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Software-Defined Vehicular Networking: Opportunities and Challenges

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ABSTRACT Over the last ten years, Vehicular Ad Hoc Networks (VANETs) have received significant attention from the academic and industrial communities alike. VANETs are a particular type of mobile ad hoc network originally designed for the purpose of facilitating the creation of spontaneous wireless networks between different vehicles, but since their inception the scope of VANETs has been extended to other types of road users such as cyclists and pedestrians. Due to the volatility of the wireless medium, VANETs face several challenges, especially when applications with a diverse set of requirements must be supported. Among the various techniques used to address such challenges, one of the most recent is Software-Defined Networking (SDN), which, by clearly separating the data plane from the control plane, allows the implementation of traditional network control and management tasks on top of a logically centralized controller. In this work, we perform a systematic review of SDN techniques tailored to the VANET domain. More specifically, we first review the literature on VANETs and SDN from an architectural and communications requirement perspective, then we report on the most recent standardization efforts, and finally, we highlight the open research areas and the most important challenges in this domain.

INDEX TERMS Intelligent transport systems (ITS), software-defined networking (SDN), software-defined vehicular networking (SDVN), Vehicle To Everything (V2X), VANET.

I. INTRODUCTION

Over the last ten years, Vehicular Ad Hoc Networks (VANETs) have received significant attention from the academic and industrial communities alike. A VANET is a particular class of Mobile Ad Hoc Network (MANET) in which the mobile nodes are vehicles. VANETs are characterized by: 1) high, geographically constrained, and predictable node mobility due to the road map layout; 2) a fast changing network topology; and 3) a highly unstable communication environment [1]. In VANETs, we can identify four types of communication patterns, as illustrated in Figure 1: Vehicle To Vehicle (V2V), Vehicle To Infrastructure (V2I), Vehicle To Pedestrian (V2P), and Vehicle To Network (V2N). Usually, Vehicle To Everything (V2X) is used to refer to the four types of communications.

While nowadays, VANETs are mostly deployed for road safety applications, there is a growing interest in their use for infotainment applications such as commercial online services, intelligent navigation information, and point-of-interest notifications. Such applications aim to provide a more comfortable driving and traveling experience, and obviously represent a business opportunity [2]. Additionally, autonomous cars are becoming a reality, with polished prototypes already available, and their commercialization is expected in the next few years [3]. Communications play a crucial role in autonomous cars since collaborating and sharing context information enables vehicles to make decisions based not only on the information collected from the local sensors but also on the information received from other cars. This received information is important as sensors have

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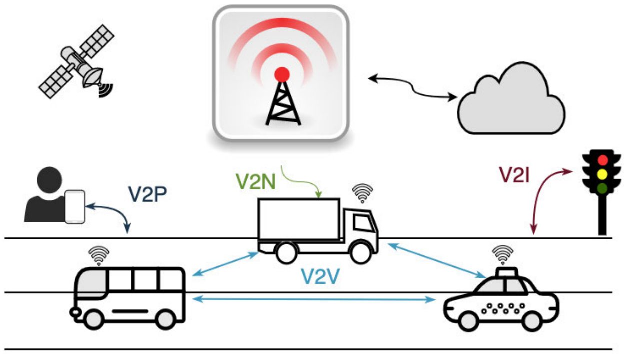


FIGURE 1. Types of communication patterns on VANETs.

several limitations, such as the inability to detect traffic jams a few blocks away due to their limited view, restricted perception capacities and operating conditions, and the difficulty in determining how the vehicle should behave when objects are detected poses another challenge. In this context, communications makes autonomous driving more efficient, and reliable by contributing to information dissemination [4].

Given that the Fifth Generation (5G) will be the architecture for future communication networks, mobility (connected cars, vehicular communications, among others) is one of the outstanding emerging markets, which are usually called 5G verticals. The 5G Automotive Association (5GAA) was created in 2016 [5], and focuses on the development of end-to-end solutions for future mobility and transportation services. 5GAA supports the idea that 5G will be the ultimate platform to enable Cooperative Intelligent Transport Systems (C-ITS) and the provision of V2X, meaning that VANETs should be integrated into the 5G architecture. 5G will be driven by software, and it will support a set of heterogeneous wireless access technologies. All this implies the need for programmability, flexibility, and network resources management in the VANET ecosystem.

The above-mentioned flexibility, programmability, co-existence in heterogeneous wireless technologies, and resource management within the 5G architecture, could be provided using a Software-Defined Networking (SDN) approach. SDN is a paradigm for telecommunications networks that breaks with the current vertical integration scheme, separating the data plane (in charge of switching/routing the packets) from the control plane (in charge of defining how the traffic is handled) in order to facilitate network management [6]. Furthermore, the 5G architecture working group conceives the network control layer as SDN in nature [7]. Specifically, the SDN controller is in charge of translating decisions from the control applications into commands to the data layer. We believe that a survey that presents SDN in the context of VANETs, namely Software-Defined Vehicular Networking (SDVN), is missing in the literature. We also consider that SDN will be a key enabler on the road towards the V2X architecture.

This manuscript aims to present the introduction of SDN into the VANET domain, and puts forward SDVN as a key enabler in meeting the network requirements within the V2X architecture. There exist surveys on emerging technologies such as Vehicular Cloud Computing (VCC) [8], [9], Information Centric Networking (ICN) [10], and Named Data Networking (NDN) [11] in the context of VANETs. These works acknowledge the importance of SDN as a key complementary technology. We also acknowledge its importance by complementing the previous works with an in-depth study of the SDVN solutions available in the literature. Existing surveys and literature reviews focus on diverse aspects of the use of SDN in the context of VANETs [12]–[17]. Chahal *et al.* [12] focus on SDN wireless solutions, and the scope of SDN they mention in the context of VANETs is narrow. Jaballah *et al.* [13] target security analysis on SDVN architectures. Al-Heety *et al.* [14] present a taxonomy based on applications and communications models supported, but it is limited to the type of communication patterns involved, such as V2V and V2I. Ghazi *et al.* [15] provide a comprehensive review of methods for emergency message dissemination in VANETs. Shabir *et al.* [16] propose a taxonomy of congestion control protocols including a dedicated focus on SDN-based strategies. Finally, Farooq *et al.* [17] survey the various schemes for multicast routing based on specific VANETs scenarios, but do not include SDVN architectures in their analysis. Our work goes a step further by not only presenting a broad in-depth study on the SDN-based solutions available in the literature, taking into account application requirements and architectures, but also examining the wireless access technologies designed for vehicular environments. We argue that the control and management of wireless access technologies, considering their features and limitations, should be included in an SDVN architecture.

The main contributions of our work can be summarized as follows:

- We provide an overview of VANET protocol stacks, standards, and wireless access technologies. We adopt a didactic approach and provide the most recent efforts in standardization.
- We classify the SDN-based solutions for VANETs available in the literature on the basis of the network architectures and network requirements.
- We discuss the lessons learnt from the different SDN hierarchies and network requirements, and link them with wireless access technologies.
- We discuss standard use cases for vehicular communications and show how SDN can outperform traditional approaches.
- We discuss the challenges facing researchers.

The overall structure of this manuscript is shown in Figure 2, and the contents are organized as follows. In Section II we briefly explain the standard communication protocols for vehicular environments, including the most recent access technologies. In Section III we present a taxonomy for the varied SDVN architectures and network

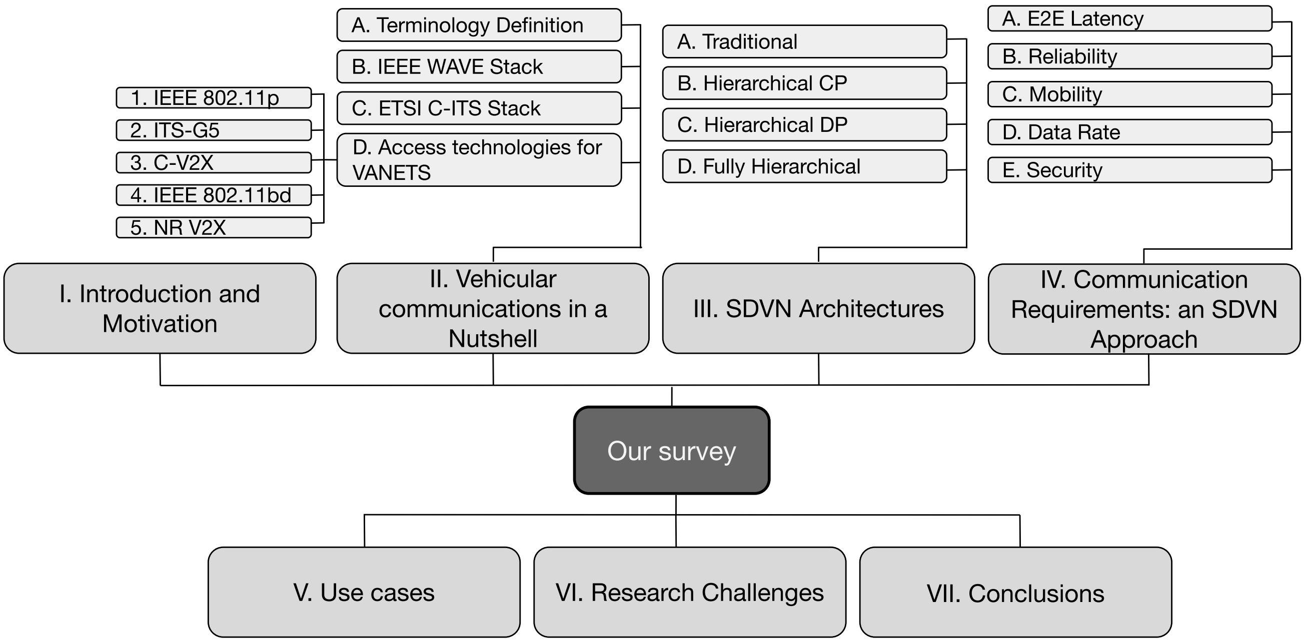


FIGURE 2. Organization of this survey.

requirements proposed in the literature. In Section IV we discuss the V2X network requirements for the automotive vertical market, employing an SDVN approach. In Section V we discuss some of the common uses cases for vehicular communications and show how SDN can outperform a traditional approach, as well as looking at the benefits of employing an SDVN approach to control and manage the wireless access technologies in vehicular environments. In Section VI we identify the major remaining challenges of SDVN. Finally, we present our conclusions in Section VII. In order to facilitate the reading and understanding of this manuscript we invite the reader to consult Appendix VII, where Table 6 lists the acronyms used in this manuscript.

II. VEHICULAR COMMUNICATIONS IN A NUTSHELL

In this section we present the de-facto protocol stacks for vehicular communications. The main goal of this section is to provide an overview of the main families of standards rather than explain each standard in detail. We provide a clearly layered taxonomy in which the reader can identify the overall architectures and the standards included. We focus our attention on the Physical (PHY) and Medium Access Control (MAC) layers. The reason for this lies in the main characteristics of VANET environments, i.e., high mobility and highly unstable communication channels are addressed in these layers. Firstly, we introduce the terminology related with VANET scenarios. Secondly, we present the family of standards for vehicular communications, *a.k.a.* the IEEE Wireless Access in Vehicular Environments (WAVE) in the U.S., followed by the I-CTS of the European Telecommunications Standards Institute (ETSI) in Europe. Lastly, we present the wireless access technologies designed for VANET environments.

