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On SDN to Support The IEEE 802.11 and C-V2X based Vehicular Communications Use-Cases and Performance: A Comprehensive Survey

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ABSTRACT SDN's ability to provide a global view, centralized control, and flexibility in orchestrating network infrastructure are expected to overcome challenges in the dynamic conditions of vehicular communications. We are looking to rely on SDN technologies to achieve Vehicular communications capacity and performance, which increase the safety of vehicles and transportation, save cost & energy, and increase the vehicles' autonomy level. The usage of SDN in vehicular communications has been the subject of considerable research. Researchers address challenges such as low latency, high throughput, reliability, dense VANET, security, and scalability. Furthermore, this paper surveys the integration of SDN and other enabling technologies with vehicular communications, both for IEEE 802.11 and the C-V2X RAT families. It begins by discussing performance comparisons and coexistence between IEEE 802.11 and C-V2X standards, implementation of SDN in various use cases, integration of SDN with other enabling technologies, the study of particular SDN components to support vehicular communications performance, and SDN usage to support the specific issues vehicular communications. Finally, open directions and challenges of the research are discussed.

INDEX TERMS SDN, V2X, IEEE 802.11, 3GPP, C-V2X, V2X standard, RAT performance comparison, RAT coexistence, use cases, MEC, network slicing, AI/ML, fog computing, cloud computing, ICN, cross-layer design

LIST OF ABBREVIATIONS

In this part, we describe several important abbreviations used frequently in this survey paper.

3GPP	The 3rd Generation Partnership Project
5GAA	5G Automotive Association
5GCAR	The Fifth Generation Communication Automotive Research and innovation
AI	Artificial Intelligence
AODV	Ad-hoc On-demand Distance Vector
AV	Autonomous Vehicle
BS	Base Station
CAM	Cooperative Awareness Messages
CoCA	Cooperative Collision Avoidance
C-V2X	Cellular-Vehicular-to-Everything
CAPEX	CAPital EXpenses
DSRC	Direct Short-Range Communication
eMBB	enhanced Mobile Broadband
eNB	eNode B
ETSI	European Telecommunications Standards Institute

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gNB	gNode B
ICN	Information-Centric Networking
IoV	Internet of Vehicles
ITS	Intelligent Transport Systems
IVC	Inter-Vehicle Communications
LiFi	Light Fidelity
MEC	Mobile (or Multi-Access) Edge Computing
MANET	Mobile Ad-Hoc Network
mMTCs	massive Machine-Type Communications
NDN	Named Data Networking
NFV	Network Function Virtualization
OPEX	OPerational EXpenses
PDR	Packet Delivery Ratio
PER	Packet Error Rate
QoE	Quality of Experience
QoS	Quality of Service
RAT	Radio Access Technology
SDN	Software Defined Networking
SDVN	Software Defined Vehicular Network
URLLCs	ultraReliable and Low Latency Communications
V2I	Vehicle-to-Infrastructure
V2N	Vehicle-to-Network
V2P	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VANET	Vehicular Ad Hoc Network
VNF	Virtualized Network Function
WAVE	Wireless Access in Vehicular Environments

I. INTRODUCTION

The increasing number of people's mobility has led to growing concerns about traffic, road saturation, accidents, inefficiencies, and pollution issues in the transportation field [1]. Information, electronics, and telecommunication technologies are proposed to address these issues, and several of them are ADAS, ITS, and AV technologies [2].

Furthermore, vehicles and transportation are becoming more advanced with integrated computational and communication components, forming the IoV [3], [4] as shown in Figure 1. The development of communication technologies has successfully produced the better-performing RAT standard (e.g., IEEE 802.11bd, NR-V2X). However, there are still many challenges to address in vehicular communications that cannot be solved by RAT improvement only.

The RAT development strategy [5], coexisting RAT families [6], and integrating RAT with enabling technologies [7] have been studied, to overcome the challenges in vehicular communications. However, more than implementing a RAT-only solution is needed to overcome the challenges, so we need an additional solution to solve these issues. SDN is a powerful enabling technology that improves network control and flexibility and saves costs. The separation of data and control planes in SDN allows flexible network behavior and resource allocation based on road traffic, vehicle position, and network traffic load [8], [9].

SDN applications in vehicular communications are being studied in academia and industry, demonstrating their effectiveness in overcoming challenges and enhancing reliability and availability in several communication networks types. This situation shows how important SDN is in vehicular communications [10].

Indeed, the existing survey papers on this subject lack explicit discussion of SDN support for the dominant RAT standards, IEEE 802.11 and C-V2X, each with distinct characteristics. Vehicular communication's unique features and challenges across different use cases, addressable through SDN, are also not adequately covered. Specific discussion on researching and enhancing SDN architecture components is absent in prior surveys. Additionally, the comprehensive exploration of SDN's integration with enabling technologies in vehicular communication is not discussed comprehensively.

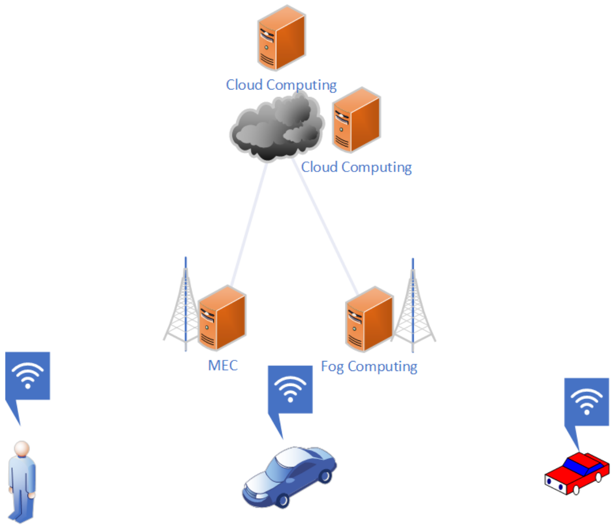

FIGURE 1. Illustration of the IoV

Meanwhile researchers need to understand the integration of SDN and various enabling technologies with vehicular communications and look at it in a complete and structured manner. Starting from the aspects of RAT standard families, the distinctive characteristics of vehicular, communications, and the components of the SDN architecture are essential.

We wrote this survey paper summarizing the research on integrating SDN and vehicular communications. This paper is written in a structure that can bring out the essential aspects of SDN and vehicular communications. With this paper survey, we hope there will be many researchers who can be helped to understand the challenges and open future research direction of SDN integration with vehicular communications.

This survey paper follows the methodology of systematic literature reviews to examine vehicular SDN-vehicular communications comprehensively. The process involved formulating research questions and creating a taxonomy for effective categorization. Extensive searches and subcategorization were performed using bibliographic packages, ensuring a thorough review of published papers while excluding predatory journals. The final paper includes valuable information on publication years, use cases, RAT, distinctive vehicular communication issues, enabling technologies, and SDN components, presenting authoritative insights for researchers and practitioners in this field.

This paper presents a comprehensive survey of the SDN support to vehicular communications. In addition, the performance comparison and coexistence between the IEEE 802.11 and C-V2X RAT families are introduced to form an extensive study of the two dominant RAT families in vehicular communications. Furthermore, the application of SDN to vehicular communications use case groups is presented to create a broader understanding of the challenges and requirements in vehicular communications to support intelligent vehicles and transportation operations. The significant contributions of this paper are listed as follows.

- Comprehensively discussed vehicular communications studies based on RAT IEEE 802.11 and C-V2X to see the advantages and disadvantages of each, study the options for coexisting implementation, and how SDN is applied to these two RAT families.
- The application of SDN on the vehicle communication use cases, SDN architecture-specific component studies, SDN integration, and enabling technologies that support vehicular communications are illustrated along with a scientific research summary published in this field.
- Based on our analysis of the potential application of SDN on vehicular communications by studying the current standards and scientific literature, we discuss some open research directions and point out some significant challenges that need to be overcome.

The remainder of this paper is structured as follows: Section II compares previous survey papers that examined the application of SDN in vehicular communications. Section III delves into the standards, performance comparisons, and coexistence of IEEE 802.11 and C-V2X RAT in vehicular communications. Section IV explores the unique characteristics of vehicular communications supported by SDN. Section V discussed the methodologies and techniques employed to address the challenges in vehicular communications using SDN. Section VI presents open and future research directions. Finally, some conclusions are drawn in section VII.

II. STATE OF THE ART ON RELATED SURVEYS

Here we highlight state of the art on surveys related to SDN applications in vehicular communications technologies. This section highlights previous SDN-vehicular communications survey papers, addressing studies not discussed in earlier surveys and proposing opportunities for a more comprehensive survey.

Authors in [11] provide a comprehensive review of previous research on SDN in VANETs, focusing on wireless communication and VANET applications. It presents an overview of the VANET structure, SDN controller, and their integration, along with an analysis of open issues and research directions. The paper explores the potential benefits of SDN in enhancing routing protocols, latency, connectivity, and security in future SDN-VANET architectures while highlighting current and emerging technologies and use cases. This survey addresses the strengths, weaknesses, and challenges in VANET infrastructures, contributing to the advancement of SDN-VANET research.

Survey [12] addresses the need for a unified view of cross-layer optimization, SDN, and SDR in wireless network design, specifically focusing MANETs. While SDN and SDR have been individually explored, their joint consideration and interaction have been largely overlooked. By extending SDN to the PHY and MAC layers through SDR, centralized control can be achieved across all layers, leading to better network optimization. The survey discusses theoretical foundations, practical aspects, contributions, challenges, and gaps associated with SDN-SDR interaction in MANETs. The findings advocate for the timely integration of SDN and SDR to achieve real cross-layer optimization and solid network control implementations.

The concept of SDN in vehicular networks has gained significant attention, offering solutions for QoS and scalability challenges in the IoV. SDN's flexibility and programmability enable network configuration in the face of fast topological changes in dynamic and dense vehicular environments. However, using a single controller in SDN has raised concerns about scalability and overall network QoS. Recent works propose the use of multiple controllers to address these issues. This paper surveys the proposed SDN-based architectures for vehicular networks, examining their impact on the control plane, evaluating the QoS improvements, and critiquing their suitability for resolving IoV challenges. The conclusion highlights the architectural challenges in IoV and emphasizes the potential of SDN in addressing QoS and scalability. The survey provides an exhaustive list of SDN architectures with proven performances. It suggests future directions, including dynamic distributed control based on traffic situations and application requirements, as well as resource optimization through slicing techniques [13].

The IoV holds the potential to enhance road safety, traffic management, and user experience by connecting vehicles, sensors, mobile devices, and the Internet [9]. However, increasing vehicles, high mobility, and diverse service requirements pose challenges for IoV operation and management. SDN and NFV technologies offer flexible and automated network management, optimization, and resource orchestration, making them crucial for the future of IoV. This article provides an overview of SDN/NFV-enabled IoV, showcasing how these technologies enhance communication, computing, and caching capabilities in IoV systems. Integrating SDN/NFV facilitates improved service delivery, reliability, connectivity, and offloading of computing tasks to edge and cloud servers. The SDN/NFV-based framework also enables adaptive caching deployment and content dissemination. Future research areas include resource slicing, access control, computation offloading, multidimensional resource orchestration, and hierarchical SDN/NFV controller deployment to fully harness the potential of SDN/NFV/MEC for IoV applications.

The emergence of 5G technologies is promising to enhance V2X communications, leading to increased vehicle safety, autonomy, energy savings, and cost reduction [7]. Integrating vehicular communication systems with 5G has

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become a significant area of research, addressing challenges related to automated and intelligent networks, cloud and edge data processing, network management, virtualization, security, privacy, and interoperability. This paper presents a survey of the latest V2X use cases and their requirements, along with an examination of various 5G enabling technologies for vehicular communications. The mapping between V2X applications, 5G use cases, and enabling technologies are highlighted. The conclusion emphasizes the challenges posed by emerging technologies. It suggests future directions, including leveraging AI techniques to enhance resource utilization and V2X capabilities and the role of Full Duplex (FD) and its integration with other technologies in meeting advanced vehicular communication requirements.

