Equipment
URLLC	Ultra-Reliable and Low-Latency Communications
V2I	Vehicle-to-Infrastructure
V2N	Vehicle-to-Network
V2P	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VANET	Vehicular Ad Hoc Network

I. INTRODUCTION

Nowadays, advances in wireless communications allow information sharing through real time Vehicle-to-Pedestrian (V2P), Vehicle-to-Vehicle (V2V), vehicles-infrastructure (V2I) and over a cellular network (V2N) communications. V2X communications use cases can be mainly divided into safety, non-safety and infotainment services. Safety services aim to minimize accidents and risks to passengers and road users. Non-safety services are used by Intelligent Transport Systems (ITS) to improve traffic management in order to maximize the efficiency of the existing road network and minimize adverse impacts of traffic such as congestion and its subsequent impacts on economic productivity and environmental quality [1], [2]. Infotainment services provide a range of services to the users of the vehicle, including access to the Internet, comfort services, video streaming and content sharing.

Vehicular networks and ITS are interconnected and evolve in parallel. For example, as 5G is expected to play a prominent role in vehicular communications [3], the Cooperative-ITS (C-ITS) reference architecture promoted by the European Commission will be improved to meet the requirements of 5G technology and beyond [4], [5].

V2X communications are primarily enabled by two major radio access technologies (RATs), one based on Wi-Fi (IEEE 802.11p) and the other on cellular (C-V2X). Each RAT has its advantages and disadvantages, which is the subject of many research papers [6]–[9]. In this survey we are focusing on C-V2X and more specifically the New Radio (NR) V2X in Rel. 16.

5G is based on three main pillars: 1) enhanced Mobile Broadband (eMBB), 2) massive Machine Type Communications (mMTC), and 3) Ultra-Reliable and Low-Latency Communications (URLLC). Enabling URLLC is a cornerstone of advanced V2X applications. However eMBB and mMTC play also an important role in vehicular communications. At the radio level, 5G leverages three main strategies: harnessing more spectral resources, reusing resources, and improving spectral efficiency. For example, Full-Duplex (FD) plays a role in improving spectral density, flexibility and reliability of dynamic spectrum allocation, as well as enabling simultaneous transmission/reception.

The strategies mentioned above are further combined with many enabling technologies and algorithms at the 5G network level. For example, network performance and monitoring can be improved through Software Defined Networking (SDN), adaptive algorithms, and optimization strategies. As a complement to SDN, Network Function Virtualization (NFV) increases network functions flexibility and reduces costs. In addition, network automation can be increased using artificial intelligence. Through edge computing, the ability to process data and enhance latency is increased, while network slicing allows the division of one physical network into multiple virtual networks, which allows the exploitation of network resources and the service of different applications.

This survey was prepared with the purpose of studying the interaction between the V2X use cases presented in the technical reports by standardisation bodies/industry consortia, and the literature on 5G enabling. In order to show the value added by this survey and its position among the recent surveys related to vehicular communications, a summary of these surveys will be presented. In addition to a table summarizing the contributions of these surveys is added at the end of this section (see table 1).

In [7], the authors surveyed the latest developments in standardization for 802.11bd and NR V2X. They indicated the need for evolution both 802.11p and C-V2X (LTE) and discussed spectrum management issues. However, [7] did not discuss the enabling technologies, the advanced V2X use cases and requirements that prompted the development of RATs. In addition, no historical overview of the past work that brought vehicular communications to this point is provided.

The survey [8] provided a more comprehensive study in the context of the evolution of emerging technology towards the Internet of Vehicles (IoV), in particular Big Data-Driven and Cloud-Based IoV. It presented a view on the historical process of the evolution of V2X beginning with the release of DSRC. However, as in the previous survey, the work [8] presented a comparison between C-V2X and IEEE 802.11 V2X communications but did not cover the advanced V2X use cases.

The survey in [10] focuses on the interaction between IoV, 5G, and V2X. The authors presented the literature review on the evolution of 5G technology and its standards, on the infrastructure associated with V2X, the features and protocols of V2X, as well as possible applications of V2X. The survey lacks, however, a historical review of pre-5G projects and research, as well as a mapping between enabling technologies, V2X requirements and use cases.

Finally, a recent survey [11] reviewed current work and challenges on LTE and 5G to support V2X communications. The research presents several enabling technologies with challenges and solutions, LTE V2X architecture and operating scenarios, in addition to discussing open research issues and trends for 5G based vehicular communications. However, the work paid little attention to the historical context and previous research, nor did it discuss links between V2X use cases and potential enabling technologies in 5G. A summary of the contributions of previous surveys in comparison to this survey is presented in the table 1. The consideration is given to the study of V2X use cases and enabling technologies, as well as the historical review and past projects.

In this paper, we present an extensive survey on the 5G enabling technologies applied to vehicular communications. In addition, V2X use case groups are presented to form a broader understanding of the challenges and requirements. The major contributions of this paper are listed below.

- V2X use case groups are presented as well as their requirements. For this, we relied on the latest publications from normative organizations and literature.
- The 5G architecture and related emerging technologies that support vehicular communications are illustrated along with a summary of scientific research and what has been published in this field.
- Based on our analysis of the potential V2X communication requirements and current standards and literature, we discuss some open directions of research and point out some major challenges that need to be tackled.

The rest of the paper is organized as follows. In Section II, a historical review of vehicular communication is provided. In Section III, V2X communication types and use cases are introduced. In Section IV, the development of vehicular communications including 5G V2X communications is presented in detail. In Section V, recommendations for open direction of research are suggested. Finally, the conclusions are drawn in Section VI.

II. HISTORICAL REVIEW

The emergence of 5G-V2X comes as an extension of previous efforts to enable vehicular communications. Continuous development through projects and research has brought V2X to exploring use 5G technologies. In this section, a historical overview of the beginnings of vehicular communication and its development stages is provided. This review includes a sequence of the most important projects, activities, milestones, technologies, and standards. Most of the milestones in the history of vehicular networks originate from the US, Europe and Japan. Therefore, we paid special attention to activities and projects in these regions. This review outlines the path for the evolution of vehicular communications to reach 5G-based V2X and the identification of more advanced use cases over time.

We can trace back the history of work on communication projects between vehicles with the aim of increasing safety, reducing accidents and helping the driver to the 1970s with projects such as US's Electronic Route Guidance System (ERGS) and Japan's CACS [12]. The beginnings of studies on Inter-Vehicle Communications (IVC) go back to the early 1980s [13], which generally refers to communications between drivers or vehicles. Media such as infrared and radio waves (VHF, microwave, millimeter waves), and protocols based on ALOHA and CSMA were used. PROMETHEUS was one of the first IVC projects in Europe [14]. Whereas, the beginnings were in the US with the PATH project in 1986 and the National Automated Highway Systems Consortium (NAHSC) program in 1994. Later many projects (e.g., ASV 1 and 2, CHAUFFEUR I and II, FleetNet, CarTALK 2000, TELCO, IVI [12], [15]) were implemented all over the world. Fig. 1 provides a summary of IVC projects throughout history.

The term Vehicular Ad Hoc Network (VANET) was introduced in the early 2000s as an application of Mobile Ad Hoc Networks (MANETs) principles to the vehicular domain [12]. The terms VANET and IVC do not differ and are used interchangeably to refer to communications between vehicles with or without reliance on roadside infrastructure, although some have argued that IVC refers to direct V2V communications only [15]. During this period many projects were funded in the EU, Japan, the US, and other parts of the world (e.g., ASV 3, 4 and 5, SAFESPOT, PReVENT, COMeSafety, NoW, IVI) [12], [15].

As we note, as a start, multiple media were used as the basis for vehicular communications, such as laser, infrared, and radio waves of all kinds (Bluetooth, IEEE 802.11, GSM, GPS, GPRS, 3G) [12], [15]. Furthermore, many acronyms have been used to refer to vehicular communications that differ from each other either in the historical context, the technology used, the standard, or sometimes even depending on the country (vehicle telematics, DSRC, WAVE, VANET, IoV, 802.11p, ITS-G5, V2X). Currently, cellular (based on 3GPP-Release 16) and WiFi (based on IEEE 802.11p) have proved to be potential communication technologies enabling connected vehicles. However, this does not negate that all previous techniques or others (e.g., VLC, ZigBee, WiMAX, microwave, mmWave) are still a vehicular communication research area. To go further, when every vehicle connected to the Internet is considered as a node, this makes the Internet of Things (IoT) available in vehicles or what is called IoV (Internet of Vehicle). IoV is one of the most active areas of research which contains a combination of vehicular networks and IoT [16].

The work in the field of vehicular communication can be divided into research and industrial work, and work on regulation and standards. Several organizations and governmental bodies are concerned with issuing standards and regulation for vehicular communication (ASTM, IEEE, ETSI, SAE, 3GPP, ARIB, TTC, TTA, CCSA, ITU, 5GAA, 5G PPP, ITS America, ERTICO, ITS Asia-Pacific). 3GPP is working on standards and specifications for cellular-based V2X communications, while IEEE is working through the study group Next Generation V2X (NGV) on the issuance of the standard 802.11bd.

On the other hand, several government agencies, in cooperation with automakers, suppliers, consultants, and academic institutions, are working to facilitate research projects. In the US, the Department of Transportation (USDOT) and through both the National Highway Traffic Safety Administration (NHTSA) and Federal Highway Administration (FHWA) works with Crash Avoidance Metrics Partners (CAMP) on several research projects (e.g., Traffic Optimization

TABLE 1. Positioning of this work among the recent similar surveys in the context of the proposed contents.

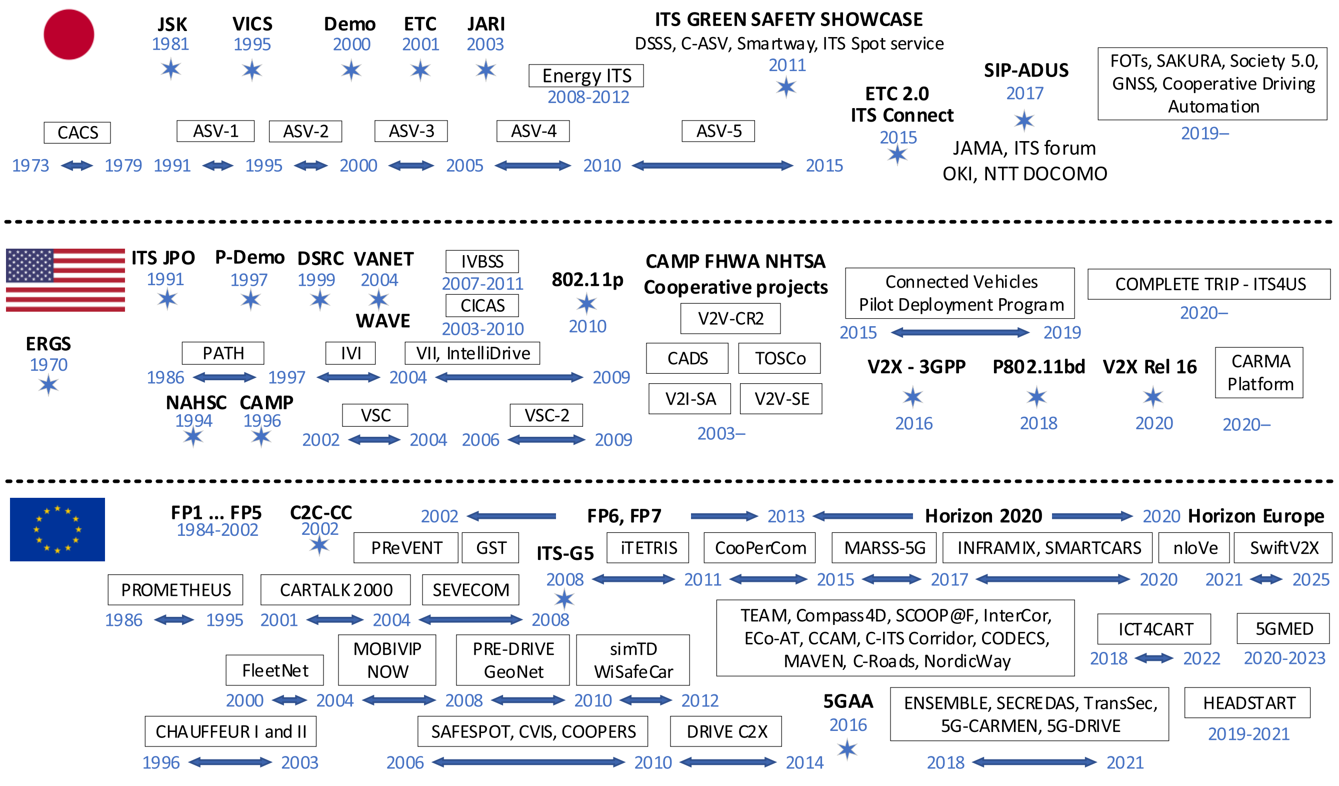
Survey	V2X use cases	Enabling technologies	Historical review	Year	Remarks
[7]	✗	✗	✗	2019	Standardization 802.11bd and NR V2X developments and challenges, with a brief reference to the requirements of advanced V2X use cases, enabling technologies for the physical layer and interfaces.
[8]	✗	Limited to IoV	✗	2020	Emerging technology advances towards big data and cloud based IoV. Comparison of C-V2X and IEEE 802.11 V2X. The advanced V2X use cases are mentioned briefly. The historical overview is shortened to the beginning of the DSRC.
[10]	✗	✗	✗	2020	Interaction between IoV, 5G, and V2X. 5G technology development and standards, and V2X-related infrastructure by IoV. No historical review of pre-5G projects and research, as well as enabling technologies, V2X requirements, and use cases.
[11]	✗	✓	✗	2021	Challenges for LTE and 5G to support V2X. Enabling technologies have been introduced with challenges and solutions, with greater emphasis on LTE V2X. Historical context or use cases are not discussed.
This survey	✓	✓	✓	2021	Interaction between use cases and enabling technologies. Researching 5G technology development, standards, and advanced V2X use cases. Historical overview includes vehicular communication projects since its inception in the 70's

for Signalized Corridors (TOSCo), Cooperative Automated Driving Systems (CADS), Vehicle-to-Infrastructure Safety Applications (V2I-SA), Vehicle-to-Vehicle Communications Research Phase 2 (V2V-CR2), Vehicle-to-Vehicle Systems Engineering (V2V-SE)). Many other initiatives are being developed with the support of the USDOT in order to accelerate the deployment of ITS, such as open source tools (CARMA^{SM}), standards, ITS data and open source code, and technical documents [17].

