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A Survey of 5G Technology Evolution, Standards, and Infrastructure Associated With Vehicle-to-Everything Communications by Internet of Vehicles

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ABSTRACT The very last wireless network technology, created to increase the speed and the connections responsiveness, the Fifth-Generation Network (5G) can transmit a great volume of data. It uses wireless broadband connections to support specific end-users and businesses services. It is specifically useful for the Internet of Vehicles (IoV), guaranteeing fast connections and security. The 5G network technology can be used to support Vehicle-to-Everything (V2X) communications and applications on autonomous vehicles. It can enable information exchanges between vehicles and other infrastructures and people. It can also provide a more comfortable and safer environment and accurate traffic knowledge. The traffic ?ow can be improved, reducing pollution and accident rates. The cellular network can be associated with V2X as a communicating base to offer enhanced road safety and autonomous driving, and also to offer the IoV connections. This survey presents the 5G technology evolution, standards, and infrastructure associated with V2X ecosystem by IoV. In other words, it presents the IoV supported by 5G V2X communications, considering its architecture, applications and also the V2X features and protocols, as well as the modes, the evaluation and the technological support in such combination. The contribution of this paper is a systematized study about the interaction among these three contents: IoV, 5G, and V2X. Eighty four works were selected to present concepts, standards and to identify the ways to overcome challenges. This survey aims to guide the development of new 5G-V2X services and technologies dedicated to vehicle communications, and also to indicate future directions.

INDEX TERMS IoV, connected vehicles, 5G networks, V2X communications.

I. INTRODUCTION

The comfort of having vehicles, things, and people fully connected is the main goal of IoV and V2X technologies. The current Vehicle Ad Hoc Network (VANET), uses each vehicle that is connected to the Internet as a node [1], and its evolution through the IoV which makes the Internet of Things (IoT) available in the cars, allows the data integration, helping to keep the traffic flow, to manage fleets, to avoid accidents, and to entertain or localize the users everywhere and whenever. By distance, speed-reducing, and acceleration sensors, the IoV enhances driving aids with, for example, the adaptive cruise control that through the vehicle Artificial Intelligence's (AI) can understand other cars' maneuvers [2]–[4].

With technological development, IoT is guiding the IoV evolution. It includes the performance to change the vehicle's trajectory by the road distributions in the city and the traffic flow, the performance to integrate humans and vehicles as extensions to each other what makes the combination among human's abilities and vehicle's intelligence, and the performance to interconnect humans, vehicles and multi-level collaboration systems by sensors and mobile devices into a global network. This integration aims to enable several

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services on board and around vehicles that work as manned computers or large cell-phones [5].

An IoV network is composed of an environment integrated by "human", "vehicle" and "thing", which are the terminology referred to specific network groups that collaborate to each other. "Human" holds people in "vehicle" or in the environment and "thing" is any kind of element that is not "human" or "vehicle". Both can consume and/or provide services and applications to/from the environment. IoV provides such services and applications by internet through the interaction between environment and "vehicle", environment and "human", environment and "thing". IoV also provides services and applications inside a "vehicle" by an intra-vehicle network to allow the interaction between "vehicle" and "thing", and "vehicle" and "human" [5], as shown in Figure 1.

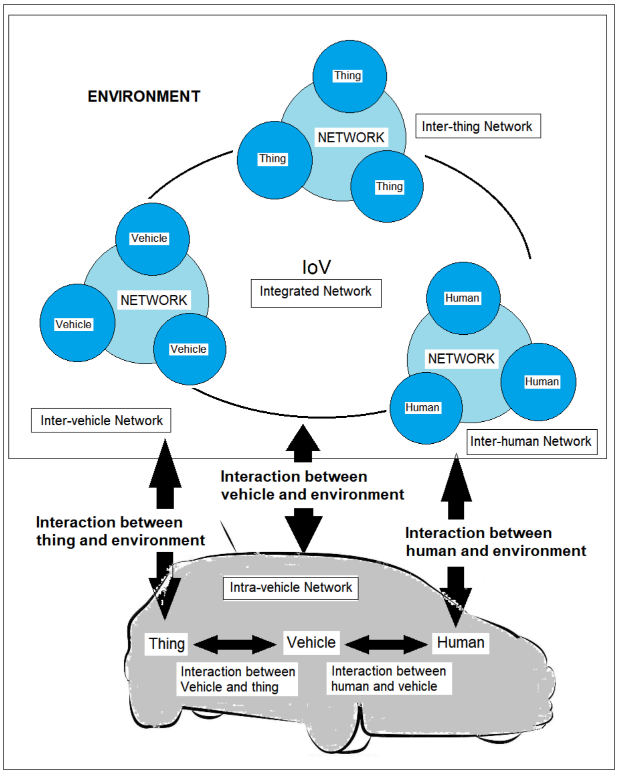

FIGURE 1. IoV network model.

The IoV platform supports all these interactions through the technologies that were developed by several academic and industrial types of researches focused especially on layers, models, security, privacy, quality of service and wireless access. These technologies shall be understood as the Information and Communications Technology (ICT) that enable modern computing by its infrastructure and components present in devices such as cell-phones, wireless networks, service applications and other systems that connect people and things "in" or "to" intelligent environments.

Created to increase the speed and the responsiveness of the connections, 5G can transmit a great volume of data by wireless broadband connections and 360^o antennas. 5G networks support specific services in vehicles, allowing the IoV to use secure and fast connections [6]. 5G cellular services provide everywhere user access to 5G cellular networks. 5G is a hundred times faster than Forth-Generation (4G) that already speeds up to 500 times faster than Third-Generation (3G). 5G has going to have a much lower level of latency, and requires larger blocks of airwaves than 4G.

The Third-Generation Partnership Project (3GPP) Release 15 supports V2X communications and applications on autonomous vehicles by the evolution from the Multiple-Input and Multiple-Output (MIMO) antenna and millimeter Waves (mmWave) [7], [8]. V2X communications enable the information exchanges between vehicles and other infrastructures and people (thing and/or human), providing vehicles accurate knowledge about the environment. The development of V2X communications must ensure reliability levels and network' scalability as the data load increases [9].

V2X creates a more comfortable and safer environment, improving traffic flow, reducing pollution and accident rates. It is up to be applied in the short term into safety, efficiency and information services applications about collisions or hazards on the roads, speed guidance, and congestion warnings. It provides improved driving experiences with route recommendations and automatic parking, but different applications require for different communication performance requirements [10].

The Cellular in association with Vehicle-to-Everything (C-V2X) is a communicating base that offers enhanced road safety and autonomous driving [11]. It uses a transmission mode called direct C-V2X, which provides longer communication range and higher reliability to connect "vehicles", "things" and "human". The C-V2X chipset solution is going to be compatible with 5G and with the Advanced Driver Assistance Systems (ADAS) sensors as part of a specific platform for the C-V2X direct communication mode. It was designed to offer IoV connections with or without cellular network for Vehicle-to-Infrastructure (V2I), Vehicle-to-Vehicle (V2V) and Vehicle-to-Pedestrian (V2P) [12], as shown in Figure 2.

A review over the Physical Layer (PHY) changes introduced under Release 14 for Long-Term Evolution-Vehicle (LTE-V), and its evolutions under discussion in Release 15 to support 5G V2X communications and autonomous vehicles' applications are provided in [13]. The communication modes 3 and 4 support direct V2V communications, being the radio resources allocated by the cellular network under mode 3. As mode 4 does not require cellular coverage, and as vehicles autonomously select their radio resources using a distributed scheduling scheme supported by congestion control mechanisms, it is considered the baseline mode for C-V2X as an alternative to Institute of Electrical and Electronic Engineers (IEEE) 802.11 protocol, the Dedicated Short-Range Communications (DSRC) developed in the United States or Intelligent Transportation System (ITS)-G5 developed in the European [14].

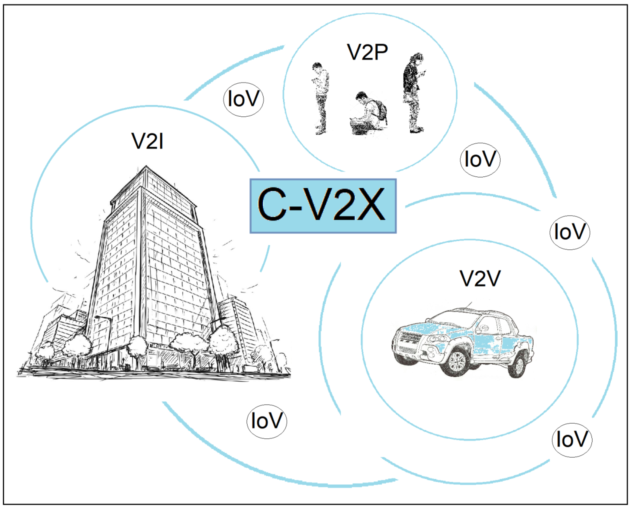

FIGURE 2. IoV on C-V2X.

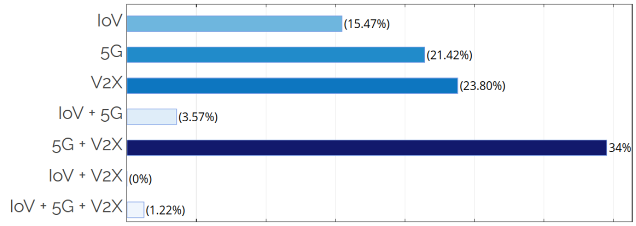

FIGURE 3. Percentage of studies about IoV, 5G, and V2X.

The work in [15] and [16], proposed an ecosystem based on the Software-Defined Networking (SDN) conception and evaluated vehicular Internet-based video services traffic and V2V communications in urban and rural scenarios, using the network simulator ns-3, employing mmWave communications to analyze data transfer rate, transmission delay, and Packet Delivery Ratio (PDR). The results have shown satisfactory performance to the IoV communications requirements when adopting the 5G network with V2X communications. Naik *et al.* [17] presented the C-V2X as an important evolution of Radio Access Technologies (RAT) to enable reliable vehicular communications since C-V2X is going to support advanced vehicular applications that are characterized by low latency, high data throughput requirements, and supplemental sensors for vehicles with autonomy.

The present survey is about IoV supported by 5G V2X communications. The adopted methodology in this study was the literature research about the 5G technology evolution and standards, about the infrastructure associated with the V2X ecosystem by IoV, considering its architecture, the possible applications and also the V2X features and protocols presented in the existing studies and projects on 5G V2X. This work is especially interested in the 5G challenges in the technologies developed for vehicular communications.

Some key-words especially used to search about the proposed context for this paper were: IoV architecture, model, challenges and technologies; vehicular networks; cellular V2X communication systems; requirements of autonomous driving; VANET applications and challenges; connected cars in cellular network; 5G infrastructure for V2X ecosystem; and others. The most consulted digital library were IEEE. Also were consulted material on ACM, Elsevier, MDPI, Springer, Wiley, and others in the period from 2009 to 2020.

In this survey were selected 109 references and, from those, 84 are studies about the three specific contents (IoV, 5G and V2X) evolved on the present study. 13 works talk about IoV only (15.47%), 18 about 5G only (21.42%), and 20 about V2X only (23.80%). 3 works have associated IoV with 5G (3.57%), 29 have associated 5G with V2X (34.52%), neither one work has associated IoV with V2X (0%), and 1 work (prepared by the same authors of this survey) has associated IoV with 5G and V2X (1.22%) as shown in the Figure 3.

This survey is written in reason to study exactly the interaction among these three contents (IoV, 5G, and V2X) as the contribution for the knowledge of the 5G development and use in several scenarios. So, the main aim of this study is to research about the 5G technological evolution, standards, and infrastructure in association with V2X communication by IoV. From those 84 works, 6 are also surveys: 2 about IoV only, 3 about V2X only, and 1 about 5G with V2X as shown in Table 1.

The remainder of this paper is organized as follows: Section II presents the IoV architecture that is going to be supported by C-V2X communications; Section III describes the standards associated to the 5G on V2X; Section IV considers the challenges involved on the 5G V2X and discusses the future directions; and Section V concludes the paper. The paper's structure is shown in Figure 4.

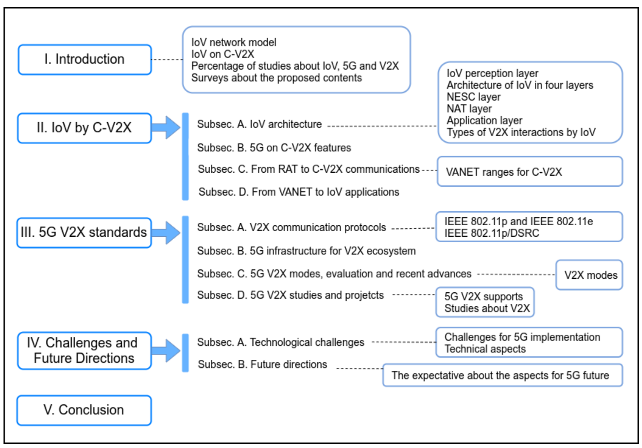

FIGURE 4. Paper's structure.

II. INTERNET OF VEHICLES BY C-V2X

This section is going to first present the IoV architecture with the types of V2X interactions, the 5G technology and its features on C-V2X, the evolution from the RAT to C-V2X communications and also from VANET to IoV applications.

TABLE 1. Surveys about the proposed contents.

Reference	IoV	5G	V2X	Year	Remarks
Yang et al. [18]	✓	✗	✗	2017	The survey reviews the different perspectives to provide a new notion from a network point of view, and to propose a new architecture with four layers. The work summarizes the key technologies, providing traffic service and sharing sensing data coordinately, which can solve the communication.
Hamid et al. [19]	✓	✗	✗	2019	The survey brings an overview of the importance to vehicle connectivity as well as the current application of IoV in the autonomous vehicle. The work highlights several issues of the IoV involving connectivity between the environment, the requirement of the wide coverage of 5G Internet as well as security concerns.
MacHardy et al. [20]	✗	✗	✓	2018	The survey has collated searches about the need to extend the perceptual bounds of sensor-equipped vehicles beyond the individual vehicle to the broad implementation of intelligent transportation systems. It has also searched for new directions and standardization efforts toward V2X technology.
Muhammad and Ali Safdar [21]	✗	✗	✓	2018	The survey presents an introduction to V2X services alongside the corresponding requirements, describing the potential benefits of using cellular infrastructure for such services and the reference architectures for cellular-based V2X systems. The work focuses on the security issues of V2X in the cellular networks.
Wang et al. [10]	✗	✗	✓	2019	The survey cares about an innovative paradigm called Cognitive Internet of Vehicles (CIoV) proposed to help address the aforementioned challenge. The work presents an evolution, related technologies, and architecture overview of CIoV including cognitive design issues and simulations.
Bazzi et al. [22]	✗	✓	✓	2019	The survey provides an insight in the comparison between IEEE 802.11p and short range C-V2X technologies for connected and automated vehicles, also trying to isolate the contribution of the physical and medium access control layers.
This Survey	✓	✓	✓	2020	The present survey presents a embracing research about 5G technology evolution and standards, and also the infrastructure associated with V2X communications by IoV.