Meanwhile, this paper attempts to make a more comprehensive survey by adding the latest SDN-Vehicular communications papers that have not been discussed in previous survey papers and covering aspects that have not been discussed in previous survey papers. It outlines past survey articles, their scope, pros, and cons. Table 1 indicates what was discussed in earlier survey papers and what was not covered, allowing the current survey study to compensate for the shortfalls.

III. STANDARDS, PERFORMANCE COMPARISON, AND COEXISTENCE OF IEEE 802.11 AND C-V2X RAT IN VEHICULAR COMMUNICATIONS

If we look briefly at history, vehicular communications technologies have evolved since their first existence in 1925, called "Radio Warning Systems for use on Vehicles". Decades later, V2I communication using a radio data system (RDS) was founded between the 1980s-1990s. Radio Frequency Identification (RFID) for vehicle tagging emerged in the 1980s. And then DSRC, an invention founded in 1990 that has been used for V2V and V2I communication in recent days [14].

The subsequent development adopted the wifi standard as a vehicular communications RAT. The IEEE 802.11p standard was published in 2010, the C-ITS standard was founded in 2013 and subsequently, the IEEE 802.11bd standard is in progress. IEEE 802.11bd is a RAT standard development in the wifi family branch. IEEE 802.11bd is a replacement standard for 802.11p, with the original 5GHz frequency being replaced with 5.9GHz and 60Ghz/mmWave frequencies. 802.11bd standard was initially planned to be completed and published in 2021. In another RAT family, the C-V2X technologies evolved from 2G used initially until the emergence of NR-V2X 5G technology [15]–[18].

Regarding the radio spectrum, the allocation requirement is formulated using traffic load mapping and queuing theory. Based on the calculation, the spectrum for the V2V and V2I basic safety applications is at least 20MHz. Meanwhile, 30MHz spectrum allocation is for other types of communication on V2V, V2I, and V2P. Cellular vehicle communication technologies are used for cars and trains [19]. In its journey, cellular technologies for railways have evolved from GSM-Railways (GSM-R) and LTE-R to 5G-R [20].

Many studies examine two family standards of RAT (both IEEE 802.11 and C-V2X) in vehicular communications. Each study with this two-family standard uses various methods to test communication performance (throughput, delay, packet delivery ratio) using various use cases and infrastructure designs. Both RAT standards were tested with simulation and field experiments, with various results. Authors in [21], [22] stated that the performance of the IEEE 802.11bd standard is better than its predecessor IEEE 802.11p, and according to [23], NR-V2X (5G) outperforms IEEE 802.11bd. Other authors in [16] concluded that the performance of IEEE 802.11p is better than LTE-V2X in specific situations: time intervals and variations in data packet size.

The competition between these two standards to become the de-facto radio access technology standard for vehicular communications is ongoing. Furthermore, many more studies are comparing these two RATs, each claiming that which is better than the other in specific ways. Hence, surveying various studies of the two standard families of vehicular communications becomes exciting to get a scientific perspective regarding the competition between these two standards. This section discusses two essential things in vehicular communications: the standards and the use cases.

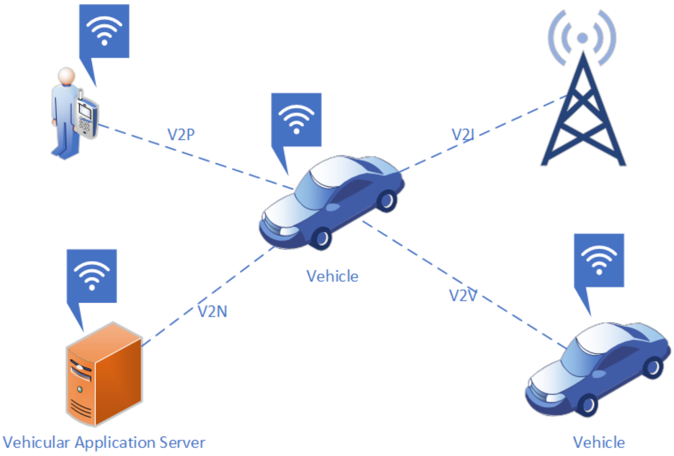

FIGURE 2. The Types of V2X Applications V2V, V2P, V2N and V2I

A. RAT STANDARDS

Inter-vehicular communications, or what we mentioned as vehicular communications in this paper, can be defined as a specific form of mobile communication where the communication nodes (the vehicles) and the neighboring nodes communicate with each other. The neighboring nodes can be either another vehicles/V2V communication, road infrastructure/V2I communication, peoples/V2P communication, and digital services on the internet/V2N communication [24] as we can see in figure 2, Vehicular communications are enabled mainly by two major RATs, one based on wifi/IEEE 802.11 family standard and the other one is cellular/C-V2X. Each

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TABLE 1. Positioning of This Survey Paper

Paper Surveys	Year	Vehicular Communications RATs Performance Comparison & Coexistence	Vehicular Communications Use Cases	SDN Integration with Other Enabling Technologies	SDN Components Implementation
[11]	2020	X	X	cloud computing, fog computing, AI/ML, MEC	SDN controller, network design & architecture, routing
[13]	2020	X	X	C-RAN, cloud computing, fog computing	SDN controller, routing
[9]	2020	X	X	NFV, cloud computing, fog computing, network slicing, AI/ML, MEC	SDN controller, network design & architecture, routing
[7]	2021	X	✓	NFV, cloud computing, fog computing, network slicing, AI/ML, MEC	SDN controller, network design & architecture, routing
[12]	2022	X	X	AI/ML	SDN controller, network design & architecture, routing, datalink layer
This survey	2022	✓	✓	NFV, cloud computing, fog computing, network slicing, AI/ML, MEC	SDN controller, network architecture & design, routing, datalink layer, security

RAT family has its advantages and disadvantages, which is the subject of many research papers [5], [16], [21]–[23], [25].

In addition to regulating the technology standards, there are several organizations on a global scale as well as a regional scale that create standardization for many aspects of vehicular communications. The standard includes the use cases, frequencies, and vehicular services communication. Some organizations that issue standards on a global scale are 3GPP, ETSI, IEEE, 5GCAR, and 5GAA. Meanwhile, on a regional scale, the example is ITS-Asia Pacific. At the country level, the standards used usually adopt standards made for a regional scale [7].

The IEEE standardized the Wifi family (IEEE 802.11), meanwhile, the cellular family was standardized by the 3GPP. Other than these two dominant RATs for V2X communications, several other communication technologies, including Bluetooth and Wimax, have also been considered for use for vehicular communications [15], [17]. The future communication technologies also planned to be used in vehicular communications include 6G cellular technology [26] and LiFi [27]. Authors in [26] discusses the potential for emerging technologies in vehicles and transportation that are supported by the presence of 6G, such as brain-vehicle interfacing, tactile communication, and satellite/unmanned-aerial-vehicle (UAV) aided V2X. While authors in [27] simple LiFi experiment using market-friendly electronics components has been set up. LiFi is a communication method for transmitting data through visible light using LEDs experiments where data is transmitted using different wavelengths of light. LiFi will be used for short-range communication (10m) but with higher throughput (1Gbps) than wifi [28].

In the United States, the Wifi based vehicular communications technologies are called DSRC, and it is implemented as a WAVE. WAVE technology is supported by IEEE 802.11p technology as the physical layer (PHY) and datalink layer (MAC) and supported by IEEE 1609 standards for the transport, network, facilities, management, and security layers. DSRC technologies have several advantages related to low end-to-end latency, low cost, and flexibility of implementation because there is no need for a centralized control system for vehicular communications infrastructure. Meanwhile, the disadvantages of these technologies are security problems and difficulty overcoming line-of-sight problems [17].

In Europe, the Wifi based vehicle communication standard is called cooperative-ITS (C-ITS), also known as the ITS generation 5 (ITS-G5) standard. The PHY and MAC layer of the C-ITS used the IEEE 802.11p standard as the basis and adopted the ETSI EN 302 663, which specified the C-ITS access layer standard [29].

Meanwhile, the RAT in the cellular family currently used are LTE-V2X and 5G. Cellular technologies have advantages related to a wide coverage area, security, performance, and better scalability. However, these technologies have weaknesses related to infrastructure, which must always be managed in a centralized manner, end-to-end latency, and a higher implementation price. IEEE 802.11-based vehicular communications technologies appeared first because the IEEE 802.11p standard has existed since 2010, while LTE-V2X technology has only emerged as a standard in 2015-2016 [5], [17].

From all papers discussed in this section, WiFi (IEEE 802.11) and cellular (C-V2X) are the main technologies enabling vehicular communications. Each has its advantages and drawbacks [5], [16], [21]–[23], [25], leading to ongoing research to optimize them. Global organizations like 3GPP, ETSI, and IEEE, along with regional entities, set standards for vehicular communications, addressing use cases, frequencies, and services [7]. Additionally, emerging technologies like 6G [26] and LiFi [27] are being explored for future vehicular communications.

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B. RAT PERFORMANCE COMPARISON

To know more about each RAT characteristic and communication performance, in the following paragraphs, we will present the performance comparison, coexistence, and also the performance improvement carried out on RATs in the IEEE 802.11 family (802.11p & 802.11bd) as well as in family C-V2X (LTE-V2X, NR-V2X). for the information summary of the RAT performance comparison can be seen in table 2.

RAT physical layer performance for V2V communications with IEEE 802.11p, IEEE 802.11bd, LTE-V2X, and NR-V2X is analyzed in [23]. Through simulation and theoretical evaluation, NR-V2X outperforms IEEE 802.11bd in transmission latency and data rates. IEEE 802.11bd improves IEEE 802.11p performance, particularly in high Doppler scenarios, with dual carrier modulation and extended range options.

IEEE 802.11p and LTE-V2X vehicular communications RATs are compared in [5], focusing on challenges like relative speed, long-distance communication range, and decentralized multiple access. The results show that LTE-V2X outperforms or matches IEEE 802.11 in all aspects, particularly the packet delivery ratio in highway scenarios.

The performance of safety application communication in vehicular communications is investigates, specifically slow vehicle indication (SVI) and rear-end collision warning (RCW). The study concludes that IEEE 802.11bd meets communication performance requirements for safety communication that IEEE 802.11p cannot fulfill [21].

Communication performance between IEEE 802.11p and IEEE 802.16e (WiMAX) standards are compared, regarding throughput and packet drop rate. The results indicate that IEEE 802.16e has lower packet drop rates than IEEE 802.11p at various speeds, with better throughput above 90 km/h [30].

System-level and link-level simulations are used to model transmission reliability for vehicle platooning. The results show that IEEE 802.11bd outperforms IEEE 802.11p in packet reception ratio and transmission range. However, long transmission times due to extended coverage can cause channel congestion and reduced communication reliability [22].

A comparison between IEEE 802.11p and LTE-V2X concerning the beacon transmission frequency, the density of vehicles, and the average speed of vehicles are discussed in [25]. According to the research findings, LTE-V2X performs better than IEEE 802.11p in most aspects because of the fewer device elements, centralized scheduling, and access control scheme.

Authors in [31] investigate the potential of LTE for use in vehicular communications as a standard RAT. Because of network overloads and costs, the results indicate that LTE provides lower support for beacon message communication concerning safety applications than WAVE.

The communication effectiveness of IEEE 802.11bd and IEEE 802.11p are analyzed and compared in [32]. Based on the findings, IEEE 802.11bd provides superior safety communication services, higher throughput, and reduced latency.

The performance of IEEE 802.11bd and IEEE 802.11p in the context of safety communication are compared in [33]. In contrast to IEEE 802.11p, SINR-based modeling demonstrates that IEEE 802.11bd satisfies QoS requirements across the physical, media access control, and application levels for various safety applications.

The channel estimation performance of IEEE 802.11p, IEEE 802.11bd-draft, and the unique-word (UW) based physical layer are examined in [34]. According to the findings, the performance of a UW-based PHY with low complexity channel estimation is comparable to that of an IEEE 802.11bd-draft implementation with high complexity channel estimation.

IEEE 802.11p, 802.11bd, LTE-V2X, and NR-V2X standard performance in data rate, latency, packet error rate, and communication distance are compared in [35]. They are using a MATLAB toolbox, theoretical evaluations, and simulations. The results show NR-V2X outperforming 802.11bd, surpassing 802.11p. IEEE 802.11bd notably enhances IEEE 802.11p performance, especially in high Doppler scenarios, and the dual-carrier modulation and extended range options further improve cell edge performance and range.