In Europe, the European Union through its programs (Framework Programmes FP1 to FP8) funds many V2X projects (e.g., 5G-DRIVE, MARSS-5G, C-ROADS, CODECS, MAVEN). An alliance named the Amsterdam Group that includes CEDR, ASECAP, POLIS and C2C-CC aims to facilitate the joint deployment of collaborative intelligent transport systems in Europe. The alliance collaborates with the infrastructure industry, road authorities, road operators, cities and regions to deploy V2X standard collaborative vehicles based on IEEE 802.11p (ETSI ITS G5, WLANp) [18]. Through the Horizon Europe program, which extends from 2021 to 2027, the European Union will continue to fund projects related to vehicular networks and ITS. Projects underway include SwiftV2X, 5GMED, BEYOND5, 5G IA and SECREDAS aiming to develop innovation at the intersection of the automotive and the mobile communications industries in order to support a fast and successful path towards safer and more efficient future driving.

In Japan, with the support of government programs, many services have been developed (VICS, ETC, Smartway, ITS Spot service) in addition to a series of projects and research (ASV, Energy ITS, ITS Green Safety). Research and development activities and the strengthening of cooperation between industry, academia and the government continue with the support of the Cross-ministerial Strategic Innovation Promotion Program (SIP) phase 1 and 2. Through SIP's Automated Driving for Universal Services (SIP-adus), the scope of automated driving will be expanded to include public roads, advancing the practical application of automated driving technology in the areas of logistics and transportation services [19]. Governmental entities together with industrialists (automobile manufacturers, telecommunications equipment manufacturers, telecommunications carriers, broadcasting companies) and universities have established the ITS Info-Communications Forum with the aim of research, development and standardization of communication systems for ITS, enhancing communication and coordination, and increasing the understanding of ITS among the general public [20].

A great interest from governments, relevant industry sectors and organizations in enabling vehicular communications is remarked. In the past couple of decades, this field has



✶ **Event (Demo/Foundation)** ⟷ **Project period**

5G-CARMEN	5G for Connected and Automated Road Mobility in the European UnioN
5G-DRIVE	5G HarmoniseD Research and TrIals for serVice Evolution between EU and China
5GMED	Sustainable 5G deployment model for future mobility in the Mediterranean Cross-Border Corridor
ASV	Advanced Safety Vehicle Program
C2C-CC	CAR 2 CAR Communication Consortium
CADS	Cooperative Automated Driving Systems
CAMP	Crash Avoidance Metrics Partners
CARTALK 2000	Safe and Comfortable Driving based upon inter-vehicle communication
CICAS	Cooperative Intersection Collision Avoidance System
CODECS	COoperative ITS DEployment Coordination Support
COOPERCOM	Cooperative Perception and Communication in vehicular technologies
COOPERS	Co-operative networks for intelligent road safety
CVIS	Co-operative Vehicle-Infrastructure Systems
DSRC	Dedicated Short Range Communications
ERGS	Electronic Route Guidance System
ENSEMBLE	ENabling SafE Multi-Brand pLatooning for Europe
ETC	Electronic Toll Collection
FP	Framework Programmes for Research and Technological Development
GEONET	Geoaddressing and Georouting for vehicular communications
GST	Global System for Telematics
HEADSTART	Harmonised European Solutions for Testing Automated Road Transport
ICT4CART	ICT Infrastructure for Connected and Automated Road Transport
ITETRIS	An Integrated Wireless and Traffic Platform for Real-Time Road Traffic Management Solutions
ITS JPO	Intelligent Transportation Systems - Joint Program Office
IVBSS	Integrated Vehicle-Based Safety Systems
IVI	Intelligent Vehicle Initiative
JAMA	Japan Automobile Manufacturers Association
JARI	Japan Automobile Research Institute
JSK	Association of Electronic Technology for Automobile Traffic & Driving
MARSS-5G	Modeling and Analysis of Random Spatial Systems for 5G Networks
MAVEN	Managing Automated Vehicles Enhances Network
MOBIVIP	Public vehicles for individual use for mobility in town/city centres
NAHSC	National Automated Highway System Consortium
NIOVE	A novel Adaptive Cybersecurity Framework for the Internet-of-Vehicles
NOW	Networks on Wheels
PATH	California Partners for Advanced Transit and Highways
P-DEMO	PATH-Demo
PREVENT	Preventive and active safety applications contribute to the road safety goals on European roads
PROMETHEUS	PROgraMme for a European Traffic of Highest Efficiency and Unprecedented Safety
SAFESPOT	Cooperative systems for road safety "Smart Vehicles on Smart Roads"
SECREDAS	Cyber Security for Cross Domain Reliable Dependable Automated Systems
SIMTD	Safe Intelligent Mobility Test Field Germany
SEVECOM	Secure vehicle communication
SIP-ADUS	Cross-ministerial Strategic Innovation Promotion Program-Automated Driving for Universal Services
SMARTCARS	Low Cost Advanced Driver Assistance Systems
SMARTWAY	Smartway Public Road test
SWIFTV2X	Smart mmWave and MultiRATs for Multihop Vehicle-to-Everything (V2X) Communications in Connected and Autonomous Vehicles
TEAM	Tomorrow's Elastic, Adaptive Mobility
TOSCO	Traffic Optimization for Signalized Corridors
TRANSSEC	Autonomous emergency manoeuvring and movement monitoring for road transport security
V2I-SA	V2I Safety Applications
V2V-CR	V2V Communications Research
V2V-SE	V2V Systems Engineering and Vehicle Integration Research for Deployment
VANET	ACM VANET Workshop
VICS	Vehicle Information and Communication System
VII	Vehicle Infrastructure integration
VSC	Vehicle Safety Communication Consortium
WISAFECAR	Wireless traffic Safety network between Cars

FIGURE 1. Overview of pioneering vehicular communication activities, milestones, enabling technologies, and standards.

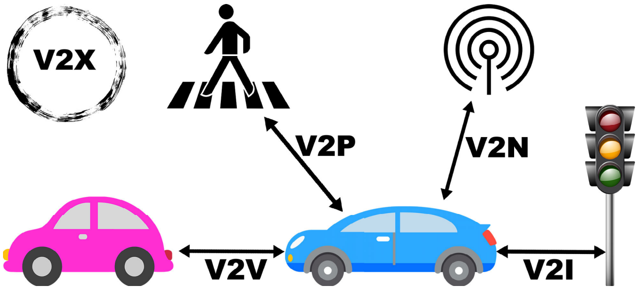


FIGURE 2. Types of V2X (V2V, V2P, V2N and V2I).

witnessed many developments, and the exploitation of 5G comes as a natural trend to meet the needs of this growing sector, especially as we enter the era of self-driving and connected vehicles.

III. V2X USE CASE GROUPS

In this section, V2X use case groups, challenges, and potential requirements are presented in detail. Fig. 2 shows V2X communications types [21]. V2X communications are generally bidirectional. V2V and V2P allow the exchange of information such as location, speed and direction to avoid accidents. V2I and V2N can include vehicle connectivity to traffic controllers or servers over 5G networks. Infrastructure like RSU can be used as a repeater to extend V2X connections. It is also worth noting that V2P User Equipment (UE) characteristics might not have the capabilities (capacity of battery, radio sensitivity) to send/receive messages with the same periodicity such as the UEs that support V2V communications.

Because of these diverse types of communications, the limited available communication resources, vehicle mobility, the varying importance of exchanged data, and the vast amount of data that can be exchanged by vehicles, there is a need to control the priorities of communications. The 5G operator should be able to control the relative priorities of different services such as regional or national regulatory services (Emergency, Public Safety), operator policies, safety-related and non-safety-related V2X application information [22].

According to [23], basic safety applications V2V/V2I need at least to allocate 20 MHz while the rest of the V2V/V2I/V2P applications need to allocate 30 MHz. The allocation of these ranges varies depending on the regions of the world and the authorities responsible for regulating it, such as ETSI and CEPT, IEEE in US and TTA in South Korea.

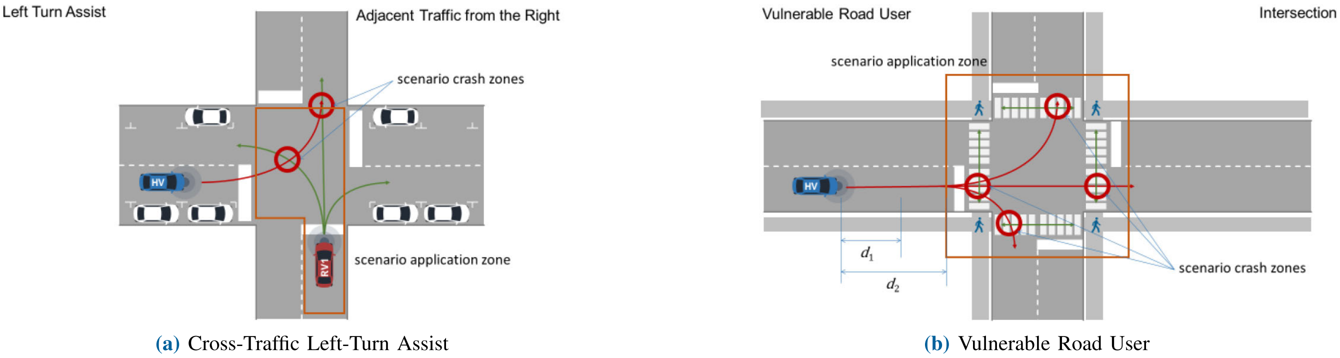
In order to frame and improve V2X operations, a variety of standardization organizations work to classify V2X services into groups, and each group includes several use cases [24]–[26]. The detail of each use case generally begins with a description and conditions in addition to several requirements that must be met. The diversity of organizations in addition to the different classifications within groups, environments or scenarios lead to diversity in use cases. Despite this diversity, the use cases eventually converge in terms of requirements and lead to the identification of vehicular communication needs, but from different perspectives.

The 5G Automotive Association (5GAA) offers a hierarchical model [24]. In the highest level, road environments are defined as the places where V2X use cases occur (intersections, urban and rural streets, high speed roads, parking, etc.). In the middle level, use cases including requirements according to specific status are presented. At the lowest level, scenarios or stories are defined as derived from use cases for different situations that may involve different specific requirements such as the situation of automatic and semi-automatic driving. 5GAA defines 12 use cases, but when considering scenarios or derivative stories, these sum-up to 30 different cases [24]. These use cases belong to one or more of the following classification groups: safety, vehicle operations management, convenience, autonomous driving, platooning, traffic efficiency and environmental friendliness, society and community. In [24], 5GAA provides a description and a detailed explanation of use cases, scenarios or stories derived from them, as well as the associated Service Level Requirements (SLR). SLR provides values (range, payload, latency, reliability, velocity, density, positioning, interoperability) that help developing solutions, creating test procedures, and assessing spectrum needs. Fig. 3 shows illustrative examples of two use cases defined by 5GAA. Fig. 3a illustrates the Cross-Traffic Left-Turn Assist use case, which is concerned with assisting the vehicle trying to turn left and warning it against vehicles approaching in the opposite direction, left or right. Fig. 3b illustrates the Vulnerable Road User use case, where the vehicle is alerted of an approaching vulnerable road user and warned of any collision risk.

The Fifth Generation Communication Automotive Research and innovation (5GCAR) in turn offers five classes of use cases: cooperative maneuver, cooperative perception, cooperative safety, autonomous navigation, and remote driving [25]. Within each of these classes, 5GCAR chooses a typical use case to represent it and identify the most pressing requirements and key performance indicators (KPIs).

In its latest technical report, the 3rd Generation Partnership Project (3GPP) identifies 25 use cases. These use cases are categorized into 4 main groups in addition to a general use case group and another for vehicle quality of services [26]. Likewise to use case stories or scenarios in [24], 3GPP defines several Level of Automation (LoA) for each use case, which creates different requirements for different automation levels (from 0 – No Automation to 5 – Full Automation). With regard to the use case groups in this survey, we mainly relied on what 3GPP reported for its comprehensiveness on the one hand (it unifies seven organizations that develop communication standards) and the novelty of its reports on the other hand (V2X scenarios Rel-16).

To better understand the challenges facing vehicular communications, we review the 4 use case groups defined by the 3GPP. While further information and requirements for all the use cases in the 4 groups are available in [26], [27]. In the next paragraphs, the end-to-end latency is the time



(a) Cross-Traffic Left-Turn Assist **(b)** Vulnerable Road User

FIGURE 3. **(a), (b) some examples of use cases defined in [24]. (a) illustrates the Cross-Traffic Left-Turn Assist use case. (b) illustrates the Vulnerable Road User use case.**

taken to transfer a certain piece of information from source to destination, which is measured at the application level, from the moment it is sent by the source to the moment it is received at the destination. While reliability (%) is the probability of transmitting X bytes during a given delay, which is the time it takes to deliver a small data packet from the radio protocol layer 2/3 SDU ingress point to the radio protocol layer 2/3 SDU egress point of the radio interface.