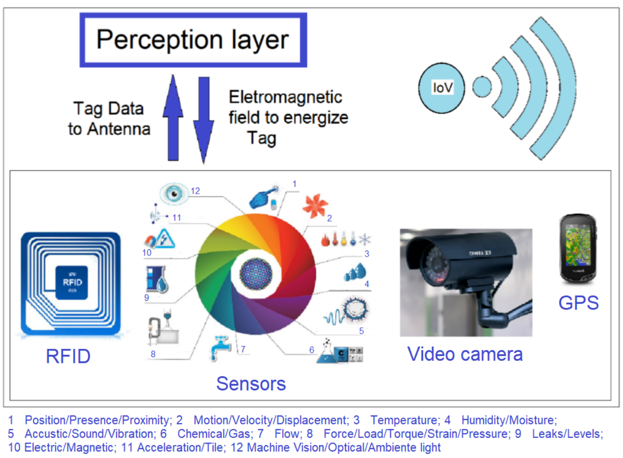

FIGURE 5. IoV perception layer.

A. IoV ARCHITECTURE

Typically, to support wireless modes as V2V, V2I, and V2P, the IoV architecture has three layers: perception, network, and applications. The perception layer keeps all the sensors that mine the environmental data inside/outside the vehicles to detect any specific interesting event or change anytime, anywhere. It includes video cameras, radar, Global Positioning System (GPS) receiver, and others such as the Radio Frequency Identification (RFID) that allows the perception of human, vehicles, and things, as shown in Figure 5.

The network layer makes the IoV applications transmission through network communications for smart devices inside/outside the vehicles. The application layer is the processing infrastructure that uses statistics tools to support data storage, analysis, decision making about the situation of risks such as traffic congestion, bad weather, and much more used in smart applications for safety and efficiency on several online services.

Besides being an IoV service network for V2X communications, C-V2X is a complex system with coordinative interaction and dynamic evolution that requires pervasive and cognitive support computing. In this direction, another proposal [18] has presented an IoV architecture divided into four layers: vehicle Network Environment Sensing and Control (NESC) layer; network access and transport layer; coordinative computing control layer; and application layer.

The NESC layer can be associated to the perception layer, because it is the IoV services recognition basis, by which the vehicles sense environment information around them. This layer technology receives and executes coordinative control instructions for cooperative control [18], as shown in the Figure 6.

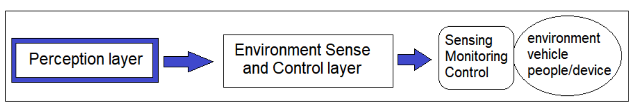

FIGURE 6. NESC layer.

Network Access and Transport (NAT) layer realizes besides the network access, data processing, data analysis, and data transmission, also realizes the remote monitoring and nodes management within the IoV. This layer can be associated to the network layer, because it makes the inter-connection and the information exchange, providing real-time, three-dimensional, and seamless heterogeneous network access. It also dispatches access resources and balances the information load [18], as shown in the Figure 7.

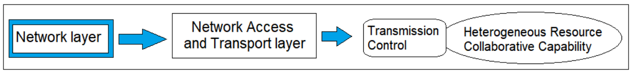

FIGURE 7. NAT layer.

The Coordination Computing Control (CCC) layer provides IoV applications with the cooperative capability for communication control and coordinative capability for intelligence computing interaction. It involves the environment, vehicles, devices and people with open services. This layer also provides technological support and interactive cognitive capability for the computing environment, involving vehicles, devices and people with closed services. The application layer of IoV provides various types of opened and closed services, while the opened ones share information to support the business operating model, the closed one is related to the specific industry applications, such as intelligent traffic command and control platform [18], as shown in the Figure 8.

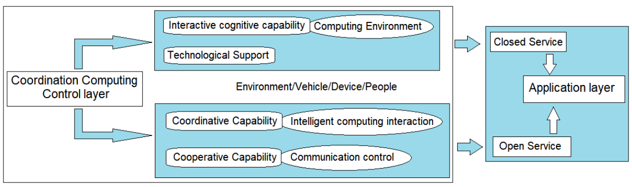

FIGURE 8. Application layer.

To better understand the IoV function on V2X, besides the V2I interaction representation, the vehicle to the Road Side Units (RSU) or better V2R and the Vehicle-to-Sensor (V2S) shall be represented when the 5G Wireless Access Technology (WAT) be incorporated into the vehicles [23]. For while, VANET still enhances safety and efficiency of the traffic, using real-time communication between the advanced WAT, with or without the RSU help, because it can be divided into three ranges (long, medium and short) with modes such as Wireless Access in Vehicular Environments (WAVE), Wi-Fi, ad-hoc, or hybrid mode which associate cellular to ad-hoc.

It is important that for the online vehicle presence in the environment, each smart car must have an Internet identifiable number or a "cyber license" that is controlled in the Vehicular Global Identification (GID) terminal. Due to this internetworking environment in IoV, different WATs are utilized to establish connections among smart cars to the network services by Vehicle-to-Network (V2N), to other vehicles by V2V, to RSU by V2R, to personal devices by V2P, to the traffic control center (eg. traffic light) by V2I, and to the environmental sensors by V2S [24], as presented in Figure 9.

There are also other ways to describe the V2X application types divided into two basic operations: Device-to-Device (D2D) involving V2V, V2I, and V2P; and V2N with evolved packet-switching communications [16]. But what matters in fact is that the IoT technology drives the VANET evolution

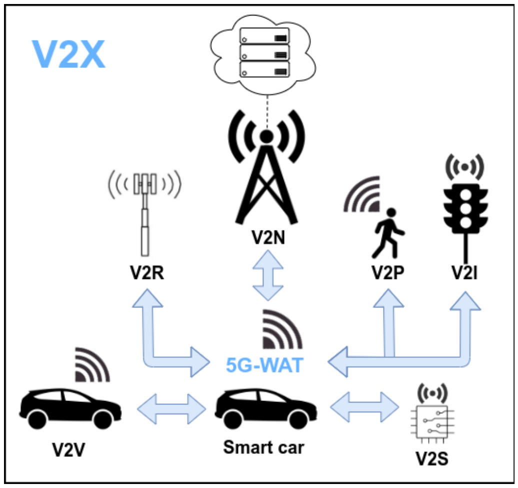

FIGURE 9. Types of V2X interactions by IoV.

into the IoV that is going to have large applications on transportation and communication fields [18]. These two different IoT technologies (VANET and IoV) are responsible by two different networking scenarios in which devices and services aspects are also different. While a vehicle in VANET is used to form just an inter-vehicle communication network, IoV is used to create dynamic intra-vehicular mobile communication systems [25] which include V2X supported by 5G. Finally, for IoV communications by 5G, user-centric network conception is required to include full V2X connections [26].

B. 5G ON C-V2X FEATURES

The 5G can be classified as an Ultra-Dense Network (UDN) and as a Heterogeneous Network (HetNets) [27], [28]. The cell densification is an expected technique in 5G in order to improve the network capacity, especially in terms of connection speeds. In this way, users are connected to Base Stations (BSs) through a virtual cell known as V-Cell [29], [30]. However, the virtual cells based on user needs formation is a still underutilized area and it lacks new mechanisms for an improvement of the services offered by the 5G network, benefiting, for example, services offered by IoV through 5G V2X communications.

The 5G network is expected to be reliable and pretty fast. The services and applications are going to be accessed by a single Internet Protocol (IP) or identification on the wireless and mobile networks interoperability. The actual system consists of an user-terminal and a number of autonomous RATs linked to the Internet, but in the mobile terminal for C-V2X a different radio interface for each RAT is going to be a need and must provide access to the Internet with Quality of Service (QoS) in its support mechanisms. In today's communication world, the 4 and 6 IP versions (IPv4 and IPv6) ensure enough control data for proper routing of packets that belong to specific connections in accordance with established user-policies.

The main point is the expectation that the C-V2X is can be able to support safety applications that demand an End-to-End (E2E) latency of around 100 milliseconds (ms) [17]. The C-V2X basic time-frequency resource structure is similar to LTE's one. The smallest allocation unit in time is one subframe that is 1 ms composed of 14 Orthogonal Frequency Division Multiplexing (OFDM) subcarriers, and the smallest frequency-granularity is 12 subcarriers of 15 kilohertz (kHz) each [31]. C-V2X devices can transmit using Quadrature Phase Shift Keying (QPSK) or 16-Quadrature Amplitude Modulation (QAM) schemes with turbo coding in each OFDM subcarrier. So, in addition to data symbols, C-V2X users also transmit control information and reference signals [13].

For this proposal, the technological advances in mobile communications allow different deployment architectures for vehicular networks to support many applications with different QoS requirements in several environments. The VANET is one of these architectures that allow communication among nearby vehicles and/or among vehicles and fixed roadside equipment by IoV [1].

V2X is a critical component of 5G networks. While the 5G aims to satisfy requirements such as reduced latency, increased reliability, and higher throughput under bigger mobility and connectivity density, the key features of V2X focus on ultra-reliable and low latency communication for safety-critical use cases [17], [32]–[35]. 5G V2X is very important for the automotive industry because of its infrastructure and a great capacity to support communication services because 5G networks shall enable vehicles to accommodate different types of V2X message deliveries to support intelligent transportation systems, where all vehicles and infrastructure systems are interconnected with each other. That is why connected vehicles are the next frontier for IoT, while the continuous 5G V2X technology evolution is required to support high-reliability and low-latency radio access for critical messages even in the high-density IoV systems [36].

C. FROM RAT TO C-V2X COMMUNICATIONS

VANET is a special Mobile Ad Hoc Network (MANET) which also presents low bandwidth, short transmission range, and omnidirectional broadcast [1]. Some other VANET characteristics that may represent problems where vehicles are connected are: 1st) it has high dynamic topology due to the vehicles speed and the radio propagation in different directions; 2nd) it has a very short time-period of connectivity, leading to frequent and fast topology changes that make the links between vehicles quickly disappear while they are transmitting information; 3rd) it has geographical localization by targets defined by Cyber-Identity (Cyber ID); 4th) it has mobility and prediction constrained to roads, streets and highways, traffic lights, speed limit, traffic conditions, and driving behaviors; and 5th) it has a propagation model which operates on free-space with reflexive signal interference in highways, or on topographic complex with reflexive and attenuation interference in rural environments, or also on variable density of vehicle numbers and the presence of obstacles causing shadows, multi-path, and/or fading effects in the cities [1].

In the way to solve all these VANET's problems before the C-V2X evolution, RAT, by its time, is able to support existing multicast, broadcast and unicast services such as download, streaming, group communication, TV reception, and others but some new ones as V2X. RAT is also able to support those services by dynamic adjustment based on user distribution and service requirements in large geographical areas. The Radio Access Network (RAN) through co-operation in the same spectrum is able to support the flexible allocation of resources considering high mobility and data flow aggregation. So, RAN architecture is able to support connectivity through multiple transmission points, and also to enable the separation of control plane signaling and user plane data from different sites. This RAN architecture is able as well to allow Network Function Virtualization (NFV) deployments and network slicing (3GPP TR 23.799) for the multiple operations. RATs enable RAN-internal localization as cell-ID and especially RAN-external operation as Global Navigation Satellite System (GNSS), Bluetooth, Wireless Local Area Network (WLAN), Terrestrial Beacon Systems (TBS) and sensors on the network layer of IoV architecture. By hybrid methods, RAT is able to exploit high bandwidth, massive antenna systems, network functionalities and the massive number of devices to deploy indoors and outdoors supporting and regulatory requirements, offering positioning services and high security on efficient connections [37], [38]. RAN design for 4G supports D2D interactions, Mission Critical Communications (MCC) for diverse types of services and efficient group or isolated communications, but also provide mechanisms to enable emergency calls including positioning/location, multimedia priority services, and public warning services. In time, RAN design for 5G/mmWave shall provide infrastructure for communication to support V2X services by cell [39], [40].

Higher levels of processing are going to be available by 5G to free the multicarrier systems to be orthogonal as OFDM what is going to provide considerably more flexibility. The 5G technology opens up the possibility of using several antennas on single equipment by their sizes and by the shorter wavelengths which allow dense networks to reduce the size of the cells providing a much more overall effective use of the available spectrum. 5G requires smart antennas to support radio positioning (switched beam), and/or to improve the capacity of wireless systems (adaptive array). In the 5G software, a single unified IP standard of different wireless networks and a broadband combination with wireless technologies such as WAT (and others) are used to enable service implementations, encryptions, flexibility, and much more.

Representing the context of IoV architecture, 5G and the features of its application on V2X communications, the scheme in Figure 10 shows the VANET ranges and each component that allows the IoV on C-V2X.

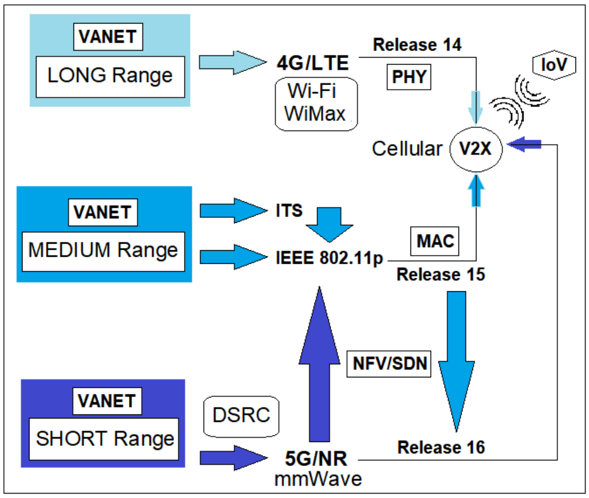

FIGURE 10. **VANET ranges for C-V2X.**

On VANET long range there is 4G working in combination with Wireless Fidelity (Wi-Fi) and/or Worldwide Interoperability for Microwave Access (WiMax) on the physical layer system under Release 14; on the VANET medium range, the ITS and the proposed developments by IEEE 802.11p and Release 15 to allow Medium Access Control (MAC) system works in the direction to support C-V2X by NFV and SDN; on VANET short-range, DSRC is being introduced by the perspectives of 5G/New Radio (NR) using mmWave under Release 16 to support C-V2X.