Figure 3 shows a heterogeneous scenario for a vehicular network. The network infrastructure is composed of Road Side Units (RSUs), WiFi Access Points (APs), 4G/LTE Evolved Node Bs (eNBs), and potential 5G Next generation Node Bs (gNBs). The vehicles are the end user devices and are equipped with an On Board Unit (OBU), which can have multiple wireless interfaces. The vehicles can use PC5, IEEE 802.11p or ITS-G5 interfaces for communications with RSUs or other OBUs (vehicles). Standard WiFi interfaces are used for communications with WiFi APs, and Uu interfaces are employed for communications with eNBs or gNBs. Depending on the interfaces involved, a device supports one or more communication protocol stacks. The vehicles can communicate with the network infrastructure (V2I), other vehicles (V2V), pedestrians (V2P), and Intelligent Transport Systems (ITS) centers (V2N).

A. DEFINITION OF TERMINOLOGY

In this section we briefly introduce, for the reader's convenience, the basic terminology typically associated with VANETs. This list includes definitions related to the VANET protocol stacks and communication standards [18]–[23], as well as some more generic 802.11 terms and definitions.

- **OBU:** In the context of VANET is the mobile communication device mounted on vehicles and equipped with one or more wireless interfaces, e.g., IEEE 802.11p, PC5, or Uu interfaces.
- **RSU:** This is used to refer to the fixed communication devices deployed along the road to provide connectivity to vehicles. RSUs can be equipped with multiple

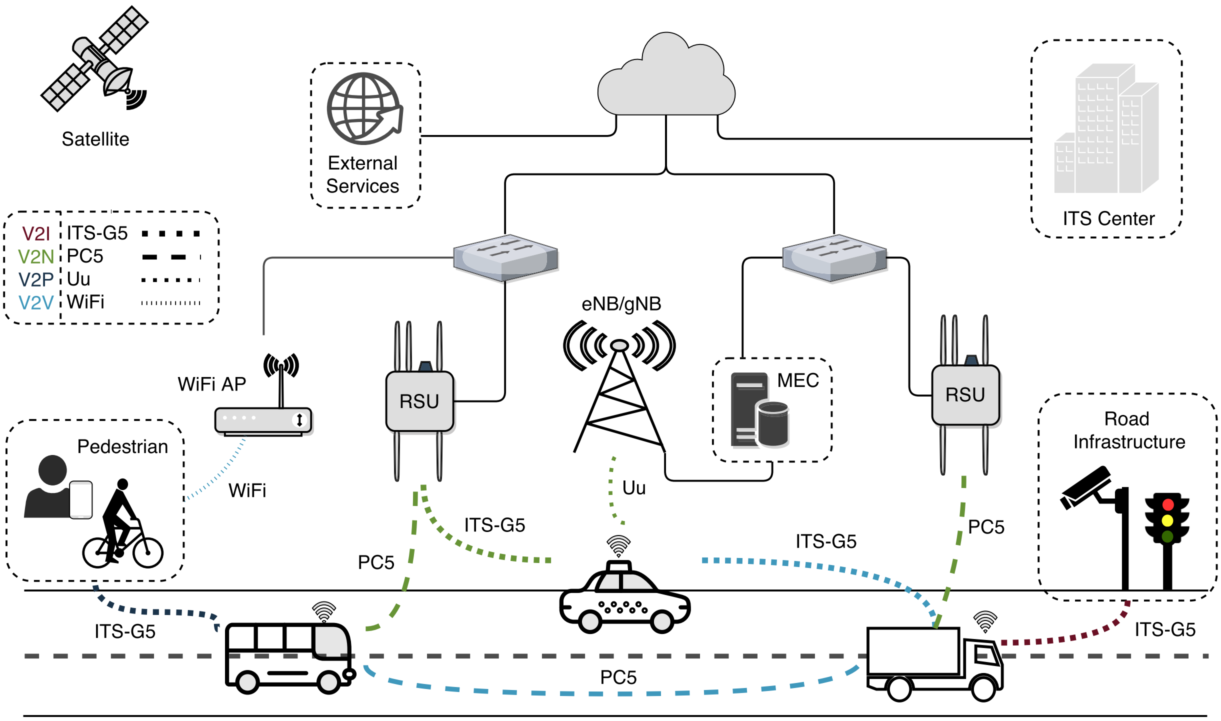


FIGURE 3. Overview of a heterogeneous V2X scenario.

wireless interfaces, e.g., IEEE 802.11p or PC5 interfaces. The RSU acts as a vehicular network infrastructure for communications using the specific wireless technologies and standards for vehicular communications.

- **WiFi AP:** An AP that is compliant with the *traditional* IEEE Std 802.11 standard. We use the term *traditional* to refer, in an informal way, to the version of the 802.11 standard typically found in home and enterprise networks. However, we refer explicitly to the 11p amendment when we wish to refer to the 802.11 version specifically tailored for vehicular communications.
- **Base Station (BS):** Generic term used to refer to the cellular network infrastructure. A BS can support 3G, 4th Generation of Broadband Cellular Networks (4G), or 5G technologies. In this survey, we use the term BS to refer to both eNB (4G) and gNB (5G).
- **IEEE 802.11p interface:** A wireless interface fully compliant with the IEEE 802.11p amendment for vehicular communications [22]. Both RSUs and OBUs can be equipped with interfaces supporting this standard.
- **ITS-G5 interface:** A wireless interface fully compliant with the ITS-G5 specifications [21]. Both RSUs and OBUs can be equipped with this interface.
- **PC5 interface:** A wireless interface fully compliant with the 3rd Generation Partnership Project (3GPP) Release 14 specification for Cellular Vehicular To Everything (C-V2X) communications [24]. Both RSUs and OBUs can be equipped with this interface.
- **Uu interface:** A wireless interface fully compliant with cellular communications, i.e., 3G, 4G or 5G. OBUs can be equipped with these interfaces.

B. VEHICULAR COMMUNICATIONS STACKS

From a purely technical point of view, there exist two de-facto stacks for V2X communications: i) the IEEE WAVE family of standards, mainly used in the USA [18]; and ii) the C-ITS stack for ITS, which is mainly used in Europe [19]. These protocol stacks can be described as follows.

1) IEEE WAVE STACK

The IEEE WAVE standards describe the architecture, components and operation for communications between vehicles and infrastructure, and communications among vehicles. Figure 4 illustrates the basic layered architecture of the IEEE WAVE stack and its relationship with the OSI model. Additionally, we present the specific standard for each layer.

In IEEE WAVE, the PHY and MAC layers are specified in IEEE 802.11 [25] and in IEEE 1609.4 [26]. Through the IEEE 802.11p amendment released in 2010 [22], some extensions to the IEEE 802.11 (*a.k.a.* WiFi) standard were introduced to support communications for WAVE systems. IEEE 802.11p includes a new mode of operation, namely the Outside of Context of a BSS (OCB) mode. A detailed description of this extension is given in Subsection II-C1. On the other hand, IEEE 1609.4 is a MAC layer extension for multi-channel operation in WAVE systems. In WAVE there exist two types

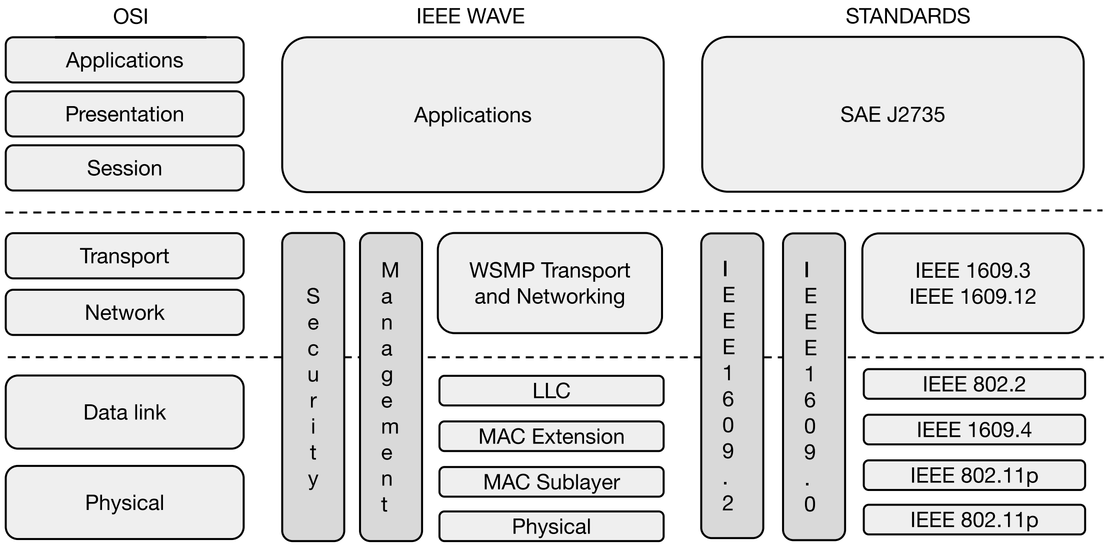


FIGURE 4. Overview of IEEE WAVE stack.

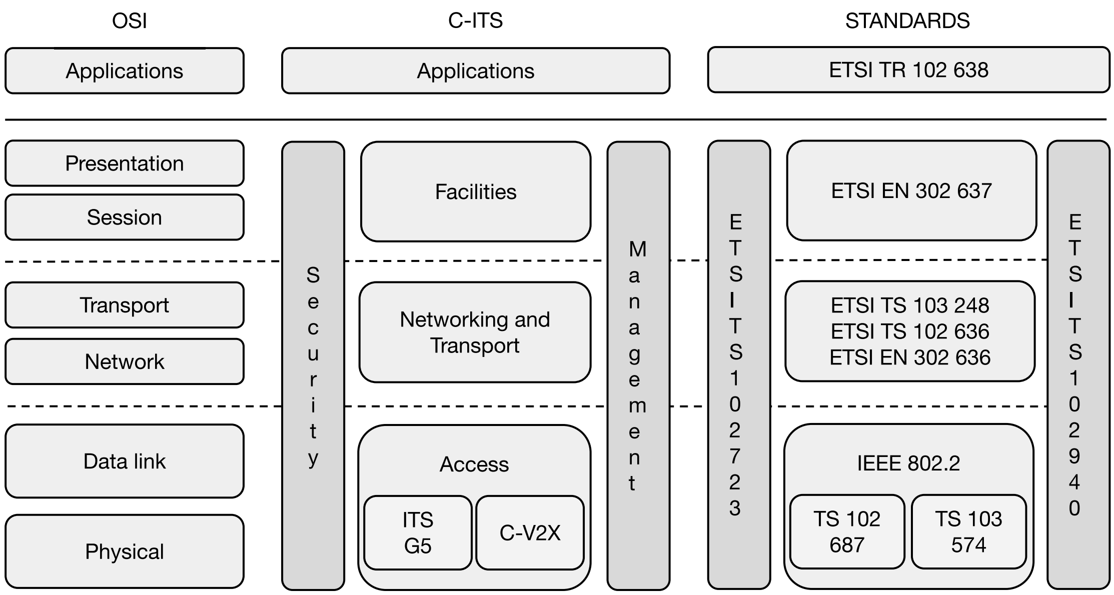


FIGURE 5. Overview of C-ITS stack.

of channel, the Control Channel (CCH) and the Service Channel (SCH), and operation between these channels is specified in IEEE 1609.4. This includes primitives designed for multi-channel operations and parameters for priority access, channel switching and routing and management services.