A. VEHICLE PLATOONING

According to [26], platooning supports the formation of a group of vehicles (i.e. platoon) that are interconnected in a virtual chain. Vehicles exchange information in the same platoon, resulting in shorter distances (between platoon members), fuel saving, and reducing the number of drivers. The *Vehicles Platooning* use case group includes a set of use cases that allows the dynamic formation of a unit of vehicles to travel together.

1) eV2X SUPPORT FOR VEHICLE PLATOONING

V2X must cover the following aspects.

- Join/Leave: vehicles exchange messages to form a platoon, to assign a platoon leader, and to allow a vehicle to join or leave the platoon.
- Announcement/Warning: the platoon exchanges messages with neighboring vehicles to announce, warn, and prevent any obstruction of the platoon's operation.
- Group communication: includes messages exchanged between the platoon's vehicles, such as taking a road, braking, acceleration, and replacement of the vehicle leading the platoon.

Fig. 4 provides an illustration of these three aspects.

Achieving this use case requires the support for at least 30 Cooperative Awareness Messages (CAM)/seconds. To prevent security threats, messages must be encrypted and an appropriate level of security must be achieved. Given the challenging situations in platooning: 1) the distance between vehicles can be as low as 1 meter, 2) the speed can be 100 km/h, 3) considering the round-trip-time, processing delay, the message transmission frequency up to 100 Hz, the system should support message sizes ranging of around 50-1200 bytes and a reliability of 90%. A detailed list of the requirements is available in [26], [27].

2) INFORMATION EXCHANGE WITHIN PLATOON

The information exchange within platoon can be divided into information exchanged between the platoon's vehicles via V2V (each vehicle has a unique label) and information received from the RSU to the platoon creator. The platoon creator (platoon manager), in turn, takes charge of sharing this information with platoon members as well as making real-time updates about the traffic data that platoon members have reported, and communicating it to the RSU via V2I. High-precision dynamic driving maps will be built based on the information that is shared within the platoon.

In this use case we are talking about supporting a maximum latency of 10 ms for V2V communications and of 500 ms with a variable payload of 50-1200 bytes for sending two V2X messages per second between a UE and a RSU over another UE.

3) AUTOMATED COOPERATIVE DRIVING FOR SHORT DISTANCE GROUPING

Cooperative driving plays an important role in ensuring a more efficient use of the road, reducing congestion, improving safety and fuel economy and reducing greenhouse gas emissions. A group of vehicles can connect automatically to enable lane changing, merging, passing between group vehicles, and inserting/removing a vehicle in the group. Cooperative Short Distance Grouping (CoSdG) indicates a scenario in which the distance between vehicles is very small, where the distance translated to time is about 0.3 seconds or shorter (6.7 meters at a speed of 80 km/h).

CoSdG is divided into two phases. The first one is a group of vehicles driven fully automatically by the system except the leading vehicle which is usually driven by a trained professional driver. In the second phase, all vehicles including the leader are fully automated by the system.

This makes the requirements for this use case different depending on the phase. Generally less than 5 ms latency

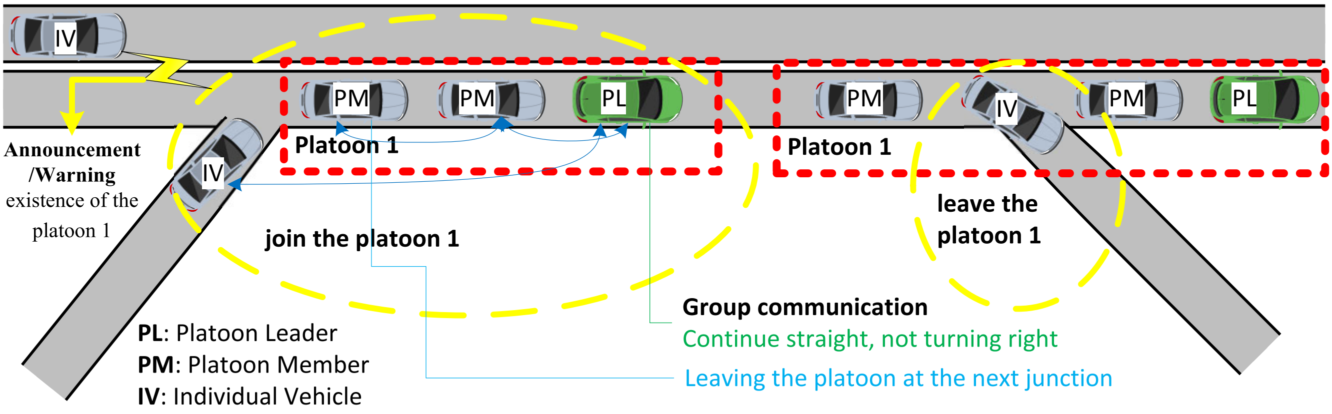


FIGURE 4. Vehicle platooning scenario shows the Join/Leave, Announcement/Warning and Group communication aspects.

should be supported for transport of messages between two UEs supporting V2V applications. For the first phase, latency no more than 25 ms must be supported for triggered and periodic transmission of data packets of 300-400 bytes with a target delivery reliability rate greater than 90%. While the second phase, less than 10 ms communication latency for transport of V2X messages between two UEs must be supported. Within a range of 80 meters, one data packet transmission of up to 1200 bytes per 25 ms with a target delivery reliability rate greater than 99.99% should be supported. Also, it is necessary to support a relative lateral position accuracy of 0.1 meters, a relative longitudinal position accuracy of less than 0.5 meters, and a high connection density for congested traffic around 3100 - 4300 cars per mile.

4) INFORMATION SHARING FOR LIMITED AUTOMATED PLATOONING

This case can be classified as an automated platooning at LoA 3, where a short distance between vehicles is assumed (2sec * vehicle speed) and it is sufficient to exchange the abstracted/coarse data. Sharing information is beneficial in cooperative perception and cooperative manoeuvre, where information about detected objects by local sensors and driving intention are shared.

These use case requirements include support for a data rate of 2.75 Mbps between UEs and a data rate of 2.5 Mbps between UE and RSU. In addition, this use case requires supporting the transmission of periodic broadcast/multicast messages with message payloads of 6500 bytes between two UEs and message payloads of 6000 bytes between UE and RSU. A maximum frequency of 50 messages per second per UE and a maximum application-layer end-to-end latency of 20 ms for transferring messages between two UEs directly or via an RSU should be supported.

5) INFORMATION SHARING FOR FULL AUTOMATED PLATOONING

As in the previous use case, this use case supports information sharing but with LoA 4 and 5 in addition to the need to exchange high-resolution data.

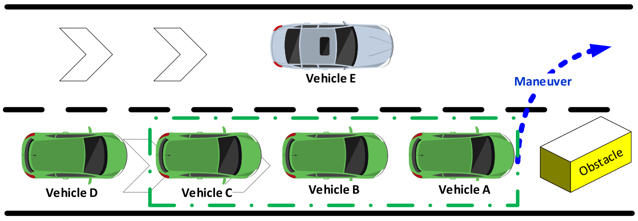


FIGURE 5. A scenario that requires changing driving-mode [26].

Regarding requirements, they are more stringent than those of the previous one. For example, a data rate of 65 Mbps between UEs and 50 Mbps between UE and RSU must be supported.

6) CHANGING DRIVING-MODE

Driving modes are classified into three types: autonomous driving, convoy, and platooning. The need to change the driving-mode lies in traffic scenarios that cause accidents if driving continues in platoon mode. Fig. 5 provides an illustration of a scenario that requires changing the driving-mode. Vehicle A is the leader of the platoon (A, B, and C), vehicle A detects an obstacle, and realizes that the vehicle E is near the platoon group. The expected vehicle collision between the platoon and vehicle E can be avoided by changing the driving-mode of the platoon (A, B, and C) to a separate autonomous driving. This use case requires reliable V2V communications between a UE and up to 19 other UEs.

After our review of the technical specifications regarding the Vehicle Platooning use case group in the 5G V2X services (Release 16) and despite its release in 2018 [26], this use case group has not received a noticeable attention in the literature. Below we review what was mentioned in the literature on the proposed techniques and solutions to meet the requirements of vehicle platooning. The work in [28] studies the platoon cooperation in the multi-lane cooperative platoon case, proposing a two-step strategy for forming a platoon and allocating resources. To maximize the size of the platoon and reduce the power consumption, an algorithm for allocating sub-channels and controlling power based on dynamic programming is designed. Reference [29] presents a design for a 5G-V2X prototype system based on cooperative autonomous driving developed using an experimental next-generation radio access network platform, cooperative driving platoon, and mobile edge computing server (MEC) providing dynamic 3D high-definition map service. In addition, the authors propose two AI algorithms in order to reduce CAPEX and OPEX and to solve complex optimization problems for 5G-V2X networks. The authors in [30] introduce the idea of cognitive network management and presents its benefits in ITS scenarios. The authors provide performance analysis for a platooning scenario and suggest increasing the network infrastructure orchestration by migrating services between RSUs. Depending on the Blockchain technology and in particular Ethereum, [31] proposes a dynamic autonomous vehicle platoon management that allows effective management of the Join/Leave aspect and guarantees the benefit of the platoon leader.

B. REMOTE DRIVING

This use case group aims to control vehicle driving remotely, whether by humans or cloud/edge computing applications. Remote driving is necessary in the event that an autonomous vehicle is not able to drive autonomously due to unexpected situations on the roads. Teleoperated Support (TeSo) enables a single human operator to remotely control autonomous vehicles for a short period of time. Remote driving can also be useful for driving vehicles operating in dangerous and harsh conditions or just so that the driver does not have to be physically present in the vehicle. Driving remotely with a person can be performed by providing video broadcasts and the ability to implement commands sent in real time. Thus, the person can perceive the surrounding environment as if he/she is in the vehicle. The need for computing will arise when replacing the human operator by programmed applications. With using computing, the ability to communicate with other vehicles will increase. We mention here the difference between self-driving using vehicle applications and remote driving that uses cloud or edge computing. Fig. 6 provides an illustration of this use case which includes an interface for remote driver or cloud/edge remote driving applications.

To support this use case group, for an absolute speed of up to 250 km/h, V2X communications must support data rate up to 1 Mbps at the downlink for vehicle reception of application related control and command messages and 25 Mbps at the uplink for video and sensors data sent from the vehicle. To avoid application malfunctions, ultra-high UL and DL reliability of (99.999 % or higher) should be supported by 3GPP system. While for fast vehicle control, feedback and safety related V2X application, 5 ms end-to-end latency between V2X application server and UE must be supported [26]. 3GPP-based LTE nor WAVE/ITS-G5 cannot meet such latency requirement [32].

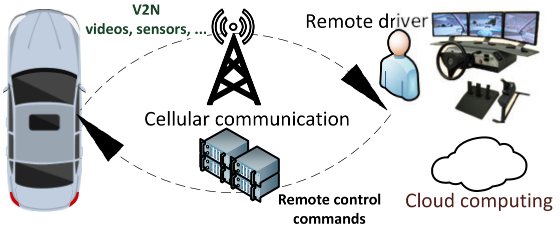


FIGURE 6. Remote driving general architecture.

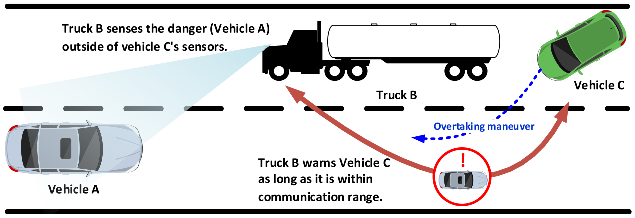


FIGURE 7. Collective Perception of Environment [26].

Ericsson's report [33] describes that developing remote driving capabilities is one of the prerequisites for introducing self-driving buses into the public transport system. Through experiments carried out by Scania in which a remote operator drives a bus around its test track, the report shows that the 5G proof-of-concept network is not the largest source of latency in the complete remote operating system. Additional factors causing the delay include servo mechanics, as well as video encoding and decoding. Although the network delay round trip time (RTT) mostly remained less than 50 ms during the study, the network latency improves significantly with 5G radio access, which reduces the network RTT to less than 4 ms. In a study on the feasibility of remote driving over 5G roadside networks, the authors in [34] recommend that remote driving in the initial phase should be limited for specific roads (the key routes with tailored network settings to provide, e.g., some specialised logistical services). Whereas, the provision of remote driving cannot be guaranteed over a wide network area especially in high load/interference conditions. Indeed, reliability requirement of 99.999% is not feasible in wide area, and situations in which remote driving fails must be identified, and effort must be focused on solving such situations locally [34].

C. EXTENDED SENSORS

This group includes three use cases: 1) Sensor and State Map Sharing (SSMS), 2) Collective Perception of Environment (CPE), and 3) Video data sharing for automated Driving (VaD). Extended Sensors use cases group enables the exchange of raw or processed data gathered through local sensors, live video images, RSUs, pedestrian devices, and V2X application servers. Vehicles can increase the awareness of their environment beyond what their sensors can detect as shown in Fig. 7.

SSMS is an extension of the Local Dynamic Map (LDM) in the reports and technical standards of ETSI and ISO [35], [36]. While SSMS has the advantage over LDM for its higher spatio-temporal fidelity, low latency and ability to transition from hyper-local to transportation link to network area of "state map" awareness. Disclosure in [37] provides a method of collective perception including receiving a local dynamic map, creating a local collective perception map based on the local dynamic map received, distributing the local collective perception map to at least one of the multiple ITS stations.