D. FROM VANET TO IoV APPLICATIONS

In the IoV heterogeneous network environment, a WAT range is going to be available for connections with several applications on smart devices and the cloud based servers. The WAT is divided into vehicular, cellular mobile and small range static communications; and since these technologies have been developed for different types of communication networks, their characteristics are different. To select appropriate WAT for a specific client application and for the QoS maintaining, there is a prioritized preference of wireless technologies based on data rate, communication range, mobility support, communication delay, security support and scalability, as shown in [24].

As the VANET still perform the communication up to the transition to the advanced WAT applications on IoV [24], VANET supports vehicle performance monitoring and analysis applications which include remote vehicle diagnostics by long-term and large-scale collection and proper mining of in-vehicle sensor data. Nowadays, the solutions to support such applications rely on cellular communications 4G adapted for data transmission but also impose severe privacy risks to vehicle drivers [41]. VANET potential applications are targeted to on-road safety, transport efficiency and information/entertainment (infotainment). The safety-related applications have real-time constraints that rely on one-hop broadcasting and multi-hop V2V and V2I communications as cooperative driving (platooning) [42]; the transport efficiency is pursued by traffic management that focuses on optimizing vehicles' flows by reducing travel time as avoiding jam situations [43]; and the comfort applications aim to provide the road traveler with infotainment to make more pleasant the journey [44].

As in a typical VANET, each vehicle has an On-Board Unit (OBU) but it is expected to exist RSUs installed along the roads as well it makes possible the communication among OBUs and RSUs by DSRC over the wireless channel. It allows arbitrary vehicles to broadcast safety messages to other nearby vehicles by V2V communications and to other RSUs by V2I communications. It makes the VANET a sensor network because it helps the traffic control center and other central servers to collect useful information about the road conditions, to offer mobility and security support in real-time [45]. For efficient VANET safety applications, a significant number of RSUs must be deployed to quantify the connectivity by the routing performance improvement in the broadcast environment to ensure scalability and mobility support [46]. Since the reliability and timeliness are two critical requirements of vehicle safety-related communication services in VANETs, the WAT is expected to play a key role in the intelligent transportation system by the DSRC, that was projected to support low-latency wireless data V2V and V2I communications, in order to work with sensors in the vehicles for safety on the road [47]. 5G-WAT applying in vehicular environments is going to lead the IoV to improve the road safety applications and is going to reduce the fatalities number that is caused by road accidents, through the development of the information sharing between moving vehicles regarding in the road. That's why safety applications are already attracting more consideration since the drivers' behavior monitoring is being used to alert the drivers about abnormal driving behaviors of other drivers on the road [48], [49].

Besides all these VANET applications, IoV is going several others applications which is bringing fundamental changes to urban management about transport, logistics, and the collective lifestyle, such as safe driving, traffic control, crash response, convenience services, social behaviors [50], [51], and many others. IoV is so the important evolution from VANET that is going to bring by the WAT the support for 5G network development to be employed on C-V2X communications which had its beginning on RAT.

III. 5G V2X STANDARDS

The steps towards 5G implementation standardization has been done in the Release 15 until March 2019. But, since then, the international scientific community has decided that while 5G is not ready to provide enhancements to support advanced services, LTE standardized by the Release 14 is going to be the only safety core for V2X communications. This decision is about the 5G V2X changes designed to enhance the carrier aggregation with support of up to eight bands, the use of frequencies above 6 Gigahertz (GHz), the flexible numerology, with the possibility of subcarrier spacing of 30 kHz and 60 kHz at 5.9 GHz, the possibility to transmit over single slots and even portions of slots, the addition of a feedback channel to allow higher reliability and lower latency, and the use of MIMO receiving antennas to enable spatial diversity especially useful to mitigate multipath in urban scenarios [22].

Nowadays, new solutions with high reliability and low latency are required to reduce congestion and the negative transportation impact on the environment and on people's quality of life. But these solutions must use the technological resources currently available and in an efficient way. V2X communication is a solution that is associated with the set of standards that will enable the vehicles to interact with the current infrastructure including roads and road users, and it can be available both by some of the major standardized technologies (DSRC/IEEE 802.11p, and its extension IEEE 802.11px) or C-V2X [52].

A. V2X COMMUNICATIONS PROTOCOLS

The IEEE specifies the 802.11 protocol to provide the MAC for WLAN communication in different frequencies. IEEE 802.11 enables easy Internet connections allowing the WLAN benefits such as the easier wireless stations deployment. Due to the wireless medium nature, radio signals are hackers vulnerable, by this kind of security problems, information such as MAC address helps adversaries to identify network devices since each MAC address has one unique assignment to network interface cards (NIC) given by the manufacturer and cleared during the data communication. It is hard to keep consistent, robust and secure communications in an IEEE 802.11 WLAN because of the connectivity, performance and security problems in the network. In fact, Wi-Fi is not going to provide consistent access to the Internet if "dead spots" are created on the physical spaces where the radio signals are hidden by network obstacles. Since some radio signals cannot head directly to the destination by obstacles or get delayed to reach there, the IEEE 802.11 increase retransmissions degrading the communication performance. The IEEE 802.11 traffic may suffer plenty of retransmissions especially in a hotspot setting, what can be used as a metric to distinguish among the wireless from the wired network, once Wi-Fi suffers a high rate of retransmissions by channel contention, interferences, or extra MAC overhead. That's why just 40% of the time is available for data packets transmitting because most part of it is used on radio signals retransmission, acknowledgment and management [53].

The IEEE 802.11p has been proposed as an amendment to IEEE 802.11. It supports traffic exchange in vehicular networks with the core mechanism of its MAC layer based on the prioritized, and with the contention based on the Enhanced Distributed Channel Access (EDCA) scheme of 802.11e and on the multichannel operation of the WAVE system [44], [54], as shown in Figure 11.

The IEEE 802.11p/DSRC standard incorporates the suite of IEEE 802.11s and IEEE 1609.x. It has modifications,

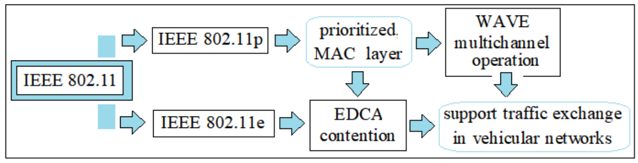

FIGURE 11. IEEE 802.11p and IEEE 802.11e.

and with decentralized architecture for which PHY protocol is OFDM based, while the MAC layer supports different QoS profiles and prioritizes data traffic. This protocol operates without network coverage in a fully distributed manner, because of the direct communication among the source and the destination endpoints that allows effective and immediate data transmission in/out the vehicles. However, the throughput and the end-to-end delay performance degrade quickly as the network load increases, and by this, the protocol is only suitable for transferring low bit rate data streams in vehicular environments and cannot be applicable to some V2X applications where transmission is not reliable beyond the communication range that typically extends to several 100s of meters. To overcome the IEEE 802.11p/DSRC deficiencies, IEEE 802.11px is the enhanced version of the protocol that brings the Space-Time Block Coding (STBC) mechanism to increase the performance under noisy channel transmissions, to improve around 40% the packet delivery rate, and to provide MIMO antenna capabilities with better OFDM layouts, as well very high throughput frame by enhancing the channel capacity [52], as shown in Figure 12.

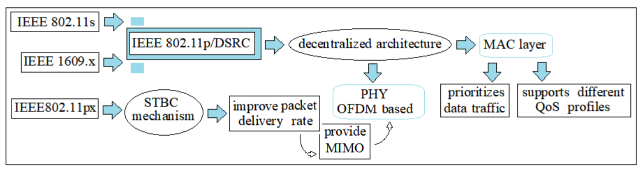

FIGURE 12. IEEE 802.11p/DSRC.

V2X communications are going to bring unlimited applications alone. In vehicles they are going to assist in better traffic management leading to several other benefits by intelligent transportation system (ITS). Nowadays, the two RATs that enable V2X communications are DSRC and C-V2X. Both of them operate in the 5.9 GHz band but C-V2X also in the cellular operators' licensed carrier. DSRC relies on the IEEE 802.11p standard and uses a MAC protocol because it is simple, well-characterized and able to realize distributed operations. While DSRC in vehicles has poor scalability and communication challenges by high-mobility environments, the 3GPP has developed C-V2X-LTE based on RAT. It enables the vehicles to operate in the lack of cellular infrastructure. To minimize the performance gap among DSRC and C-V2X and to support additional operation modes and to increase the offered throughput, the NR is being developed in Release 16 to associate the 5G NR, that was standardized in Release 15, as advanced support for V2X applications. C-V2X operates in or out of coverage scenarios and defines data transmission modes that enable direct V2X communications using the basic time-frequency resource structure similar to that of LTE. C-V2X users also transmit control information and reference signals such as the Demodulation Reference Signal (DMRS) which is used for channel estimation in LTE, inserted in two of the fourteen OFDM symbols or in a C-V2X sub-frame designed for high-mobility environments [17].

B. 5G INFRASTRUCTURE FOR V2X ECOSYSTEM

The 5G cellular systems are going to have the mmWave technology that operates in the spectrum between 30 GHz and 300 GHz, while the carrier frequencies are spread around 60 GHz with a 2.16 GHz channelization. Through beamforming, this technology is going to achieve high array gains by implementing large antennas which are going to get higher data rates up to several gigabits-per-second. Under ideal propagation conditions, mmWave systems outperform the IEEE 802.11p/DSRC standards for V2X communication.

To understand how 5G applications can be available, it is important to understand that a network slice is a combination of a Core Network (CN) and RAN functions. It has several functional requirements such as security and mobility support, and delivery performance such as latency, reliability, and throughput. An operator can compose different network slices in parallel. The data communication in one slice must not negatively affect services in other slices. Network slicing isolates functions and resources that are specifically tailored to the market needs. Slicing the CN segment affects Control Plane (CP) functionalities, such as mobility management, session management and authentication. It also affects User Plane (UP) functionalities, which become programmable and auto-configurable. By the shared nature of wireless resources, slicing the RAN is a less mature and challenging practice and encompasses various RATs. In order to offer strict latency and scalability of some applications, an E2E slice can be composed of different slice instances in the RAN and in the CN segments with a proper binding mechanism among them to support the targeted service.

To enable this technology of network slicing, the control (C) and the user (U) planes (P) functionalities shall be decoupled, but also the open Application Programming Interface (API) principles and the programmability of NFV and SDN shall be leveraged. With this CP and UP functionalities decoupling it is going to be possible to displace them in convenient locations: UP functions can be distributed close to the user to reduce service access latency, while CP functions can be placed in a central site which makes management and operation less complex. In the V2X ecosystem, the NFV can be dynamically instantiated, relocated, and horizontally/vertically scaled in accordance with the requirements of the services supported by a given slice, also with the network demands and to underlying infrastructure dynamics. A SDN controller can configure NFV chains in a given slice, and can flexibly interconnect UP/CP functionalities running over distributed hardware through the setup of paths that can be automatically reconfigured either to handle traffic engineering requirements or to react to possible network failures. In the V2X ecosystem, network slicing can effectively cope with a wide variety of use cases with divergent demands provided over the 5G infrastructure by multiple tenants [55]–[57].

The V2X is going to offer increased environmental perception to enable sensor-data sharing among vehicles and infrastructures. It will enhance the automated driving control, allowing the cooperation between the vehicles by the perception and the control subsystems of 5G [58].

A proposed 5G-V2X ecosystem has put the network intelligence on the SDN controller enabling the network dynamic management [15]. The OpenFlow (OF) protocol was adopted at the CN as a suitable alternative for 5G-V2X scenarios once it enables secure and direct communication with the SDN controller. To support V2X over 5G systems, the slices can logically isolate CP and UP as the 3GPP specifications to compose the network functions, the reference connection points, and the V2X communication modes (V2V, V2P, V2I, and V2N). The SDN function is the PHY network remote configuration that ensures the resources reserve for the various slices which are being demanded by different types of V2X services. In this way, each vehicle is going to require separate slices, one for each type of service.

The virtual cell allows approaches to be created centered on the user. It basically consists of several transmission points with an association pattern for each user and his/her respective mobility [59], [60]. The virtual cells are formed by the association of a user with several Transmission Points (TPs) around him/her. It is highlighted that TPs should act in a cooperative way and can adapt themselves to user mobility. With this, the V-Cell moves because of the user. For this, a controller is required to dynamically configure and manage virtual cells, which can be instantiated by network slice according to specific service requirements. Sahin *et al.* [60] present a V-Cell concept, that can be applied in several V2X use cases where broadcast communications for a group of vehicles occur, for example, in Cooperative Awareness Messages (CAM) and Decentralized Environment Notification Messages (DENMs). For this, the authors have adopted the steps of intra-VC optimization (transmission weight selection), power control and admission control. The authors assume that through co-operative beamforming all the TPs in a V-Cell are transmitting the same data in parallel to a vehicle so there is no intra-VC (V-Cell) interference. However, inter-V interference needs to be considered. A "s" data symbol of a data flow in a V-Cell is transmitted with a "p" transmission power and distributed throughout all TPs of the V-Cell according to the "w" weighting factors. This proposal was evaluated by the interactive software called MATrix LABoratory (MATLAB) used on simulations considering LTE systems channel parameters.

C. 5G V2X MODES, EVALUATION AND RECENT ADVANCES

Cellular-based V2X is the main radio interface to support V2V 5G communication. It is realized in three distinct modes: I) C-V2X refers to the uplink/downlink communication. It takes place within a base station. It can happen within RSUs too, that are going to be deployed to improve coverage and throughput, but also to reduce latency by fast radio access, handover, and coordinated resource allocation. II) Cellular assisted by V2V is a scheme where the base station coordinates the communication between vehicles by providing control information and instructions to vehicles, being well-suited for extremely low latency and high reliability V2V communication, as the network infrastructure ensures resource availability when requested, and time-consuming data transmission over the cellular network is avoided. III) Cellular unassisted by V2V is a mode where vehicles communicate without direct assistance from the base station. The resources are under control of the cellular network and the out-of-coverage users further remain synchronized to the cellular network and follow a common time reference because they are part of the cellular network.

The transition to one of the other modes can be very fast. In these three modes, the cellular network controls the data transmission between vehicles at different levels and ensures that their data rate, reliability, and latency needs are satisfied, as shown on Figure 13.