With regards to the upper layers, a specialized protocol for VANET environments, namely the WAVE Short Message Protocol (WSMP), is used. This protocol was designed to minimize communication overheads, and it provides network and transport layers. A WAVE device should implement WSMP, IPv6 in conjunction with UDP/TCP, or both. IPv4 is not considered in this stack.

2) ETSI C-ITS STACK

The ETSI C-ITS stack is the family of standards adopted in Europe for Intelligent Transport Systems (ITS). VANETs are a particular case of an ITS system where the mobile stations are the vehicles and the fixed stations are the wireless network infrastructure, specifically the RSUs. Figure 5 illustrates the basic architecture of the ETSI C-ITS stack and its relationship with the OSI model. Additionally, we present the specific standard for each layer.

The C-ITS stack includes two access technologies: first, ITS-G5 [21], [27], which operates at 5.9 GHz and is based on IEEE 802.11p, with some modifications to comply with

European regulations; second, C-V2X, which is a 3GPP technology that was recently included in this stack [28]–[30]. A detailed description of these technologies is given in Subsections II-C2 and II-C3, respectively.

It is important to mention two types of messages on the facilities layer: Cooperative Awareness Messages (CAMs) [31] and Decentralized Environmental Notification Messages (DENMs) [32]. CAMs are used for cooperative awareness, and are transmitted periodically. DENMs contain information about road hazard warnings, and are event-triggered. The content of CAMs and DENMs is derived from the applications layer, specifically from the road safety applications. These messages are interchanged with all the communication entities in the network, and contain all the basic information about the vehicles such as GPS position, speed, etc.

C. ACCESS TECHNOLOGIES FOR VANETS

In this subsection we review in more detail the access technologies that are being designed specifically to implement VANET environments, namely, IEEE 802.11p, ITS-G5, and C-V2X. We then go a step further and introduce the envisioned access technologies for vehicular communications, *a.k.a.* IEEE 802.11bd and New Radio V2X (NR-V2X). There exist other wireless access technologies that can be used for VANETs such as IEEE 802.11, 3G, and 4G, but these technologies were conceived for other purposes. We focus solely on specific VANET-oriented technologies.

1) IEEE 802.11p

This amendment was based on IEEE 802.11a and its main goal is to address the specific challenges of vehicular communications, such as, 1) the Doppler effect shifts induced by the relative velocities between vehicles, and the scattering environment (hindering signal reception) [33]; 2) fast changes in the multipath conditions; 3) quick establishment of a communication link; and 4) data exchange in very short times. To overcome these challenges, IEEE 802.11p introduces several changes with respect to the legacy IEEE 802.11, such as different Enhanced Distributed Channel Access (EDCA) parameters, a 10 MHz channel width, and only 3 mandatory data rates (3 Mbps, 6 Mbps and 12 Mbps). Additionally, the following modifications require a special mention since they only apply to vehicular environments.

- **Spectrum allocation**. IEEE 802.11p operates in the 5.9 GHz band. The spectrum is allocated from 5.850 GHz to 5.925 GHz. The band is divided into 7 channels of 10 MHz, as illustrated in Figure 6(a).
- **Outside of Context of a BSS (OCB) mode**. A new communications mode, namely OCB, is introduced. The main goal of OCB is to establish a communication link faster than IEEE 802.11. The OCB mode is enabled when the *dot11OCBActivated* variable is set to true. In OCB: 1) each station uses a wildcard Basic Service Set Identifier (BSSID), i.e., the BSSID is a wildcard where all bits are 1; 2) scanning, association, authentication, and de-authentication processes are disabled; 3) the channel must be known in advance; 4) power save is not allowed; 5) no beacon frames are transmitted or received; 6) no encryption is used; and 7) higher layer protocols ensure security properties.

The features related to multi-channel operation, i.e., operation between CCH and SCH, are specified in IEEE 1609.4. This standard includes primitives designed for multi-channel operations and parameters for priority access, channel switching and routing and management services.

2) ITS-G5

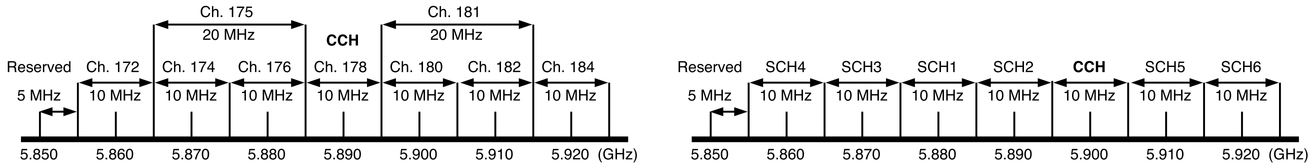
This standard defines one of the access layers in the C-ITS stack for vehicular communications in Europe. ITS-G5 is based on IEEE 802.11p, which means that the spectrum allocation, data rates, EDCA parameters and the OCB mode in IEEE 802.11p apply to ITS-G5. The most noteworthy differences between ITS-G5 and IEEE 802.11p are the following:

- **Control and Services Channels**. CCH is located on channel 180 (5.900 GHz), while the rest are for the services, as illustrated in Figure 6(b).
- **Congestion Control**. ITS-G5 requires a Decentralized Congestion Control (DCC) component to manage the channel load and unstable behaviour. DCC is a mandatory cross layer component of ITS-G5 and is in charge of transmitting rate control, data rate control, and power control, among other signals.

3) C-V2X

In order to meet the requirements for vehicular environments, C-V2X has been introduced in Rel-14 [34]. C-V2X inherits the PC5 interface and *sidelink* transmission from Rel-12. This allows vehicles to broadcast messages to each other, with or without infrastructure coverage. C-V2X *sidelink* transmission supports two modes of operation, namely, mode 3 and 4. Both methods operate in the 5.9 GHz spectrum.

- ***Sidelink* transmission mode 3**. The eNB assists in the resource scheduling and interference management of V2V communications by using control signaling via the Uu interface. In this mode the eNB selects the resources for each vehicle by using a dynamic method. Mode 3 is an infrastructure-assisted mode of communication.
- ***Sidelink* transmission mode 4**. Each vehicle independently decides which radio resources to use for each transmission. Given the fact that V2V communications are mainly periodic, a semi-persistent transmission-based method is used. Each vehicle senses the congestion on a resource (in terms of the received power from other devices), predicts future congestion, and thus reserves resources on the basis of that prediction. The above mechanism implies that each vehicle will select the same resource unless a collision is detected, and therefore, it enhances resource separation. Mode 4 is an infrastructure-less mode of communication.



(a) Spectrum allocation IEEE 802.11p

(b) Spectrum allocation ITS-G5

FIGURE 6. Spectrum allocation for IEEE-based technologies.

4) IEEE 802.11bd

As mentioned above, IEEE 802.11p is based on the IEEE 802.11a standard, which was released in 1999. Most of the PHY enhancements developed over the last two decades for 802.11 standards, such as Multiple-Input Multiple-Output (MIMO), and Dual Carrier Modulation (DCM), have still not being adopted in IEEE-based vehicular technologies. With that in mind, the IEEE 802.11bd Task Group was created in January 2019. The idea of 802.11bd is to include some of these enhancements in vehicular environments. IEEE 802.11bd is intended to support [35]:

- At least one mode that achieves a two times higher MAC throughput.
- At least one mode that achieves twice the communication range.
- Interoperability, coexistence, backward compatibility, and fairness with deployed 802.11p devices, especially with OCB mode.
- At least one positioning scheme in conjunction with V2X communications.
- A target mobility of 500 Km/h.

This standard is still under development, and the first draft is expected by January 2021. Some of the improvements include the use of mmWave frequency bands (60 GHz) for use cases where high throughput over small distances is needed, increased reliability by employing multiple spatial diversity, and spatial multiplexing MIMO, among others [36], [37].

5) NR-V2X

In 2018 3GPP created a study item for NR-V2X, which will bring enhancements to both Uu and PC5 interfaces. The objective of NR-V2X is not to replace C-V2X, but to support the use cases that C-V2X cannot, such as vehicle platooning, where messages can be delivered only to a specific subset of vehicles. The main design objectives of NR-V2X are [38]:

- Enhancements for PC5 and Uu interfaces in order to support advanced V2X applications.
- The coexistence of C-V2X and NR-V2X communications on a single device.
- Mechanisms to select the best interface (C-V2X, NR-V2X, Uu) given a frame transmission.

It is expected that the first specifications for NR-V2X will be available in Release 16 in 2020. Some of the envisioned enhancements in NR-V2X (mode 2) are the use of mmWave frequency bands (60 GHz), and support for unicast, groupcast, and broadcast transmissions, among others [37]–[39].

III. SDVN ARCHITECTURES

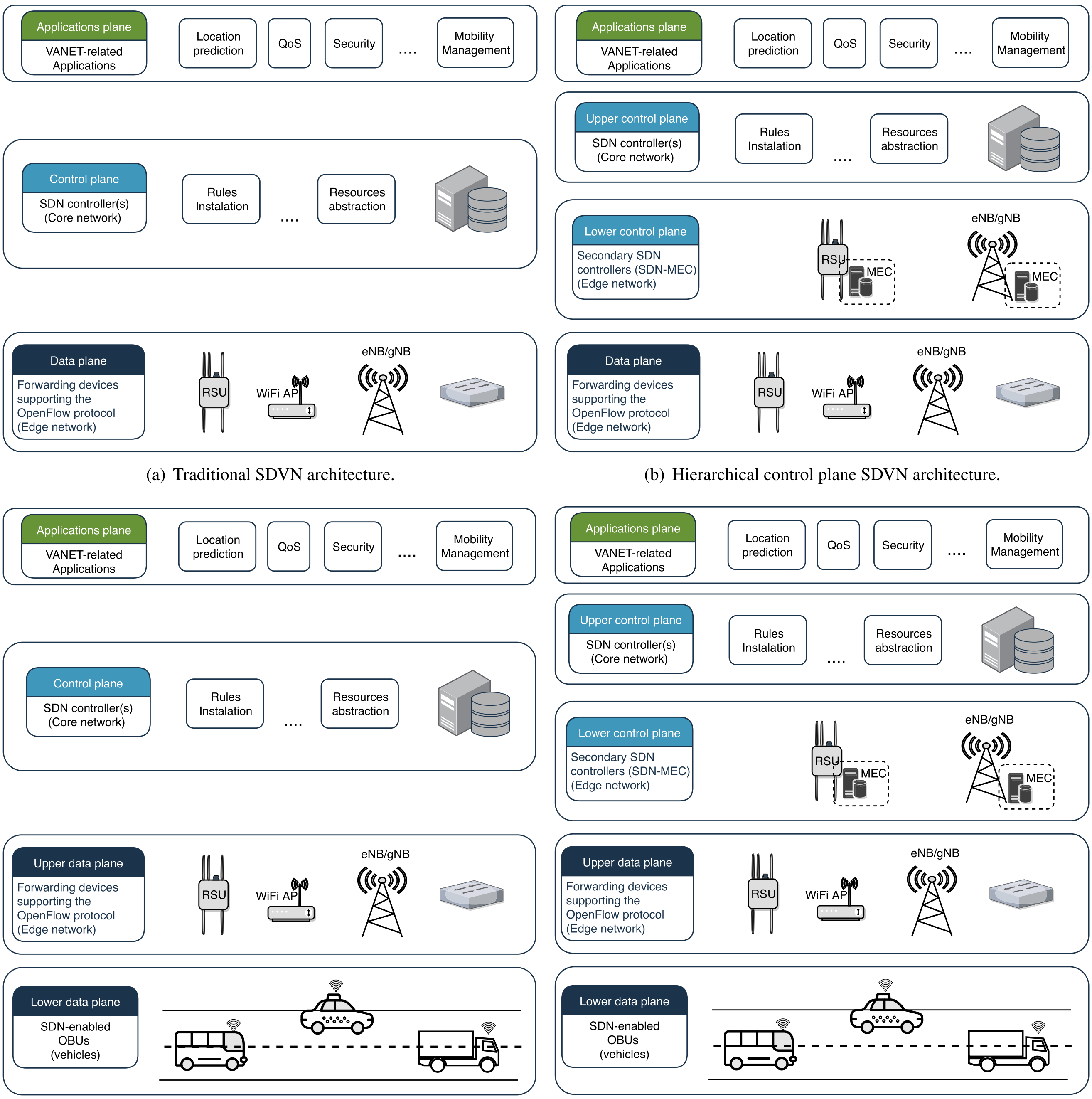
A. SOFTWARE-DEFINED VEHICULAR NETWORKING TAXONOMY