CPE enhances vehicle environment perception to avoid accidents by sharing real-time information (based on vehicle sensors information or sensor data from RSU) with the purpose of building an all-around view. This information sharing allows to increase the limited sensor horizon to detect objects and obstacles in areas invisible to local sensors, for example behind crests, curves, or objects behind corners of homes. The pre-processed sensor information is used to enhance the environment perception for a range of cooperative automated driving use cases (e.g., automated forward collision avoidance, overtaking and lane changing). While VaD can complement the role of CPE in some cases where previously processed data sharing is not sufficient. Sharing HD video data better supports drivers to make maneuvering decision according to their driving capability and safety preferences.

The performance requirements for the extended sensor group vary depending on the use case and LoA. The requirements can be summarized in a high data rate of 10-1000 Mbps, a latency from 3 ms to 1000 ms, at least 1600 payload byte, with a reliability ranging from 90% to 99.999% [26].

The authors in [38] provide an analytical model for analyzing the performance of LTE-V-based collective perception service. The study included the contribution of the service to the environmental perception of the vehicle, the detection redundancy, and the novelty of information for the objects perceived. LTE-V based service could significantly enhance all of the previously mentioned metrics, but further improvements may be needed to meet the latency requirements of vehicle safety applications such as cooperative Adaptive Cruise Control (c-ACC) and the Lane Change Assistance (LCA). The analysis also showed that the Decentralized Congestion Control (DCC) is necessary for some scenarios. While the authors in [39] believe that the intense exchange of sensor data with the increasing demand on the bandwidth will exacerbate the problem of increasing the load on radio channels in the future C-ITS use cases. Therefore, the authors present a collective perception service modeling in an environment with changing vehicular traffic and communication conditions. The study focuses on the Channel Busy Ratio (CBR) in Cooperative Awareness (CA) and Collective Perception (CP) scenarios. The simulation results show that the quality of the provided CP service degraded significantly when the two services (CA and CP) were used simultaneously on the same channel. The authors support deployment of multi-channel V2X solutions and suggest that data-intensive applications use distinct channels. As mentioned earlier in [38], it is imperative that each channel, if possible, have its own DCC.

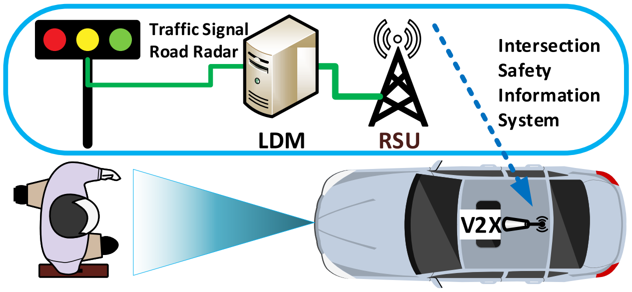


FIGURE 8. Concept of intersection safety information system [26].

D. ADVANCED DRIVING

Advanced driving enables high LoA to reach fully automated driving assuming longer inter-vehicle distance. Each vehicle and/or RSU shares data obtained from its local sensors with vehicles in proximity, thus allowing vehicles to coordinate their trajectories or maneuvers. In addition, each vehicle shares its driving intention with vehicles in proximity. The benefits of this use case group are safer traveling, collision avoidance, and improved traffic efficiency. This group includes 7 use cases.

- Cooperative Collision Avoidance (CoCA)
- Information sharing for limited automated driving
- Information sharing for full automated driving
- Emergency Trajectory Alignment (EtrA)
- Intersection Safety Information Provisioning for Urban Driving
- Cooperative lane change (CLC) of automated vehicles
- 3D video composition for V2X scenario

What distinguishes the advanced use case CoCA is that it is intended for connected automated vehicles. With 3GPP V2X communications, vehicles are enabled to better assess the likelihood of an accident and coordinate maneuvers. The usual CAM, DENM safety messages, data from the sensors and the action list such as braking and acceleration commands are exchanged, in addition to lateral control as well as longitudinal control between vehicles to coordinate the road traffic flow. In order to conduct a coordinated safe driving maneuver at intersections and exchange pre-planned routes between vehicles, [27] specifies requirements for a latency of less than 10ms, reliability higher than 99.99%, in addition to a throughput of 10 Mbps and a message size of up to 2 KB.

The difference between information sharing for limited and fully automated driving is LoA as defined in [40]. For limited automated driving (LoA 3 and LoA 2), coarse data exchange is sufficient and the driver is also expected to be in full control when the automatic driving system is no longer able to support the automation. As for fully automatic driving (LoA 5 and LoA 4), high-precision data exchange is required and the automated driving is expected to be available for control without human intervention. In both use cases it requires the sharing of the cooperative perception and cooperative maneuver aspects. These aspects vary according to LoA from sharing abstracted object information detected by local sensors to sharing high resolution perception data (e.g., camera, LIDAR, occupancy grid) and from coarse driving intention (e.g., changing lanes or moving/ stopping/ parking)/ to detailed planned trajectory among all involved vehicles via V2X for collaborative manoeuvre. The required data rate ranges from 0.5 to 50 Mbps per link for cooperative perception. 0.05 to 3 Mbps per link for collaborative maneuver. High reliability and low application-layer end-to-end latency (100 ms) is required. The minimum required communication range depends on the vehicle speed and can be calculated by multiplying the maximum relative speed m/s by 10 or 5 seconds in the case of limited or full automated driving, respectively [26].

To increase traffic safety, EtrA complements cooperative automated driving to assist the driver in dangerous and challenging driving situations and unpredictable road conditions (i.e., accident detection, pedestrians on the road, loss of goods, and deer crossing). When a vehicle from on-board sensors obtains information about obstacles on the road, it calculates the maneuverability to avoid an accident and informs other vehicles. Nearby vehicles begin to align trajectories to collaboratively perform emergency response. Required KPIs are less than 3 ms end-to-end latency, throughput of 30 Mbps, and 99.999% reliability within the 500 m communication range.

Fig. 8 shows the concept of intersection safety information system, which consists of road radar, traffic signal, LDM server, and RSU. We note the similarity to the 5GAA's use case in Fig. 3b, where a pedestrian is detected and the vehicle is warned or automatically controlled to avoid collision. A Local Dynamic Map server (LDM) receives vehicle location, movement information, pedestrian and traffic lights information to generate LDM information. RSU sends the LDM information by request or broadcasts it to UEs. This system allows to provide more accurate LDM for the automated vehicle to pass through the intersection safely and offers various services (i.e., pedestrian or vehicle alert warning, automated vehicle control by detecting pedestrian, vehicle, and traffic signal).

To ensure smooth CLC maneuvering, vehicles exchange their intended trajectories to coordinate their lateral (steering) and longitudinal (acceleration/deceleration) controls. Two sets of KPIs are supported to exchange CLC packets (the update trajectory plan for the lane change manoeuvre) between the involved vehicles. The first, the vehicle is semi-automated driving that requires a message size of 300-400 bytes, end-to-end latency of less than 25 ms, and reliability of 90%. The second: the fully automated vehicle requires a message (UE location, sensor data) size up to 12 Kbytes, end-to-end latency less than 25 ms, and 99.99% reliability.

The last use case within this group is the creation of a 3D video of the environment by a server in the cloud or at the edge (edge computing). The server receives videos about the environment from the UEs, and then processes and merges the data to build the 3D video. Location, relative speed, distance of vehicles, pedestrians, and any objects in that area are accurately represented within the video. This use case can be useful for analysis in various scenarios, such as sharing video with end users in a car race, assessing potential accidents by law enforcement, etc. To support 4K/UHD video, system must support uplink 10 Mbps data rate per UE. UEs should be able to calculate 50 absolute location fixes per second and the server must also be able to synchronize the different videos received from different UEs [26].

As a summary of the advanced driving KPIs, the 3GPP system should support a message payload ranging from 300 to 12000 bytes, 10 to 100 exchanged messages per second, end-to-end latency between 3 and 100 ms, and a reliability ranging from 90% to 99.999% [26].

The authors in [41] present system design and field testing to enable CoCA/EtrA for cooperative automated driving in a critical traffic scenario (emergency braking due to an unexpected obstacle such as a pedestrian). The study showed that ultra low latency allows for nearly simultaneous braking between two vehicles, allowing them to drive smaller distances between them. Delays also affect system performance more than packet delivery rates (PDR), when the delay increases to 100 ms and there is 90% PDR, a collision occurs between the two cars. In [41], several KPIs were measured (one-trip time, experienced user throughput, PDR, latencies and packet losses) but other KPIs were not evaluated (e.g., traffic volume density). In addition to field testing, [29] provides a design for a cooperative autonomous driving prototype system. The system consists of a NG-RAN experimental platform, a cooperative driving vehicle platoon and a MEC server that provides HD 3D dynamic mapping service. Field testing showed that the KPIs of the prototype system could meet the 5G-V2X QoS requirements in terms of low latency 3ms and high reliability 99.999%. While these results demonstrate that, to an extent, this field test system can provide services that meet 5G-V2X QoS data rate requirements. Field test results also prove that the 5G-V2X has a significant promotional effect on autonomous driving technology. But in order to meet the requirements of ultra-reliable, low latency, high traffic, and high mobility, a large investment of resources such as equipment and frequency is required. Therefore, two AI algorithms (based on deep-learning and swarm intelligence) are suggested as optimization tools to reduce CAPEX and OPEX during the commercial deployment of the 5G-V2X network. Besides these tools, the authors in [29] recommend the introduction of multi-hop technology and cognitive radio technology with the effect of expanding the range of V2V communications and increasing frequency resources. To address the requirements of cooperative automated driving, a kinematic information aided user-centric ultra-dense vehicular network architecture is proposed in [42]. In particular, a distributed local access and application center hosted at the MEC server are designed to acting both as application centers and user-centric access control centers. The results showed that the requirements regarding supportable vehicle density, data rate, reliability

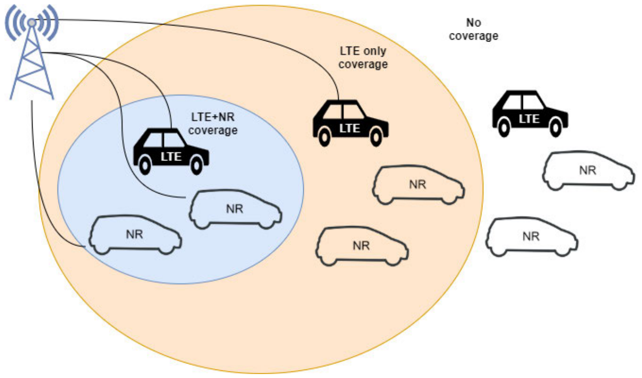


FIGURE 9. Scenario of different 3GPP RATs deployment.

and latency can be met at the same time, but with careful selection of key parameters. However, more works is needed regarding the proposed performance measurement strategy set. Practical algorithms must be developed and their performance evaluated in different scenarios, with realistic assumptions and constraints, and an examination of the effects of errors in kinematic states on the system's performance is vital.

A summary of the requirements for the previous groups is presented in table 2, where ranges in values is due to message size, practical use cases whose requirements differ within the same group, and the aspect LoA.

Table 3, lists the solutions, limitations, and future research of V2X use cases. The proposed solutions discussed above are summarized. The challenges, limitations mentioned in literature or future prospects for developing these solutions are listed.

In addition to the previous four groups, two other groups are defined in [26]. The first concerns general use cases, and the second includes the QoS aspect of each group. On of the general use cases is communication between vehicles of different 3GPP RATs and in different scenarios (no coverage, LTE coverage only, LTE/NR coverage), as the vehicle can be equipped with modules supporting either LTE or NR (see Fig. 9). If the V2X UE supports multiple RATs (including LTE and 5G NR), the best technology to support the given application of interest should be chosen. The selection for the best RAT is based on several factors including the number of V2X UEs using a given technology, the presence of RSUs, the information configured by the network (e.g., mapping between application ID and RAT), or QoS-related requirements. The use of multi-RAT to improve the V2X communication reliability is addressed in [43]–[45]. The authors in [43] evaluate different, independent and coordinated transmission schemes, where packets are transmitted through both the LTE-Uu and PC5 interfaces. While [44] introduces enabling efficient coexistence between DSRC and LTE. Reference [45] goes further by introducing an architecture and set of protocols for DSRC and C-V2X vehicular networks, addressing the problem of RAT selection, vertical handover, and data dissemination in a highway environment.

The general group also includes a use case related to the system's ability to support message transfer between UEs or between a UE and a UE-type RSU, regardless of whether or not they subscribe to the same PLMN. As for the use case outside the 5G coverage, the 3GPP system shall allow UEs supporting V2X application to use 5G RAT for direct communication when the UEs are not being serviced by a 5G cell. Another general use case is dynamic ride sharing where the vehicle shares information about itself such as current occupancy, available capacity, destination, estimated time of arrival, interstitial stops, etc. Pedestrians may share information about themselves such as destination, some personal information, credentials, etc. If the conditions expressed by both parties are met, then ride sharing can be arranged and started. In addition to ride sharing, the vehicle can provide network access to passengers, pedestrians, etc. The benefit for phone users lies in reducing battery consumption by lowering the transmission power in the phone and lowering the reception sensitivity. Increased throughput can be achieved by reducing the network overhead by aggregating many individual users in one context. Tethering via vehicle also benefits Mobile Network Operator (MNO) by increasing network densification associated with active users, and reducing network overhead due to grouping individual users into a single context [26]. The last use case relates to the Electronic Control Unit (ECU) software update. ECU needs regular updates including major security checks which is an important topic in the automotive industry. When the vehicle communicates with a nearby RSU and detects that an ECU software update is required, RSU will notify UE that the update is required. The user will be able to choose the required update from the list of updates for example. The user must also be able to reject/postpone the requested update to ECU.