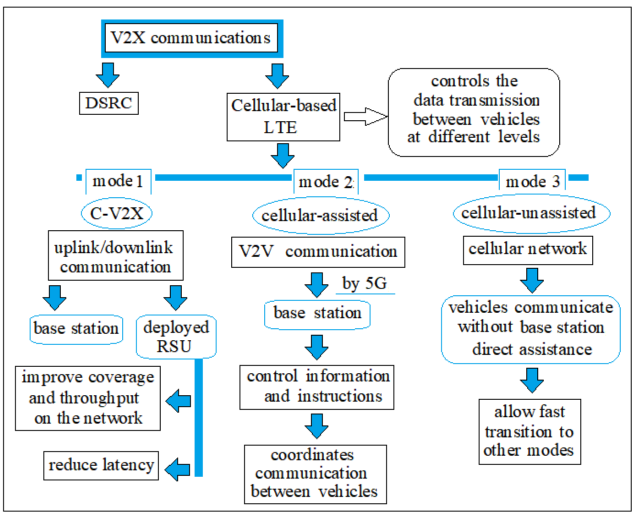

FIGURE 13. **V2X modes.**

One of the most challenging requirements of cellular-based V2X is the time and the frequency synchronization. C-V2X-LTE based and 5G V2X are going to require users to be synchronized among each other in order to avoid inter-symbol and inter-carrier interference, which are caused by the misalignment of multi-carrier signals transmitted over the air. The problem is the V2V and C-V2X coexistence in only one frequency band further that needs BSs and RSUs synchronization, which is in contradiction with the unsynchronized base stations typical scenario on the same or different network operators. That is why the common time reference distribution and the agreement among all involved network entities must be achieved before any data communication can be established [28].

To evaluate the V2X implementation, the 5G-DRIVE is a study-project that is going on in the European Union (EU) and in China to harmonize researches and trials on interoperability of the 5G networks in both areas and the evolution of the services that are operating at 3.5 GHz bands for Enhanced Mobile Broadband (eMBB) and at 3.5 and 5.9 GHz bands for V2X scenarios. In this direction, three levels of V2X testing were realized: 1st) in the laboratory, by conducted/wired mode or no over-the-air transmissions, to evaluate ITS-G5 and LTE-V2X (PC5) devices against the European Telecommunications Standards Institute (ETSI) harmonized standard for the 5.9 GHz band on the European Norm 302-571. 2nd) in large and small anechoic chambers, by a radiated mode that is only over-the-air transmissions, to measure harmful interference between ITS-G5 and PC5 devices in the 5.9 GHz band on co-channel and split band scenarios. 3rd) in outdoors, also by radiated mode to deploy ITS-G5 and PC5 devices, to compare and to contrast both technologies from a user experience point of view [61].

The goals of this harmonization are structured into the technical area to build pre-commercial E2E testbeds in two cities with sufficient coverage to perform extensive eMBB and IoV trials; to develop and trial key 5G technologies and services, including (but not limited to) MIMO at 3.5GHz, E2E network slicing, Mobile Edge Computing (MEC) for low latency services and V2X, SDN for transport and CN, and network and terminal security; to develop and trial cross-domain network slicing techniques across the two regions for new services; to demonstrate IoV services using V2N and V2V communications operating at 3.5 GHz and 5.9 GHz, respectively; to analyze potential system interoperability issues identified during the trials in both regions; and to submit joint contributions to 3GPP and other 5G standardization bodies regarding the key 5G technologies developed and evaluated in the project. The spectrum usage at 3.5 GHz for indoor and outdoor environments in selected trial sites is also a subject of interest of the project. It aims to joint evaluation reports and recommendations on 5G key spectrum bands in Europe and China; and to investigate regulatory issues regarding the deployment of V2X technologies, such as the V2V and C-V2X coexistence in the 5.9 GHz band [62].

A 5G V2X framework for social-enhanced communications is built upon the cellular V2X architecture specified by 3GPP considering the MEC and SDN technologies as expected in 5G systems. The SDN controller manages switches and other network elements, including the social V2X network application which is going to be augmented with the capability to configure social routing paths at different priorities. This controller can create social paths to connect friends, by injecting proper rules in the flow table of traversed switches through the OF southbound interface.

So, it can enforce algorithms that prioritize the data delivery to a given set of friends, because by having a topology global view it can define rules to configure a path towards among the access routers to which the intended destinations, avoiding packets duplication. While including the SDN in the CP, separated by the data plane, all the forwarding data is under CP commands which decisions trigger the establishment of direct communications among vehicles. In this way, the SDN potentials in the framework are empowered with MEC to clearly identify specific modules and their roles in the established communication, managing and exploiting the social relationships [63].

Besides SDN can realize the network transmission and control, it can also control network traffic flexibly by separating the control and the data planes, as allowing a dynamic load balancing for data plane traffic [64]. Vehicle communication architecture based on SDN was proposed to shield the heterogeneous access technologies differences produced in processing the vehicular data using different communication technologies such as cellular network and DSRC. It also can eliminate the differences among cellular and broadcast network by a multi-RAT integration based on a content distribution network which is able to satisfy audio and video services. By its turn, MEC integrates the Internet and the wireless network effectively. It adds the functions of computing, storage, and data processing in the wireless network, while builds an open platform for applications implant, and opens the information interaction between wireless networks and service servers by wireless application interface [65]–[68]. It upgrades the traditional base station to an intelligent base station. For the 5G network transmission and control, it is going to reduce the communication delay to help the road information be promptly transmitted to the data platform which accurately controls the traffic and implements V2X communication applications [18].

D. 5G V2X STUDIES AND PROJECTS

Several 5G studies and specification projects are taking place in many countries. Some of them are about the International Mobile Telecommunications for 2020 (IMT-2020) and beyond, targeting: radio regulations, operational aspects, protocols, test specifications, performance, QoS, Quality of Experience (QoE), and security; the 5G specifications, targeting: RAN, service and systems aspects, CN and terminals; the 5G technologies, targeting: mmWave transmission, 5G protocols, MEC and NFV; the 5G initiative, targeting: technology evolution towards 5G; the 5G Public-Private Partnership (5G-PPP) projects, targeting: 5G infrastructure and 5G architecture; the technical community, targeting: 5G development and deployment; the 5G network development on Americas, targeting: support and promotion for the full development of wireless technology capabilities; the 5G research and development by the industry, targeting: 5G RAT and network technologies; and much more [15].

The 5G development is going to benefit IoV. The RAT needs new networking schemes to assure the QoS demanded by the users and, for that, network slicing techniques are going to enable traffic differentiation to ensure flow isolation, resource assignment, and network scalability. To guide the 5G network slicing for IoV, an accurate bandwidth control with a full flow-isolation which is essential for vehicular critical systems was developed based on a MEC architecture. The MEC provides flexibility for the dynamic placement of the VNFs in charge of managing network traffic. This solution is able to integrate heterogeneous radio technologies such as cellular networks and specific IoT communications with potential in the vehicular sector, creating isolated network slices without risking the CN scalability [57].

Since the WAT is not able to answer all the vehicular network requirements, 5G is going to enable super-fast, reliable, and low latency connections. In fact, a 5G system is not just able to overcome previous generations in requirements such as capacity and latency, but it is also going to allow new applications and usage scenarios with very different requirements on capacity, reliability, and latency such as scenarios with autonomous vehicles. In this direction, it was proposed that the 5G vehicular network is going to be based on the integration of flexible and reconfigurable on-the-fly radio interfaces, so that the provided performance is going to include higher throughput, the possibility of sharing the same radio resources among users communicating through the infrastructure and V2V users, and the improvement of the spectrum usage and the overall system capacity. It is also going to offer lower latency in V2V communications, ultra-high reliability through V2V extended network coverage and through the exploitation of V2V network as fall back solution in the absence of the infrastructure, higher connectivity density, higher mobility and full coverage [69].

5G is going to develop the best technological solution to enable V2X improvements like road safety, traffic efficiency, and the availability of infotainment services, to provide V2V, V2P, V2I, V2N communications [70], [71]. Many groups are working on the integration of RAT into the cellular system architecture as a key concept in 5G mainly meant for Wi-Fi and/or ITS, as presented in Table 2.

Some studies have been carried out in various countries on the best ways of applying and using V2X, which have evolved chronologically in convergent directions, as shown in Table 3.

The LTE-V2X standards or PC5 (also known as LTE sidelink) and IEEE 802.11p (also known as DSRC or ITS-G5), both operating in the 5.9 GHz band provide direct communications between road users. 3GPP has covered, in 2016, the LTE by the Release 14 encompassing two interfaces: 1st) Uu interface connects end-user devices and vehicles to mobile network base stations and mobile core networks, for provision of Internet and V2N services; and 2nd) the PC5 that connects V2V to V2I and to V2P, providing low-latency and high-reliability for vehicular services, but not necessarily requiring assistance from a mobile network. The Protocol 802.11p/2012 is an extension of 802.11a/2010 (about Wi-Fi), and was standardized by the IEEE in 2009 including the multiple access mechanism on Carrier Sense Multiple

TABLE 2. 5G V2X supports.

Support	Specifications	Location	Responsible Group	Use Cases
ITS	Traffic message channel (TMC) and electronic fee collection (EFC) developed in the context of real-time traffic information (RTTI).	Europe	International telecommunication union (ITU), 3GPP, standards development organization (SDO), ETSI, national standardization organizations (NSO), and commission for European normalization (CEN) by technical committees (TCs) and European norms (ENs).	Department for Transport of London, United Kingdom.
Wi-Fi	DSRC with allocation of 5.9 GHz frequency band, spectrum subdivided into 10 MHz channels, using OFDM, a widely used multi-carrier transmission.	USA	ITU, 3GPP international organization for standardization (ISO), SDO, society of automotive engineers (SAE) and IEEE 802.11 by categorizing and learning modules (CALMs), PHY, MAC and WLAN.	Federal Communications Commission (FCC) drives 5.9 GHz proposal for C-V2X, Wi-Fi use forward in the USA.

TABLE 3. Studies about V2X.

Project	Location/Year	Main Contributions
[32]	China, Australia and USA / 2017	This paper considers the V2X communication network where each vehicle broadcasts its safety information to its neighborhood in each transmission period.
[72]	European Union / 2017	This report presents a quantitative analysis about the ability of cooperative intelligent transport systems (C-ITS) using short-range ad-hoc on direct communications to reduce the number of fatalities and serious injuries caused by motoring accidents.
[75]	Canada / 2017	This work presents DSRC and cellular technologies for V2X communication which keys are: 1st) VANET, developed specifically for the purpose of vehicular communication, and MANET.
[35]	USA, Germany, Finland, France and South Korea / 2018	In this paper it is explained that for real-time V2X communications success, it is paramount that 5G mobile networks be resilient, highly reliable, and secure in the delivery and reception of information to and from the vehicle.
[73]	Germany / 2018	This reference shows that in reason to provide QoS to the wireless system, new applications are going to be enabled by the 5G network which includes V2X communication that requires low E2E latency and ultra-high reliability.
[74]	Germany / 2018	This work presents how hybrid V2X communications enables multiple communication technologies coordination to efficiently adapt to the time-varying channel and road traffic conditions and also to increase the reliability and throughput of transmissions by combining multiple RATs in parallel.
[20]	Japan / 2018	In the research and standardization efforts toward the V2X, the technology is intended to enable the communication among vehicles and supporting road infrastructure.
[76]	USA and Japan / 2019	This work presents V2X as the technology able to allow vehicles to directly communicate with each other, with the roadside infrastructure, and with other road users to deliver an array of benefits in the form of road safety, traffic efficiency, smart mobility, environmental sustainability, and driver convenience.

Access (CSMA) protocols with Collision Avoidance (CA) as a protocol of statistical for direct communications [9], [10], [13], [17], [44], [52], [72].

On the V2X communication network, as each vehicle broadcasts safe information by low latency and high reliability, the Non-Orthogonal Multiple Access (NOMA) is used to reduce the access latency and to improve the packet reception probability. In this context, there are centralized scheduling and resource allocation in which the users and time/frequency elements are considered as disjoint sets of objects to be matched with each other [9], [13], [18], [32], [52], [55], [58], [63], [70]. Since the legacy from the cellular networks is not going to meet the service requirements for QoS to the wireless system, new applications that require low E2E latency and ultra-high reliability are going to be enabled by the 5G network, such as V2X communication. In addition, as due to the high-reliability requirement that avoids a single V2X transmission technology application to meet the targets in some scenarios, the multi-RATs scheme where the data packet travels through both the LTE-Uu and PC5 interfaces to obtain a diversity gain is an interesting proposal [9], [10], [22], [57], [63], [69], [73].

On the RAN, besides the Uu interface enhancements used for unicast and multi-/broadcast between network and vehicles, the most prominent feature is the D2D extension of the communication over PC5 interface to better support V2X communication. It is because, different from 802.11 protocol, PC5 does not implement carrier sensing to defer from channel access in case the channel is detected to be busy. The 5G-V2X 3GPP standards, from Release 14 to 16, consider the 5G splitting up in two tracks: the enhanced LTE that on V2X supports only fixed Transmission Time Intervals (TTI) of 1 ms, and the NR that is new spectrum and waveform, whose access design is going to enable a flexible and scalable TTI structure with intervals below 1 ms (500 μs is expected) in order to reduce air interface latencies, especially for time-critical V2X applications [22], [28], [41], [48], [57], [58], [69], [70], [74].

For V2X communication, DSRC and cellular technologies are keys, first because VANET was developed specifically for the purpose of vehicular communication, and MANET plays an important role in the development of ITS; then, cellular systems, WiMAX, microwave, Wi-Fi, DSRC, ZigBee (that is a specification for a suite of high level communication

TABLE 4. Uses and challengers of the existing technology.

Technology	Use	Challenger
Current Cellular	It provides connectivity up to 2 km with latency between 1.5 and 3.5 seconds. It is also moderately suitable for V2V applications, and more suitable for V2I.	It enables a high rate for data transmission to support U/L up to 75 Mbps and D/L up to 300 Mbps. It has high communication costs.
DSRC	It provides 300 to 1000 m medium range connectivity. It provides around 200 μs of ultra low latency. It enables adequate rate up to 27 Mbps for data transmission. It is highly suitable for V2V applications and moderately suitable for V2I applications.	It requires visibility. It is not suitable for multimedia features requiring high bandwidth. It also lacks extensive network coverage.

protocols used to create personal area networks built from small, and low-power digital radios, based on an IEEE 802 standard), Bluetooth, and mmWave are in some way already being used for wireless communication; and at the end, cellular (based on 3GPP-Release 14) and DSRC (based on IEEE 802.11p) have proved to be potential communication technologies enabling connected cars [75]. The researches in the field of MANET and VANET have shown that the use of DSRC supported by the IEEE 802.11p standard was supplemented by IEEE 1609 about wireless communication, including definitions of the architecture, management structure, security, and physical access for WAVE. Considering the communication between OBUs and RSUs infrastructures, DSRC-based communication provides a number of benefits for V2X applications, including low end-to-end latency, flexible organization due to a lack of centralized control, and relatively low cost. DSRC is the longest considered candidate for V2X applications and has been proposed as a mandated standard by the United States Department of Transportation (USDOT), as well as the ETSI and the Commission for European Normalization (CEN) among others. But another candidate access technology for V2X is the C-V2X based on LTE technology and the potential future 5G developments, which advantages include a much larger coverage area, pre-existing infrastructure, deterministic security, and QoS guarantees, as well more robust scalability. V2X is a specific case of ITS, dealing with wireless communication and coordination between vehicles and their environment. V2X communication occurs in the context of a dynamically changing VANET and, leveraging low-latency communications and information sharing, V2X technologies aim to help drivers of today and the autonomous systems of tomorrow coordinate more economically, efficiently, and safely [20], [45], [61], [70], [71].