In-depth evaluation of LTE-V2X and 802.11p technologies concerning traffic message patterns for the ETSI Cooperative Awareness Messages (CAM) standard are conducted by authors of [16]. With various scenarios for LTE-V2X and IEEE 802.11p, the experiment reveals that IEEE 802.11p better handles message size variation and time intervals between messages. LTE-V2X sensing-based semi-persistent scheduling also faces inefficiency when transmitting aperiodic messages with varying sizes, except under low channel load conditions where IEEE 802.11p outperforms LTE-V2X.

The research findings from various studies indicate that NR-V2X generally outperforms IEEE 802.11bd regarding transmission latency and data rates [5], [23], [25], [35]. LTE-V2X performs in many aspects compared to IEEE 802.11p, particularly in packet delivery ratio for highway scenarios. IEEE 802.11bd improves upon IEEE 802.11p's performance, especially in high Doppler scenarios, through dual carrier modulation and extended range options [21], [22], [32], [33]. Additionally, IEEE 802.11bd meets communication performance requirements for safety applications that IEEE 802.11p cannot fulfill [21], [33].

C. RAT COEXISTENCE

In the following paragraphs, we present some papers that discuss the coexistence between two vehicular communications standard families in one vehicle and network infrastructure as depicted in Fig 3, instead of competing to be the de-facto winner of the standard RAT for vehicular communications. The two RATs can be used together to cover each other's shortcomings and gain advantages from each [36]. Other than that [37] state that with the high mobility and rapid change of network topology in VANET, it is difficult to fulfill ITS service quality with the only use of one RAT. The summary of the coexistence of these two RATs can be seen in table 3.

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TABLE 2. Performance Comparison of vehicular communications RATs

Paper	Year	Area of Concern	Compared RATs	Result
[23]	2019	Physical layer V2V communication performance comparison	IEEE 802.11p, IEEE 802.11bd, LTE-V2X, NR-V2X	NR-V2X outperformed IEEE 802.11bd, and IEEE 802.11bd outperformed IEEE 802.11p regarding latency and data rates. IEEE 802.11bd improve the performance of IEEE 802.11p in high Doppler scenarios. The dual carrier modulation and extended range options in IEEE 802.11bd could improve cell edge performance and communication range.
[5]	2017	Communication range and packet delivery ratio	IEEE 802.11p, LTE-V2X	The LTE-V2X communication range better than IEEE 802.11p, and LTE-V2X PDR better than IEEE 802.11p.
[21]	2021	Safety communication: slow vehicle indication (SVI) and rear-end collision warning (RCW)	IEEE 802.11bd, IEEE 802.11p	The safety communication performance requirements can be met by IEEE 802.11bd but not with IEEE 802.11p.
[30]	2018	Throughput and packet drop rate	IEEE 802.11e, IEEE 802.11p	The packet drop rate of IEEE 802.16e is lower than IEEE 802.11p at various speeds. Communication throughput for IEEE 802.11p is better than IEEE 802.16e for speeds below 90km/hour; above 90km/hour, IEEE 802.16e is better.
[22]	2020	Packet reception ratio and communication range for vehicle platooning use case communication	IEEE 802.11p, IEEE 802.11bd, IEEE 802.11bd DCM RE	PRR of IEEE 802.bd with or without DCM+RE is better than IEEE 802.11p. IEEE 802.11bd with DCM+RE extends the communication range; however, it creates channel congestion.
[25]	2014	Communication performance in the case of beacon transmission frequency, vehicle density, and average vehicle speed	IEEE 802.11p, LTE-V2X	LTE-V2X has better performance than IEEE 802.11p in terms of beaconing frequency, vehicle mobility, and scalability.
[31]	2012	Beacon messages for safety applications	IEEE 802.11p, LTE	The ability of IEEE 802.11p to support the communication of beacon messages for safety applications is better than LTE.
[32]	2020	Communication performance in case of throughput, latency, and packet reception ratio	IEEE 802.11bd, IEEE 802.11p	The IEEE 802.11bd standard has a higher throughput and lower latency than the IEEE 802.11p standard. And also packet reception ratio of IEEE 802.11bd also better than IEEE 802.11p: 88% vs 75%.
[33]	2021	RAT performance support for safety communication.	IEEE 802.11bd, IEEE 802.11p	IEEE 802.11bd can fulfill QoS at the PHY, MAC, and Application layers for several safety applications that IEEE 802.11p cannot fulfill.
[34]	2022	Channel estimation performance for three different frame structures	IEEE 802.11p, IEEE 802.11bd, UW-based physical layer	The UW-based PHY with low-complexity channel estimation has the same performance as high-complexity channel estimation in IEEE 802.11bd standard draft.
[35]	2022	Communication performance in terms of data rate, latency, packet error rate, and communication distance	IEEE 802.11p, IEEE 802.11bd, LTE-V2X, NR-V2X	The IEEE 802.11bd standard performance is better than the IEEE 802.11p standard, especially in high Doppler scenarios. IEEE 802.11bd also has a better communication range than IEEE 802.11p.
[16]	2020	Communication performance comparison of periodic and aperiodic messages with a constant or variable message size for the ETSI Cooperative Awareness Messages (CAM) standard	LTE-V2X and IEEE 802.11p	The IEEE 802.11p standard can better overcome variations in message size and time intervals between messages than LTE-V2X. However, under shallow channel load conditions, the inefficiency of IEEE 802.11p is higher than that of LTE-V2X.

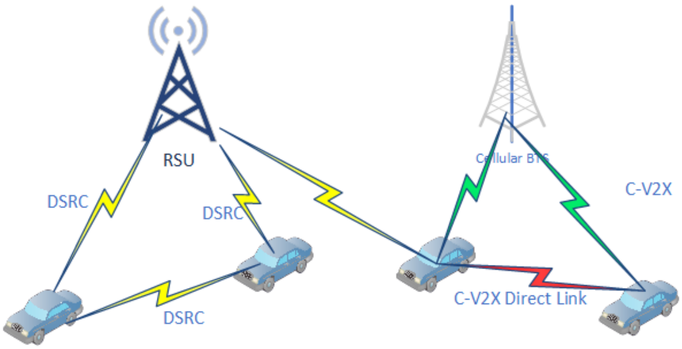

FIGURE 3. Illustration of Multi-RATs Implementation

Low data rate and high latency in multi-hop V2X communication are addressed in [6]. The proposed solution divides vehicles into clusters with a cluster head responsible for relaying information. Vehicles choose between cellular or DSRC communication based on network performance, using cellular only when DSRC falls short. This approach improves V2X communication QoS, reduces network load, and minimizes unnecessary handovers.

In 2016, 3GPP introduced LTE-V2X, a part of cellular-V2X (C-V2X), which encompasses LTE and 5G. C-V2X includes both downlink/uplink (Uu interface) and sidelink (PC5 interface) communications. Sidelink resource alloca-

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TABLE 3. RAT Coexistence

Paper	Year	Area of Concern	Coexisted RATs	Result
[6]	2020	Vehicle clustering and vehicle head cluster as an intermediate node for inter-cluster communication & RAT selection based on a current communication performance indicator	IEEE 802.11p, LTE-V2X	The implementation of vehicle clustering and RAT selection result in better communication QoS and reduce the network load and the number of handovers.
[38]	2022	Single channel coexistence in 5.9 GHz frequency & How to minimizing co-channel interference between the two RATs by inserting the IEEE 802.11p fix preamble in the initial LTE-V2X communication	IEEE 802.11p, LTE-V2X	The application of methods has successfully reduced collision between two RATs and proof the effectiveness of the proposed solution on the dense vehicle's condition.
[36]	2020	Safety communication case study with CAM communication	IEEE 802.11p, LTE-V2X	IEEE 802.11p standard performance can meet the safety communication performance requirements in low-moderate vehicle density condition and LTE-V2X communication performance requirements in high vehicle density condition.
[39]	2020	QoS aware relying algorithms (QR) created to choose the neighbor with the most reliable link in multiple-RAT implementation environment based on SINR and communication range	IEEE 802.11p, LTE-V2X	The application of the QR algorithm has succeeded in forming an error-prone wireless channel.
[40]	2020	The implementation of architecture and protocol stack for a hybrid vehicular network RATs	IEEE 802.11p, LTE-V2X	Implementing architecture and protocol stack for hybrid vehicular network RATs create fewer vertical handovers, higher reliability, and lower delays.

tion can be network-controlled (Mode 3 in LTE, Mode 1 in 5G) or autonomously managed by stations (Mode 4 in LTE, Mode 2 in 5G) [41]. [38] proposes a solution to overcome frequency spectrum scarcity in vehicular communications by coexisting IEEE 802.11p and LTE-V2X mode 4 in the same geographical area and channel. An IEEE 802.11p fixed preamble is inserted into the LTE-V2X sidelink initial transmission signal to minimize interference between the two technologies. This results in collision reduction, increased sensing capability for IEEE 802.11p, and effectiveness in high vehicle density conditions.

Using only one RAT cannot meet all communication performance requirements, such as CAM communication. The study in [36] encourages multiple RAT coexistence and interoperability on the shared 5.9GHz frequency. IEEE 802.11p is suitable for low-moderate vehicle density, while LTE-V2X excels in high vehicle density situations.

An algorithm for selecting the best radio link in a multiple-RAT environment based on SINR conditions and communication range is proposed in [39]. The QoS-aware relying algorithm (QR) chooses the most reliable link for the next hop in CAM communication. The simulation results show the QR algorithm's effectiveness in error-prone wireless channels.

Moreover, the last one, [40], proposes a radio resource management (RRM) strategy, including RAT selection, vertical handover algorithms, and 5.9GHz frequency sharing between two RATs. The study uses various communication performance metrics, such as the number of vertical handovers, PDR, throughput, and latency. The results show fewer vehicle handovers, higher reliability, and lower delays, with seamless connectivity offered by combining competing standards.

The research findings suggest that the coexistence of multiple RATs can address challenges in vehicular communication, such as low data rate and high latency in multi-hop V2X communication [6]. Clustering vehicles and allowing them to choose between cellular and DSRC communication based on network performance improves V2X communication QoS, reduces network load, and minimizes unnecessary handovers [6]. Additionally, the coexistence of IEEE 802.11p and LTE-V2X in the same geographical area and channel with a fixed preamble insertion helps overcome frequency spectrum scarcity. It reduces collisions, particularly in high vehicle density conditions. Using multiple RATs on the shared frequency, such as IEEE 802.11p and LTE-V2X, improves performance in varying vehicle density situations [38].

IV. SDN APPLICATION TO SUPPORT VEHICULAR COMMUNICATIONS DISTINCTIVE CHARACTERISTICS AND HIGH PERFORMANCE REQUIREMENTS

In general, the purpose of the implementation of SDN on vehicular communications is either to support the specific vehicular communications use case standards or to improve vehicular communications performance. The vehicular communications use case can be categorized into four groups, according to the 3GPP standard [42]: (1) Vehicle platooning. (2) Remote Driving. (3) Extended Sensors. (4) Advance Driving. Meanwhile, vehicular communications performance improvement by using SDN can be categorized into seven groups: (1) Improve communication performance, such as throughput and latency. (2) Increasing reliability in the form of PDR or PER. (3) Supporting mobility. (4) Increasing scalability. (5) Overcome problems in high-density VANET conditions. (6) Minimalizing protocol overhead. (7) Network Security.

A. SDN APPLICATIONS TO SUPPORT THE VEHICULAR COMMUNICATIONS USE CASES

The service and the needs of V2X communication services in a standard called "Technical Specifications Group Ser-

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vices and System Aspects and service requirements for V2X services" issued by 3GPP [24]. The types of applications supported by V2X communication and the specific service requirements are mentioned as follows: (1) Types of V2X communication: V2V, V2I, V2N, V2P. (2) Latency Requirements: V2V or V2P general application: max latency 100 ms, particular use such as pre-crash sensing: 20 ms, V2I max latency 100 ms, V2N max latency 100 ms, no re-transmission allowed for all communication. (3) Message size 200 bytes excluding security messages. (4) Message transmission frequency: 10 messages per second per user equipment (5) Range requirements: sufficient to give the driver response time. (6) Relative velocity between user equipment: 500 km/h.