IV. 5G V2X METHODOLOGY

Vehicular communications were originally designed based on Wi-Fi technology, namely IEEE 802.11p with Dedicated Short Range Communications (DSRC) in the 5.9 GHz band, to enable Vehicular Ad-Hoc Networks (VANETs). The terms Wireless Access in Vehicular Environments (WAVE) and ITS-G5 in the U.S. and Europe, respectively, refer to a set of accompanying standards for vehicular mobile wireless radio communications. Since these original developments, cellular-V2X (C-V2X) have also been proposed where C-V2X can operate both in the 5.9 GHz band as well as in the cellular licensed bands [7]. Both the DSRC and C-V2X are undergoing significant enhancements in order to support advanced vehicular applications, such as the ones assembled in the previously presented use cases, and that require high reliability, low latency, and high throughput. IEEE 802.11bd or next generation V2X (NGV) (based on WLAN technologies), in addition to 5G-V2X/NR-V2X are developed as solutions to fulfill these new needs of V2X communications [46]. According to the theoretical calculations in [46], NR-V2X outperforms IEEE 802.11bd. Nevertheless, the 802.11-based

TABLE 2. Performance requirements for use cases groups.

Group	End-to-end latency (ms)	Payload (Bytes)	Message/ Sec	Data rate (Mbps)	Min range (m)	Reliability (%)
Vehicle platooning	10-500	50-6500	2-50	50-65	80-350	90-99.99
Remote driving	5	-	-	UL: 25 DL: 1	-	99.999
Extended sensors	3-100	1600	10	10-1000	50-1000	90-99.999
Advanced driving	3-100	300-12000	10-100	10-53	360-700	90-99.999

V2X is the subject of extensive literature research and development [47]–[49].

Today, vehicles have a large number of sensors such as radar, ultrasonic, LiDAR, and camera. The limited range of WLAN-based V2X (less than 1 km) in addition to its limited throughput hinders the ability to fulfill the requirement of these advanced vehicular applications, while NR-V2X is based on technology designed for high-speed mobile applications and developed specially for V2X use cases. By using device-to-device and sidelink communication, NR-V2X supports direct communication between vehicles, infrastructure and pedestrians, even out of coverage. In addition, 5G-V2X supports device-to-network communication thus contributing to the expansion and diversification of V2X applications.

Below we capture the latest techniques and studies on how to support advanced V2X use cases in 5G networks. We will start with applications of 5G use cases in the field of vehicular communications, then we will present the strategies followed by researchers at the radio level to meet the requirements of V2X applications in a 5G context, and finally the techniques used to enable them.

A. 5G USE CASES APPLIED TO V2X

5G developments efforts are directed toward three main pillar types of services according to standardization organizations such as ITU and 3GPP. In this section we review these types of services and link them to V2X use cases as shown in Fig. 10.

1) eMBB

The eMBB is one of the first scenarios developed to deploy 5G NR, aiming to increase the data rate in data-driven use cases that require high data rates across the coverage area, and to ensure reliability with a packet error rate in the range of 10^{-3} [50]. This will allow access to services such as virtual reality, augmented reality and direct video transmission in UltraHD or 360 degrees while respecting the latency and reliability requirements [51].

The importance of eMBB for V2X applications comes from its ability to meet the needs of advanced V2X use cases with regard to high data rate requirements. By providing data rates of at least 10 Gbps for uplink and 20 Gbps for downlink channels, eMBB plays an essential role in various multimedia services (e.g., in-car video conferences/games, HD map downloading) [52].

In the context of eMBB use cases, [53] proposes a network slicing-based solution for the vehicles on the highway that have heterogeneous traffic requirements, focusing on the two slices of autonomous driving and infotainment that include safety messages and video streaming respectively. While [54] is discussing the RAN slicing problem to support eMBB and V2X slice on the same RAN base, a solution is proposed to improve splitting and using of resources between the two slices based on offline reinforcement learning (Q-learning and softmax decision-making) and a low-complexity heuristic method.

We note the importance of eMBB for V2X applications, especially given the high data rates requirements for the extended sensors group (see table 2) or sharing high-precision video as in the case of remote driving. eMBB even has non-safety applications such as infotainment and multimedia services.

2) URLLC

As with eMBB, URLLC is one of the use cases supported by 5G NR, as stated by 3GPP Rel. 15 and sequential improvements in Rel. 16. It is developed to meet the needs of latency sensitive applications. We talk about 1 ms latency or less, end-to-end security, small data packet loss of 10^{-5} and reliability of 99.999%. The usefulness of URLLC appears in practice when an external event occurs as a warning or alarm, so we need to send a small amount of data to a limited number of UEs without delay and with very high reliability [50]. URLLC transmissions are aperiodic, and are supported by scheduling (grant-based, grant-free/configured grant scheduling) to guarantee high reliability and efficient exploitation of resources. Sporadic communication requirements are met through predictability of available resources,

TABLE 3. Solutions, limitations and future research of V2X use cases.

Use Case Group	Solutions	Limitations and Future Research
Vehicle platooning	• Multi-lane cooperative platoon scenario, platoons move cooperatively, two-step strategy for forming a platoon and allocating resources based on branch and bound algorithm [28]. • Cooperative autonomous driving prototype system, AI algorithms to reduce CAPEX and OPEX [29]. • Machine learning-based cognitive network management, full architecture design, traffic and mobility data taken into account [30].	• Operating only under the support of network [28]. • More resources required (equipment and frequency). Introducing cognitive radio, multi-hop communication [29]. • More improved machine learning interactions are necessary with all managers to increase robustness, lack of implementation in real test-beds [30].
Remote driving	• Scania 5G proof-of-concept test network devoted to controlling a bus remotely [33]. • Remote driving test over three carriers using ray tracing software to calculate channel path loss [34].	• RTT network up to 50 ms, lower RTT promised with 5G arrival [33]. • In high load/interference conditions, remote driving or 99.999% reliability cannot be guaranteed over a wide area, situations where remote driving fails must be identified and solved locally [34].
Extended sensors	• Analyzing the performance of CP service, redundancy and the information freshness [38]. • Collective perception service modeling in an environment with changing vehicular traffic and communication conditions [39].	• Improvements needed to meet the latency requirements of safety applications like c-ACC and LCA with 5G arrival [38]. • Deploy of multi-channel V2X solutions. Data-intensive applications should use distinct channels. DCC is essential for some scenarios [39].
Advanced driving	• Combination of 5G-V2X, MEC, AI, and cooperative autonomous driving to meet 5G-V2X QoS requirements and reduce CAPEX and OPEX [29]. • System design and field-testing to enable CoCA and EtrA for cooperative automated driving [41]. • Distributed local access and application center hosted at MEC server, acting both as application centers and user-centric access control centers [42].	• Using permutation static methods and Markov chain framework to analyze the two AI tools theoretically [29]. • Not all KPIs are evaluated, important for platooning scenarios [41]. • More works needed regarding the proposed performance measurement strategy set. Developing practical algorithms and evaluating their performance in different scenarios [42].

diversity using multiple frequencies or spatial resources in addition to random access [50], [55].

Most of the V2X use cases can be considered as latency sensitive applications. With URLLC, high levels of automation, as in Connected Autonomous Vehicles (CAVs) applications, can be enabled. Returning to table 2, we note that use cases such as platooning, remote driving, advanced driving, and extended sensors all require low latency from soil of 1 ms and reliability of up to 99.999%. V2X applications can benefit from URLLC functionality but within the provided network coverage [56]. URLLC is an important topic in V2X research which is undergoing continuous development, in the literature research focuses on resource allocation, energy savings, and integration of URLLC with MEC to improve latency, throughput and computation-intensive processing [56]–[58].

3) mMTC

As in URLLC, mMTC communications are sporadic and data is transmitted randomly, but mMTC supports a huge number

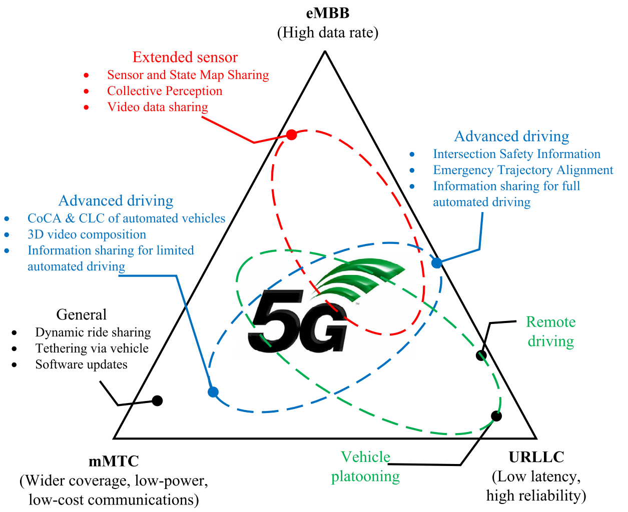


FIGURE 10. Mapping V2X use cases to the three pillars of 5G.

of connected machines/objects over a wider area for enabling low-power, low-cost, low complexity, and low transmission rate communications with a packet error rate of 10^{-1} [50], [59]. Since the number of active devices using a radio resource is variable, it is necessary to provide the available resources through random access. Narrowband IoT (NB-IoT) and enhanced MTC (eMTC) are specified by 3GPP to support long and medium range IoT applications respectively and can meet 5G mMTC needs [59].

Thanks to mMTC, vehicles will be able to constantly sense and learn environmental changes from built-in sensors deployed in cars or within infrastructure. mMTC plays an important role within a dense connected environment to support non-delay-sensitive V2X applications (e.g., dynamic ride sharing, software update) or even to provide more data for safety-related applications.

B. ENABLING STRATEGIES

The enabling technologies to achieve the above scenarios for vehicular communication are diverse but can be categorized into three main objectives or strategies. The first strategy is to exploit the new/underused spectrum, as is the case for the band around 5 GHz or the millimeter wave band. The second is the reuse of resources through the spatial densification of the network and its division into smaller cells as well as the use of resources in an efficient and intelligent manner. Finally, improving spectral efficiency, which includes advanced coding and modulation systems, multi-cell interference management, smart antenna, and multi-antenna systems.

1) SPECTRUM EXPLOITATION

Exploitation of new/underutilized spectrum is one of the most straightforward strategies. The under-utilized spectrum can be shared over different nodes within the same network. The allocation of new spectrum, such as the bands around 5 GHz and Millimeter Wave (mmWave) band, are strong candidates for the coming generation of mobile communication [60], [61]. The use of unlicensed and shared spectrum poses several challenges. Therefore, work is being done to develop several techniques for managing and accessing resources such as different RANs, RATs, and cognitive radio. However, the complexity produced by the algorithms of these methods is one of the drawbacks to consider. Reference [54] suggests an effective RAN slicing scheme based on off-line reinforcement learning and a low-complex heuristic algorithm to improve network performance in terms of resource use, latency, achievable data rate, and outage potential. The work in [62] proposes combining multiple RATs in parallel to ensure the various requirements of V2X use cases. The spectrum sharing problem for V2X communications in a heterogeneous network environment, and the coexistence problem of V2X users, VANET users, and other smart wireless devices over the unlicensed spectrum are studied in [63]–[65].

2) REUSE OF RESOURCES

Nowadays, the main way to achieve this goal is by intensifying the network. The spatial densification of cellular networks is achieved by dividing the coverage area into smaller and smaller cells [66]. This allows the system to reuse the frequency more, thereby increasing the network capacity per area. Thus, micro-cells, small-cells, pico-cells, and femto-cells will be widely deployed in 5G. However, network densification will result in additional costs.

3) IMPROVING SPECTRAL EFFICIENCY

This strategy is the preferred approach for both operators and researchers for affordability and reliability reasons. Many methods have been investigated in this area, like slicing strategy based on AI [54], combining multiple RATs in parallel [62], [64], and virtualisation the network [67]–[69]. However, in the past few years, these methods became very complex with current technologies, so AI algorithms are being involved to reduce complexity [67].

C. NR V2X INTERFACES

1) NR SIDELINK

The design of NR SL for V2X is a development to LTE SL, and based on the direct device-to-device communication. 3GPP in [70] categorizes the operation scenarios into Multi-Radio Dual Connectivity (MR-DC) and standalone scenarios based on the architecture of V2X SL communications as shown in Fig. 11. In the standalone scenarios, a Master Node (gNB, ng-eNB or eNB) is controlling/configuring a UE's V2X SL communication Fig. 11 (a). In MR-DC scenarios, the UE is configured in (NE-DC, NGEN-DC or EN-DC) while a UE's V2X SL communication is controlled/configured by Uu interface Fig. 11 (b).

V2X NR SL synchronization depends on SL primary synchronization signal (S-PSS), SL secondary synchronization signal (S-SSS), physical SL broadcast channel (PSBCH), and SL synchronization sources and procedures. The sources of

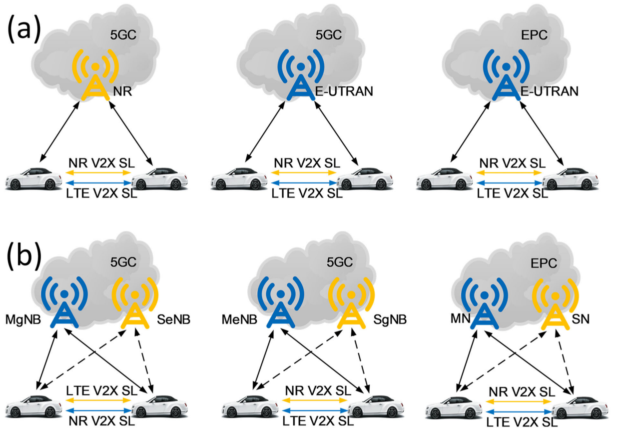


FIGURE 11. NR V2X operation scenarios. (a) V2X SL standalone scenarios, (b) V2X SL MR-DC scenarios [27].

synchronization (GNSS, gNB, eNB, and NR UE) are linked to a synchronization priority [71].