The efforts to get 5G for V2X communications are being considered by 3GPP with the C-V2X designed to operate in two modes: I) D2D for V2V, V2I, and V2P direct communication without necessarily relying on the network involvement for scheduling. That is going to help in providing ultra-low latency communication and in transferring large amounts of data reliably among neighboring vehicles; and II) Device-to-Network (D2N) for V2N communication, which uses the traditional cellular links to enable cloud services to be part of the E2E solution by means of 5G network slicing architecture for vertical industries. In this PHY design, 5G NR is used as a key technology enabler to channel modeling aspects for V2X services [34], [35]. V2X is being considered essential for the autonomous driving ability development. Its features are non-line-of-sight sensing capability which allows vehicles to detect potential hazards, traffic, and road conditions from longer distances and sooner than other in-vehicle sensors such as cameras, radar, and Light Detection and Ranging (LiDAR). Although the legacy V2I technologies are currently in operational use worldwide for Electronic Toll Collection (ETC), advanced V2X systems are beginning to gain broad commercial acceptance with two competing technologies: IEEE 802.11p/DSRC standard, and the relatively new 3GPP-defined C-V2X which has a forward evolutionary path towards 5G. With an initial focus on road safety and traffic efficiency applications, Toyota and General Motors have already equipped some of their vehicle models with IEEE 802.11p-based V2X technology in Japan and North America [76].

Most of these studies converge to the fact that any 5G V2X access technology must be able to realize the transmission of basic safety and service messages between vehicular and infrastructural nodes. The most frequently studied WAT used in conjunction with V2X is based on IEEE 802.11p/DSRC and/or cellular/LTE. Besides much of the data passed to and from the connected car can also make use of the cellular, there is a great collection of requirements and new technology challenges which the overcoming is seen as the next step for 5G cellular networks.

IV. CHALLENGES AND FUTURE DIRECTIONS

The current cellular technology provides connectivity up to 2 km with latency between 1.5 and 3.5 seconds. It enables a high rate for data transmission to support U/L up to 75 Mbps and D/L up to 300 Mbps. It is also moderately suitable for V2V applications, more suitable for V2I but it has high communication costs. The DSRC technology provides 300 to 1000 meters medium range connectivity. It provides around 200 μs of ultra low latency, and it enables adequate rate up to 27 Mbps for data transmission. It is highly suitable for V2V applications and moderately suitable for V2I applications but it requires visibility and it is not suitable for multimedia features requiring high bandwidth. It also lacks extensive network coverage [75], [77]. These analyses can be better observed on Table 4.

TABLE 5. Issues and solutions of IoV technology.

Technological Aspects	Issues	Solutions
Big Data	Great number of connected vehicles creates a large volume of data to be processed and storage.	Mobile cloud computing will handle the big data.
Security and Privacy	IoV is a target for intrusions and cyber-attacks that may lead to physical damage and privacy leakages.	Efficient data security and privacy system are needed.
Reliability	The system has to deal with incorrect data, as well as faulty communications.	Vehicle safety shall to be offered before entertainment.
Mobility	When vehicles are moving fast and the network topology changes continuously, it is difficult to keep nodes connected and to transmit and receive in real-time.	Stability for no-stop connections shall to be offered to the network.
Standards	One international standard for effective V2V communication is lacked.	Governments shall participate and encourage industries to collaborate in the technological development.

Among the IoV issues and their respective solutions the following ones can be cited:

- *Big Data*: great number of connected vehicles creates a large volume of data to be processed and storage, such as driverless cars that are expected to process 1 GB of data per second. So, the mobile cloud computing and the big data analytics will play an important role in handling big data [78].
- *Security and Privacy*: as an open public network which involves many different integrating technologies, services and standards, IoV is a target for intrusions and cyber-attacks that may lead to physical damage and privacy leakages. So, it is going to need an efficient data security and privacy system [21], [79].
- *Reliability*: as cars, sensors, and network hardware can have bad function, the system has to deal with incorrect data, as well as faulty communications such as service denial attacks. For that the technology shall offer safety to the vehicle before entertainment [80].
- *Mobility*: It is difficult to keep the nodes connected and provide them with resources to transmit and receive in real-time when vehicles are moving fast and the network topology keeps changing continuously. To solve that, the system shall offer network stability for no-stop connections [81].
- *Standards*: the lack of one international standard makes difficult the effective V2V communication. That is why governments shall participate and encourage industries to collaborate in the technological development of the best practices and to accelerate adoption, standardization, and network interoperability by open standards to enable smooth sharing of information [71], [82], [83].

The summary of the issues and solutions of IoV technology can be observed on Table 5.

A. TECHNOLOGICAL CHALLENGES

The specific challenges that are being faced by the 5G implementation are: 1st) standards integration is a great challenge because there are multiple groups working around of the interoperability and the backward compatibility with older technologies such as 3G and 4G. 2nd) there is no common architecture for the engineering interconnection that would allow the technological knowledge to be shared and regularized for international use. 3rd) the infrastructure installation is a huge task that deals with the spectrum and installing new antennas, because 5G network is going to rely, at least in part, on higher-frequency bands where is going to exist more space in the available airwaves, but signals cannot nearly travel as far as they could over the frequencies used for 4G. 4th) obstacles like buildings, trees, and even bad weather can also cause interference on the communications requiring more BBs using MIMO antennas to ensure better coverage.

There are several challenges for 5G V2X wireless accesses but the greatest is related to the mmWave technology. It is referred to a communication pattern that uses Extremely High Frequency (EHF), between 30 and 300 GHz band of the radio frequency spectrum. Before the 5G application, mmWave had a historical use on the automotive industry when the 77 GHz band has already been used in the context of Long Range Radar (LRR) in automatic cruise control and other car sensor applications.

As mmWave technology has very strong directional high radio frequencies characteristics, it requires Line-Of-Sight (LOS) connection between a transmitting and a receiving car, or an infrastructure element. It is difficult to achieve in mobile scenarios across different road infrastructure and geographic settings. This means that pre-sense crash warning systems that rely on wireless communication occurring in conditions, when LOS is not available, will not be an easy task. There is also the issue about the car roof that is unsuitable for 360^o antenna coverage which is necessary for V2X applications. The low antenna height, the strong directional properties of the band and the cars themselves blocking the transmissions on de road are other significant issues for the 5G use [20]. The summary of the challengers for 5G implementation can be observed on Table 6.

In this context, it is also important to realize that DSRC is a mature technology that has been widely tested and commercialized in many countries. But it still has some coexistence troubles with LTE-V2X (PC5) which has only started to be standardized in 2015, and therefore it is not yet present in commercial services [83]. Since these two technologies have to coexist in the future generation wireless network to provide V2X communications on IoV, they shall be compared to

TABLE 6. Challenges for 5G implementation.

Technology	Challenges	Specification
5G	Standards integration	There are multiple groups working around of the interoperability.
	Architecture	There is no common technology to be shared and regularized for international use.
	Infrastructure installation	The 5G network requires spectrum and installing new antennas to rely on higher-frequency bands.
	Obstacles	Whatever those cause interference on the communications make the connections ask for better coverage by MIMO BBs.
	Device support	It is an already overcome challenge because there are available 5G-enabled smart-phones for ubiquitous network and autonomous vehicle technology is in the market even still in limited forms.
	Cost	The new great challenge is to make such an expensive network become available in remote and rural areas.
5G V2X	mmWave technology	It has EHF that requires LOS connections.
	Other significant issues	Car roof is unsuitable for antenna escapable of the 360^o coverage which is necessary for V2X applications. Low antenna height, strong directional properties of the band, and cars themselves block the transmissions on de road.
	Security and privacy	It is also an already overcome challenge because the 5G has standards and sophisticated cyber-security warnings designed to establish trust between networks.
	Transfer data increase	The great new challenge is the ability to let multiple cars negotiate the best way to traverse an intersection or share sensor data like video cameras and radar by a device for unifying all vehicles in the road together.
6G and beyond	Connection in remote areas	Updates on 5G deployment experiences, further technology development, and new business models are expected to guide the telecoms industry on the super-efficient connectivity.

allow a better overview on their challenges [83], as shown in Table 7.

LTE-V2X provides much better performance with regard to data transmission rate supporting high bandwidth demand for applications. In 5G V2X, data rate and reliability are going to be even higher than the current values of LTE-V2X which enhance cellular base stations to cover larger areas. Compared to DSRC, the mobility support of LTE-V2X is worse. But even if terminals and base stations have to be upgraded, LTE-V2X can be associated to cellular infrastructure and be largely reused. The existing facility can allow telecommunication operators to expand in the IoV market.

By its turn, DSRC is more cost-effective than LTE-V2X, as the latter leans on a worked-on version of cellular networks, which usually offer more services, and therefore is more complex and expensive. It provides smaller coverage due to its intrinsic short-range characteristic and, consequently, high-speed vehicles can only connect to RSUs for short periods of time. Even if multi-hop communication is employed to extend the coverage, a route to an RSU cannot always be guaranteed, especially in networks with low vehicle density. DSRC supports more robust dissemination of safety messages than LTE-V2X. DSRC presents good performance as mobility support, but the lack of perspective in the standard evolution can be a serious limitation for its future development. Even though its technology has over 15 years offering products available on the market and already currently deployed on the road in the United States, Europe, Japan, Australia, and Korea [83], the DSRC future perspective is not promising.

Despite the differences among both technologies, some challenges are common for them:

- *Low data rates*: to achieve fully automated safety-critical functions, the autonomous vehicles constantly exchange raw sensor data by different V2X modes. This can create a huge amount of data transmission. Neither DSRC nor LTE-V2X can currently support the required data rate for real autonomous vehicles.
- *Low PDR and high latency*: due to the IEEE 802.11 standards design, in highly dense networks, CSMA can cause high channel contention among vehicles and it may further degrade the performance of a network, causing low PDR and increased latency. In LTE-V2X, instead, data packets are required to be sent to the base station before being forwarded to the destination vehicle. It is mainly because of the centralized control nature of the cellular network. Even if the cellular D2D feature can provide direct communication between two vehicles, such connections are not going to be authenticated. Therefore the authentication capability provided by the base station will be needed.
- *Lack of multi-hop routing*: the technique of multi-hop packet relaying has not been widely standardized neither by DSRC nor LTE-V2X. Also, the ETSI/TC-ITS architecture is the only one that involves geographical routing functionality to support road transport and telematics. The heavyweight design of LTE-V2X translates into a higher overhead, and without multi-hop routing, in a high dense network, base stations could be overloaded, causing high latency. Therefore, there is the need to avoid all packets being sent to base stations for either authentication or reaching other vehicles.
- *Lack of ad hoc networking*: under severe natural disasters like flooding and earthquakes, traditional

TABLE 7. Technical aspects.

Technical Aspects	DSRC	LTE-V2X	4G	5G V2X
Theoretical bit rate	3-27 Mb/s	20 Mb/s (uplink) 80 Mb/s (downlink)	75 Mb/s (uplink) 300 Mb/s (downlink)	10 Gb/s (uplink) 20 Gb/s (downlink)
Practice bit rate	3.5 Mb/s	-	20 Mb/s	1 Gb/s
Theoretical coverage	500 m	More than 1 km	5 km	1732 m (rural) 500 m (urban macro) 200 m (urban micro)
Practice coverage	Less than 500 m	Up to 150 m (urban) Up to 320 m (highway)	Up to 2 km	-
Theoretical mobility support	More than 250 km/h	Less than 140 km/h	Between 120 and 350 km/h	Up to 500 km/h
Theoretical latency	Less than 50 ms	Less than 100 ms or less than 20 ms in emergency situations	Less than 10 ms	Less than 4 ms
Frequency band	5.9 GHz	5.9 GHz	0.45 - 3.8 GHz Unlicensed band (5 GHz)	0.45 – 6 GHz (Frequency range 1) 24 - 52.6 GHz (Frequency range 2)
System bandwidth	10 MHz	10 MHz	20 MHz	50, 100, 200, 400 MHz (above 6 GHz)
Subcarrier spacing	156.25kHz	15kHz	15kHz	15, 30, 60 kHz (Frequency range 1) 60, 120 kHz (Frequency range 2)
Multi-tier RAT	2-tier	2-tier	3-tier	n-tier
Number of subcarriers	52	600	1200	3300
Power limits [Effective Isotropic Radiated Power (EIRP)]	33 dBm (Private RSUs and mobile OBUs) 40 dBm (Public safety mobile OBUs) 44.8 dBm (Public safety RSUs)	23 dBm (OBU) 33 dBm (RSU)	23 dBm (OBU) 33 dBm (RSU)	33 dBm (OBU and RSU) 46 dBm (BSs)

infrastructure communication networks can be damaged and cause communication paralysis. This creates big problems for firefighters and emergency rescue teams (even though usually they might use their low-frequency emergency communication capabilities). Therefore, it is necessary to involve ad hoc communications among vehicles, and vehicles and RSUs to handle the growing vehicle generated data traffic [83].

One of the V2X communication problems, associated with DSRC, is related to the vehicles high-speed mobility, to the currently incomplete infrastructure, and to the vulnerable reliability of service connection. It means that, V2X with DSRC alone cannot meet requirements for future autonomous driving scenarios. Under agreed communication protocol and data interaction standard, wireless communication and information exchange may be conducted on IoV by V2X. With the evolution of mobile communication industry, 5G network service is closer to answer the user requirements by its enhanced customization capability, deep integration among network and business, and more friendly services.