Several works proposing novel SDVN architectures and solutions can be found in the literature [40]–[47]. All of them preserve the main idea behind the SDN paradigm, i.e., the separation of the data plane (in charge of switching/routing the packets) from the control plane (in charge of defining how the traffic is handled) [6]. Similar efforts can also be found in the wireless and mobile networking domains under the name of Software-Defined Wireless Networking (SDWN) [48]. Nevertheless, the specific characteristics of VANETs require the adaptation and extension of the basic SDN and SDWN architectures and concepts in order to meet the needs of vehicular communications.

In this section we first provide a brief tutorial on SDWN. Then, we introduce a novel taxonomy which identifies four distinct the SDVN architecture archetypes: (i) standard SDVN architecture; (ii) the hierarchical Control Plane architecture; (iii) the hierarchical data plane architecture; and (iv) the fully hierarchical architecture. For instance, the hierarchical control plane architecture splits the control plane into two or more entities that are organized in a precise hierarchy, while the hierarchical data plane architecture splits the data plane into multiple layers, introducing one or more aggregation points. This separation of planes allows programmers to control diverse segments of the network with varied control/data levels. On the other hand, these levels bring new challenges, such as the need for the definition of new interfaces within the control/data planes, and maintaining information consistency. Figure 7 depicts the taxonomy used in this paper.

B. SOFTWARE-DEFINED WIRELESS NETWORKS

SDN has already played a key role in taming the ever growing complexity of data centres and wired networks by leveraging the concept of control-user plane separation through a well-defined interface (with the southbound interface with OpenFlow [49] playing the role of de-facto standard). Attempts to bring similar concepts to wireless and mobile networks do exist in the literature for the radio [50], [51] and the core networks [52] alike. Similarly, SDN solutions for non-cellular



(a) Traditional SDVN architecture.

(b) Hierarchical control plane SDVN architecture.

(c) Hierarchical data plane SDVN architecture.

(d) Fully hierarchical SDVN architecture.

FIGURE 7. Our proposed taxonomy for SDVN architectures.

wireless networks have also appeared [53]–[55]. Significant research has also been conducted in the field of programming abstractions for SDN. This includes both theoretical/conceptual [50], [56], [57] works as well as system research works [53]–[55], [58], [59]. In this section we aim to provide the reader with a brief introduction to the SDWN paradigm, with a particular focus on Control User Plane Separation (CUPS).

CUPS has become a cornerstone of the 3GPP 5G architecture [60], [61]. However, full control/user plane separation is not trivial, and is currently the subject of extensive research [62], [63]. This is the target of SoftRAN [50], where control operations can be centralized or distributed according to time requirements. This approach is also explored in Softmobile [57] by abstracting the control plane into several layers with the aim of issuing the control functions through Application Programming Interfaces (APIs). Conversely, FlexRAN [58] delivers a platform enabling Radio Access Network (RAN) programmability and introducing a south-bound API to enforce various levels of centralization for allocating the resources of the slices. With regards to resource scheduling, RadioVisor [64] extends SoftRAN in order to enable resource sharing between control functions and to perform resource allocation according to the traffic demands of each slice. Nevertheless, isolation between slices is not ensured. The platform proposed in [65], [66] allows flexible slice definition based on descriptors that characterize the policies and resources to be used. However, the resources are preallocated at the eNB according to the specific policy of the slices. Although most of these works consider isolation and resource allocation features across network slices, they ignore the signalling needed to ensure control/user plane separation in the traditional RAN architecture.

C. STANDARD SDVN ARCHITECTURE

The standard SDVN architecture is composed of the same layers as the SDN paradigm and is illustrated in Figure 7(a). The application plane is in charge of the network applications, the control plane is composed of the SDN controller and the data plane is composed of OpenFlow switches and routers in conjunction with the wireless access infrastructure, i.e., RSUs, WiFi APs, eNBs, and gNBs. The architectures following this approach are discussed in [44]–[46].

Campolo *et al.* [44], [45] address the network slicing functionality for Fifth Generation Vehicle To Everything (5G-V2X) services through a standard SDN architecture. In their proposals, different V2X services can be flexibly mapped onto different V2X dedicated logical networks (i.e., slices) with customer specific functionality. First, the authors [44] identify the main use cases and related Key Performance Indicators (KPIs) for V2X. Then, they propose the main use case that should be mapped onto each slice. In addition, the authors provide the configuration for each slice in order to obtain the KPIs. The slice configuration includes communication modes, scheduling mechanisms, and Quality of Service (QoS) management among other features. The authors [45] claim that this degree of flexibility and programmability could be provided by SDN in conjunction with other emerging technologies such as Multi-Access Edge Computing (MEC) and Network Function Virtualization (NFV). Here, SDN allows the remote configuration of the physical network in order to reserve on-demand networking resources for the slices. It can also be used to automatically reconfigure paths and react to possible network failures.

Shah *et al.* [46] present a tutorial perspective on vehicular communications using the building blocks provided by 5G. First, they identify and describe key requirements of emerging vehicular communications and assess existing standards to determine their limitations. Then they provide an overview of the relevant 5G building blocks in the context of vehicular communication. There is a general understanding that technologies such as ProSe (Proximity Service), MEC, and network slicing in 5G, together with new access technology, will address some of the deficiencies of IEEE 802.11p. ProSes not only provide a platform for the most desirable vehicular safety communications, but also pave the way for determining the source of autonomous vehicle attacks. MEC promises to reduce latency for vehicular applications such as the traffic information system. Similarly, by translating the vehicular use case requirements into technical specifications, network slices can be created for services such as dedicated vehicular safety applications, IPTV with QoS requirements, and emergency response applications. In their proposal, SDN is considered one of the enablers of network slicing.

D. HIERARCHICAL SDVN CONTROL PLANE

In this architecture, the control plane is composed of the upper control plane and the lower control plane. The upper control plane comprises one or more SDN controllers that have a global view of the network. The lower control plane is in charge of controlling one part of the network. It communicates with the upper control plane through wired interfaces, and is deployed at the edge of the network. As is shown in Figure 7(b), depending on the configuration, devices in the wireless infrastructure can act as secondary controllers (lower control plane), or as forwarding devices supporting the OpenFlow protocol (data plane).

The data plane is divided into service areas controlled by secondary SDN controllers, and part of the application information and network state can remain locally. This approach brings more flexibility to the control plane. On the other hand, since this is a distributed control approach, new challenges to maintaining the state of the control plane arises. SDVN approaches that adopt this architecture can be found in [41], [42], [47], [67].

Zheng *et al.* [41] propose a Cloud-RAN architecture for heterogeneous vehicular networks, namely the *software-defined heterogeneous vehicular network* (SERVICE). In SERVICE, different wireless technologies, such as Long Term Evolution (LTE) and Dedicated Short Range Communications (DSRC), coexist. The cloud resources can be exploited to provide satisfactory QoS to vehicles. The authors consider three tiers of cloud resources: Micro Cloud, Local Cloud and Remote Cloud. The Micro Cloud is deployed on the vehicles, the Local Cloud is deployed at the edge of the network, e.g., at BS sites, and provides services to a service area. In SERVICE, the control plane is located in the middle of the network infrastructure and is conceived as a hierarchical control plane. The primary controller (upper control plane) is responsible for the global service network, while the secondary one is responsible for the network control of a service area.

Conversely, Yaqoob *et al.* [42] conceived the control plane as hierarchical but also as a traditional control plane. Additionally, the authors present a more generic overview of the research advances and SDVN concepts, and identify the key requirements for SDVN, showing how SDN can provide enhanced synergy with emerging technologies such as cloud computing, fog computing and the Internet of Things (IoT).

Wang *et al.* [47] focus on collaborations among different edge computing anchors and propose a novel collaborative vehicular edge computing framework, called CVEC. They first investigated and compared multiple edge computing solutions for vehicular networks, such as mobile edge computing, fog computing, and cloudlet. Then, they propose CVEC, which can support more scalable vehicular services and applications by using both horizontal and vertical collaborations. They propose vertical collaboration between remote computing, edge computing and local computing, which is located on the vehicles themselves. The horizontal collaboration is between the controllers on the edge computing layer. The authors propose an SDN-based solution to manage the collaboration, with a logically centralized controller installed globally that connects each edge computing scenario. This controller is associated with a cloud computing or big data platform. The vehicular devices can be allocated with the most appropriate fog node and associated with this node according to the local controller.

Slamnik-Krijestorac *et al.* [67] propose the 5G-CARMEN Cooperative, Connected and Automated Mobility (CCAM) platform, which consists of a distributed and multi-layer network-embedded cloud architecture. The authors consider core orchestrators deployed in the core network and embedded MEC orchestrators. The MEC orchestrator (lower control plane) communicates with the core orchestrator (upper control plane), to provide information for automated NFV placement and migration. The platform will be deployed in cross-border scenarios, spanning three different countries, and will serve multiple uses cases such as cooperative maneuvering, back-situation awareness, and green driving.

E. HIERARCHICAL SDVN DATA PLANE

In this architecture the data plane is composed of the upper data plane and the lower data plane. As is shown in Figure 7(c), the upper data plane comprises OpenFlow switches and routers in conjunction with the wireless access infrastructure, i.e., RSUs, IEEE 802.11 APs, eNBs, and gNBs. The lower data plane is composed of the OBUs, i.e., the vehicles act as end users and forwarding elements equipped with both OBUs and the OpenFlow protocol.

Here, the control plane is also in charge of the OBUs. This fact fosters a more fine-grained control, more flexibility and programmability. By contrast, since OBUs are reachable through the wireless channel, the control channel is more unstable and may not be available. [68]. Akhunzada *et al.* [68] describe this SDVN architecture as composed of three planes. The data plane is divided into the upper data plane and the lower data plane. The upper data plane is composed of OpenFlow switches, routers, hosts, SDN agents, and other infrastructure elements. The lower data plane mainly comprises vehicular networks built through V2I and V2V communications. In addition, the authors present a taxonomy of SDVN security vulnerabilities, attacks and challenges for both the upper and lower data planes, SDVN APIs and external communication APIs.