The authors in [71] propose two SL resource allocation modes. In the first one, the base station (BS) schedules the SL resources to be used by UEs for SL transmissions. While in mode 2, UE specifies SL transmission resources within SL resources configured by BS/network or pre-configured SL resources. NR SL allows V2X communication in different modes (RRC_CONNECTED, RRC_IDLE and RRC_INACTIVE). For idle and inactive modes, V2X SL communication is implemented using V2X-specific system information block (SIB) that includes cell-specific configurations [71].

2) NR Uu

The communication between UE and base station is provided by NR Uu or LTE Uu interface [72]. As we said in IV-C1, in addition to long range communication, the Uu interface is used to control and configure the resource for direct short range communication NR SL. The technique High-Reliable Low Latency Communication (HRLLC), based on shortened Transmission Time Interval (sTTI) frame, is used in LTE Rel-15 to enable 32 bytes packet transmission within 1 ms latency and with 10^{-5} block error ratio. In Rel-15 and Rel-16, the feature NR Ultra-Reliable Low Latency Communication (URLLC) is introduced as one of the improvements to Uu interface. Within a cell and for a specific bandwidth part, multiple active UL configured grants can be supported by NR, but UE uses just one to transmit at once. Multimedia broadcast single frequency network (MBSFN) and single-cell point-to-multipoint (SC-PTM) are two technologies previously defined in LTE for Uu-based multicast/broadcast. NR Uu multicast/broadcast is expected to be standardized in in Rel-17 that will enhance the resource utilization for some use cases scenarios.

D. ENABLING TECHNOLOGIES

Below we review the most important technologies and their applications in the field of vehicular communications. These technologies often overlap or use other techniques to meet the needs of V2X communications. For each enabling technology, a brief definition of the technology, a technical discussion of how the technology addresses V2X requirements, and relevant studies in the literature are provided. Fig. 12 presents a high-level architecture covering these technologies. In the following paragraphs, this architecture is analyzed through technical discussion and review of applications in the literature.

1) NFV

NFV is a concept appeared in October 2012, virtualization technology is used to introduce a new form of network services with the aim of facilitating the network design and reducing the costs (i.e., CAPEX and OPEX). The main point of NFV is the separation between the physical network devices and their functions [73].

3GPP, ETSI and 5G PPP make unremitting efforts to provide vision and technical specifications to improve the management and deployment of 5G depending on NFV. This later plays a fundamental role in enabling network slicing, Cloud Radio Access Network (C-RAN), mobile edge computing, multi-domain and multi-provider orchestration, and network programmability [68], [74], [75].

The terms VNF and NFV are sometimes used interchangeably. With reference to NFV Releases published by ETSI [76], a distinction can be made between the two acronyms, although they have related meanings. Whereas VNF refers to the implementation of a network function using a program separate from the underlying hardware, NFV refers to a more comprehensive meaning of operating software-defined network functions, regardless of any specific hardware platform. In other words, VNF can be described as a component of the NFV framework in addition to other components such as NFV Infrastructure (NFVI), and Network Functions Virtualization Management and Orchestration (NFV-MANO) architectural framework.

NFV can be used to enable intelligent onboard system (IOS) by simulating services such as software applications that can be implemented on computing platforms [69]. The closed architecture of the current IOSs with associated hardware/software, of different car brands, makes the mission of developing IOS complex and expensive. A research [77] takes advantage of NFV in V2X and has developed a new packet classification algorithm. The method resolves the overflow of the OpenFlow switches due to excessive policy rules, as networks suffer from long packet delay and frequent packet losses thus fail to support V2X services. To alleviate traffic congestion and jams, the authors in [78] present an approach that takes advantage of NFV and MEC technologies, where they use NFV to emulate cellular base stations with virtual machines (VMs). The work has demonstrated the utility of the method through a realistic emergency use case. To address the problem of network congestion and scheduling vehicular network resources, In [79], an intelligent NFVs selection strategy is proposed. To satisfy the

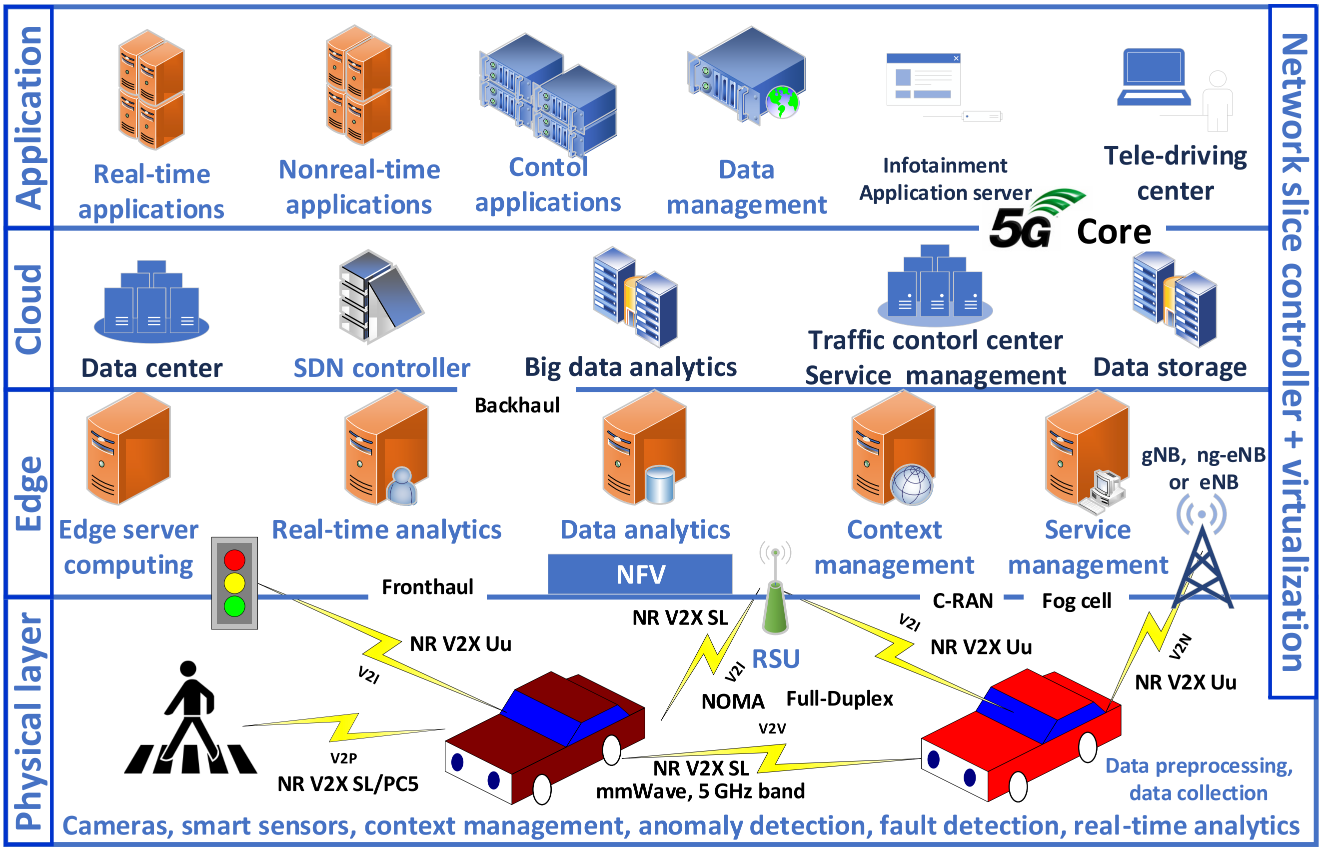


FIGURE 12. Hierarchical 5G V2X high-level architecture.

quality requirements of different vehicular services, the strategy relies on the method of traffic identification. This method, in turn, uses deep neural network and multi-grained cascade forest to classify different service behaviors. Whereas, the authors in [80] deal with resource allocation at the physical layer for NFV deployment. Since the resources of the physical layer are limited especially to support URLLC communications, as well as the various requirements of NFV nodes, there is a need for robust and efficient resource allocation algorithms. The study [80] presented a modified shuffled frog-leaping algorithm based on improved extremal optimization to design the resource allocation algorithms.

NFV, SDN and network slicing are interconnected technologies that form an architecture that allows the control and management of a highly dynamic network such as V2X, supporting both resource allocation and handover management.

2) SDN

SDN is a method to manage networks without knowing the details in the lower layers. It makes the network programmable, open and dynamic by centralizing network intelligence and separating the control plane from the data plane [81], [82].

SDN and NFV can be considered as solutions to V2X communication requirements, overcoming the limitations of traditional network architecture particularly in the use cases of advanced driving, platooning, remote driving and extended sensors. SDN can be exploited throughout the network from mobile backhaul access to the Evolved Packet Core (EPC), allowing utilization of the flow-based SDN model, granular policy management, NFV, and traffic routing capabilities. Essentially, solutions based on 5G and SDN will allow the provision of resources and knowledge of the surrounding environment of vehicles according to the requirements of vehicular communication. More technically, the SDN controller will dynamically create policies and rules according to V2X requirements and share them with RSUs. RSUs send the collected data to data centers through SDN controllers. In other words, support for SDN protocols allows RSUs, vehicles, and cellular networks to be considered as data-level SDNs. This allows the SDN controller to continuously update the network topology and periodically broadcast the beacon message to let the vehicles know the surrounding environment (information about traffic data, road map, location, speed and sensor data). The critical point here is to respect the latency requirements of vehicular communications due to the high cost of cellular networks for transferring control events. Therefore, methods for controlling and reducing latency of control plane are active topics in the literature regarding SDN implementations in V2X [83]–[85].

Advanced V2X use cases have created the need for technologies such as NFV and MEC. This is because the traditional approach of deploying a few large data centers to provide cloud services can lead to critical problems. For example, the centralized SDN controller approach can lead to control plane congestion on the one hand and to indefinite latencies for policy updates and flow table management on the other. These latencies can be intolerable for many V2X use cases. The flexibility offered by SDN introduces at the same time limitations on flow table capacity and switch/controller overhead, which requires finding solutions to improve the efficiency of flow table management. Fuzzy theory and machine learning techniques can be used to address these issues and select recurring flow entries that should be saved in the flow table. The authors of [86] present an overview of efforts that have been made to ensure a stable SDN performance. Specifically, they presented solutions to improve controller processing load, mitigate malicious attacks, and improve the efficiency of flow table management. The centralized structure of SDN faces significant constraints such as scalability and network partitions, prompting efforts on how to apply decentralization in managing multiple clusters. In [87], the authors present an overview of the decentralized SDN control plane for a distributed edge infrastructure. Infrastructure-as-a-service (IaaS) networking services were analyzed in the context of this distributed architecture managed by multiple virtual infrastructure managers. However, the distributed architecture also presents its own challenges that need to be addressed in terms of network information (granularity, scope, and availability of information) and in terms of technology related to cross-site networking services (automated interfaces and networking technologies).

SDN can be used with other technologies to support vehicular communications, [88] offers an architecture that combines SDN and fog computing as a potential solution to enhance connectivity, scalability, flexibility, and centralize intelligence in vehicular networks. But according to [89], SDN did not meet the delay requirements for vehicular networks, so a new SDN architecture has been proposed to prioritize delay requirements. Reference [90] proposes a vehicular network architecture integrated with 5G SDN using fog cells at the edge to improve coverage and avoid frequent handover between vehicles and RSU. While [91] goes further and introduces a SDN-based approach to detect driver alertness by developing the safety-oriented vehicular controller area network. Most of the research relied on theory or simulation results, but the authors in [92] proposed designing a complete prototype of SDN vehicular network, where the SDN-based backbone was tested in real hardware consisting of OpenFlow switches, and the SDN-based wireless access was tested based on WiFi access points. Which supports Click Modular Router and OpenvSwitch/OpenFlow. Reference [67] proposes an efficient network slicing management and a resource allocation SDN-Based vehicular network framework in addition to enabling machine learning to meet the complex requirements of modern vehicular network infrastructure.

As mentioned in IV-D1, both SDN and NFV are promising technologies for V2X communications, since these technologies are able to reduce network load, thereby reducing latency and improving reliability.

3) MEC

The increasing use of computer applications in vehicular environments necessitates meeting the computational requirements of these applications. Possible solutions to meet these requirements are either by upgrading the on-board computers or by cloud computing that provides central servers connected to the network. These solutions already have problems, whether with the high cost of upgrading on-board computers or the long latency and unstable connections of conventional centralized cloud computing in vehicular environments. Thus, by bringing computing and data storage closer to vehicles, MEC is the most suitable solution to enhance data processing and computational power with latency that is suited to the vehicular environment [93].

ETSI's Industry Specification Group (ISG) is working on the MEC initiative. Specifically, the ISG is working to define the elements required to enable application hosting in a multi-vendor, multi-access edge computing environment. In addition, the MEC ISG is working to develop standard specifications to unify the world of cloud communications, as well as the provision of computing and cloud computing capabilities within the RAN. The project [94] aims to define what V2X applications require from MEC. The challenges faced by MEC in supporting V2X are discussed, and potential requirements and emerging challenges are identified. Work item [95] aims to define the necessary API with the data model and data format. The same document also focuses on MEC V2X information service to facilitate V2X interoperability in a multi-vendor, multi-network, and multi-access environment. ETSI also provides a framework for use by the ETSI ISG MEC to coordinate and enhance multi-vendor Proof of Concept (PoC) projects that illustrate key aspects of MEC technology. In order to control mobile network congestion, the Proof-of-Concept (PoC) 11 project focuses on how to coordinate and prioritize network traffic sent to vehicles using MEC services [96].