To define and structure the services and performance standards for various types of vehicular communications services, various standardization organizations classify vehicular communications services into several groups, each of which will contain use cases [7]. Generally, three standard bodies publish use case standards for vehicular communications: 5GAA, 5GCAR, and 3GPP. 5GAA identifies seven use case groups: Safety Vehicle Operations Management, Convenience, Autonomous driving, Platooning, Traffic Efficiency and Environmental friendliness, Society, and Community. Each use case has its service-level requirements (SLR) definition, value, and user story. The example SLR value is range, payload, latency, reliability, velocity, density, positioning, and interoperability. The SLR definition, value, and user story help develop solutions, create a procedure for testing purposes, and define the spectrum needs [43].

5GCAR [44] defines five use case classes: cooperative maneuvering, cooperative perception, cooperative safety, autonomous navigation, and long-distance driving. 5GCAR selects one most relevant and representative use cases from each use cases class (UCCs) with the highest impact and their key performance indicators (KPIs). The chosen use cases are (1) Lane merge (UCC1: Cooperative maneuver). (2) See-through (UCC2: Cooperative perception). (3) Network-assisted vulnerable pedestrian protection (UCC3: Cooperative safety). (4) High-definition local map acquisition (UCC4: Autonomous navigation), and (5) Remote driving for automated parking (UCC5: Remote driving).

3GPP [45] defines 25 use cases, and each use case is categorized into four main groups besides the general use case group and another grouping based on the QoS of vehicle services. For each use case story, 3GPP defines several Levels of Automation (LoA), from LoA zero, which is no Automation, to LoA five, which is fully automated. The main use case groups in 3GPP are (1) vehicle platooning. (2) remote driving. (3) Extended Sensor. and (4) Advance Driving. Furthermore, standard document [46] stated that the use cases defined by 3gpp are applied not only for the RAT from 3gpp (LTE-V2X, NR-V2X) but also for non-3GPP RATs (ITS-G5, DSRC, ITS-Connect). Moreover, each use case group in 3GPP defines latency, reliability, throughput, and the size of messages as communication performance parameters [42].

1) Vehicle Platooning

Platooning is defined as two or more connected vehicles in a convoy using an automated driving system and is supported by V2V communication as depicted in figure 4.

By adopting platooning, vehicles are made close to each other in a travel segment to reduce fuel consumption and improve the driving experience. In a platoon, a vehicle in the front position becomes the leader, and other vehicles behind will follow the leader's movements [46], [59].

In platooning use case study, there are various technologies used, from 5G RAT as in [47], [48], [60], MEC [61], even with the application of emerging technology such as blockchain [62].

In addition, there are also specific vehicle platooning, such as a study on the application of platooning on trucks [63], [64].

On the other hand, [59] views vehicle platooning as a software service; meanwhile, [65] discusses the method to maintain safety level in vehicle platooning by maintaining the communication reliability in vehicle platooning.

Moreover, of course, several papers discuss the usage of SDN in vehicle platooning use case as the primary concern of this subsection [47]–[50].

The capability of NFV, and network slicing supports the vehicle platooning use case by providing core cellular network functionality and network resources to the vehicle platoons are studied in [47].

Authors in [48] propose a handover authentication scheme by integrating SDN and aggregated message authentication codes (AMACs) to reduce the number of handover signaling and reduce delays during authentication.

The risk of cyber attacks on the use case of the vehicle platoon system and proposes an attack detection method based on the invariant state set are discussed in [50].

Exploit the low communication latency in the close range of the vehicles inside a platoon to create a parallel MEC is studied in [51].

Based on the papers discussed in this section, we can conclude that platooning optimizes vehicle grouping for fuel efficiency and driving benefits. Various technologies, including 5G RAT, MEC, and blockchain, enhance platooning. SDN tackles challenges like authentication and security, while NFV aids network support. Close-range communication in platoons is used for low-latency parallel MEC [47]–[51].

The research suggests potential solutions to enhance vehicle platooning use cases. Leveraging low communication latency within platoons to create a parallel MEC can further improve the efficiency of data processing and decision-making within the convoy [51]. Integration of SDN with authentication methods and aggregated message authentication codes (AMACs) can reduce handover delays and improve the security of platooning systems [48]. Developing robust attack detection methods can also help safeguard platooning systems from cyber threats [50].

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TABLE 4. SDN-V2X Communication Use Cases

Paper	Use Case Group Reference	Problem or concern
[47]	Vehicle Platooning	SDN-based network slicing and NFV
[48]	Vehicle Platooning	SDN-based handover authentication scheme
[49]	Vehicle Platooning	The implementation of SDN and NFV on MEC
[50]	Vehicle Platooning	Cyber security attack mitigation on SDN-based platoon system
[51]	Vehicle Platooning	MEC based on Vehicle platoon network nodes
[52]	Teleoperation/Remote Driving	SDN-based scheme for anticipating the occurrence of handovers in the teleoperation use case
[53]	Teleoperation/Remote Driving	Study of the effect of cellular BTS density on communication performance for teleoperation
[54]	Teleoperation/Remote Driving	Impact of the video streaming quality and vehicle speed to the remote driving performance
[55]	Teleoperation/Remote Driving	SDN, NFV, and fog computing-based remote driving schema
[52]	Extended Sensors	Collective perception (CP) communication behavior in the various network and vehicle traffic conditions
[41]	Extended Sensors	Collective perception (CP) communication performance and data redundancy issue
[49]	Extended Sensors	The accuracy of steering and navigation of an AV by relying solely on sensors attached to the vehicle
[56]	Advance Driving	SDN-based vehicular network for inter-UAV communication
[57]	Advance Driving	Cooperative Collision Avoidance for Pedestrian and vehicle
[58]	Advance Driving	The implementation of SDN-based physiology and psychology anomaly detection for driving safety purposes

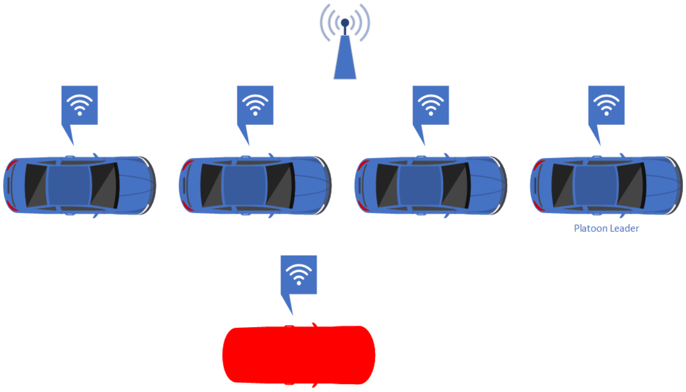

FIGURE 4. Illustration of Vehicles Platooning Use Case

2) Remote Driving

Teleoperation or remote driving, as depicted in figure 5, is a critical backup for automatic driving when the autonomous system cannot handle an unexpected situation. There is a need for good communication infrastructure performance in terms of throughput and latency to enable the remote driver to control the vehicle properly.

Good throughput facilitates the streaming of high-definition video from the car to the remote driving station, and low latency allows remote drivers to react fast when driving [53]. Meanwhile, [54] studies the impact of video streaming quality and vehicle speed on driving performance in remote driving.

Authors in [66] discusses an SDN-based scheme for anticipating handovers in the teleoperation use case to reduce latency and support seamless mobility.

Authors in [55] proposes an architecture, modeling, and implementation of vehicular communications for remote driving cars using YANG data modeling language, NETCONF, SDN, and NFV technologies. The vehicles in this experiment are controlled remotely, with applications placed on fog computing infrastructure.

The research findings in the remote driving use case for vehicular communication emphasize the critical role of communication infrastructure performance in enabling effective remote driving [53]. Good throughput is essential for streaming high-definition video from the vehicle to the remote driving station, while low latency is crucial for enabling remote drivers to quickly react when controlling the vehicle [54]. Studies have explored the impact of video streaming quality and vehicle speed on driving performance in remote driving scenarios, highlighting the importance of optimizing communication parameters for a seamless and responsive driving experience.

The research suggests potential solutions to enhance the remote driving use case for vehicular communication. Optimizing communication infrastructure to provide high throughput and low latency is crucial for enabling remote drivers to have real-time control and situational awareness while operating the vehicle remotely. Leveraging SDN-based schemes can help anticipate handovers and reduce latency during remote driving, ensuring a seamless and responsive driving experience [55], [66].

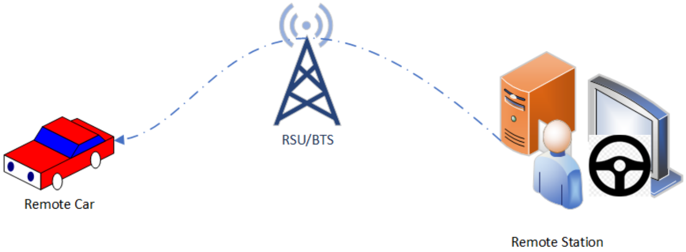

FIGURE 5. Illustration of The Teleoperation Use Case

3) Extended Sensors

AV requires sufficient information about their conditions when operating on the road. The goal, of course, is to do the steering correctly and safely. However, often the capabilities of the sensors in the vehicle cannot provide sufficient information needed to carry out the steering process. So information from other vehicles can be taken to get more comprehensive information about the vehicles surrounding environment [67], [68] as depicted in figure 6.

Authors in [52] discuss collective perception (CP) communication behavior in the form of channel busy ratio (CBR) in a dynamic environment where the network condition and vehicle traffic are changing.

Performance evaluation of CP service when utilizing the C-V2X communication ad-hoc mode is discussed in [41].

Authors in [49] proposed a solution to the problem of processing and storing large amounts of data that can affect the QoS for cooperative driving by using SDN, NFV, and MEC-based network architecture.

The research findings in the extended sensors use case for vehicular communication highlight the importance of gathering comprehensive information about the vehicle's surrounding environment to ensure safe and accurate steering in autonomous vehicles [67], [68]. When the vehicle's onboard sensors may not provide sufficient data, information from other vehicles can be utilized to enhance the perception of the surrounding environment.

Potential solutions involve further exploration and implementation of CP communication [52]. Evaluating the CP service's performance using different communication modes, can help identify the most efficient and reliable vehicle information-sharing approaches [41].

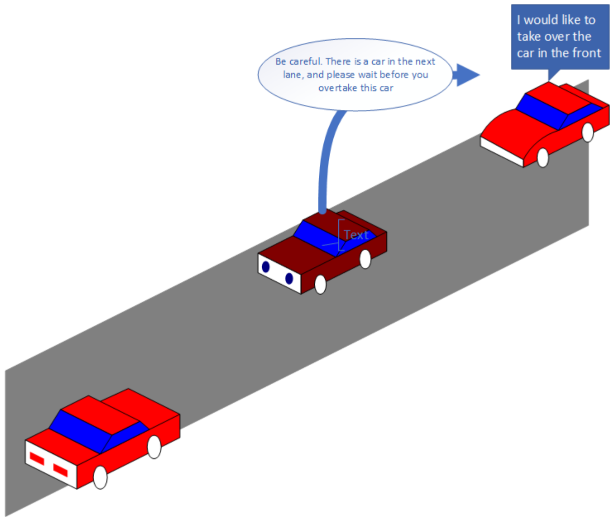

FIGURE 6. Illustration of The Collective Perception

4) Advance Driving

According to [24], the advance-driving use case group include seven use case: CoCA for AV, Information sharing for limited automated driving, information sharing for fully automated driving, Emergency Trajectory Alignment (EtrA) Intersection Safety Information Provisioning for Urban Driving, Cooperative lane change (CLC) of automated vehicles, 3D video composition for V2X scenario. CoCA is implemented in the automatic driving scheme to reduce the possibility of accidents by exchanging information about maneuvers carried out with other vehicles. The data exchanged in the CoCA scheme are data other than those in CAM and DENM. These data come from sensors and information about accelerating or braking the vehicle.

Several papers discuss CoCA using different RATs, such as [69], which discusses the emergency breaking communication effectiveness via 5G RAT. Furthermore [70] -ion between AV about inverse reinforcement learning based on overtaking dan lane changing maneuvers.