F. FULLY HIERARCHICAL SDVN ARCHITECTURE

This architecture is a combination of hierarchical data and control plane SDVN architectures, as is depicted in Figure 7(d). Both the control and the data planes are divided into upper and lower planes. The upper control plane has the same functionality, i.e., it has a global view of the network and distributes the control on the lower control plane. The lower control plane installed at the edge of the network is in charge of the SDN-enabled wireless access infrastructure (upper data plane) as well as the SDN-enabled OBUs on the vehicles (lower data plane).

This type of architecture has a superior level of flexibility and programmability since a part of the network can be assigned to different secondary SDN controllers, and the OBUs can be controlled with a centralized approach. Furthermore, this architecture allows multiple controller domains and multiple data plane domains. On the other hand, the network and control management state are more challenging. Fully hierarchical SDVN architectures are addressed in [40], [43].

Ning *et al.* [43] propose the concept of the Software Defined Internet of Vehicles (SD-IoV). This concept is a fully hierarchical architecture where multihop communications for control path implementation through V2V are considered. Additionally, they establish three key functions on the SD-IoV: vehicular packet transmission control, access handoff, and network virtualization.

Fontes *et al.* [40] address the potentials of SDVN and analyze how the traditional SDN should be adapted to the context of vehicular communications. The authors proposed a fully hierarchical architecture in which control is distributed between RSUs and SDN controllers, and even the vehicles can act as forwarding switches supporting the OpenFlow protocol. In addition, the authors describe an extension they conceived for SDN-enabled VANET scenarios, and they design and implement a suitable node car architecture in Mininet-WiFi. The node car is emulated as an end user station and a *Root-Spine* switch. The node car can have multiple wireless interfaces that are connected to the *Root-Spine* switch. The node car architecture allows SDN programmability using all the available interfaces at the same time, without introducing constraints on the choice of centralized or distributed OpenFlow controllers. Additionally, the authors present a proof of concept scenario, where a car is streaming video to an operation center, and the SDN controller is responsible for managing all the emulated nodes (cars, RSUs, eNB). The emulation shows that the SDN controller selects the most appropriate wireless technology to transmit the video stream.

To conclude this review, Table 1 summarizes the publications that are focused on presenting SDVN architectures and their main contributions and differences.

TABLE 1. Summary of the SDVN architectures proposed in the literature.

Reference	Type of architecture	Emerging technologies involved	Main contribution
[40]	Fully hierarchical	MEC, cloud computing	Presents an emulation approach to showcase the applicability and some expected benefits of SDN in VANETs
[41]	Hierarchical CP	Cloud-RAN	Proposes a Cloud-RAN architecture for heterogeneous vehicular networks
[42]	Hierarchical CP	-	Presents key challenges and requirements for SDVN
[43]	Fully hierarchical	-	Presents the key requirements for SDVN and describes control path implementation in multihop communications
[44,45]	Standard SDVN	MEC, Cloud Computing, NFV	Provides a set of design guidelines and requirements for 5G-V2X network slicing
[46]	Standard SDVN	MEC	Presents a tutorial perspective on vehicular communications using the building blocks provided by 5G
[47]	Hierarchical CP	MEC	Proposes a novel collaborative vehicular edge computing framework, called CVEC
[68]	Hierarchical DP	-	Presents a taxonomy of SDVN security vulnerabilities, attacks and challenges
[67]	Hierarchical CP	MEC, NFV	Presents an architecture for cross-border scenarios

IV. COMMUNICATIONS REQUIREMENTS: AN SDVN APPROACH

VANETs have different protocol stacks, wireless access technologies, and regulations, among other characteristics. Although the KPIs are driven by the application requirements, they could vary depending on the protocol stack used as reference, e.g., IEEE-based, 3GPP-based, ITU, or others. Nevertheless, there are some KPIs that are common to different standards and protocol stacks. In this section, we provide an in-depth review of the communications requirements for SDVN solutions proposed in the literature. Our approach does not correspond to any particular standard. On the contrary, these KPIs are a summary taken from different standards and specifications [2], [69]–[71].

Figure 8 depicts examples of use cases and the required KPIs. Regarding autonomous driving (use case in white), higher data rates are not required, but high reliability and low latency are necessary. Information society on the road (blue) services, such as point-of-interest notifications, and commercial online services, have risen sharply for VANETs. With regards to information society, data rate requirements are higher, but latency and reliability are not as critical as compared with autonomous driving. In this section we explain how SDVN can address these KPIs and even outperform the traditional solutions.

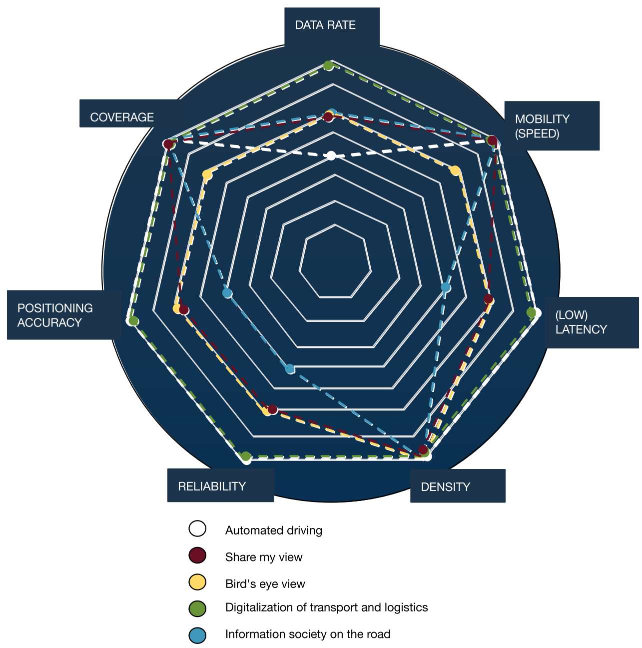


FIGURE 8. Network KPIs for 5G automotive vertical. Adapted from [71].

A. END-TO-END (E2E) LATENCY

End-To-End (E2E) latency can be defined as the maximum tolerable time elapsed from the instant a data packet is generated at the source application to the instant it is received by the destination application [2]. When the infrastructure is used, E2E includes the time needed for the packet to go and come back, i.e., the uplink, network routing and downlink time. If the infrastructure is not used, E2E latency is just the over-the-air latency. Several works propose solutions to meet the E2E requirements for 5G-V2X networks [72]–[97].

Wang *et al.* [88] propose an SDVN architecture assisted by MEC that incorporates different technologies (IEEE 802.11p, LTE and wired). The main goal is to provide low latency and a reliable communication. The authors propose a standard SDN architecture in which the SDN controller is located in the BS. MEC cloud servers are placed at the edge of the access network in order to reduce the round trip time of the data packets. The service request packets received on the MEC servers, should be processed at the edge rather than being delivered to the remote data center. Furthermore, the authors evaluate three use cases namely the Cooperative Collision Avoidance System (CCAS), the Bird's Eye View System (BEVS), and the Intelligent Navigation System (INS) on the NS3 simulator. The use cases are tested with different vehicle densities. The authors found that the delay time of IEEE 802.11p V2V communication in CCAS is less than 10 ms for all density levels, and the latency performance does not degrade suddenly for the highest vehicle density (100 vehicles). The reliability of BEVS is low, but still meets the requirement. The authors performed an analysis on the data rate performance on the cellular network, and found that the cellular network could meet the data requirements in the most congested scenario (100 vehicles).

Dong *et al.* [80] present an SDN-based vehicle ad-hoc on-demand routing protocol. Their main work focuses on redesigning the network control layer and the data transfer layer in VANETs, thus implementing SDN in VANETs. They propose a link stability coefficient which takes into account the number of hops between adjacent roadside control units (named LCs), the vehicle speed, and the standard variance of the vehicle speed. In addition, they propose a hierarchical control plane architecture, including a distributed global level and a centralized local level. The global level uses a ranked query scheme to query the objective vehicle information, and an improved method to calculate the route among numerous LCs. The local level uses a Bellman-Ford algorithm to maintain a stable route between two adjacent LCs. The LCs will collect all the hello information from the vehicles on the road, and try to build a network topology. The authors simulate their proposal using NS3 and SUMO, and their results show that, in terms of packet reception rate and average packet delay, it performs better and is more stable than traditional ad-hoc routing protocols such as DSR, DSDV, or DB. However, this scheme is not very suitable for sparse VANETs.

B. RELIABILITY

Reliability refers to the maximum tolerable packet loss rate at the application layer. A packet is considered lost if it is not received by the destination application within the maximum tolerable end-to-end latency for that application [2]. Reliability is addressed in [80], [81], [86], [88], [89], [92], [93], [95], [97]–[107].

Liu *et al.* [102] proposes an SDVN architecture for GeoBroadcast in VANETs. The architecture is a standard SDN architecture in which the data plane is composed of the RSUs supporting the OpenFlow protocol. The main idea behind it is that the SDN controller acts as an ITS control center. The SDN controller only needs to process the first warning message received by the source RSU as a packet-in message. After that, the SDN controller uses topological and geographical information to set up the routing paths to the destination RSUs by installing appropriate flow entries on the corresponding OpenFlow RSUs and intermediate switches. This design successfully handles the conversion of warning messages between GeoNetworking and the IPv6 of the existing ITS solutions. In addition, the authors implement RSU location management and GeoBroadcast components in the SDN controller by means of employing an experimental OpenFlow message called the Vendor message. The authors compare their proposal with traditional ITS solutions by considering two scenarios: a static event such as a car breaking down, and a moving event such as creating a path for an ambulance. They found that reliability in terms of packet delivery ratio is similar in both the SDN and ITS solutions, while SDN achieves a significant bandwidth reduction of 84% in the controller overhead, and 60% in network bandwidth consumption with respect to the ITS solutions.

Bozkaya *et al.* [98] present a software-defined flow and power management model to enhance the Quality of Experience (QoE) of vehicles by minimizing interference. In this architecture, the control plane is in charge of topology management as well as applying flow and power management model. The data plane is composed of RSUs and vehicles, which communicate using IEEE 802.11p, while the control plane uses the OpenFlow protocol. Information about vehicles, such as position, speed, direction, distance between vehicles and RSUs, and signal level, is stored in the RSUs, which are modeled using a queuing theoretic approach.

For flow management, the controller schedules the flows in each RSU with a global view of the network. If the QoE of a vehicle is unsatisfactory, the controller fairly distributes the vehicle to a new RSU with an acceptable level by keeping the QoE above a given threshold. The signal levels of the unsatisfactory vehicle are adjusted according to the power management model. The controller updates the information about the vehicle in both new and former serving RSUs. The power management model estimates the right amount of transmission power an unsatisfactory vehicle needs in order to connect to the newly assigned RSU. The authors use ordinary Kriging interpolation techniques to estimate the transmission power of the unsatisfactory vehicle and compare diverse estimation methods such as exponential, Gaussian, linear, and the static case (no flow and power management model). The findings show that the exponential method is the most suitable option as it makes possible to serve 8% more vehicles.

C. DATA RATE

The data rate is the minimum required bit rate for the application to function correctly [2]. Data rate optimization is addressed in [78], [79], [88], [106]–[112].