Due to its elasticity and expandability, 5G network slicing may explore and release the telecommunication technology potentiality, enhancing efficiency and reducing cost. It can easily attempt the potential market demand in fields such as vehicles, smart city, and industrial manufacturing. Moreover, with the network slice broker introduction, the 5G network slicing technology may realize network resources sharing, integration and allocation. These tasks were mutually independent originally. They may be realized in real-time including special requirements network resources dynamical scheduling. The DSRC and the C-V2X technologies combination shall be a good solution for connected vehicles, because it does not just enable the safe driving but it can supply high-quality telematics services to the drivers [84]. With the availability increasing of vehicles which are able to support higher automation levels, the need for coordination among vehicles becomes even more important. Safety requirements and automated driving are defined as the most stringent tasks [58].

Cooperative lane change, collision avoidance, and convoy management are typical examples of V2X use cases that are eventually expected to lead to fully connected automated vehicles. There is also a list of functional requirements that should be supported by communication technologies also for other V2X use cases implementation. They are different modes of dissemination, single-hop or multi-hop V2X communication ranges, connection management, V2X message prioritization and capability for congestion control and data retransmission [85], [86].

In fact, communication technologies such as DSRC can help to provide greater benefits to drivers, as automotive industry increases the number of vehicles with additional sensors, including radars and cameras. In the USA, DSRC currently communicates using seven channels in the 5.9-GHz spectrum. The basic safety message (BSM) use as a V2V base that is extended to the roadway infrastructure and users establishes a V2X ecosystem. As this technology does not require a cellular or a data network, vehicles equipped with DSRC do not require coverage or infrastructure costs, nor incur in any cellular network carrier charges. DSRC provides a foundation key for interoperability of messages by V2X and a pathway for the deployment of other radio frequency technologies, such as long-term evolution LTE-V2X and 5G V2X. With the superior performance and the evolutionary path to 5G, C-V2X is the communication technology that is better to be the global solution for V2X communications. C-V2X supports the wireless communication advances and new automotive applications that are needed for enhancements in safety and autonomous driving, and traffic efficiency [87].

The C-V2X direct communications integrated into an LTE-based telematics unit, this technology is also cost-effective in the broader transportation ecosystem [88]. Although DSRC can provide reliable V2I and V2V communications, the achievable data rate may not satisfy many emerging vehicular applications such as video/image transmission and autonomous driving. In this case, 5G V2X combine the advantages of both cellular and ad hoc connectivity among vehicles to the vehicular communications development. Compared with DSRC, 5G employs more advanced techniques, such as MIMO that can significantly improve the reliability and efficiency of vehicular communications, leading to high data rate and low latency [89].

B. FUTURE DIRECTIONS

The summary of the futures directions can be observed in Table 8.

To generate a more promising solution for vehicular communications, 5GAA suggests allocating separate 10 Megahertz (MHz) channels to both technologies to avoid any interference between them. These communications can make the combination with the advantages of both technologies DSRC and C-V2X, creating a hybrid approach. It is working in Europe but in the massive V2X communications scenarios, the traffic load produced by several automotive devices is difficult to handle with the conventional cellular and DSRC solutions. In this context, the use of SDN for vehicle (SDN-V) or Software-Defined for IoV (SDIoV) presents a promising architecture which can enable the DSRC and C-V2X coexistence, because it is going to allow the management and the centralized control of the heterogeneous 5G [15], [83], [90]–[93].

With a global view, SDIoV is going to provide distinguishing features such as intelligent multi-hop routing, dynamic resource allocation, and advanced mobility support. It is also going to allow the creation of an ad hoc network to guarantee robustness and seamless communication. Through SDIoV, artificial intelligence mechanisms can be deployed on the control plane in vehicles as part of the V2X technology. It can provide traffic control, intelligent routing strategies, and joint scheduling in real-time [2].

The SDIoV architecture involves multiple communication technologies that can be used to support fully autonomous driving by allowing a network with the DSRC and the C-V2X coexistence. The SDIoV also presents enough scalability to upgrade the current network to 5G and beyond features, to enhance the communication quality.

The 5G technology is going to offer significant benefits from a range of mechanisms and capabilities to the future automotive systems, especially on the V2X context. It is going to improve the driving experience with safety and infotainment applications. 5G requires the mmWave that is an EHF used to achieve the requirements for better reliability, lower latency, and higher data rate [94]. Such 5G cellular systems employing mmWave at EHF provide Gigabit-per-second (Gbit/s) throughputs [80], [95]. So, the connection among 5G wireless standards and vehicular communication systems is made by mmWaves transmissions because they are able to provide Gbit/s data rates, required for raw sensor data exchange among vehicles with applications on V2X communications [96]. The very high the numbers of sensors, that are going to be deployed on vehicles, the very hard is the initial access procedure due to massive connection attempts [94].

In short time, 5G is going to promote great model business change enabling new services and improving the existing ones, due to the technology enablers in RAT areas for V2X communications and network virtualization. These enablers are already bringing components such as network slicing [33], [55], sidelink [13], [22], and others [97]. But the way they affect business relationships is also changing.

The automotive sector that has typically been a well-defined and specialized "value chain", due to connectivity guided by the new 5G technologies, now is being transformed into a "value network" in reference to economic ecosystems where every market "node" relies on others to create a common value proposition [98].

In this context, V2X communications and the technologies associated with 5G are going to disrupt current business relationships and create more collaborative business environments. It is almost impossible that only one company can have the competence to create all solutions for the increasing industrial and commercial demands in this new universe of possibilities. The universe will be a place where cooperation among different sectors is essential [99].

V2X is a technology that demands a reliable Internet connection. The IoV feature can help autonomous vehicles use in smart cities and highways, where the reliable and fast Internet connection shall be developed by 5G network [19]. This demands cooperation among governmental sectors and industries, also because IoV can be easily manipulated by irresponsible sides, which creates security concerns about the network connectivity, the user privacy, and autonomous vehicles' effective control [21], [45], [79], [100]. On another side, 3GPP has developed some functions to provide cellular standards enhancements specifically for V2V. Concentrated on V2X standards, direct V2V communications can be

TABLE 8. The expectatives of future 5G aspects.

Aspect for search	Expectative
Vehicular communications associating the advantages of DSRC and C-V2X technologies.	It allocates separate channels to both technologies to avoid any interference between them, creating a hybrid approach. The traffic load produced by several automotive devices in the massive V2X communications scenarios is difficult to handle with the conventional cellular and DSRC solutions.
Use of SDN-V or SDIoV architecture.	It enables DSRC and C-V2X coexistence to allow management and centralized control of heterogeneous 5G network.
SDIoV provide features such as intelligent multi-hop routing, dynamic resource allocation, and advanced mobility support.	It allows the creation of an ad hoc network to guarantee robustness and seamless communication.
SDIoV artificial intelligence mechanisms are deployed on the control plane in vehicles as part of the V2X technology.	It provides traffic control, intelligent routing strategies, and joint scheduling in real-time.
SDIoV architecture involves multiple communication technologies to support fully autonomous driving by allowing a network with the DSRC and the C-V2X coexistence.	It presents enough scalability to upgrade the current network to 5G and beyond features, to enhance the communication quality.
5G technology offers significant benefits from a range of mechanisms and capabilities to the future automotive systems, especially on the V2X context.	It improves the driving experience with safety and infotainment applications.
5G requires mmWave as EFH to achieve the requirements for better reliability, lower latency, and higher data rate.	It provides Gbit/s throughputs required for raw sensor data exchange among vehicles with applications on V2X communications. The very high the numbers of sensors, that are going to be deployed on vehicles, the very hard is the initial access procedure due to massive connection attempts.
5G promotes great model business change enabling new services and improving the existing ones, due to the technology enablers in RAT areas for V2X communications and network virtualization.	These enablers are already bringing new components and affecting business relationships. V2X communications and the technologies associated with 5G are going to disrupt current business relationships and create more collaborative business environments.
V2X technology demands a reliable Internet connection and the IoV feature helps autonomous vehicles use in smart cities and highways.	It asks for reliable and fast Internet connection to be developed by the 5G network. It demands cooperation among governmental sectors and industries.
5G V2X development involves the IoV technological needs for commercial business, with the improvement of vehicle surveillance and real-time tracking, with monitoring and analysis of traffic data, and logistic movement, and also with centralized storage and management of massive data in the data center.	It indicates that future business growth depends on the establishment of an agile 5G V2X data center architecture, which includes efficient storage, network, and computing performance to support the IoV demands and growth.
Modern vehicles connected through multi-RAT exchange massive information with their surrounding environment.	It needs VANET evolves to support V2X on the IoV architecture for an efficient and intelligent prospect for future communications and transportation systems.
Technological advances in communications and control systems have changed the cars into formidable sensor platforms.	These absorb information from the environment and from other cars to feed themselves back, assisting in safe navigation, pollution control, and traffic management.
5G V2X solutions ready for deployment by hardware/software are commercially available.	5G V2X communication allows the autonomous driving by perceptions, path planning, real-time local updates, and coordinated driving.
With CARMEN, cars with different levels of autonomy are 5G connected anyway.	It provides a platform that leverages the most recent advances of this technology to support safer and intelligent transportation by communications. 5G promotes awareness about the extended road situations, enabling vehicles and infrastructure to share information, exploring different network architectures and configurations to guarantee the coverage at all times.

allowed by the distributed scheduling, which uses a mechanism based on sensing with the semi-persistent transmission, without introducing a detour through the BS.

Some tests, realized in South Korea and German, have already shown that 5G performance is going to support V2X services. They also have shown implemented new key 5G capabilities with multiple devices operating in the mmWave and multiple connected-car-use cases. V2V communication represents the very first step toward achieving fully autonomous driving in the 5G era [99]. Other tests have been reported by [61], [62], [101]–[104], and [105]. These tests have accelerated 5G research and development and have the intention to facilitate the integration of the technical requirements of various industries into upcoming international 5G-standardization activities.

Some perspectives for the 5G V2X development involve the IoV technological needs for the commercial business, with the improvement of vehicle surveillance and real-time tracking, with monitoring and analysis of traffic data, and logistic movement, and also with centralized storage and management of massive data in the data center. It indicates that future business growth depends on the establishment of an agile 5G V2X data center architecture, which includes efficient storage, network, and computing performance to support the IoV demands and growth [106].

Modern vehicles are going to be connected through heterogeneous RAT (multi-RAT) and they are going to exchange massive information with their surrounding environment as the automotive telematics are being developed. As the network scale is expanding both the real-time and the long-term information processing, the traditional VANET shall evolve to support V2X on the IoV architecture. It is a promise for an efficient and intelligent prospect for future communications and transportation systems [78].

Traditionally, the vehicle has been the extension of the man, obeying the driver's commands, but the technological advances in communications and control systems have changed the cars into formidable sensor platforms. These platforms absorb information from the environment and from other cars to feed themselves back, assisting in safe navigation, pollution control, and traffic management. The next step in this evolution is the autonomous vehicles as an important instance of the IoT, where the IoV is going to have communications, storage, intelligence, and learning capabilities to anticipate the customers' intentions [107].

Finally, with the commercial availability of the 5G V2X solutions ready for deployment by hardware/software, the expectative for 5G V2X communication is on the autonomous driving by perceptions, path planning, real-time local updates, and coordinated driving [108].

With the Connected and Automated Road Mobility in the European Union (CARMEN), the cars with different levels of autonomy are going to be 5G connected anyway. It provides a platform that leverages the most recent advances of this technology to support safer and intelligent transportation by communications about speed, position, intended trajectories and much more. 5G is going to promote awareness about the extended road situations, enabling vehicles and infrastructure to share information, exploring different network architectures and configurations to guarantee the coverage at all times [109].

That is why public authorities, groups of Original Equipment Manufacturer (OEM) and road operators have worked together to create an economic low-latency communication system which can improve road safety, traffic management, and road transport performance. In this context, V2X provides direct connections within a C-ITS also called ITS-G5 technology that is associated with WAVE and/or DSRC, which is based on the IEEE 802.11 standard (WiFi) or ETSI EN 302 663. Nowadays, there is already, in several countries, a great number of manufacturers able to provide ITS-G5 technological solutions.

V. CONCLUSION

This survey is a study about the 5G technology evolution, its standards and the infrastructure associated with the V2X ecosystem by IoV. The 5G challenges in the technologies developed for vehicular communications were especially considered. Initially, the survey presents the IoV architecture with the types of V2X interactions, the 5G technology with its features on C-V2X, the evolution from the RAT to C-V2X communications, and also from VANET to IoV applications. Then, the survey introduces the steps towards the 5G implementation standardization by Release 15. It also points that only the LTE standardized by the Release 14 is still the safety core for V2X communications, despite the challenges such as low data rates, low PDR and high latency, lack of multi-hop routing, and lack of ad hoc networking, noticed as also compared to DSRC and 4G. After the analysis of 84 literature works, the present paper has identified the connectivity between vehicles and cellular networks as a big research challenge because of the fast vehicular mobility and the legacy networks signaling patterns. As a secular technology, vehicular upgrades tend to take a long time to change, consuming all types of used features that can be controlled by software. Besides that, there will still be millions of cars connected by 5G networks, behaving like cell phones for communication, identification, and network services. With superior performance and evolutionary path already crossed, 5G technology is well-positioned to be the global solution for V2X communications. It supports advancements in wireless connections and in new automotive applications that are expected for enhancements in safety, autonomous driving, and traffic efficiency. Therefore, wireless communications become paramount and are the pillars of vehicular systems. New network requirements, such as high data transmission rates (between 1 to 20 Gbps), massive connections (estimated at 1 million connected devices and cars), low latency ultra-low communications (1ms), and high-speed mobility support (up to 500 km/h), are still awaited. The great identified IoV technology issues were the ones about big data, security, privacy, reliability, mobility, and also standards. In the end, it is expected that the vehicular communications will associate the advantages of DSRC and C-V2X technologies, the use of SDIoV architecture, and other interesting aspects that are pointed to be considered in future works.

REFERENCES

[1] F. D. da Cunha, L. Villas, A. Boukerche, G. Maia, A. C. Viana, R. Mini, and A. Loureiro, "Data communication in VANETs: Survey, applications and challenges," *Ad Hoc Netw.*, vol. 44, pp. 90–103, May 2016.

[2] M. Chen, Y. Tian, G. Fortino, J. Zhang, and I. Humar, "Cognitive Internet of vehicles," *Comput. Commun.*, vol. 120, pp. 58–70, May 2018.

[3] H. Ye, L. Liang, G. Ye Li, J. Kim, L. Lu, and M. Wu, "Machine learning for vehicular networks: Recent advances and application examples," *IEEE Veh. Technol. Mag.*, vol. 13, no. 2, pp. 94–101, Jun. 2018.