Authors in [56] applied the SDN-based vehicular communications on the UAVNet. UAVnet connects multiple UAVs that monitor conditions in a particular area.

Authors in [57] states that the discussion of collision avoidance is not carried out from the point of view of group use a case in 3GPP as the reference, but uses standard group use cases in 5GAA, namely: Collision avoidance, VRU safety, and hazardous situation detection.

In [45], we can see that the CoCA use case applies not only between vehicles and vehicles but also between vehicles and pedestrians as the VRU-safe application applied.

Authors in [58] discusses an SDN-based approach to developing the safety-oriented vehicular controller area network. This system is created to improve traffic safety based on driver fatigue detection and emotional recognition, which are monitored through the driver's physiological and psychological state.

The research findings in the advanced driving use case for vehicular communication emphasize the importance of information sharing and cooperation among vehicles to enhance driving safety and efficiency [24]. CoCA is a significant use case where vehicles exchange information about their maneuvers and actions to reduce the possibility of accidents. This includes data from sensors and information about vehicle acceleration and braking. Various papers explore CoCA using RATs like 5G RAT and SDN-based vehicular communications [56], [69]. Additionally, using CoCA is not limited to vehicle-to-vehicle communication, as it can also involve communication between vehicles and pedestrians to improve pedestrian safety [45].

Potential solutions to further enhance the advanced driving use case for vehicular communication involve continued research and development in CoCA and other safety-oriented applications. Exploring the integration of different RATs and communication technologies can improve the reliability and effectiveness of information sharing between vehicles and other road users. Additionally, leveraging SDN-based approaches can enable more efficient and flexible network management, improving traffic safety and vehicle coordination [58].

B. SDN AND VEHICULAR COMMUNICATIONS ISSUES

This subsection lists different objectives for vehicular communications research to improve communication performance. The objectives are to lower latency, maximize process mobility, improve scalability, increase throughput, decrease bandwidth use, address issues caused by the dense population of vehicle nodes, and reduce protocol overhead. This section will provide summaries of numerous research publications that aim to enhance particular areas of vehicular communications, along with issues that the researchers addressed. This section contains tables that summarize the papers in a particular category. Several papers can be included in more than one category. However, to make an efficient explanation, a paper will be put into a category based on the most dominant aspects of the problem discussed in the paper.

1) Low-Latency Issues in Vehicular Communications

Communication latency or delay is a crucial component of vehicular communications due to its enormous impact on productivity and safety on the road. When there is latency, it can be difficult for vehicles to coordinate their operations, the reaction times of automated systems can slow down, and crucial information can be delayed. By enabling centralized and dynamic administration of network resources, SDN can reduce latency issues in vehicular communications. This may involve applying traffic engineering and QoS strategies to reduce delays while prioritizing critical messages. SDN also allows real-time network monitoring and adaptation to reduce latency and respond to changing conditions. The papers in this section focus on various techniques for addressing latency and delay issues in-vehicle communication networks. The summary of SDN vehicular communications latency research papers surveyed in this paper can be seen in table 5.

2) Mobility Issues in Vehicular Communications

Mobility in vehicular communications refers to a vehicle's ability to move between network access points while maintaining QoS during the handover procedure. Reliable mobility management is necessary to guarantee a seamless transition between access points. Handover refers to changing an access point in a vehicle's network connection. Several SDN-based systems have been developed to manage handovers, reduce latency handover duration, and enable seamless mobility. The summary of SDN vehicular communications mobility research papers surveyed in this paper can be seen in table 6.

3) Scalability Issues in Vehicular Communications

In vehicular communications, scalability refers to a system's ability to deal with a growing number of vehicles and networking equipment without compromising effectiveness, dependability, or security. It is an essential part of vehicular communications since it ensures the system can handle the enormous growth in connected vehicles while still addressing the needs of different applications like traffic control, road safety, and entertainment. Load balancing, hierarchical architecture, and effective routing are just a few methods that can be used to scale vehicular communications. These methods can reduce system complexity, increase response time, and distribute load across various network components. In real-world scenarios with a growing number of connected vehicles, scalability is crucial to ensure the performance of vehicular communications. The summary of SDN vehicular communications scalability research papers surveyed in this paper can be seen in table 7.

4) Reliability Issues in Vehicular Communications

Vehicular communications' reliability is the ability to deliver dependable and consistent communication service. Due to how it could affect both drivers' and passengers' safety, this is significant. A low packet delivery rate can lead to poor communication, and a high packet error rate can affect the data transfer rate; these metrics impact the performance and level of service provided to clients. Various methods are suggested in papers to increase communication reliability in vehicles. The summary of SDN vehicular communications reliability research papers surveyed in this paper can be seen in table 8. Service, packet delivery, and packet error rates are also included.

5) High Density VANET Nodes in Vehicular Communications

Density is considered in the study of dense VANETs as a situation where the node density decreases the communication performance in VANETs. Since overcoming the issue of communication performance degradation in dense-VANET is one of the keys to increasing driving safety, the dense VANET condition is crucial to studies. According to the literature reviewed, no quantitative definition exists to explain dense-VANET. However, from several papers that discuss Dense Vanet, it can be seen that the specifications of the experiments carried out in several papers are as follows: (1) The experiment in [113] is conducted by using 40 - 100 vehicles, with an area 100 x 100 m, and using manhattan grid model. (2) The experiment in [114] uses 100 - 200 vehicles with an area of 1500 x 1500 m and the Manhattan grid model. (3) The experiments in [115] are conducted by using 40 - 120 vehicles, with the distances between the vehicles being 2 - 4 m, and using an urban scenario. From these three papers, we conclude that the term dense VANETs does not have a clear limit regarding the number of vehicles or vehicles per unit area. Papers that talk about dense VANETs study the occurrence of a decrease in communication performance, methodologies, and techniques to improve communication performance in an area with many vehicle nodes [113]–[115].

6) Throughput, Bandwidth Usage and Network Congestion Issues in Vehicular Communications

The performance and reliability of communication between vehicles and between vehicles and infrastructure are directly impacted by throughput, bandwidth utilization, and network congestion, making them critical elements in vehicular com-

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TABLE 5. Vehicular Communications Latency Issue

Paper	Issues Discussed in The Papers	Enabling Technologies and SDN Components	Remarks
[71]	latency	network slicing, AI/ML and other algorithms, security	The effort to overcome the limitation of the encryption-based network isolation
[72]	latency	NFV, MEC	The limitation of AV to navigate and steer by only relying on sensors in the vehicle
[73]	latency	MEC	The effort to overcome the challenges of aerial MEC for data sensing and acquisition
[74]	latency	SDN controller	Performance comparison of four free-opensource SDN controllers
[51]	latency	NFV, cloud computing, AI/ML and other algorithms	Low latency vehicle platooning as a parallel MEC provider
[75]	latency, throughput, reliability	AI/ML and other algorithms	Communication performance improvement in the case of information dissemination to vehicles in a particular area
[76]	latency	MEC, cloud computing, AI/ML and other algorithms	Efficient computing communication workload offloading scheme
[77]	latency	fog computing, AI/ML and other algorithms	Mobile delay-sensitive vehicular services
[78]	latency, channel busy ratio	routing protocol	Implementation of HetVNet (WAVE and LTE) in vehicular communications poses challenges of load balancing and optimal routing

munications. Low bandwidth consumption helps to maximize communication resources, while high throughput ensures that vast volumes of data may be transferred quickly. A better QoS for the users is achieved by preventing network congestion so that delays and packet loss do not impact communication. Numerous SDN-based strategies have been implemented to increase throughput, reduce bandwidth consumption, and prevent congestion in vehicular networks. The summary of SDN vehicular communications throughput, bandwidth, and congestion issues research papers surveyed in this paper can be seen in table 9.

7) Protocol Overhead Issues in Vehicular Communications

To provide effective and reliable communication between vehicles and between vehicles and infrastructure, reducing communication overhead in vehicular communications is crucial. High overhead can result in increased latency, reduced packet delivery rates, and poorer communication performance [86]. This is exceptionally vital in safety-critical applications like traffic control and collision avoidance [57]. Additionally, lowering overhead might result in energy savings, essential for AV and electric vehicles [118].

8) Security Issues in Vehicular Communications

The vehicular communications network has a vulnerability to attacks from internal sources. This vulnerability is due to the characteristics of vehicular communications with vehicle nodes that can dynamically connect and disconnect to vehicular network infrastructure. Cryptography implementation can overcome external attacks, in-contrast internal attacks originating from vehicular communications nodes are difficult to handle because internal attackers are authenticated nodes in the network infrastructure [119].

Authors in [120] divides security threats in vehicular communications into two categories. The first category is classic attack. Security attacks in this category are attacks that generally attack communication systems and also impact vehicular communications systems. Examples are signal jamming and eavesdropping. The second category is vehicular communications-specific attacks. This type of security attack is unique because it only exists in vehicular communications. Examples are security threats in vehicle platooning, collaborative collision avoidance, and other use cases. Meanwhile, [121] divide the security threats in VANET into (1) Session hijacking, (2) location tracking, (3) eavesdropping, and (4) DoS/DDoS. Furthermore, the last one [122], VANET security problems can be categorized into (1) communication protocol hacking. (2) Man-in-the-middle attacks. (3) Protocol hacking. (4) authentication failure. (5) Malicious nodes.

Apart from the above discussion, the use of SDN for security purposes is also carried out for intra-vehicular communications (IVC), as in [133], which integrates time-sensitive networking (TSN) and SDN on ethernet-based intra-vehicular communications and implements security by implementing network-level isolation. Moreover, in [134] an IVC prototype is creating using a real-world car to implement SDN based security system for intra-vehicular communications infrastructure.

Another novel solution that can be implemented for vehicular communication security is blockchain-based smart contracts with SDN technologies to implement immutable, verifiable, adaptive, and automated access control policies for IoT devices. This technology can mitigate the security challenges associated with vehicular communication access control policy management and security like the system previously implemented on the IoT [135].

9) Other Issues in Vehicular Communications

The papers in this subsection discussed other than common issues that are usually studied in other SDN-vehicular communications research papers. Authors in [136] discusses caching and forwarding optimization for NDN-based vehic-

TABLE 6. Vehicular Communications Mobility Issues

Paper	Issues Discussed in The Papers	Enabling Technology and SDN Component	Remarks
[79]	mobility	datalink layer, SDN cross-layer	Optimizing the handover process between one RSU and another RSU for vehicles that enter an RSU coverage area
[80]	mobility, latency, reliability	network architecture and design, SDN controller, fog computing, routing	Manage network infrastructure resources and divide the workload between different SDN controllers
[81]	mobility	network architecture and design, SDN controller	High mobility of vehicles leads to a decrease in QoS and QoE during the handover process for MEC services
[82]	mobility	AI/ML and other algorithms	The limitation of the existing centralized handover algorithms that do not consider load from the network access point and vehicle mobility
[66]	mobility	AI/ML and other algorithms	The latency and lack of seamless mobility caused by handovers in the teleoperation use case
[83]	mobility, throughput, reliability	MEC, AI/ML and other algorithms	Vehicles communication through the cluster head that forwarded via eNodeB LTE, causing potential delays and changes in packet data order
[84]	mobility, latency	datalink layer	Handover preparation and completion time duration reduction
[85]	mobility, latency, reliability	routing	Guarantee low latency and seamless handover process
[86]	mobility, latency, protocol overhead	AI/ML and other algorithms	The handover execution time in C-V2X communication
[87]	mobility, latency, reliability	AI/ML and other algorithms	QoE issue in the handover of the vehicular communications
[88]	mobility, latency, throughput	routing, MEC	The effort to overcome the existing SDN-based distributed mobility management (DMM) limitation
[89]	mobility, protocol overhead, latency	AI/ML and other algorithms	Frequent handover and signaling overhead in Ultra-dense networking (UDN), and the additional complications caused by fast-moving vehicle nodes
[90]	mobility, protocol overhead, reliability	AI/ML and other algorithms	Centralization, and hierarchy issues in conventional networks cause a decrease in communication performance
[91]	mobility, scalability, latency	network architecture and design, AI/ML and other algorithms, fog computing	Handover overhead and radio resource management
[92]	scalability, throughput, latency, high-density VANET node	network slicing, AI/ML and other algorithms	The needs of the different QoS and QoE to support the different applications in the 5G network

TABLE 7. Vehicular Communications Scalability Issues

Paper	Issues Discussed in The Papers	Enabling Technology and SDN Component	Remarks
[93]	scalability, latency	network architecture and design, SDN controller	Latency in a software-defined vehicular network due to communication overhead and route setup time
[94]	scalability, reliability	network architecture and design, routing, cross-layer design	The needs to optimizing the performance of the SDVN
[95]	scalability, latency	fog computing, cloud computing, AI/ML and other algorithms	Traditional load balancing algorithms for cloud computing and specific load balancing algorithms for fog computing cases
[96]	scalability, protocol overhead, latency	network architecture and design, SDN controller	SDVN scalability, and single point of failure in the SDN controller
[97]	scalability	network slicing, network design, architecture, SDN controller	The need for flexibility and scalability in SDVN by implementing virtualization and multitenancy on one physical network.
[98]	latency, reliability, throughput	MEC, Cloud Computing, network architecture, and design, controller	Overcome the limitation of the RAT-only implementation performance

ular communications. Authors in [137] discusses optimizing communication resources at the MAC layer. Management resource computing and communication as discussed in [138]. Furthermore, there is also a paper that discusses SDN-based vehicular communications to optimize the charging process for electric vehicles [139], [140]. The summary of papers in this section can be seen in table 11.