Ge *et al.* [78] propose a new vehicular network architecture that is integrated with 5G mobile communication technologies in combination with SDN, fog, and cloud computing. The proposed architecture divides both the data and control planes, and includes cloud and fog computing clusters. The fog cells are established at the edge of the 5G SDVN in order to reduce the frequent handovers between the RSUs and vehicles, and to reduce the transmission delay of warning messages. Vehicles and RSUs are provided with information collection and communication modules. The RSU controller and the SDN controller are equipped with network status, computation, and hot caching modules. The authors analyzed and compared, via simulation, throughput and transmission delay. The simulation results indicate that the transmission delay is mainly dependent on the re-transmission delay in each hop of vehicle communication. Moreover, the throughput of fog cells in the 5G SDVN is better than that of traditional transportation management systems.

Duan *et al.* [108] propose an SDN-enabled 5G VANET in which neighboring vehicles are adaptively clustered according to real-time road conditions using SDN's global information gathering, and network control capabilities. The framework uses a standard SDN architecture in which the wireless network infrastructure is provided with a local database and an application module. In general, the database stores information about vehicles within the cell, including the clustering information, the geo-location of vehicles, traffic requirements, and transmission schemes. This information is updated when a new vehicle accesses or leaves the current cell. Here, SDN provides an enabling platform to apply intelligence and a consistent policy for the 5G-VANET network, which will predict road traffic to achieve adaptive vehicle clustering. Within each vehicle cluster, a cluster head is selected to aggregate traffic from other vehicles and communicate with the cellular BS to reduce the signaling overhead. A dual cluster head design is also proposed to guarantee robust and seamless trunk link communication. The proposed framework is evaluated via simulation using Matlab. The authors compare their proposal with a traditional method, which chooses the center vehicle as cluster head, and the scenario in which there is no clustering mechanism. The results show that the signaling overhead of a VANET is significantly lower and the communication quality is higher.

D. MOBILITY MANAGEMENT

Mobility is related to the maximum relative speed at which the specified reliability should be achieved [2]. Mobility is studied, or more specifically, mobility, handover management, and migration of the state information of the vehicles are studied in [79], [92], [94], [106], [110], [112]–[119].

Lai *et al.* [79] design a buffer-aware QoS for multimedia streaming. The main goal is to tackle the handover latency caused when a vehicle initiates the handover process between eNBs while achieving a minimum delay and a better QoS. The authors use a hierarchical data plane SDVN architecture. The SDN controller configures the network connection between the core network and the wireless base stations. A module needs to be deployed on the vehicle for network status reports, estimating the time when the vehicle will handover, and appraising the direction of the vehicle. This module communicates with the SDN controller to obtain the information on handover making and multimedia data transport. When the vehicle initiates a handover between eNBs, the network latency will not meet the QoS requirement for multimedia streaming. Considering the speed and the direction of the vehicle, and the amount of multimedia content stored in the buffer, the proposed mechanism provides the appropriate handover timing, i.e., when the handover should be initiated, and the transmission path configuration. Two key factors are considered: the time of handover, evaluated by using the range of overlapping signal coverage between eNBs; and the priority of streaming multimedia content evaluated by the buffer storage status of the vehicle. According to the experimental results, the bandwidth can be higher than 1280 Mb/s when the vehicle is handed over between the eNBs at a speed of 60 km/h, and the peak signal to noise ratio analysis shows that the streaming media quality can be increased by 3 dB.

Huang *et al.* [106] propose a prediction control scheme called Offloading with Handover Decision based on Software-Defined Network for the offloading of the V2I communications. The authors employ a hierarchical data plane architecture. The main idea is to collect the context information about all the vehicles and RSUs at the SDN controller so that it can have a global view of the network, and then perform the evaluation of whether it is worth offloading from the cellular network to an RSU offering IEEE 802.11p. Comparing it with a simple scheme where only signal strength is considered, the proposed control scheme takes into account both the network quality and the estimated time for staying inside an RSU coverage zone in order to make the decision. The SDN controller transmits the control messages to the related vehicles to perform the corresponding configurations after the calculation and decision. The simulation results show that by using the proposed control scheme, the cellular network's load and traffic can be reduced, and the link quality between RSUs and vehicles can be assured. From the performance analysis, it can be seen that the proposed scheme performs better than the simple scheme.

The authors extended their work to consider V2V data offloading, and a fully hierarchical architecture [110]. In the proposed method: 1) the vehicles' context information is used; 2) the control of the network is also at the edge; and 3) a V2V path for vehicles that are currently communicating with each other using the cellular network is established. Vehicles report information to the edge controller, namely the SDN-MEC controller (lower control plane), which decides whether to switch the communication using a V2V IEEE 802.11p link. The authors propose two algorithms in order to: 1) find the V2V (multihop) route when V2V is possible, and 2) recover the communication link in case of failure. The performance analysis for the proposed offloading control shows better throughput in both the cellular links and in the V2V paths in a medium vehicle density. These schemes are evaluated using the NS-3 simulator in a highway scenario.

E. SECURITY

Security application requirements for 5G-V2X includes user authentication, data authenticity, data integrity, confidentiality, and user privacy [2]. Security in SDVN is addressed by Akhunzada *et al.* [68], [81]. The authors describe an SDVN

TABLE 2. Architectures vs. communication requirements.

Architecture	Ref.	CT	Scenario	WAT	Eval.	E2E Latency	Reliability	Data Rate	Mobility	Security
Standard SDVN	[81]	-	Urban	11p	ns2	x	x			
	[86]	-	-	-	-			x		x
	[88]	MEC	CCAS, BEVS, INS	11p, LTE, Wired	ns-3	x	x	x		
	[89]	NDN	-	11a	-	x	x			
	[90]	-	-	-	-	x				
	[94]	-	-	11p, 5G	-	x		x		
	[96]	-	-	-	-	x				
	[98]	-	High Density	11p	Matlab		x			
	[100]	-	-	-	-		x	x		
	[101]	-	Urban	-	ns-3	x		x		
	[102]	-	Static and mobile	-	OpenNet		x	x		
	[103]	Cloud	Urban		ns-3		x			
	[108]	-	-	11p	Matlab			x		
	[112]	-	-	11p	-		x	x		
	[114]	-	Urban	WiFi		x	x	x	x	
	[116]	MEC, Cloud	Urban	WiFi	mininet WiFi	x		x	x	
	[120]	-	-	WiFi, LTE	ns-3	x				
Hierarchical control plane	[80]	-	-	-	ns-3	x	x			
	[91]	Fog	-	-	-	x				
	[92]	-	Highway	11p	mininet WiFi	x	x		x	
	[93]	-	Urban	11p, LTE	ns-3	x	x			
	[95]	Fog	-	11p, LTE	OmNET	x	x			
	[97]	Fog, Cloud	-	-	-	x		x		
	[109]	Satellite	-	-	-		x			
Hierarchical data plane	[68]	-	-	-	-					x
	[79]	-	Video streaming	5G	-	x		x	x	
	[106]	-	-	WiFi, LTE	ns-3		x	x	x	
	[118]	-	Urban	WiFI, LTE	ns-3	x			x	
Fully hierarchical	[78]	Fog, cloud	-	LTE, 5G	-	x		x		
	[107]	ICN	Urban	11p	OmNET		x	x		
	[110]	MEC	Highway	-	ns-3			x	x	

CT = Complementary technologies, WAT = Wireless Access Technology, Eval = Evaluation Tool architecture composed of three planes, namely the application, control, and data planes. The data plane is divided into an upper data plane and a lower data plane. The upper data plane is composed of OpenFlow switches, routers, hosts, SDN agents and other infrastructure elements. The lower data plane mainly comprises vehicular networks built through V2I and V2V communications. In the lower data plane, vehicles act as end users and forwarding elements equipped with the OpenFlow protocol. The authors also present a taxonomy of SDVN security vulnerabilities, attacks, and challenges for each plane, including the upper and lower data plane, SDVN APIs and external communication APIs. Additionally, they claim that security plays a crucial role and may hamper the adoption of SDVN. The trend of launching sophisticated attacks is expected to increase massively. Furthermore, the lack of standardized SDVN APIs could create opportunities for launching attacks on different layers of the SDVN architecture. Finally, it seems clear that SDVN control should be extended to the wireless environment.

Table 2 summarizes the information in this section and shows the relationship between the architectures and the communications requirements. Additionally, we show the most common evaluation tools, the complementary and access technologies involved, and the scenarios. We can see that standard SDVN is the most common architecture among the different solutions, while a fully hierarchical architecture is not widely used. As we stated in Section III, more flexibility implies greater complexity in terms of control, implementation, and the interfaces between planes.

V. USE CASES

In this section, we illustrate how the use of SDVN can be exploited to control the network in a centralized, flexible and programmable way in vehicular environments. To this end, we explain three use cases: 1) the back-situation awareness of an emergency vehicle arrival; 2) the video streaming; and 3) the information sharing using V2P. These use cases are examples taken from different standards [2], [69]–[71], and are being studied in several European projects [121]–[123].

A. BACK-SITUATION AWARENESS OF AN EMERGENCY VEHICLE ARRIVAL

Back-situation awareness aims to provide in-advance warning/information about the arrival of emergency vehicles (e.g., ambulances, police vehicles, fire trucks) that have the right of way. The road/highway is cleared only when the emergency Vehicle (emV) draws drivers' attention through its blaring siren. Usually, this is only possible in direct proximity. Several works have attempted to improve the efficiency of this message delivery by, for example, forming clusters of vehicles with a low communication overhead [124]. The short notification time makes it hard for drivers in the path to somehow make way by moving to the sides. The problem is severe if there is a high traffic density, not only on inner-city roads (possibly near traffic signals, where vehicles do not have much space to maneuver, thus hampering critical emergency efforts), but also on highways where the speed and the noise (e.g., radio, engine) could be relevant. The use case is to ensure an early warning of approaching emVs to only those vehicles that are on the emV's route.

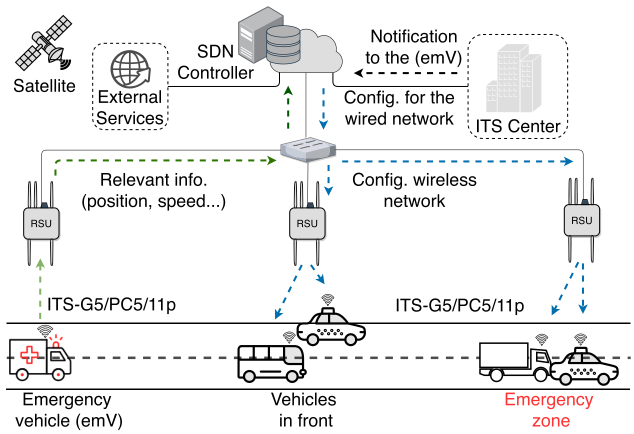


FIGURE 9. Back-situation awareness scenario.

TABLE 3. Communication requirements for a back-situation awareness scenario.

KPI	Value
Frequency (Hz)	10
Latency (ms)	100
Data rate (Mbps)	-
Reliability (%)	95

Figure 9 provides an overview of the back-situation awareness scenario and Table 3 shows the network requirements. As illustrated, the scenario involves emVs that are being dispatched towards the emergency zone. The relevant information (CAM) is forwarded to the vehicles in front, employing OpenFlow-enabled RSUs. That means that the information is forwarded to the points outside the emV's wireless coverage, and the vehicles are made aware earlier about the situation.