[4] L. Liang, H. Ye, and G. Y. Li, "Toward intelligent vehicular networks: A machine learning framework," *IEEE Internet Things J.*, vol. 6, no. 1, pp. 124–135, Feb. 2019.

[5] F. Yang, S. Wang, J. Li, Z. Liu, and Q. Sun, "An overview of Internet of vehicles," *China Commun.*, vol. 11, no. 10, pp. 1–15, Oct. 2014.

[6] D. Kombate and Wanglina, "The Internet of vehicles based on 5G communications," in *Proc. IEEE Int. Conf. Internet Things (iThings) IEEE Green Comput. Commun. (GreenCom) IEEE Cyber, Phys. Social Comput. (CPSCom) IEEE Smart Data (SmartData)*, Dec. 2016, pp. 445–448.

[7] F. J. Martin-Vega, M. C. Aguayo-Torres, G. Gomez, J. T. Entrambasaguas, and T. Q. Duong, "Key technologies, modeling approaches, and challenges for millimeter-wave vehicular communications," *IEEE Commun. Mag.*, vol. 56, no. 10, pp. 28–35, Oct. 2018.

[8] B. Coll-Perales, J. Gozalvez, and M. Gruteser, "Sub-6GHz assisted MAC for millimeter wave vehicular communications," *IEEE Commun. Mag.*, vol. 57, no. 3, pp. 125–131, Mar. 2019.

[9] 5G-PPP Automotive Working Group. (2018). *A study 5G V2X Deployment*. [Online]. Available: https://5g-ppp.eu/wp-content/uploads/2018/02/5G-PPP-Automotive-WG-White-Paper_Feb. 2018.pdf

[10] J. Wang, Y. Shao, Y. Ge, and R. Yu, "A survey of vehicle to everything (V2X) testing," *Sensors*, vol. 19, no. 2, p. 334, Jan. 2019.

[11] M. Kutila, P. Pyykonen, Q. Huang, W. Deng, W. Lei, and E. Pollakis, "C-V2X supported automated driving," in *Proc. IEEE Int. Conf. Commun. Workshops (ICC Workshops)*, Shanghai, China, May 2019, pp. 1–5.

[12] Qualcomm. (2019). *Cellular Vehicle-to-Everything*. [Online]. Available: https://www.qualcomm.com/invention/5g/cellular-v2x

[13] R. Molina-Masegosa and J. Gozalvez, "LTE-V for sidelink 5G V2X vehicular communications: A new 5G technology for short-range Vehicle-to-Everything communications," *IEEE Veh. Technol. Mag.*, vol. 12, no. 4, pp. 30–39, Dec. 2017.

[14] V. Mannoni, V. Berg, S. Sesia, and E. Perraud, "A comparison of the V2X communication systems: ITS-G5 and C-V2X," in *Proc. IEEE 89th Veh. Technol. Conf. (VTC-Spring)*, Kuala Lumpur, Malaysia, Apr. 2019, pp. 1–5.
[15] C. Storck and F. Duarte-Figueiredo, "A 5G V2X ecosystem providing Internet of vehicles," *Sensors*, vol. 19, no. 3, p. 550, Jan. 2019.
[16] C. R. Storck and F. Duarte-Figueiredo, "5G V2X ecosystem providing entertainment on board using mm wave communications," in *Proc. IEEE 10th Latin-Amer. Conf. Commun. (LATINCOM)*, Guadalajara, Mexico, Nov. 2018, pp. 1–6.
[17] G. Naik, B. Choudhury, and J. Park, "IEEE 802.11 bd & 5G NR V2X: Evolution of radio access technologies for V2X communications," *IEEE Access*, vol. 7, pp. 70169–70184, 2019.
[18] F. Yang, J. Li, T. Lei, and S. Wang, "Architecture and key technologies for Internet of vehicles: A survey," *J. Commun. Inf. Netw.*, vol. 2, no. 2, pp. 1–17, Jun. 2017.
[19] U. Z. A. Hamid, H. Zamzuri, and D. K. Limbu, "Internet of vehicle (IoV) applications in expediting the implementation of smart highway of autonomous vehicle: A survey," in *Performability in Internet of Things*, F. Al-Turjman, Ed. Cham, Switzerland: Springer, 2019, pp. 137–157, doi: 10.1007/978-3-319-93557-7_9.
[20] Z. MacHardy, A. Khan, K. Obana, and S. Iwashina, "V2X access technologies: Regulation, research, and remaining challenges," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 3, pp. 1858–1877, 3rd Quart., 2018.
[21] M. Muhammad and G. A. Safdar, "Survey on existing authentication issues for cellular-assisted V2X communication," *Veh. Commun.*, vol. 12, pp. 50–65, Apr. 2018.
[22] A. Bazzi, G. Cecchini, M. Menarini, B. M. Masini, and A. Zanella, "Survey and perspectives of vehicular Wi-Fi versus sidelink cellular-V2X in the 5G era," *Future Internet*, vol. 11, no. 6, p. 122, May 2019.
[23] J. M. Lozano Domínguez and T. J. Mateo Sanguino, "Review on V2X, I2X, and P2X communications and their applications: A comprehensive analysis over time," *Sensors*, vol. 19, no. 12, p. 2756, Jun. 2019.
[24] O. Kaiwartya, A. H. Abdullah, Y. Cao, A. Altameem, M. Prasad, C.-T. Lin, and X. Liu, "Internet of vehicles: Motivation, layered architecture, network model, challenges, and future aspects," *IEEE Access*, vol. 4, pp. 5356–5373, 2016.
[25] J. Wan, J. Liu, Z. Shao, A. Vasilakos, M. Imran, and K. Zhou, "Mobile crowd sensing for traffic prediction in Internet of vehicles," *Sensors*, vol. 16, no. 1, p. 88, Jan. 2016.
[26] S. Chen, F. Qin, B. Hu, X. Li, and Z. Chen, "User-centric ultra-dense networks for 5G: Challenges, methodologies, and directions," *IEEE Wireless Commun.*, vol. 23, no. 2, pp. 78–85, Apr. 2016.
[27] M. Boban, K. Manolakis, M. Ibrahim, S. Bazzi, and W. Xu, "Design aspects for 5G V2X physical layer," in *Proc. IEEE Conf. Standards Commun. Netw. (CSCN)*, Berlin, Germany, Oct. 2016, pp. 1–7.
[28] M. Fallgren, R. Vilalta, M. Dillinger, J. Alonso-Zarate, M. Boban, T. Abbas, K. Manolakis, T. Mahmoodi, T. Svensson, and A. Laya, "Fifth-generation technologies for the connected car: Capable systems for Vehicle-to-Anything communications," *IEEE Veh. Technol. Mag.*, vol. 13, no. 3, pp. 28–38, Sep. 2018.
[29] R. Riggio, K. Gomez, L. Goratti, R. Fedrizzi, and T. Rasheed, "V-cell: Going beyond the cell abstraction in 5G mobile networks," in *Proc. IEEE Netw. Operations Manage. Symp. (NOMS)*, Krakow, Poland, May 2014, pp. 1–5.
[30] A. Behnad and X. Wang, "Virtual small cells formation in 5G networks," *IEEE Commun. Lett.*, vol. 21, no. 3, pp. 616–619, Mar. 2017.
[31] H. S. Ma, E. Zhang, S. Li, Z. Lv, and J. Hu, "A V2X design for 5G network based on requirements of autonomous driving," SAE Tech. Paper 2016-01-1887, 2016, doi: 10.4271/2016-01-1887.
[32] B. Di, L. Song, Y. Li, and G. Y. Li, "Non-orthogonal multiple access for high-reliable and low-latency V2X communications in 5G systems," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 10, pp. 2383–2397, Oct. 2017.
[33] A. Kousaridas, P. Spapis, L. Gallo, B. Villeforceix, Y. Li, W. Sun, M. Condoluci, L. Hu, T. Mahmoodi, R. Vilalta, and M. Dilinger, "Architecture and enablers of 5G V2X network slice for reliable and low-latency communications," in *Proc. Eur. Conf. Netw. Commun. (EUCNC)*, Ljubljana, Slovenia, 2018, pp. 1–2, doi: 10.5281/zenodo.2525604.
[34] S. Husain, A. Kunz, A. Prasad, E. Pateromichelakis, K. Samdanis, and J. Song, "The road to 5G V2X: ultra-high reliable communications," in *Proc. IEEE Conf. Standards Commun. Netw. (CSCN)*, Oct. 2018, pp. 1–6.
[35] S. S. Husain, A. Kunz, A. Prasad, E. Pateromichelakis, and K. Samdanis, "Ultra-high reliable 5G V2X communications," *IEEE Commun. Standards Mag.*, vol. 3, no. 2, pp. 46–52, Jun. 2019.
[36] Y. Yang, S. Dang, Y. He, and M. Guizani, "Markov decision-based pilot optimization for 5G V2X vehicular communications," *IEEE Internet Things J.*, vol. 6, no. 1, pp. 1090–1103, Feb. 2019.
[37] H. Wymeersch, G. Seco-Granados, G. Destino, D. Dardari, and F. Tufvesson, "5G mmwave positioning for vehicular networks," *IEEE Wireless Commun.*, vol. 24, no. 6, pp. 80–86, Dec. 2017.
[38] H. Wymeersch, N. Garcia, H. Kim, G. Seco-Granados, S. Kim, F. Wen, and M. Frohle, "5G mm wave downlink vehicular positioning," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Abu Dhabi, United Arab Emirates, Dec. 2018, pp. 206–212.
[39] *5G; Study on Scenarios and Requirements for Next Generation Access Technologies*, 3GPP TR document 38.913 version 15.0.0 Release 15, 2018. [Online]. Available: https://www.3gpp.org/DynaReport/38913.htm
[40] *Study enhancement 3GPP Support for 5G V2X Services*, 3GPP TR document 22.886 version 16.2.0 Release 16, 2018. [Online]. Available: https://www.3gpp.org/DynaReport/22886.htm
[41] Z. Li, C. Liu, and C. Chigan, "VehicleView: A universal system for vehicle performance monitoring and analysis based on VANETs," *IEEE Wireless Commun.*, vol. 19, no. 5, pp. 90–96, Oct. 2012.
[42] G. Nardini, A. Virdis, C. Campolo, A. Molinaro, and G. Stea, "Cellular-V2X communications for platooning: Design and evaluation," *Sensors*, vol. 18, no. 5, p. 1527, May 2018.
[43] M. R. de Brito and F. D. L. P. Duarte-Figueiredo, "D-hop: A dynamic and distributed protocol for vehicle routing," in *Proc. IEEE Symp. Comput. Commun. (ISCC)*, Jul. 2017, pp. 1073–1078.
[44] M. Amadeo, C. Campolo, and A. Molinaro, "Enhancing IEEE 802.11p/WAVE to provide infotainment applications in VANETs," *Ad Hoc Netw.*, vol. 10, no. 2, pp. 253–269, Mar. 2012.
[45] T. W. Chim, S. M. Yiu, L. C. K. Hui, and V. O. K. Li, "VSPN: VANET-based secure and privacy-preserving navigation," *IEEE Trans. Comput.*, vol. 63, no. 2, pp. 510–524, Feb. 2014.
[46] S.-I. Sou and O. K. Tonguz, "Enhancing VANET connectivity through roadside units on highways," *IEEE Trans. Veh. Technol.*, vol. 60, no. 8, pp. 3586–3602, Oct. 2011.
[47] J. Zhang, X. Ma, and T. Wu, "Performance modeling and analysis of emergency message propagation in vehicular ad hoc networks," *Wireless Commun. Mobile Comput.*, vol. 14, no. 3, pp. 366–379, 2014.
[48] S. Al-Sultan, A. H. Al-Bayatti, and H. Zedan, "Context-aware driver behavior detection system in intelligent transportation systems," *IEEE Trans. Veh. Technol.*, vol. 62, no. 9, pp. 4264–4275, Nov. 2013.
[49] C. Andrade, S. Byers, V. Gopalakrishnan, E. Halepovic, D. Poole, L. Tran, and C. Volinsky, "Connected cars in cellular network: A measurement study," in *Proc. Internet Meas. Conf. (IMC)*, New York, NY, USA, 2017, pp. 235–241.
[50] Z. Ning, X. Hu, Z. Chen, M. Zhou, B. Hu, J. Cheng, and M. S. Obaidat, "A cooperative quality-aware service access system for social Internet of vehicles," *IEEE Internet Things J.*, vol. 5, no. 4, pp. 2506–2517, Aug. 2018.
[51] K. M. Alam, M. Saini, and A. E. Saddik, "Toward social Internet of vehicles: Concept, architecture, and applications," *IEEE Access*, vol. 3, pp. 343–357, 2015.
[52] H. Ullah, N. Gopalakrishnan Nair, A. Moore, C. Nugent, P. Muschamp, and M. Cuevas, "5G communication: An overview of Vehicle-to-everything, drones, and healthcare use-cases," *IEEE Access*, vol. 7, pp. 37251–37268, 2019.
[53] D. Takahashi, Y. Xiao, Y. Zhang, P. Chatzimisios, and H.-H. Chen, "IEEE 802.11 user fingerprinting and its applications for intrusion detection," *Comput. Math. with Appl.*, vol. 60, no. 2, pp. 307–318, Jul. 2010.
[54] A. Molinaro and C. Campolo (2019), *5G for V2X Communications*. [Online]. Available: https://www.5gitaly.eu/2018/wp-content/uploads/2019/01/5G-Italy-White-eBook-5G-for-V2X-Communications.pdf
[55] C. Campolo, A. Molinaro, A. Iera, and F. Menichella, "5G network slicing for Vehicle-to-Everything services," *IEEE Wireless Commun.*, vol. 24, no. 6, pp. 38–45, Dec. 2017.
[56] C. Campolo, R. Fontes, A. Molinaro, C. E. Rothenberg, and A. Iera, "Slicing on the road: Enabling the automotive vertical through 5G network softwarization," *Sensors*, vol. 18, no. 12, p. 4435, Dec. 2018.
[57] R. Sanchez-Iborra, J. Santa, J. Gallego-Madrid, S. Covaci, and A. Skarmeta, "Empowering the Internet of vehicles with multi-RAT 5G network slicing," *Sensors*, vol. 19, no. 14, p. 3107, Jul. 2019.