Apart from that, this section also contains a review of papers that equally discuss more than one issue in vehicular communications as described in table 12

V. SDN KEY NEABLING TECHNOLOGIES AND METHODOLOGIES TO ADDRESS VEHICULAR COMMUNICATIONS CHALLANGES

A. SDN COMPONENTS IMPROVEMENT TO SUPPORT VEHICULAR COMMUNICATION

1) SDN Controller

SDVN requires efficient network communication and control management, and SDN controllers play a crucial role in achieving this goal. Depending on their level, SDN controllers can have various functions, such as managing traffic,

TABLE 8. Vehicular Communications Reliability Issues

Paper	Issues Discussed in The Papers	Enabling Technology and SDN Component	Remarks
[99]	reliability, mobility, protocol overhead	AI/ML and other algorithms, network architecture and design	Optimize the information dissemination process on SDVN using I2V communication
[100]	reliability	routing, cross-layer design	The selection of neighbor nodes in a routing mechanism oriented to forming routes with guaranteed end-to-end communication performance
[101]	reliability	fog computing	The poor connectivity, scalability, flexibility, and intelligence of the VANET infrastructure
[102]	reliability	routing, AI/ML and other algorithms	The selection of routing paths in a network that ensures that the nodes passed in the routing path are not malicious
[103]	reliability, latency	network architecture and design, SDN controller, AI/ML and other algorithms, MEC	Lack of efficient implementation of the three-tier (edge controller, domain controller, root controller) SDN controller for IoV
[104]	reliability	routing protocol	The need for an efficient vehicular network framework that can support multiple RATs
[105]	reliability	routing, fog computing	The challenge of implementing a communication scheme without using RSUs in VANET research due to the economic overhead and geographical limitations of RSU
[106]	reliability, latency, throughput	routing, AI/L and other algorithms	The tendency for vehicle clusters to form on the road in VANETs and the weaknesses of previous routing protocols in terms of latency
[107]	reliability, latency	routing, AI/ML and other algorithms	Limitations of Geographic routing protocols, leading to local maximum and sparse connectivity problems due to an obsolete neighbor list and lack of global information
[108]	reliability, latency, throughput, energy efficiency	security, AI/ML and other algorithms	Security attacks on the controller and the inefficiency of energy use in SDN-IoV scheme
[109]	reliability, throughput, latency	network architecture and design, routing	The inefficiency of distributed routing algorithms in dynamic vehicle movement conditions due to poor network congestion control
[110]	reliability, latency, protocol overhead, throughput	routing	The lack of efficiency in using ROAMER for IoV routing
[111]	reliability	SDN controller	The loss of connection from the SDN controller to the network infrastructure
[112]	reliability, latency, protocol overhead	routing	In multi-hop communication, packets have small time windows before route termination, leading to potential packet drops and unsuccessful connections

TABLE 9. Vehicular Communications Throughput Issues

Paper	Issues Discussed in The Papers	Enabling Technology and SDN Component	Remarks
[116]	throughput	cross-layer design, datalink layer	The inefficiency of MAC layer performance
[117]	throughput, latency, reliability	network slicing, fog computing, cloud computing	The need to optimize the throughput performance of vehicular services in 5G networks

regulating inter-area communications, and enforcing SDVN-wide policies.

To address scalability and reduce single points of failure, [96] proposes using Enhanced Hierarchical Software-Defined Vehicular Networks (E-HSDV), which employs local SDN controllers.

Meanwhile, [81] demonstrates that multiple controllers in the SDN domain can alleviate the load on a single controller and effectively handle MEC service handover.

Additionally, [74] compares four free-open sources SDN controllers (POX, Floodlight, ONOS, and OpenDaylight) and shows that OpenDaylight has lower latency, among others.

To minimize latency and protocol overhead between the SDN controller and network devices, [93] suggests deploying a local controller near RSUs.

Finally, [94] proposes a hierarchical SDVN architecture with shared functions between global and local controllers.

The research findings highlight the importance of SDN controllers in achieving efficient network communication and control management in SDVNs [74], [81], [93], [94], [96]. The controllers' functions vary depending on their level, including managing traffic, regulating inter-area communications, and enforcing SDVN-wide policies.

Dynamic load balancing algorithms can be implemented within the SDN domain to address scalability and distribute the load effectively [81]. These algorithms can intelligently allocate network resources and traffic across multiple controllers based on real-time network conditions and demands, ensuring that no single controller becomes overloaded. To enhance SDN controllers' reliability and fault tolerance, redundant controller architectures can be employed [96]. Redundancy can help ensure continuous operation even if one

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TABLE 10. Vehicular Communications Security Issues

Paper	Issues Discussed in The Papers	Enabling Technology and SDN Component	Remarks
[123]	security	NFV	The limitations of traditional communication networks and VPN
[124]	security	AI/ML and other algorithms	Security system architecture in VCC (vehicular cloud computing)
[125]	security	AI/ML and other algorithms, network architecture and design	The problem of providing end-to-end security and privacy in C-V2X 5G communication and the detection and handling of different types of attacks
[119]	security	AI/ML and other algorithms, network architecture and design	The problem of providing secure and context-aware communication in vehicular networks
[126]	security	AI/ML and other algorithms, MEC	Securing data sharing and storage on vehicular edge computing and networks
[127]	security	AI/ML and other algorithms, MEC	The lack of access control and unauthorized SDN controllers on SDVN can cause security issues
[128]	security	AI/ML and other algorithms	Weaknesses in previous defense mechanisms against topology poisoning attack
[118]	security, energy efficiency	AI/ML and other algorithms	The implementation of an intrusion detection system (IDS) in a centralized database system causes bottlenecks, single points of failure, scalability issues, storage usage, communication overhead
[129]	security, controller load reduction during attacks	AI/ML and other algorithms	The periodic detection trigger mechanism implementation to overcome DDoS attacks weakness in terms of slow identifying and countering attacks causing an overload on the SDN controller and switch
[130]	security	AI/ML and other algorithms	Security risks in vehicular communications: taking over vehicle resources, jamming communication channels, confidentiality, availability, integrity, accountability, and high latency caused by security attacks
[119]	security	AI/ML and other algorithms, network architecture and design	The weakness of the existing pseudonym-changing strategies for connected vehicles: static, rigid, non-adaptive schema
[131]	security	AI/ML and other algorithms, routing	VANET communication reliability and security not fully examined in previous research
[132]	security	AI/ML and other algorithms, routing	Malicious vehicles in SDVN potential problems providing false information, misbehaving, and disrupting communication

controller fails, reducing the risk of single points of failure and maintaining network stability during critical situations.

2) SDN Routing

The vehicle communication routing protocol is uniquely designed compared to the general routing protocol. VANET routing protocols are either topology-based or position/geographic-based. Link information is used in topology-based routing technologies to construct routes. Meanwhile, geographic-based routing protocols create routes using a node's GPS or RSU location [159].

According to [157], VANET has four routing protocol types: position-based, map-based, road-based, and topology-based. Map-based routing protocol considers map information, while road-based routing protocol considers road segment communication as the metric. In the SDN routing schema, the SDN switch forwards according to the controller's flow table. Furthermore, VANET's high node mobility, design, and traffic characteristics are also considered in SDN-VANET routing. The proposed routing algorithms in various papers aim to improve end-to-end communication performance in vehicular networks.

Authors in [100] proposed a multi-step neighbor selection algorithm based on link reliability, node speed, movement angle, and expected forwarding movement distance called

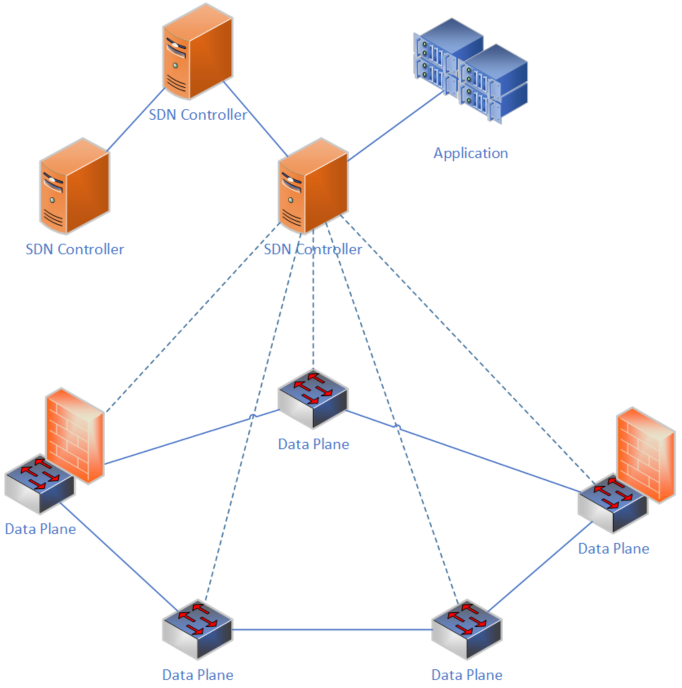

FIGURE 7. Illustration of the SDN Network Components

TABLE 11. Vehicular Communications Other Issues

Paper	Issues Discussed in The Papers	Enabling Technology and SDN Component	Remarks
[136]	Optimal caching and forwarding	NDN	Optimizing vehicular communications performance
[137]	Communication resource management in MAC and PHY layer	datalink layer, network architecture, and design	Managing communication resources at the MAC and PHY layers in an SDN-based network for vehicular communications infrastructure
[141]	SDN-SDR integration architecture	cross-layer design	The integration of SDN and SDR in USRP devices
[142]	novel network architecture and design	NDN	The weaknesses in SDVN and Vehicular NDN (VNDN)
[139]	Charging service time	AI/ML and other algorithms, cloud computing	Long queues at charging stations caused by limited power resources and limited space for parking at charging points
[140]	Energy efficiency in charging station buildings	fog computing, cloud computing	Increases the electricity consumption in buildings that provide charging stations
[143]	Explaining the IoV concept	network architecture and design, AI/ML and other algorithms	IoV vs. conventional vehicular communications
[144]	VM replication schema	cloud computing, network architecture, and design	The need for flexibility in updating vehicle software
[145]	traffic prediction and optimization problem	AI/ML and other algorithms	Reduce the CAPEX and OPEX costs of implementing 5G-V2X infrastructure and how to optimize 5G-V2X performance
[146]	throughput, reliability, load balancing	AI/ML and other algorithms, network architecture and design	Communication resources coordination on cellular network infrastructure
[147]	network slicing functionality	network slicing	Multiple network slicing point of view
[148]	resource usage optimization	Network slicing, NFV, edge computing	network slicing scheme for 5G networks to handle critical and non-critical traffic efficiently
[149]	operational cost, configuration complexity	MEC, AI/ML and other algorithms	RSU cloud architecture causes additional traffic and data congestion
[150]	All issues in vehicular communications	MEC, AI/ML and other algorithms	Challenges in implementing MEC for cooperative, connected, and automated mobility (CCAM)
[138]	communication resource management and computing offloading	MEC, AI/ML and other algorithms	Allocating communication resources and offloading computing tasks efficiently in an SDN-assisted MEC network architecture for vehicular network
[151]	latency, throughput, packet loss	AI/ML and other algorithms	Congestion detection, messages data clustering by using K-means algorithms, congestion control

EFMD. This approach outperformed AODV-R and GPSR regarding packet delivery ratio and link failures for various node densities.