In the wired domain, OpenFlow-enabled RSUs receive the CAMs from the emVs and send them to the SDVN controller as a *PACKET-IN* message. With this message, the controller is aware of the emVs and installs OpenFlow rules on all the RSUs and OpenFlow switches. The rules are composed of <match, action> sets to classify the packets from the emV. Given that OpenFlow does not support WAVE and C-ITS, the rules match fields at the link layer level, such as Ethernet type and LLC, among others. Moreover, given that RSUs support WAVE and C-ITS and are SDN-enabled, which means they are programmable, it is possible to install an agent and to expose the CAM information, and thus to identify the emV. The action set is to forward the CAM from the emV to the RSUs in front.

In the wireless domain, the controller, which is gathering statistics and monitoring the wireless environment (interference, channel occupancy, etc.), applies real-time configurations on the wireless interfaces to prioritize the downlink

TABLE 4. Communication requirements and configuration of the slices.

	Communication requirements				Configuration of the slices		
Slice	Frequency (Hz)	Latency (ms)	Data rate (Mbps)	Reliability (%)	Protocol	Wired domain (OpenFlow rules)	Wireless domain
Road safety	1	100	-	95	CAM or WSMP	ETH_TYPE = 0x88DC ‖ 0x8947	Low MCS High Airtime
Traffic efficiency	2	100	-	95	DENM or WSMP	ETH_TYPE = 0x88DC ‖ 0x8947	Low MCS
Video streaming	-	-	1.3∼14.2	-	IPv6	ETH_TYPE = 0x86DD, NW_PROTO = 17	High MCS Low Airtime

in the RSUs in front, allowing the vehicles to receive the message. In IEEE-based technologies, the controller assigns the optimal airtime [125]–[127]. In 3GPP-based technologies, scheduling techniques to prioritize the emV traffic can be applied [128]. These configurations in the wireless domain guarantee the communication requirements presented in Table 3 since they are driven by the KPIs.

When the emV arrives in the emergency zone, the controller (MEC/Cloud) installs new rules in the wireless domain in real-time to provide QoS policies in the uplink for the emV. When the emergency is over, the controller, on the basis of the gathered statistics and monitoring, will recognize this fact and switch to the initial configuration. All this flexibility offered by SDVN, i.e., applying configurations in real-time, automatically and in a programmed way, and removing them when they are not necessary, is difficult to achieve when employing a traditional approach, in which there is no global view of the network.

B. VIDEO STREAMING

The on-demand streaming of movies, live broadcasts and high definition videos is one of the most popular forms of entertainment and dominates Internet traffic today. Therefore, passengers will expect to be able to enjoy the same service in an autonomous vehicle, i.e., an always-on connection which meets the requirements such as the data rate needed for high-quality video streaming, no matter where they are. Especially with high levels of autonomous driving, passengers' expectations will be to sit back and enjoy multimedia entertainment (e.g., a movie) during their daily commute, just as if they were in the comfort of their homes.

SDVN can provide video streaming without disturbing the essential services for which VANET was conceived by employing network slicing [44], [116]. In accordance with the communication requirements and protocols involved, the controller configures three slices, as illustrated in Table 4. The configurations differ depending on the communication requirements, the protocols involved, and the domain. Road safety and traffic efficiency applications send periodical messages, and require a low data rate but also high reliability. The data rate in video streaming depends on the quality required (HD, UHD, 4K), but high reliability is not crucial. In the wired domain, OpenFlow rules are applied to match the protocols involved (CAM, DENM, WSMP or IPv6) and apply QoS policies using DSCP for video streaming. In the wireless domain, the configuration of the wireless interfaces is included. The video streaming slice prefers higher Modulation Code Scheme (MCS) since higher data transmissions are employed. In contrast, lower MCS should be preferred for safety and efficiency applications, since this increases the probability of receiving the messages.

Additionally, if the network infrastructure is composed of complementary technologies such as MEC or Fog, the controller, which continuously monitors wired and wireless links, can instruct the RSUs via CAMs or DENMs at the edge, releasing the link between the edge and the cloud server where the video is hosted. In this way, the video is closer to the end-user, and the costs and latency are reduced.

C. EXPLOITING V2P COMMUNICATIONS IN A DEPLOYED INFRASTRUCTURE

This scenario considers a city-urban scenario in which pedestrians and vehicles share the infrastructure. In this case, the vehicles do not use de-facto technologies for vehicular communications, such as IEEE 802.11p, ITS-G5, or C-V2X. What they do use are technologies and infrastructure that are already deployed, such as 4G or legacy WiFi. In this scenario, the need for interoperability and coexistence among diverse wireless technologies emerges. The goals are to maximize the use of the existing resources and to protect vehicular applications with respect to pedestrians' non-priority applications.

Given the access technologies involved, the vehicle must be associated with the network at the link-layer, i.e., the handshake process must be performed at each AP (eNBs, gNB, WiFi APs). Meeting network requirements can be achieved by using network slicing in the same way as video streaming. However, the new challenges in this use case are: 1) to maintain the connection of all users (vehicles and pedestrians) when they move from one AP to another; and 2) to guarantee interoperability among wireless technologies.

SDN-based techniques are entirely appropriate in this scenario, in which seamless handovers and interoperability are required. In Figure 10, the Vehicle1 is moving from AP1 to AP2, and is sharing resources with pedestrians. The controller is protecting the services using network slicing. At the same time, the controller continually monitors the connection status of each connected user. Based on diverse parameters (signal power, network requirements), the controller can

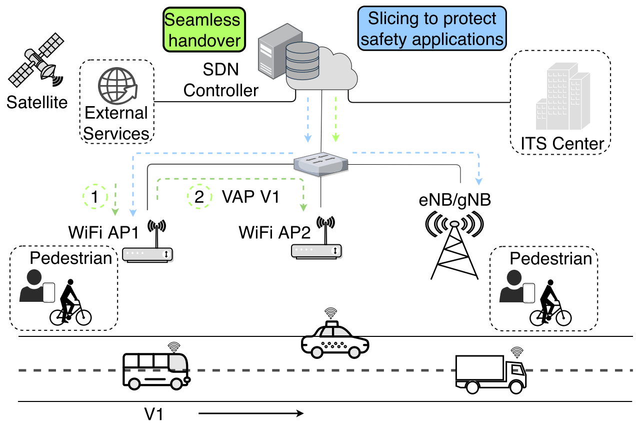


FIGURE 10. Exploiting a deployed infrastructure.

TABLE 5. Information exchanged for seamless handover.

Message	Information
del_lvap	MAC adress, CSA counter
add_lvap	SSID, BSSID, MAC address, HT capabilities

migrate the vehicle's connection from AP1 in the network to AP2. This can be done in two steps using Virtual Access Points (VAPs) [129]. First, the controller removes the VAP for Vehicle 1 (V1) from AP1 and then instantiates the VAP V1 in AP2. The information exchanged is presented in Table 5. In addition, considering that the client can have multiple wireless interfaces, the controller can perform a vertical handover from the WiFi of AP2 to the eNB/gNB without losing the connection to the network.

A hierarchical control plane architecture can also be employed to perform this migration. A fully hierarchical SDVN architecture could be implemented together with SDN-enabled end-user devices, where the SDN-MEC controller configures and monitors these end-devices. Approaches ensuring seamless handovers and interoperability are however challenging to implement without an SDN perspective, especially in WiFi networks, where the end-user governs the association process.

VI. RESEARCH CHALLENGES

In this section, we identify and discuss a set of research challenges for 5G Software-Defined Vehicular Networks. Furthermore, we highlight the main gaps we have identified in the state of the art considering technical aspects, deployment, and management.

A. STANDARD NORTHBOUND AND SOUTHBOUND INTERFACES

Although SDVN architectures are well defined in terms of building blocks and functionalities, there is a lack of definition of standardized interfaces to enable communication for those building blocks. For instance, when a standard SDVN is used, northbound and southbound interfaces are well defined since they are inherited from the standard SDN architecture. Nevertheless, when hierarchical control plane or data plane architectures are proposed, interfaces within control planes and within data planes are not properly defined. It is not clear how the SDN controller on the upper control plane should communicate with the controllers on the lower control plane. Moreover, when hierarchical data planes are considered, there is no standardized protocol to enable communication for the upper and lower data planes. The latter could be more challenging since, the control messages for the vehicles (lower data plane) employs the wireless interfaces, which means these messages are exposed to the same challenges as those of vehicular communications, such as a large Doppler effect, a highly unstable communication environment and the high mobility of the vehicles. The control message should be able to rely on a stable communication channel. A clear definition of the type of messages as well as the necessary information to enable communication in these blocks is still an open issue.

SDVN interfaces should be adequately unified for effective inter-network communication and operation [42]. Abstraction and virtualization are helpful in hiding the heterogeneous details of different networks and vehicles. The incorporation of complementary technologies such as the IoT, MEC, and VCC typically require operational independence from network type and devices.

B. RESOURCE ABSTRACTION

The heterogeneity of vehicular networks increases the complexity of fine-grained resource allocation [43]. SDVN is a multiple access technology ecosystem in nature, and it includes several complementary technologies such as MEC and cloud computing, giving rise to the need for not only network resources, but also storage and processing resources. The management of this wide variety of resources is complex. One way to alleviate this problem is the abstraction of physical resources. In MEC and cloud computing the abstractions are well-defined since they are inherited from other environments. Nevertheless, the physical resources of wireless access technologies need to be abstracted. Most of the existing works consider the network infrastructure as an OpenFlow switch and the wireless interfaces as ports. A more fine-grained abstraction including the wireless interfaces might improve packet transmission. A higher level of granularity could bring more flexibility and programmability and enable diverse ways of handling different services.

Given the inherent complexity of resource abstraction and efficient management in SDVNs, Artificial Intelligence (AI) and Machine Learning (ML) are starting to position themselves as powerful enablers of abstracting and optimizing resource classification and management on the control plane. Examples of works analyzing this problem are [130], where the authors leverage deep learning, and [131], where they use reinforcement learning techniques. This enabler, together with the close relationship with MEC and cloud computing, has led the research community to look at MEC systems as a means to offload computing tasks. This poses a new problem in terms of resource abstractions (including computing resources, storage resources, and network resources) and effective resource scheduling [132], [133], especially considering the large number of heterogeneous systems and the sporadic nature of vehicular connections.

C. LACK OF EXPERIMENTATION

Experimentation employing SDVN principles is only vaguely addressed in the literature. Some works aim to provide some inputs about how SDVN can be employed on real hardware, but these approaches are still insufficient [40], [111], [116]. First, an ideal SDVN environment should expose, control, and configure the wired resources as well as the wireless resources. Second, the communications stacks, and, therefore, the access technologies explicitly designed for VANETs, such as C-ITS and IEEE WAVE, should be used even when SDVN is introduced. Third, although emulation is a convenient tool for prototyping and research, the aleatory nature of a real environment is difficult to study when employing only software tools.

It is necessary to have open-source SDVN tools, as well as guidelines and frameworks for SDVN that can be integrated with the plethora of hardware available for vehicular communications. Moreover, with the new arrival of C-V2X hardware on the market, experimentation employing this new hardware and its integration with SDVN is now needed. Experimentation on real hardware using SDVN frameworks and tools could bring new insights into the network (core, edge, vehicles), and the requirements for greater flexibility and programmability. Some examples of these prototypes are starting to appear such as in [134], which provides a preliminary design composed of OpenFlow switches, allowing experimentation on IEEE 802.11. Similarly, the authors in [135] introduce an open-source testbed providing IEEE 802.11p connectivity and the possibility of evaluating application-layer latency between nodes. Nevertheless, these prototypes are still at an early stage and lack several functionalities such as basic inter-technology support (WiFi and LTE) and connectivity modes (V2X, V2I, and V2V).