MEC allows to enable many computationally-intensive applications that may be useful in vehicular environments (driver and passenger assistance applications) such as augmented reality, speech recognition and natural language processing. 5G, through the NR V2X interfaces referred to in IV-C1 and IV-C2, enables significant improvements in MEC communication quality. MEC is sometimes referred to in the vehicular environment by the term Vehicular Edge Computing (VEC) and is an active research topic that includes areas from autonomous vehicles, to offloading and intelligent offloading AI-assisted, security and privacy challenges etc [97]–[101].

As previously shown in the use cases for remote driving through MEC application or for creating a 3D video of the environment by a server in the cloud or on the edge in III-B and III-D respectively, MEC has direct applications in the vehicular environments. To meet 5G-V2X QoS requirements in terms of low latency and high reliability, [29] introduces a NG-RAN experimental platform, a cooperative driving vehicle platoon and a MEC server that provides HD 3D dynamic mapping service. In addition, in [42], a functional entity or so-called Local Access & Application Center is hosted on a MEC server to take responsibility for both application implementation and access control. While [58] introduced a collaborative MEC network architecture that supports V2X cellular networks, allowing vehicles to offload their tasks to MEC servers, and distributed MEC servers can collaborate with each other.

MEC has also been exploited with other enabling technologies to meet vehicular communication requirements. Reference [90] uses 5G in edge and fog, by building the fog cell structure at the edge of 5G software defined vehicular networks, which allowed to avoid frequent handover between RSU and vehicles, and to adopt an adaptive bandwidth allocation scheme for vehicles in fog cells. Another enabling technology that MEC has exploited with is 5G C-RAN, [102] proposes a hybrid strategy of MEC and C-RAN to reduce the computational efforts of the integer programming model when edge computing resources are located in physical nodes.

MEC, in collaboration with support technologies such as SDN and NFV, aims to meet the requirements of V2X communications in terms of responsiveness, reliability and flexibility. Despite MEC's promises of providing the required response time and computational capabilities, the aspect of security and maintaining privacy is an important challenge.

4) 5G NETWORK SLICING

Network slicing allows for splitting a single physical network into multiple virtual networks, this is accomplished by SDN and NFV that enable the implementation of open, programmable, application aware, flexible and scalable network slices [103].

In terms of vehicular networks, the solutions are still limited due to the heterogeneous traffic and the complexity of network in addition to the mobility and the dynamic density of vehicles.

Thus, [104] proposes a new method to integrate network slicing with fog radio access network to improve resource utilization. The slice scheduling proposed is based on Cross-Entropy Method and Monte Carlo Tree Search-Rapid Action Value Estimation algorithm. Slicing of network resource by itself is not enough to meet URLLC requirements of vehicular networks, [105] adds service and function slicing to the network slicing solution, thereby improving reliability and latency to support URLLC in 5G vehicular networks. While [106] discusses the problem of network slicing with multi-dimensional heterogeneous resources as part of their proposal for an air-ground integrated vehicular network architecture, and provides three differentiated services, i.e., high definition map for navigation slice, file of common interest slice and on-demand transmission slice. The optimization of network resource allocation ends with complex non-convex and nonlinear mathematical programming formulas. Therefore, a recent research, presents a model-free approach to network slicing using MEC and deep reinforcement learning to enable better utilization of channel resources. The channel, power allocation, slice selection, and vehicles grouping were taken into consideration [107]. Fig. 13 provides a simple illustration of the concept of slicing in V2X networks and their association with SDN and NFV.

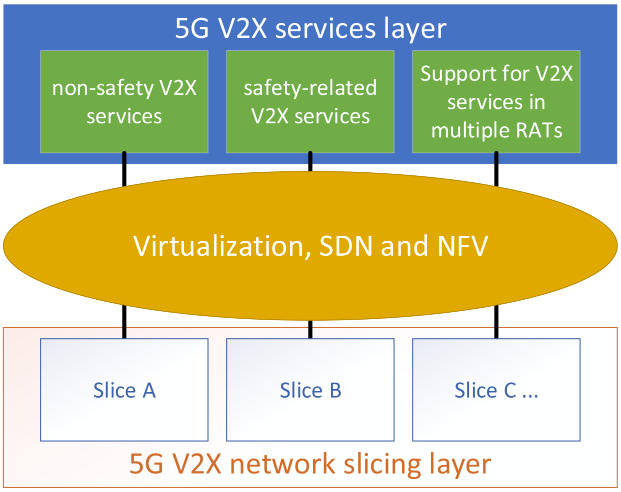


FIGURE 13. 5G V2X network slicing.

Through SDN-controlled network slicing technology in association with NFV, a common physical infrastructure can be divided into multiple logical networks, e.g., a self-driving slice, an infotainment slice, and a remotely operated driving slice.

5) C-RAN

C-RAN helps to minimize CAPEX and OPEX for the equipment of mobile operators by making the radio access networks architecture based on cloud computing. Data processing functions are grouped into a central server by separating the Baseband Unit (BBU) and Remote Radio Unit (RRU) from the mobile base station radio unit; allowing multiple radio units to be controlled from one server, improving network efficiency, as well as reducing interference in high-density areas [81]. C-RAN can be a central controller with access to communication channels for dynamically creating and managing the association process between TPs and peripheral device to create a Virtual Cell that moves with and always surrounds the user [108].

C-RAN is a supportive technology for V2X use cases. By separating the BBU and RRU from the base station, the BBU is centralized into a shared resource pool for heavy computations using virtualization from the cloud. Since V2X applications are highly latency sensitive with a need to share large amounts of data, pooled resources make it easier to deploy services at the edge, improving latency, optimizing resource usage, and reducing data transmission pressure. In addition, C-RAN plays an important role in building solutions for the coexistence of multiple wireless technologies in the vehicular environment and reducing inter-channel interferences. However, C-RAN carries many technical challenges, including at the network transport level; strict latency requirements for V2X does not exceed 1 ms, the heavy load on communication links between RRUs and BBU pool is about 50 times higher than the backhaul requirements. Furthermore, an enormous amount of data must be transmitted to the cloud as the BBU central pool supports about 10 to 1000 base station sites [109]. With regard to virtualization, C-RAN imposes more critical requirements on cloud infrastructure in terms of data rate of Gbps range, extremely short data life time, and allowed recovery time of ms range.

For slicing RAN, [110] has merged eMBB and URLLC into C-RAN which increases C-RAN revenue and greatly saves system power consumption by accepting slice requests correctly according to resource constraints. To facilitate effective management and central processing of high independence and versatility vehicular networks, [111] provides a C-RAN vehicular network architecture and data compression method based on discrete cosine transform and Lloyd-Max algorithm. Reference [102] also introduces C-RAN to solve the problem of providing reliable and low latency services in vehicular scenarios by sharing C-RAN baseband resources with multi-access edge computing resources using an Integer Linear Program to allow joint deployment with reliability against single-edge node failure.

C-RAN and previous enabling technologies overlap to form an architecture that increases network virtualization and improves the ability to dynamically exploit and manage network resources.

6) NOMA

Non-Orthogonal Multiple Access (NOMA) is based on the principle of serving more than one user in the same resources, whether they are time, frequency or code resources, depending on different energy levels. Thus, NOMA enhances connectivity, reduces latency, improves user equity and spectral efficiency, and increases reliability compared to conventional OMA [112]. When using OMA, connecting thousands of vehicles in vehicular networks requires thousands of bandwidth channels while NOMA can service these users in the use of one channel, due to the greater NOMA throughput while ensuring user fairness [113]. However, the issue of imperfect Successive Interference Cancellation (SIC) is the subject of many recent research [114]–[116].

NOMA is a major player in the deployment of vehicular communications. In the use case of safety information V2X broadcasting, NOMA can provide solutions to the issue of scheduling and resource allocation. In a dense network, latency can be reduced and reliability can be improved by NOMA [117]. However, NOMA has some drawbacks that should be taken into consideration. Although the power consumption point is not a critical factor in a network node like a vehicle, every vehicle within the cluster needs to decode the information of all other users which leads to complexity in the receiver. In addition, any user error caused by the SIC will cause an error in decoding all other users' information. NOMA is also sensitive to obtaining the required channel gain measurements from each user as feedback to the base station.

In the literature, NOMA has been introduced along with other techniques such as FD in order to build the NOMA-V2X architecture. In the context of reducing complexity, [118] uses vehicle clustering, and discuses the issue of trade-off between relative speed of cluster-head vehicles and power allocation. Reference [118] suggests a NOMA-based power control method to equilibrate the power allocation between the cluster-head vehicles and thus increase the downlink throughput. In the same direction and to solve the problem of calculation complexity, [119] presents a decentralized V2X system based on full duplex NOMA (FD-NOMA) showing improved performance with increased number of V2X users. The authors give approximate expressions with controllable errors to solve the complex calculation problems. Reference [120] proposes a novel joint precoding, user scheduling and NOMA implementation in V2X networks to improve spectral efficiency, the unfair spectrum efficiency problem between cell center users and cell edge users has been resolved by using centroid of users' channel vectors.

For broadcasting/multicasting in 5G V2X, [121] suggests half-duplex and FD relay-assisted approaches based on NOMA in addition to investigating power allocation problems to maximize the lowest achievable rate for all users. The authors ensure the quality of service of vehicles with poor channel conditions using bisection-based power allocation algorithm. As part of building the NOMA-V2X architecture, [122], [123] propose combining NOMA and resource sharing based on spatial reuse D2D to improve notably the network performance, spectrum efficiency, transmission efficiency and network throughput. Reference [122] tackles the interference and resource allocation problem by creating a weighted interference hypergraph-based 3-dimensional matching resource allocation protocol. According to [107], NOMA can help enhance the capacity of V2X networks. To solve the problem of NOMA power allocation, the work [107] proposes an online MEC-based scheme, network slicing, and deep reinforcement learning.

NOMA allows serving more than one user on the same resources depending on different power levels. Although NOMA improves connectivity, reduces latency, improves user fairness, spectral efficiency, and increases reliability, other factors such as receiver complexity, outage probability, power allocation factors, imperfect SIC, and fading must be considered.

7) MmWave

MmWave is one of the 5G enabling technologies that plays an important role in meeting capacity requirements by providing a larger bandwidth from around 30 GHz to 300 GHz, i.e., a shorter wavelength between 10 mm and 1 mm, narrow beams, in addition to increasing security and reducing interference [124]. Despite the advantages of this technique, challenges and limitations are discussed in the literature.

When relying on contiguous bandwidths of up to 800 MHz, mmWave is expected to provide extremely high data rates of up to 20 Gbps. At these extreme data rates, 5G NR mmWave technology improves the V2X experience for use cases such as 4K/8K video, augmented reality, extended sensors, autonomous platooning, remote driving, and advanced driving. 5G mmWave can also play an important role in improving the reliability of the cellular primary access procedure in massive V2X communication scenarios [125].

Regarding mmWave applied to V2X networks, [126] proposes an online learning algorithm based on contextual multi-armed bandits that addresses the problem of beam selection in mmWave vehicular systems. Reference [127] explains that one of the challenges to deploying mmWave for the 5G V2X is the latency to achieve beam alignment, algorithms and designs are proposed for beam sweeping that ensure the optimized latency to achieve beam alignment. While [128] discusses this problem (beam realignment) that occurs frequently when mmWave is integrated with V2X networks. In addition to taking into account the problem of transmission interruption due to blockage, the authors propose an energy-angle domain initial access and beam tracking scheme for a V2X scenario, through which the signals are labeled by different directions with multi-power level. Reference [129] also deals with the topic of beam alignment and the routing stability problems because of vehicles' rapid mobility. The authors introduce a 3D-based position detection method and a group-based routing algorithm to select beam alignment, in addition to define a secure path to achieve reliable data transfers. For data compression and files encryption, Huffman coding and elliptic curve algorithms are used.

Considering the problem of vehicle-cell association in mmWave communication networks, [130] proposes a distributed solution based on deep reinforcement learning to increase the sum rate along with ensuring the minimum service rate for all vehicles, thus reducing service outages for vehicle users. More specifically, [131] addresses the problem of user (vehicle) association in vehicle platoon systems. The authors present spatial framework for platoon-based mmWave V2X networks. Poisson point process and multiple Matérn hard-core processes are used for modeling base stations and distributing vehicles respectively. Vehicle-caused blockage process and its relationship with the number of lanes and the height of blocking vehicles are demonstrated. Three user association techniques are proposed to enable the platoon communication with both platoons and road-side units, in addition to determine the probabilities of theoretical coverage [131]. As a result of the study, the platoons have a higher road spectral efficiency than conventional individual vehicles. Reference [132] examines the satellite and terrestrial channel characteristics of the mmWave band (22.1-23.1 GHz) for V2X communications, taking into account weather conditions and interference between the two links. After analyzing parameters such as received power, Rician K-factor, root-mean-square delay spread, and angular spreads, the research provides a number of results related to the maximum excess attenuation, the contribution of line-of-sight and multi-path components, and the influence of small-scale objects.

MmWave is a common candidate for 5G V2X communications, since advanced V2X use cases require high-speed links in the Gbps range to obtain the sensory information needed especially at high levels of automation. However, the transmission range of carriers remains limited due to the severe attenuation of the signal.

8) FULL-DUPLEX

Full-Duplex is one of the enabling technologies for 5G, allowing simultaneous transmission and reception of the radio transceiver. The most important challenges facing FD are interference, and one of the techniques used to solve this problem is self-interference cancellation (SIC) [133].