[58] H. Cao, S. Gangakhedkar, A. R. Ali, M. Gharba, and J. Eichinger, "A 5G V2X testbed for cooperative automated driving," in *Proc. IEEE Veh. Netw. Conf. (VNC)*, Columbus, OH, USA, Dec. 2016, pp. 1–4.
[59] T. Sahin, M. Klugel, C. Zhou, and W. Kellerer, "Multi-user-centric virtual cell operation for V2X communications in 5G networks," in *Proc. IEEE Conf. Standards for Commun. Netw. (CSCN)*, Sep. 2017, pp. 84–90.
[60] T. Sahin, M. Klugel, C. Zhou, and W. Kellerer, "Virtual cells for 5G V2X communications," *IEEE Commun. Standards Mag.*, vol. 2, no. 1, pp. 22–28, Mar. 2018.
[61] T. Chen, "C-V2X trial activities in 5G-DRIVE," in *Proc. Workshop 5G Era Connected Cars (EuCNC)*, Valencia, Spain, 2019, pp. 1–12. [Online]. Available: https://5gcroco.eu/images/TCEUCNC.pdf
[62] A. Kostopoulos, I. Chochliouros, A. Dardamanis, O. Segou, E. Kafetzakis, R. Soua, K. Zhang, S. Kuklinski, L. Tomaszewski, N. Yi, U. Herzog, T. Chen, M. Kutila, and J. Ferragut, "5G trial cooperation between EU and China," in *Proc. IEEE Int. Conf. Commun. Workshops (ICC Workshops)*, Shanghai, China, May 2019, pp. 1–6.
[63] C. Campolo, A. Molinaro, and A. Iera, "A reference framework for social-enhanced Vehicle-to-Everything communications in 5G scenarios," *Comput. Netw.*, vol. 143, pp. 140–152, Oct. 2018.
[64] L. S. Silva, C. R. Storck, and F. Duarte-Figueiredo, "A dynamic load balancing algorithm for data plane traffic," in *Proc. Latin Amer. Netw. Oper. Manage. Symp. (LANOMS)*, Niterói, Rio de Janeiro, 2019, pp. 1–7.
[65] S. K. Datta, J. Haerri, C. Bonnet, and R. Ferreira Da Costa, "Vehicles as connected resources: Opportunities and challenges for the future," *IEEE Veh. Technol. Mag.*, vol. 12, no. 2, pp. 26–35, Jun. 2017.
[66] V. Frascolla, F. Miatton, G. K. Tran, K. Takinami, A. De Domenico, E. C. Strinati, K. Koslowski, T. Haustein, K. Sakaguchi, S. Barbarossa, and S. Barberis, "5G-MiEdge: Design, standardization and deployment of 5G phase II technologies: MEC and mmWaves joint development for tokyo 2020 olympic games," in *Proc. IEEE Conf. Standards Commun. Netw. (CSCN)*, Sep. 2017, pp. 54–59.
[67] V. Frascolla, J. Englisch, K. Takinami, L. Chiaraviglio, S. Salsano, K. Yunoki, S. Barberis, V. Palestini, K. Sakaguchi, T. Haustein, A. de Domenico, and E. C. Strinati, "Millimeter-waves, MEC, and network softwarization as enablers of new 5G business opportunities," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Barcelona, Spain, Apr. 2018, pp. 1–5.
[68] L. Li, Y. Li, and R. Hou, "A novel mobile edge computing-based architecture for future cellular vehicular networks," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, San Francisco, CA, USA, Mar. 2017, pp. 1–6.
[69] B. M. Masini, A. Bazzi, and E. Natalizio, "Radio access for future 5G vehicular networks," in *Proc. IEEE 86th Veh. Technol. Conf. (VTC-Fall)*, Toronto, ON, Canada, Sep. 2017, pp. 1–7.
[70] S. Chen, J. Hu, Y. Shi, Y. Peng, J. Fang, R. Zhao, and L. Zhao, "Vehicle-to-Everything (v2x) services supported by LTE-based systems and 5G," *IEEE Commun. Standards Mag.*, vol. 1, no. 2, pp. 70–76, 2017.
[71] A. Festag, "Standards for vehicular communication—From IEEE 802.11 p to 5G," *e & i Elektrotechnik und Informationstechnik*, vol. 132, no. 7, pp. 409–416, 2015.
[72] 5G Automotive Alliance. (2017). *An Assessment of LTE-V2X (PC5) and 802.11p Direct Communications Technologies for Improved Road Safety in the EU*. [Online]. Available: https://5gaa.org/wp-content/uploads/2017/12/5GAA-Road-safety-FINAL2017-12-05.pdf
[73] J. Lianghai, A. Weinand, B. Han, and H. D. Schotten, "Multi-RATs support to improve V2X communication," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Apr. 2018, pp. 1–6.
[74] R. Jacob, N. Franchi, and G. Fettweis, "Hybrid V2X communications: Multi-RAT as enabler for connected autonomous driving," in *Proc. IEEE 29th Annu. Int. Symp. Pers., Indoor Mobile Radio Commun. (PIMRC)*, Sep. 2018, pp. 1370–1376.
[75] Frost & Sullivan Group. (2017). *Vehicle-to-Everything Technologies for Connected Cars DSRC and Cellular Technologies Drive Opportunities*. [Online]. Available: https://www.researchandmarkets.com/reports/4391696/vehicle-to-everything-technologies-for-connected
[76] SNS Telecom & IT Report List. (2019). *The V2X (Vehicleto-Everything) Communications Ecosystem: 2019–2030-Opportunities, Challenges, Strategies & Forecasts*. [Online]. Available: https://www.researchandmarkets.com/reports/4759721/the-v2x-vehicle-to-everything-communications
[77] S. Selvanesan, R. R. Thomas, T. Fehrenbach, T. Wirth, and C. Hellge, "Towards advanced V2X multimedia services for 5G networks," in *Proc. IEEE Int. Symp. Broadband Multimedia Syst. Broadcast. (BMSB)*, Jun. 2018, pp. 1–6.
[78] W. Xu, H. Zhou, N. Cheng, F. Lyu, and W. Shi, "Internet of vehicles in big data era," *IEEE/CAA J. Automatica Sinica*, vol. 5, no. 1, pp. 19–35, Jan. 2018.
[79] V. Sharma, I. You, and N. Guizani, "Security of 5G-V2X: Technologies, standardization and research directions," 2019, *arXiv:1905.09555*. [Online]. Available: http://arxiv.org/abs/1905.09555
[80] A. Orsino, O. Galinina, S. Andreev, O. N. C. Yilmaz, T. Tirronen, J. Torsner, and Y. Koucheryavy, "Improving initial access reliability of 5G mmWave cellular in massive V2X communications scenarios," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Kansas City, MO, USA, May 2018, pp. 1–7.
[81] M. Lauridsen, L. C. Gimenez, I. Rodriguez, T. B. Sorensen, and P. Mogensen, "From LTE to 5G for connected mobility," *IEEE Commun. Mag.*, vol. 55, no. 3, pp. 156–162, Mar. 2017.
[82] X. Wang, S. Mao, and M. X. Gong, "An overview of 3GPP cellular Vehicle-to-Everything standards," *GetMobile: Mobile Comput. Commun.*, vol. 21, no. 3, pp. 19–25, Nov. 2017.
[83] L. Zhao, X. Li, B. Gu, Z. Zhou, S. Mumtaz, V. Frascolla, H. Gacanin, M. I. Ashraf, J. Rodriguez, M. Yang, and S. Al-Rubaye, "Vehicular communications: Standardization and open issues," *IEEE Commun. Standards Mag.*, vol. 2, no. 4, pp. 74–80, Dec. 2018.
[84] Z. Xu, X. Li, X. Zhao, M. H. Zhang, and Z. Wang, "DSRC versus 4G-LTE for connected vehicle applications: A study on field experiments of vehicular communication performance," *J. Adv. Transp.*, vol. 2017, pp. 1–10, 2017.
[85] M. Boban, A. Kousaridas, K. Manolakis, J. Eichinger, and W. Xu, "Connected roads of the future: Use cases, requirements, and design considerations for Vehicle-to-Everything communications," *IEEE Veh. Technol. Mag.*, vol. 13, no. 3, pp. 110–123, Sep. 2018.
[86] S. A. A. Shah, E. Ahmed, M. Imran, and S. Zeadally, "5G for vehicular communications," *IEEE Commun. Mag.*, vol. 56, no. 1, pp. 111–117, Jan. 2018.
[87] A. Papathanassiou and A. Khoryaev (2017). *Cellular V2X as the Essential Enabler of Superior Global Connected Transportation Services*. [Online]. Available: https://futurenetworks.ieee.org/tech-focus/june-2017/cellular-v2x
[88] E. Uhlemann, "Time for Autonomous Vehicles to Connect," *IEEE Veh. Technol. Mag.*, vol. 13, no. 3, pp. 10–13, Sep. 2018.
[89] X. Cheng, R. Zhang, and L. Yang, "Wireless toward the era of intelligent vehicles," *IEEE Internet Things J.*, vol. 6, no. 1, pp. 188–202, Feb. 2019.
[90] H. Peng, L. Liang, X. Shen, and G. Y. Li, "Vehicular communications: A network layer perspective," *IEEE Trans. Veh. Technol.*, vol. 68, no. 2, pp. 1064–1078, Feb. 2019.
[91] K. Z. Ghafoor, L. Kong, D. B. Rawat, E. Hosseini, and A. S. Sadiq, "Quality of service aware routing protocol in software-defined Internet of vehicles," *IEEE Internet Things J.*, vol. 6, no. 2, pp. 2817–2828, Apr. 2019.
[92] X. Ge, Z. Li, and S. Li, "5G software defined vehicular networks," *IEEE Commun. Mag.*, vol. 55, no. 7, pp. 87–93, Jul. 2017.
[93] G. Han, M. Guizani, Y. Bi, T. H. Luan, K. Ota, H. Zhou, W. Guibene, and A. Rayes, "Software-defined vehicular networks: Architecture, algorithms, and applications: Part 1," *IEEE Commun. Mag.*, vol. 55, no. 7, pp. 78–79, Jul. 2017.
[94] J. Choi, V. Va, N. Gonzalez-Prelcic, R. Daniels, C. R. Bhat, and R. W. Heath, "Millimeter-wave vehicular communication to support massive automotive sensing," *IEEE Commun. Mag.*, vol. 54, no. 12, pp. 160–167, Dec. 2016.
[95] R. He, B. Ai, G. Wang, Z. Zhong, C. Schneider, D. A. Dupleich, R. S. Thomae, M. Boban, J. Luo, and Y. Zhang, "Propagation channels of 5G millimeter-wave vehicle-to-vehicle communications: Recent advances and future challenges," *IEEE Veh. Technol. Mag.*, vol. 15, no. 1, pp. 16–26, Mar. 2020.
[96] B. Antonescu, M. T. Moayyed, and S. Basagni, "MmWave channel propagation modeling for V2X communication systems," in *Proc. IEEE 28th Annu. Int. Symp. Pers., Indoor, Mobile Radio Commun. (PIMRC)*, Montreal, QC, Canada, Oct. 2017, pp. 1–6.
[97] M. Fallgran, M. Dillinger, Z. Li, G. Vivier, T. Abbas, J. Alonso-Zarate, T. Mahmoodi, S. Alli, T. Svensson, and G. Fodor, "On selected V2X technology components and enablers from the 5GCAR project," in *Proc. IEEE Int. Symp. Broadband Multimedia Syst. Broadcast. (BMSB)*, Jun. 2018, pp. 1–5.
[98] B. Martínez de Aragón, J. Alonso-Zarate, and A. Laya, "How connectivity is transforming the automotive ecosystem," *Internet Technol. Lett.*, vol. 1, no. 1, p. e14, Jan. 2018.

[99] E. Uhlemann, ''Initial Steps Toward a Cellular Vehicle-to-Everything Standard,'' *IEEE Veh. Technol. Mag.*, vol. 12, no. 1, pp. 14–19, Mar. 2017.
[100] J. Contreras-Castillo, S. Zeadally, and J. A. Guerrero-Ibanez, ''Internet of vehicles: Architecture, protocols, and security,'' *IEEE Internet Things J.*, vol. 5, no. 5, pp. 3701–3709, Oct. 2018.
[101] V. Vukadinovic, K. Bakowski, P. Marsch, I. D. Garcia, H. Xu, M. Sybis, P. Sroka, K. Wesolowski, D. Lister, and I. Thibault, ''3GPP C-V2X and IEEE 802.11p for Vehicle-to-Vehicle communications in highway platooning scenarios,'' *Ad Hoc Netw.*, vol. 74, pp. 17–29, May 2018.
[102] B. Toghi, M. Saifuddin, H. N. Mahjoub, M. O. Mughal, Y. P. Fallah, J. Rao, and S. Das, ''Multiple access in cellular V2X: Performance analysis in highly congested vehicular networks,'' in *Proc. IEEE Veh. Netw. Conf. (VNC)*, Taipei, Taiwan, Dec. 2018, pp. 1–8.
[103] B. Toghi, M. Saifuddin, Y. P. Fallah, and M. O. Mughal, ''Analysis of distributed congestion control in cellular Vehicle-to-Everything networks,'' in *Proc. IEEE 90th Veh. Technol. Conf. (VTC-Fall)*, Honolulu, HI, USA, Sep. 2019, pp. 1–7.
[104] Qualcomm. (2018). *V2X Technology Benchmark Testing*. [Online]. Available: https://www.qualcomm.com/media/documents/files/5gaa-v2x-technology-benchmark-testing-dsrc-and-c-v2x.pdf
[105] D. Hetzer, ''5GCroCo tests and trials: User stories and 5G technologies,'' in *Proc. Workshop 5G Era Connected Cars (EuCNC)*, Valencia, Spain, 2019, pp. 1–27. [Online]. Available: https://5gcroco.eu/images/DHEUCNC.pdf
[106] Xu Yingwei. (2017). *Data Center Architecture for Internet of Vehicles*. [Online]. Available: https://www.intel.com/content/dam/www/public/us/en/documents/case-studies/xeon-e5-e7-transwiseway-paper.pdf
[107] M. Gerla, E.-K. Lee, G. Pau, and U. Lee, ''Internet of vehicles: From intelligent grid to autonomous cars and vehicular clouds,'' in *Proc. IEEE World Forum Internet Things (WF-IoT)*, Mar. 2014, pp. 241–246.
[108] M. Flament, ''Making connected cars a reality with 5G,'' in *Proc. Workshop 5G Era Connected Cars (EuCNC)*, Valencia, Spain, 2019, pp. 1–37. [Online]. Available: https://5gcroco.eu/images/MFLEUCNC.pdf
[109] R. Riggio, ''5G for connected and automated mobility in the European Union,'' in *Workshop 5G Era Connected Cars, EuCNC*, Valencia, Spain, 2019, pp. 1–15. [Online]. Available: https://5gcarmen.eu/wp-content/uploads/2020/04/5G-CARMEN-FMW2019-Executive-Summary-1.pdf

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