D. FREQUENT HANDOVER AND MOBILITY MANAGEMENT

In an SDVN the handover mechanism is more complex than in a traditional cellular network [42], [78], [88], [42]. This is because: 1) the radio resources might need to renegotiate with a new SDN controller; 2) a set of flow tables needs to be updated according to the change in topology; 3) if a MEC cloud server is present, live migration and service redirection are necessary actions, which increases the complexity of handover; and 4) the handover will be simultaneously generated for MEC services and for multihop links. By using the vehicle's position, direction, velocity, and destination, the trajectory prediction component can estimate the vehicle's position in the near future, which helps to complete service migration and flow table entry updates in advance. At the same time, if the handover mechanism fails, the mechanism for failure recovery and error handling also needs to be considered carefully since the propagation delay of the warning message needs to be minimized. Although several solutions have been proposed to address this challenge, they are still in their infancy and cannot be adopted in SDVN. The inclusion of the movement behavior of vehicles in predicting network stability can be a solution for the high mobility problem. In this respect, learning-based methods can be further exploited to identify potential patterns for improved load balancing and handover. In [136] we can find an example where reinforcement learning is used by taking as input context information from the base stations in the form of vehicular speed, number of users and historical handover data. Similarly, the authors of [137] proposes an online probabilistic neural network for predicting the next serving access point using the vehicles' mobility information. Strictly related is the ability to predict the vehicles trajectory, and that can be a valuable indicator for effective mobility management and routing protocols [138]. Nevertheless, the issue in these ML algorithms comes from the difficulty in formulating a proper objective that jointly optimizes the performance of the various links and the definition of a numeric reward, especially in settings where energy consumption must be taken into consideration.

E. SECURITY AND PRIVACY

Security on SDVN has not been studied in depth in the literature. Nevertheless, it is recognized as a challenge for SDVN environments since the propagation of misinformation from unauthorized entities can lead to serious accidents [40], [42], [43], [68]. Therefore, security is one of the key concerns that require serious attention. First, if the controller is exploited by unauthorized entities, the whole network may come under the control of an attacker, which may cause denial of service attacks. Second, the controller should be protected because it is the centralized decision point in SDVN. In the control plane, the controller requires descriptions of the status of all vehicles, such as speed, locations, and destinations. If the information can not be trusted, it will cause several privacy issues for vehicular end users. Other threats include those based on distributed multi-controllers, threats from applications, illegal access, and security rules and configuration conflicts. Although several solutions have been proposed, they cannot be directly adopted in VANETs because they have different characteristics. The high mobility nature of VANETs requires security mechanisms that can perform real-time authentication; otherwise, latency can cause a level of traffic congestion that impedes the operation of SDVN. This real-time factor increases the difficulty of strengthening security.

Blockchain and ML-based approaches such as deep Q-learning have recently been envisioned as an essential part of VANETs [94], [139]–[142] with the aim of guaranteeing immutability and authentication in the information interchanged, and satisfying the demand for center-less trust. Most, if not all, recent works leverage a simulations

TABLE 6. List of acronyms used in this survey.

Acronym	Definition
3GPP	3rd Generation Partnership Project
4G	4th Generation of Broadband Cellular Networks
5G	Fifth Generation
5GAA	5G Automotive Association
5G-V2X	Fifth Generation Vehicle To Everything
AI	Artificial Intelligence
AECC	Automotive Edge Computing Consortium
AP	Access Point
API	Application Programming Interface
BS	Base Station
BSA	Basic Set of Applications
BSS	Basic Service Set
BSSID	Basic Service Set Identifier
BSM	Basic Safety Message
BTP	Basic Transport Protocol
C-ITS	Cooperative Intelligent Transport Systems
C-V2X	Cellular Vehicular To Everything
C2C-CC	Car 2 Car Communications Consortium
CAM	Cooperative Awareness Message
CCAM	Cooperative, Connected and Automated Mobility
CCH	Control Channel
CSMA	Carrier Sense Multiple Access
CUPS	Control User Plane Separation
D2D	Device To Device
DCC	Decentralized Congestion Control
DCM	Dual Carrier Modulation
DENM	Decentralized Environmental Notification Message
E2E	End-To-End
EDCA	Enhanced Distributed Channel Access
eNB	Evolved Node B
ETSI	European Telecommunications Standards Institute
emV	emergency Vehicle
FCNs	Future Communication Networks
GSA	Global Mobile Suppliers Association
gNB	Next generation Node B
GNSS	Global Navigation Satellite System
ICN	Information Centric Networking
IoT	Internet of Things
ISO	International Organization for Standardization
ITS	Intelligent Transport Systems
KPIs	Key Performance Indicators

Acronym	Definition
LOS	Line Of Sight
LTE	Long Term Evolution
M2M	Machine To Machine
MAC	Medium Access Control
MANET	Mobile Ad Hoc Network
MCS	Modulation Code Scheme
MEC	Multi-Access Edge Computing
MIB	Management Information Base
MIMO	Multiple-Input Multiple-Output
ML	Machine Learning
NDN	Named Data Networking
NFV	Network Function Virtualization
NLOS	Non Line Of Sight
NR	New Radio
OBUs	On Board Units
OCB	Outside of Context of a BSS
OFDM	Orthogonal Frequency Division Multiplexing
OSI	Open System Interconnection
PHY	Physical
PSID	Provider Service Identifier
QoS	Quality of Service
QoE	Quality of Experience
RSU	Road Side Unit
SAE	Society of Automotive Engineers
SCHs	Service Channels
SDN	Software-Defined Networking
SDVN	Software-Defined Vehicular Networking
SDWN	Software-Defined Wireless Networking
SLA	Service Level Agreement
TDMA	Time Division Multiple Access
V2I	Vehicle To Infrastructure
V2N	Vehicle To Network
V2P	Vehicle To Pedestrian
V2V	Vehicle To Vehicle
V2X	Vehicle To Everything
VAP	Virtual Access Point
VCC	Vehicular Cloud Computing
VANETs	Vehicular Ad Hoc Network
WAVE	Wireless Access in Vehicular Environments
WSM	WAVE Short Messages
WSMP	WAVE Short Message Protocol

environment to introduce these security enhancements, which highlights yet another vertical side of SDVNs lacking experimentation on real devices. Moreover, it should be noted that the introduction of AI in vehicular networks also poses tremendous challenges and risks, given that it can produce harmful or unexpected results. The use of ML models brings another potential point of attack into the system, through which the network could be compromised. Although federated learning has been shown to achieve good results in this respect [143], [144], significant efforts need to be made in improving the robustness and security of AI itself in SDVN environments in order to find a satisfactory trade-off between security and privacy risks and performance.

F. QUALITY OF SERVICE FOR DIFFERENT APPLICATIONS

Vehicular networks applications specify communications requirements according to the use cases. However, the resources in the integrated network exhibit a high degree of heterogeneity. Moreover, resource availability for vehicular services varies over time, since each network segment dynamically allocates resources to support its legacy services [109]. The 5G architecture suggests network slicing to logically separate networks, thus guaranteeing QoS. However, the use of network slicing in 5G creates several challenges [46]. Most of the concerns about network slicing arise from the unclear specifications of its operation. For instance, to adopt a truly modular approach for different sliced networks, vehicular application requirements must be carefully translated and categorized into technical specifications. This will ensure that one sliced network does not affect another, and changes from one slice to another are seamlessly integrated.

An intelligent network slicing engine would be of great benefit in providing a satisfactory QoS, and this is why ML technologies have become the main actor in automating this operation. This method would facilitate the extraction of network dynamics, the translation of vehicular requirements (e.g., high bandwidth for infotainment, and low latency for autonomous driving services), and efficient resource allocation to the network slices in the control plane. In this respect, reinforcement learning is one of the most widely used techniques to achieve this goal [145], [146]. Despite the progress made by AI, the majority of current works focus on the RAN [147], and extensive research is needed into solutions addressing inter-slice mobility management in end-to-end fashion, where diverse resource pools come into play. Moreover, in an attempt to enhance the slice Service Level Agreement (SLA) provided, ML is being used as a complementary tool to predict future QoS levels and anticipate resource adaptation to the varying wireless environment [148], [149]. Most of this research tackles performance, bandwidth and traffic flows as prediction targets, but does not address how transmission delays evolve over time and affect ultra-low latency services in particular, which is undoubtedly important in vehicular operations.

G. INTEROPERABILITY

In VANETs, there exist several access technologies that have already been standardized, such as IEEE 802.11p, C-V2X, and ITS-G5. In addition, the standardization of two new technologies, namely IEEE 802.11bd and NR V2X, is underway. Given this diversity of technologies, the need for interoperability and coexistence is evident. The VANET environment is a heterogeneous wireless environment in nature, and guaranteeing communications regardless of the wireless technology is a challenging task. Additionally, the three current technologies share the same spectrum (5.9 GHz), meaning interference is a crucial factor. Moreover, if the medium access techniques are considered, i.e., contention-based for IEEE-based and semi-persistent schemes for 3GPP-based, some technologies may be penalized.

In an intra-domain scenario, a vehicle that only supports IEEE-based wireless access technology, e.g., ITS-G5, will not be able to communicate directly with a vehicle that only supports 3GPP-based technologies. In inter-domain scenarios [67], it is necessary to maintain communications between different wireless technologies but also to maintain services between different operators.

In this context, the management of the network infrastructure (RSUs, eNBs) plays a fundamental role, and SDVN can leverage this interoperability and coexistence. The SDVN controller, which has a global and centralized view of the network resources and the available interfaces, receives the messages and disseminates them through the necessary interfaces. In the inter-domain scenario, SDVN controllers in each domain can exchange information about supported wireless technologies, and the QoS policies that are necessary, and take immediate actions to ensure communication and KPIs. However, additional research is needed to achieve this interoperability and coexistence. In intra-domain scenarios, the infrastructure needs to exchange messages with the network controller, and since there may be different vendors, standard interfaces for the wireless domain and research into the overhead for these new messages are needed. In the inter-domain case, standardized messages, interfaces, overhead, and protocols to exchange information between controllers are needed.

VII. CONCLUSION

This survey aims to present the adoption of SDN in a vehicular communication environment, namely SDVN. We show that SDVN could provide the flexibility and programmability that V2X requires. With this in mind, we discuss a taxonomy for the varied SDVN architectures proposed in the literature and explain the main differences and similarities between them. The proposed taxonomy is sufficiently general to be adopted in different vehicular scenarios. We consider diverse levels of control, and diverse levels of programmability in the data plane, which involves different degrees of complexity and flexibility in the network.

In considering an SDVN approach, we adopted a novel perspective by analyzing the network requirements envisioned for the automotive vertical market. We attempt to illustrate how SDVN is a key enabler in meeting those requirements. Furthermore, we show that SDVN is complementary to emergent technologies, such as MEC, VCC, and NFV. Together, all these technologies can enable the management, control, and operation of VANET environments.

We describe most of the critical challenges from both a technical and research point of view. The lack of well-defined abstractions on the wireless side of the network and the lack of experimentation employing the de-facto communications standards are just some of the challenges that need to be addressed in order to create an actual SDVN ecosystem. Thus, our survey paves the way for an efficient, flexible, and programmable vehicular network architecture, which is an essential basis for future lines of research.

APPENDIX
ACRONYMS

See Table 6.

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