Authors in [104] proposed an SDN-based vehicular network framework with multiple RATs and tested its use in multi-hop communication between two platoon vehicles, which showed better performance than AODV in terms of packet delay, setup delay, communication overhead, and packet delivery ratio.

Authors in [141] proposed CrossFlow, a framework that integrates SDN and SDR with the ability to control parameters at the MAC and PHY layers, including frequency hopping, transmission power control, adaptive modulation & coding, QoS provisioning, and adaptive routing. The cross-layer routing protocol in vehicular networks uses information from the PHY and MAC layers to determine the best route and achieve better QoS.

The SDN controller uses a routing protocol based on geographical position information and measures communication duration, idle capacity, and error occurrence logs to determine the reliability of each vehicle. Vehicular communications challenges, such as scalability, dynamic topology, and heterogeneity, are addressed in [156] by implementing a hybrid SDN geographic routing algorithm (HSDN-GRA). The HSDN-GRA algorithm results in lower end-to-end delay than the comparison routing algorithm (Multi Agent-Highly dynamic destination-sequenced distance-vector routing) when the number of vehicle nodes is less than 40. However, the delay on HSDN-GRA increases when the number of vehicle nodes increases.

In [160], a routing protocol named ROAMER uses the RSU to send routing information, but its performance decreases in an IoV environment. The enhanced ROAMER protocol [110] called SURFER [161] uses SDN to run a routing protocol based on a distributed SDN architecture and has the highest packet delivery rate compared to QRA and SD-IoV in experiments with varying numbers of vehicles and speeds.

In [157], an SDN-based on-demand routing mechanism (SVAO) improves routing and forwarding efficiency. It has the best packet reception rate compared to other routing protocols in experiments with varying vehicle density, speed, and communication distance.

Heterogeneous vehicular networks (HetVNet) present load balancing and routing challenges between multiple RAT families, such as WAVE and LTE. [78] proposed an Optimal Resource Utilization Routing Scheme (ORUR) using an SDN controller to regulate routing, balance traffic, and minimize delays.

Authors in [109] suggested using Multi-Flow Congestion-

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TABLE 12. Vehicular Communications Multiple Equal Issues in One Paper

Paper	Issues Discussed in The Papers	Enabling Technology and SDN Component	Remarks
[151]	latency, throughput, packet loss	AI/ML and other algorithms	Congestion detection, messages data clustering by using K-means algorithms, congestion control
[152]	throughput, latency	network slicing, AI/ML and other algorithms	The needs of the performance optimization of the URLLC and eMBB communication services in 5G network
[153]	throughput, latency	MEC	SDN-based MEC framework, which complies with the architecture issued by ETSI and 3GPP
[154]	latency, throughput, migration frequency	NFV, MEC	MEC service that complies with QoS standards for various applications and computing services in vehicular communications environment
[112]	reliability, latency, protocol overhead	routing	Potential packet drops and unsuccessful connections in multi-hop communication
[105]	latency, reliability	routing	The challenge of implementing a communication scheme in VANET without RSU
[107]	reliability, latency	routing	Local maximum and sparse connectivity caused by an obsolete neighbor list and lack of global information in geographic routing protocol
[106]	delay, throughput, communication range	routing	The tendency for vehicle clusters to form on the road and weakness of previous routing protocols in terms of latency
[155]	throughput, latency, protocol overhead	routing, security	Improve security and communication efficiency in a communication infrastructure
[156]	latency, reliability	routing	Challenges faced in vehicular communications: high scalability network, high dynamic network topology, and heterogeneous nature
[157]	reliability, latency	routing, network architecture, and design	The need to improve routing and forwarding efficiency in SDN-based on-demand routing mechanism
[158]	latency, protocol overhead	MEC	Delivering and processing data to fulfill the QoS and QoE needs of certain applications in MEC

Aware Routing (MFCAR), a hierarchical SDN architecture with local and global controllers.

Study conducted in [155] improved security and communication efficiency in a routing process through a scheme that identifies malicious vehicles based on trust value calculations.

Authors in [106] proposes an RL-SDVN routing scheme that uses Q-learning and Gaussian Mixture Model (GMM) to overcome latency problems in previous routing protocols. The scheme was tested and showed better cluster stability, transmission delay, and throughput results than other schemes such as CPB, DMMCA, M.Ren, MFCAR, and SCF.

Authors in [107] proposed the SDN-based geographic routing (SDGR) protocol that uses nodes' location information, density, and digital maps to improve PDR and delay time compared to AODV and GPSR.

Authors in [105] proposed SFIR, a scheme using SDN and fog computing to make routing decisions at road intersections, which showed better results regarding the delay, packet delivery ratio, and packet loss compared to AODV, GPSR, and TORA.

Authors in [162] proposed innovative cluster-based dual-phase routing protocol that uses fog computing (ICDRPF-SDVN), an SDN-based VANET routing protocol with a cluster-based dual-phase routing mechanism and fog computing that shows improved flexibility, scalability, and well-connected routes.

Authors in [112] proposed a routing framework that outperforms traditional VANET routing protocols regarding PDR, delay, and protocol overhead.

Authors in [163] discusses methods for minimizing packet loss and delay by implementing a routing algorithm to select the optimal next hop to provide the best route between the vehicle source and the base station.

Authors in [164] proposed a prediction scheme regarding the location of the vehicles and the network topology formed by the node vehicles in a particular area at a particular time interval.

Authors in [111] proposed a broadcast technique for safety messages and clustering for high vehicle density.

Authors in [94] implements a hierarchical SDVN architecture with components such as the SDN controller, local controller, and forwarding nodes.

Authors in [85] presents an SDN-based mobility management scheme that anticipates handovers by using two wireless interfaces and implementing a more optimal routing scheme. The scheme reduces the time and number of flow messages for route formation and shows improved packet loss ratios and round-trip time delays.

However SDN-based routing is not only made for inter-vehicular communications but also intra-vehicular communications. Authors in [165] discussed SDN-based routing for time-sensitive networking (TSN) for in-vehicle communication.

The research findings presented in this paragraph underscore the diversity of routing protocols developed explicitly for vehicular communications, including VANET routing protocols categorized as topology-based or position/geographic-based approaches. The SDN-based VANET routing employs the controller's flow table for for-

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warding traffic, while also considering high node mobility and traffic characteristics to optimize routing algorithms and enhance end-to-end communication performance in vehicular networks [78], [85], [94], [100], [104]–[107], [109], [111], [112], [141], [155]–[157], [157], [159], [160], [162]–[165].

Potential solutions to enhance SDN routing in vehicular communications include (1) integrating machine learning and AI techniques into SDN controllers for more intelligent routing decisions based on real-time traffic patterns and network conditions, (2) exploring blockchain technology for enhanced security and trust in vehicular communications, and (3) designing efficient and scalable routing algorithms to address challenges in heterogeneous vehicular networks with multiple RAT families, ensuring optimal resource utilization and traffic balancing.

3) SDN Network Architecture and Design

A hierarchical architecture is often used to design an SDN-based network for vehicular communications. This architecture typically consists of multiple layers, including a vehicle, infrastructure, and internet layer. The SDN controllers are distributed across these layers to manage the network traffic and ensure efficient communication. The implementation of SDN in the access network aims to increase network reliability, while in the core network, it is for traffic and service orchestration [166].

The hierarchical SDVN architecture proposed in [97] has three layers (vehicle, infrastructure, and internet) and multiple levels of SDN controllers. The L1 controller is located at RSU, L2 at the VANET backbone, and L3 at the internet layer. This architecture addresses the scalability challenge in SDVN.

In [96], the Enhanced Hierarchical Software-Defined Vehicular Networks (E-HSDV) scheme is proposed to divide SDVN into smaller clusters with a local SDN controller and a global SDN controller to orchestrate information. It enhances the scalability of SDVN.

Authors in [76] proposes an architecture that combines cloud, MEC, and Vehicular Edge Computing (VEC) technologies to offload tasks based on QoS requirements. An SDN controller determines the offloading of tasks on the MEC or the VEC.

The network model of IoV is presented in [143], where a vehicle has computing and storage capabilities, and AI is used for control.

The SDN controller manages the security using dynamic key distribution. Software-defined-IoV (SD-IoV) itself is different from Software-defined IoT (SD-IoT). While both SD-IoT and SD-IoV use SDN to provide dynamic and programmable features, the focus of each concept is different. SD-IoT is focused on networking resource-constrained sensors/devices/things, while SD-IoV is focused on networking vehicles and their associated infrastructure [167].

In [144], the SDN-based Vehicular Cloud architecture (SVC) is proposed, which combines SDN and cloud computing to increase the flexibility of vehicle software updates. The SDN controller at the RSU or Base Station (BS) manages the replication of Virtual Machines (VMs) on the vehicle and the nearest data center.

Research findings emphasize the importance of hierarchical SDN network architectures for vehicular communications. These architectures consist of multiple layers, including the vehicle, infrastructure, and internet layers, with distributed SDN controllers managing traffic and communication efficiency. Researchers focus on scalability, reliability, and traffic orchestration to address the specific challenges of vehicular networks [96], [97], [166].

Future research could explore further enhancements in hierarchical SDN network architectures for vehicular communications, addressing the challenges of dynamic and heterogeneous environments.

B. SDN INTEGRATION WITH OTHER ENABLING TECHNOLOGIES

According to research findings, the performance of vehicular communications systems can be significantly enhanced by combining SDN with enabling technologies, and ITS will be able to communicate more effectively and reliably.

1) SDN and NFV

NFV is a concept that involves using virtualization technology to decouple network functions from proprietary hardware and instead run them as software on commodity hardware. VNFs are the individual network functions implemented and executed in a virtualized environment as part of an NFV architecture. VNFs can include functions such as firewalls, load balancers, and routers, among others.

Authors in [55] proposes using YANG data modeling, NETCONF, and SDN/NFV technologies for remote driving. The proposed architecture can facilitate remote driving services and provide a secure and flexible network infrastructure.

In [49], a cooperative driving solution with SDN and NFV on MEC is proposed to improve resource management and accuracy of AV. The proposed architecture enables cooperative perception and prediction by sharing real-time vehicle data, such as location, speed, and trajectory.

Authors in [57] explores the implementation of MEC-based and Cloud VNF systems for collision avoidance. The study shows better performance in small OBU scenarios with MEC and high scalability with NFV Cloud.

Authors in [47] studies the implementation of SDN-based network slicing and NFV for vehicle platooning. The proposed architecture enables the creation of multiple virtual networks with different Quality of Service (QoS) requirements. The study also proposes a library for C-V2X connectivity and NFV security.

Finally authors in [51] focuses on using SDN and NFV for resource orchestration and improving the performance of edge computing in vehicle platooning. The proposed archi-

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tecture can provide low-latency communication and efficient resource management for edge computing.

The research findings emphasize the significance of network slicing in vehicular communications to efficiently utilize network and computing resources, leading to reduced infrastructure costs. SDN and NFV are essential in realizing network slicing, enabling dynamic allocation of radio communication resources and VNFs in the core network. Implementing network slicing on RAN or the core network in cellular networks allows for optimized throughput performance and QoS provisioning for different applications [47], [49], [51], [55], [57].

Future research in SDN and NFV for vehicular applications holds promising directions. Investigations could encompass refining SDN/NFV architectures to ensure seamless and secure remote driving experiences [55], optimizing cooperative driving through enhanced cooperative perception and prediction mechanisms [49], exploring advanced collision avoidance strategies leveraging MEC and Cloud-based VNF systems [57], delving into dynamic network slicing algorithms for vehicle platooning scenarios [47], and further enhancing edge computing performance in platooning by refining resource orchestration strategies [51]. These directions can contribute to developing more efficient, reliable, and secure vehicular communication systems.