In literature, several FD applications are discussed on V2X networks. The results in [134] show that the use of a FD transceivers on board vehicles contributes to improving timeliness and packet transmission reliability. Where the on-board FD transceivers increases the accuracy of the sensing stage, improves resource reallocation process, and enhances packet decoding/packet reception capability during transmission by using SIC [134]. In weak or imperfect SIC cases, [135] proposes a model for detecting and avoiding FD collision by means of energy detection in V2X networks. The channel's energy level is sensed and compared to a specific dynamic threshold based on the probability of target detection, transmitter power, sensing time, and SIC factor. As we discussed in IV-D6, NOMA is integrated with FD in order to offer more effective vehicular communication solutions. FD-NOMA is applied to broadcast/multicast in 5G V2X communications to improve the information sharing, power allocation, fairness and QoS for the users with poor channel conditions [121]. While the proposed scheme in [121] is centralized, [119] suggests a FD-NOMA-based decentralized V2X scheme to fit the requirements for this type of communication (URLLC, QoS, number of V2X devices).

FD transceivers can be an effective and practical solution to reduce end-to-end latency in vehicular communication systems. However, the main challenges facing FD are interference, since the received signal has a much lower power that of the transmitting signal, in addition the imperfect linearity of the transmitter amplifier.

9) AI

Artificial intelligence has become an integral part of most engineering research projects. In fields such as robotics, data science, natural language processing and game theoretic learning, AI is applied to design prediction algorithms. The latter is an effective data-driven approach that allows for more rigorous handling of sparse and heterogeneous data. AI methods vary greatly and are related to wide fields, prominent examples of these techniques are heuristic methods, swarm intelligence, expert systems, evolutionary algorithms, inference, fuzzy logic, machine learning, etc [136]–[138].

AI with V2X can enable applications such as real-time traffic flow forecasting and management, location-based applications, autonomous transportation facilities, vehicle platoons, vehicle data storage, and congestion control. To enable basic features of human driving in autonomous driving application, AI and V2X together can play a critical role. However, profiting and developing AI tools to meet V2X challenges is still an area of research in its infancy [139].

In [140] the authors addressed the safety of overtaking involving multiple users. They proposed an expert system based on a predictive planning method of a linear model of multiple vehicles. Their approach dynamically adapts the course of maneuver in the event of unforeseen situations. Reference [29] has proposed two AI algorithms in order to reduce CAPEX and OPEX and to solve complex optimization problems for 5G-V2X networks. The first, based on deep learning, aims to accurately predict user and network traffic to reduce CAPEX and OPEX. The algorithm can predict the spatial and temporal data of not only grid based segmentation but also irregular segmentation. The second algorithm, based on swarm intelligence, aims to solve the complex global optimization problems related to V2X. The latter can improve the convergence rate and optimization precision of cuckoo search through subpopulation collaboration based dynamic self-adaption cuckoo search. The authors in [141] proposed a deep learning algorithm to optimize 5G base station allocation for platooning vehicles underway. The trained AI model can be used for platooning management in 5G-V2X vehicular networks. A recent research [142] has addressed a new vehicular network architecture that supports AI with fog computing in its core. The architecture harnesses the benefits of both deep learning intelligence and fog computing network architecture in proportion to the specifics of vehicular networks. The authors provide an analysis of implementing deep reinforcement learning for resource allocation and task offloading in the proposed architecture. Moreover, they addressed employing federal learning algorithms to provide reliable V2V communications. The collaboration between connected vehicles and RSUs improves road safety and vehicle traffic management at signalless intersections. The work in [143] has investigated AI solutions along with V2X communication technologies to provide data-based intersection management methods. The research focused on a multi-agent learning approach to manage multiple intersections to demonstrate the effectiveness of the proposed signalless intersection solution. In [107], the importance of AI in reducing complexity is particularly evident in models with non-convex and nonlinear mathematical formulas resulting from resource allocation issues. The research presented a model-free approach to enable better use of channel resources using deep reinforcement learning algorithms.

AI applications are still in their infancy in V2X communications due to the lack of data needed to train an AI model although some government agencies provide access to data sets created using ITS technologies [17]. This is evident as in [141] where a deep Q-network reinforcement learning method to train the AI model was used where experimental data was retrieved from a network simulation environment. Conventional/centralized machine learning schemes are not always feasible in V2X communications applications for two main reasons: the lack of access to private data, and the large communication overhead required to transmit this data to the central entity. The model presented in [142] is characterized by its reliance on distributed/federated learning in which all private data is preserved at the locations where it is created and only locally trained models are transmitted to the central entity. As a result, this approach: enhances the security of the generated data, exploits its ability to suit real-time/delay sensitive applications, and is efficient in both communication/bandwidth and energy. This improvement brings additional overhead and complexity at the edge of the network or even connected vehicles.

The applications of AI in vehicular networks are not limited to a specific network layer. Through the studies that have been presented, we note the applications of AI to the entire network, where the pace of virtualization and slicing is accelerating. AI supports V2X communications with data-driven decisions at the level of network management, services, and operations.

Table 4 provides a summary of potential applications of these enabling technologies within V2X use case groups. The proposed mapping does not limit research applications in other aspects and does not necessarily mean that the requirements for a use case have been completely met, e.g., requirements for use cases in a high LoA.

V. OPEN AND FUTURE RESEARCH DIRECTIONS

Through the literature review on the applications of 5G communications to vehicular networks, one can notice the important progress that has been made to leverage 5G communications in a vehicular context. But this progress often lacks linking the proposed solutions to specific vehicular applications and their requirements as stated in the standards. For example, 3GPP provides access to all established standards regarding V2X communications [26], [27]. Details of each use case, from descriptions and conditions to requirements, are described in the technical specifications issued by standards organizations. However, research discussing V2X use cases is scarce.

As this survey demonstrates, 5G wireless networks will integrate many emerging technologies such as massive MIMO, NR sidelink communications, multi-radio access technology, full-duplex, millimeter waves, cloud/edge technologies, and SDN. At the same time that these technologies

TABLE 4. Mapping between V2X use case groups and enabling technologies.

Use case / Technologies	**Vehicle platooning**	**Remote driving**	**Extended sensors**	**Advanced driving**
NR Sidelink	[27], [71]		[27], [71]	[27], [71]
NFV	[69], [80]	[80]	[79], [80]	[69], [78]–[80]
SDN			[91]	[67], [90], [91]
MEC	[29], [58], [102]	[58], [102]	[42]	[29], [42], [90]
Network slicing	[104], [105]	[105]	[106]	[105], [106]
C-RAN	[102]	[102]	[111]	
NOMA	[118], [119], [121]	[119], [120]	[119], [122], [123]	[121], [123]
MmWave	[130], [131]		[128]–[130]	[126], [130]
Full-Duplex	[119], [121], [134]	[119]	[119]	[121]
AI	[29], [141], [142]	[29], [80], [140]	[140], [142]	[29], [140], [142], [143]

provide solutions, they also pose different challenges for 5G based vehicular communications. As mentioned in IV-B2, small cells and spatial densification as well as heterogeneous networks will be widely deployed in 5G. These structures face challenges in terms of providing user mobility due to frequent handovers. With regard to millimeter waves, there are many challenges to vehicular communications; shadowing effect, Doppler spread, delay, reliability, security and broadcasting issues. As for massive MIMO, it suffers from multi-user interference in the absence of accurate information on the state of the channel, in addition in the case of high mobility, SINR and achievable rate is limited due to pilot contamination.

In terms of cloud computing, the challenge of providing an appropriate and accurate mobility model and the challenge of resource use and management cannot be overlooked, in addition to security, virtualization management, selection and deployment of VNFs issues. Vehicular SDNs may face challenges in network management due to the multiplicity of specifications of the various devices and services provided in addition to the limited interoperability between the different vehicular standards and communications technologies. Also, the high dynamism and heterogeneity of vehicular networks cause a difference in the availability of resources over time and thus instability in the quality of service.

The challenges related to edge computing can be summarized in two main points, the first is related to the methods of pre-fetching content, where the vehicle mobility and the distribution of traffic cause unbalanced and different dwell time. Another challenge relates to post-fetching content by optimizing the scheduling of content distribution according to vehicles, traffic, and link capacity requirements. The network slicing, in turn, faces several challenges at the level of security, managing slices and providing trust relationships between the various actors. The need to know when network functions should be centralized or sliced and to create multiple slices per device simultaneously. In terms of security, network slicing can present security threats due to the difference in security services by slice. Finally, the dynamic spectrum sharing (such as cellular spectrum, DSRC and millimeter wave spectrum) is subjected to challenges due to the high mobility of vehicles and the heterogeneity of the spectrum, which limits the availability of these resources.

Although artificial intelligence (AI) is considered as a key technology for dealing with the huge amount of data handled in vehicular networks, the applications of AI in V2X systems are still in their beginning. AI has the potential to assist in many applications in real time such as traffic flow management, location-based applications, vehicle platooning, and congestion control [139]. With the increase in the number of vehicles with sensor and computing capabilities, the importance of AI to enhance privacy protection is evident. Benefiting from the collective sensor data may greatly contribute to the enrichment of V2X applications and enhance their development. This concept is called crowdsensing, which requires motivating the largest number of participants to perform sensing tasks. It will be important to provide an incentive mechanism in the crowdsensing of the vehicular environment to recruit participants under the protection of private information and minimizing the data aggregation error. Since it is difficult to obtain accurate sensor models for platforms and participants in practice, resorting to machine learning and reinforcement learning are possible solutions [144], [145]. In terms of data sources, some programs, such as ITS DataHub [17], may facilitate access to some datasets created using ITS technologies, but data sources remain scarce. Some solutions depend on training the proposed methods through the retrieved results from the network environment simulation. While other methods rely on distributed or federated learning, but it also requires that the equipment at network edge have larger computational and storage capacity.

From our point of view, the majority of research in the field of vehicular communications is built on three main axes, i.e., utilizing more spectrum resources, increasing the possibility of reusing these resources, and finally improving spectral efficiency. But the complexity of the used algorithms, additional CAPEX and OPEX, and maintenance stand in the way of further developments. Here we go back and mention the benefit of AI to build algorithms that help develop the three aforementioned axes.

FD, which allows the wireless node to transmit and receive at the same time presents many benefits for vehicular communications. Many research has already started developing hybrid solutions that use FD along with other technologies to meet the vehicular communication needs [119], [121], [133]–[135].

We summarize our recommendations for future research directions:

- Linking research to standard use cases or highlighting a lack of technical specifications and studies for other use cases.
- Better leverage AI, whether to build resource allocation algorithms, to facilitate communication between different radio access technologies or to build hybrid solutions and data processing.
- Using FD as a building brick to double the spectral efficiency and to reduce the latency as well as reliability and flexibility in dynamic spectrum allocation and enabling small cells in 5G-enabled V2X.

In addition to the current use cases, enabling technologies, and challenges they pose, V2X communications will present further challenges and research prospects in the future. The number of connected autonomous vehicles is expected to grow rapidly in parallel with the massive increase in communication devices and V2X applications to enable intelligent autonomous vehicles. These applications range from 3D displays, immersive entertainment, and improved in-vehicle infotainment to holographic control display systems [146]–[148]. The next generation of cellular networks (i.e., 6G) will face new scientific and technical challenges for V2X networks. Future V2X applications will impose stricter requirements in terms of intelligence, energy efficiency, higher data rate (e.g., Tbps), lower latency (i.e., down to sub-milliseconds), and new privacy/security concerns. While the current use cases discuss communication between vehicles on the one hand and vehicles, pedestrians, infrastructure and network on the other hand, future use cases will include communication of non-terrestrial communication networks such as satellite communication networks and unmanned aerial vehicles (UAV) [147]. We are talking here about ubiquitous intelligent vehicular communication systems that demand 3D coverage and ultra-fast wireless broadband access (i.e., billions of communications devices connected) [146]–[148]. Many technologies and concepts are being researched and developed to be the basis for the next generation of communications. Some of them are under development in the current generation, such as FD, heterogeneous network, AI, and edge computing, but more broadly and effectively with superior computational capabilities that are suitable for future V2X applications (e.g., using quantum computing technology) [146]–[148]. Other technologies include cell free architecture and Intelligent Reflecting Surfaces (IRS) [146], [147], [149], which contribute to the full utilization of the transmitted power and ensure that it reaches all users. Cell free and IRS will be important in an urban vehicular environment that suffers from fading effects. The concept of coverage may change completely in the next generation with the holographic radio. The latter represents a large group of direct, indirect and reflected paths. These paths can eventually be imagined as 3D phantoms connecting access points, devices and reflecting surfaces. In this case, there is no longer handover between cells or base stations because the UE will be constantly connected to many access points. Instead, during the movement, UE maintains links with the network and updates them. Finally, the jump to terahertz (THz) communications will allow a very wide bandwidth of up to tens of GHz for each user, and therefore very high data rates [146]–[148]. However, the deployment of these frequencies suffers from challenges, starting with the development of electronic components and then devices and systems that operate at these high frequencies. In addition to the physical phenomena that accompany the THz deployment, different from the low frequencies. Moreover, both the high power consumption and wireless signal attenuation present challenges for this deployment. THz communication is suitable for short-range V2X communications, and may be used for certain use cases, where extremely high throughput and low latency communication are required [147].

VI. CONCLUSION

This article provides a survey of 5G V2X-enabling technologies. We introduced various V2X use cases and their requirements. We summarized literature on technologies and solutions that support V2X communications in a 5G context. We also mapped V2X applications and 5G use cases and then linked them to enabling technologies. Finally, we indicated different challenges posed by the emerging technologies and some interesting directions for future works in 5G-enabled V2X. Particularly, we think that new and advanced V2X applications can further take advantage of AI techniques to enhance resource use and V2X capabilities. Additionally, FD and its integration with other technologies such as NOMA can play an important role in meeting new and advanced vehicular communication requirements.

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