2) SDN and MEC

MEC is a scheme to provide computing services at the edge nodes, which provide reliable services with lower latency. MEC is present in 5G-based vehicular communications infrastructure because of the need to provide faster and more reliable services to end users, which cloud computing cannot provide [154]. With MEC, application execution and computing that require low latency can be carried out on the edge network area. Meanwhile, the existence of SDN will create an orchestration of computing and network resources.

In [168] MEC is implemented for storage and computing purposes for application execution and computing that require low latency. The implementation is carried out at the edge of the mobile network, usually close to the eNB.

The existence of information about the communication channel from the Radio API originating from the eNB gives MEC the ability to run applications that are aware of network conditions and can deliver QoS-aware services [153].

In [88], an SDN-based DMM with QoS-driven route decision, edge, and cloud computing resources management is proposed. Integrating SDN and edge computing aims to enhance autonomous driving systems by reducing latency and enabling real-time computations. However, this integration can lead to reduced mobility support. To overcome this challenge, the solution proposes using DMM, which separates control and data planes to address scalability and reliability concerns in mobility management.

Authors in [158] proposes an architecture that integrates networking, caching, and computing to overcome congestion. The scheme reduces network overhead and task execution time. MEC is essential in the proposed architecture as it brings caching and computing resources closer to the vehicles, reducing latency and improving overall system performance.

Study in [75] integrates SDN and MEC for information dissemination in a vehicular network using cluster heads and eNB-RSU. Simulation results show that the scheme meets the latency requirements of various vehicular services.

Study in [51] discusses vehicle platooning as a parallel MEC provider, utilizing SDN and NFV for resource orchestration and task distribution. A vehicle in the platoon can temporarily share its resources. This scheme improves overall edge computing performance.

Authors in [57] focuses on collision avoidance and implementing MEC and Cloud VNF systems. The results show that MEC performs better with a few OBUs, while Cloud VNF excels in high scalability scenarios.

In [49], the implementation of cooperative driving solves the problem of accuracy of steering and navigation of AV and high-definition maps providing. The solution utilized the network architecture called AVNET, which uses SDN and NFV on MEC to improve resource management and shorten the time for computing facilities.

Study in [76] proposes an architecture that combines cloud, MEC, and vehicular cloud computing (VEC) for vehicular applications. Cloud computing has more extensive storage and computing capacity but also delays significantly. MEC has a low delay, but also it has small storage and computing capacity, and VEC is for offloading tasks to nearby vehicles. SDN determines where the offloaded task should be based on QoS needs.

Authors in [154] discussed the challenge of creating a MEC service with QoS standards for various applications in a vehicular environment. The solutions are proposed the classification of QoS requirements and SDN-based orchestration to manage the network infrastructure and MEC resources, reducing the service migration frequency and latency.

In [138], SDN-assisted MEC network architecture is proposed for the vehicular network to increase control over V2X infrastructure and allocate resources.

In [72], MEC with multiple RATs and NFV is implemented for AV to overcome limitations in navigation and steering. Cloud computing and MEC servers use a two-tier server structure for optimal resource allocation.

In [150], MEC combined with NFV and SDN is proposed to be implemented in cooperative, connected, and automated mobility. Various RAT and network paths, SDN controllers, NFV and offloading tasks, spectrum sharing, and pseudonymity are utilized to address the challenges.

In [103], a three-tier SDN controller (edge controller, domain controller, root controller) is implemented on the MEC server for IoV.

Authors in [169] discusses moving applications and data from one MEC server to another and uses an SDN framework to coordinate the migration process. ETSI has issued MEC architecture standards and components such as Mobile

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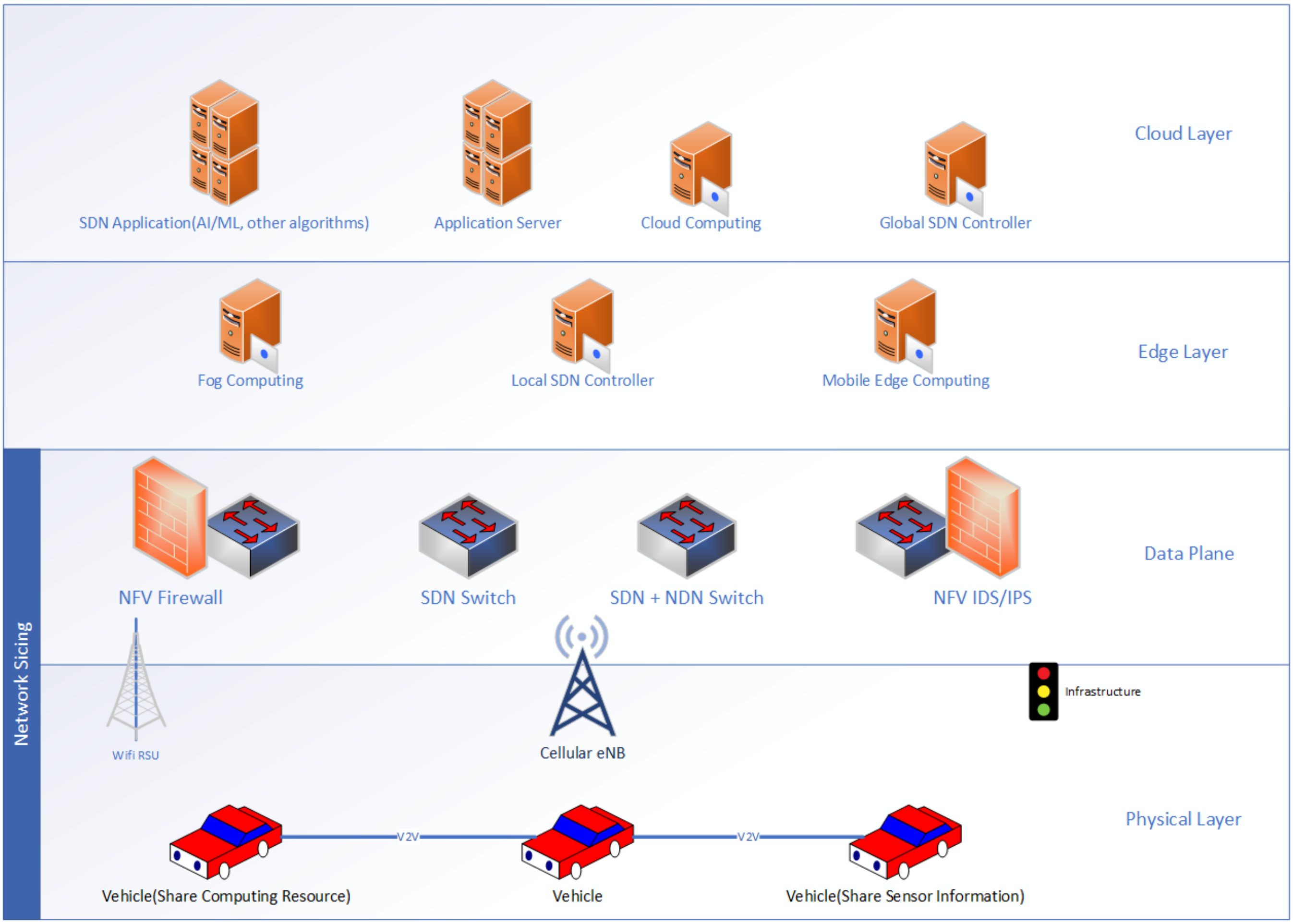

FIGURE 8. Illustration of SDN and Enabling Technologies

Edge Host (MEH), MEC platform, MEC orchestration, and application instance relocation.

Studies in [153] focuses on the gaps in the MEC standard and the integration of MEC into the 3GPP architecture and implements an SDN-based MEC framework.

Authors in [149] proposes a cloud resource management system for vehicular cloud architecture, which uses SDN to orchestrate virtual machine deployment, migration, and replication.

Meanwhile, [73] integrates unmanned aerial vehicles (UAVs) and MEC to form a new concept called aerial MEC and uses SDN to manage the network topology and improve network performance.

In [98], an SDN-enabled architecture combining SDN, cloud computing, MEC, and two RATs (IEEE 802.11p and NR-V2X/5G-V2X) is proposed to meet the application performance requirements that cannot be met by RATs alone. The architecture is tested on three applications (CCAS, BEVS, and INS) under varying conditions of vehicle density and outperforms performance requirements.

Integrating MEC with SDN technology presents a pivotal solution in vehicular communications. Operating at the network edge, MEC ensures low-latency computing services [154]. This synergy enables applications demanding real-time execution to leverage edge capabilities, as evidenced by cooperative driving improvements [49], [88] and collision avoidance strategies [57]. Dynamic resource orchestration in vehicle platooning [51] and QoS-driven route decisions [88] are further enhanced. The integration of multiple RATs and NFV addresses navigation challenges for autonomous vehicles [72]. SDN-assisted MEC optimizes network and resource management, reducing service migration frequency and latency [154]. These findings highlighted SDN-based MEC's pivotal role in elevating vehicular communication systems.

In the future, researchers can explore optimizing MEC service delivery with QoS standards for various vehicular applications. Further development of SDN-based orchestration methods can efficiently manage the network infrastructure and MEC resources, reducing service migration frequency and latency. Additionally, investigations into the seamless migration of applications and data between MEC servers using SDN coordination could lead to more efficient resource allocation.

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3) SDN and Network Slicing

Network slicing is the key to utilizing network and computing resources with high utilization and reducing the cost of building infrastructure. NFV and VNF are used in SDN-based network infrastructure to realize network slicing. Network slicing can be deployed on RAN or a core network in cellular networks. The SDN controller will then determine the RAN's radio communication resource allocation and implement the VNF in the core network device [148].

The architecture proposed in [97] has three layers with three levels of SDN controllers to manage traffic, apply policies, and then implement virtualization and multitenancy on one physical network.

Study in [117] proposes a network slicing scheme for 5G that optimizes throughput performance. The scheme has two layers (local and shared resource allocation), and an SDN controller manages a virtual resource pool.

Study in [148] implements a network slicing scheme for RAN and core networks using SDN, NFV, and edge computing. The scheme adjusts slicing dynamically for optimal bandwidth and uses a genetic algorithm for resource optimization.

The authors propose an SDN-based transmission protocol (SDTP) for addressing congestion control techniques and general transport protocols in [170]. On the virtual network, dedicated resources like caching, processing, and transmission are assigned to each service as network slices to support end-to-end packet delivery of different applications, enabling service-oriented QoS provisioning.SDN real-time loss detection and congestion mitigation. A video streaming service tests the protocol, reducing network congestion.

Study in [123] proposes using SDN-NFV based 5G core network slicing with symmetric key encryption to enhance security in communication.

Authors in [92] discusses dimensioning network slicing for various communication services in 5G networks based on KPIs like URLLC, eMBB, and eMBB.

Authors in [147] studied network slicing from a business perspective and discusses the framework for automation and orchestration.

Study in [152] proposes time-scales RAN slicing mechanisms using SDN controller and machine learning to optimize the performance of URLLC and eMBB communication services in 5G networks.

Moreover, authors in [71] discusses the implementation of virtual VANETs and proposes an overlay isolation solution to balance security and performance. The solution is found through a non-cooperative game, reducing average latency while meeting QoS for each virtual VANET.

The research findings highlight the significance of network slicing in vehicular communications for efficient utilization of network and computing resources, leading to cost reduction in infrastructure deployment [71], [92], [123], [147], [152], [170]. NFV and VNFs are crucial components in SDN-based network infrastructure to achieve network slicing [148]. Network slicing can be applied to both the RAN and the core network in cellular networks, enabling the SDN controller to dynamically allocate radio communication resources and implement VNFs in the core network device [148].

Potential solutions can focus on deploying network slicing in edge computing environments to support real-time computing tasks and applications with ultra-low latency requirements. The development of dynamic RAN slicing mechanisms can be extended to support the performance optimization of other communication services in 5G networks These advancements align with the evolving demands for improved network efficiency and enhanced service quality.

4) SDN and AI/ML, Other Algorithms

Combining AI, ML, and other algorithms with SDN in vehicular communications can increase performance, efficiency, and reliability. Using ML and AI, we can develop intelligent, responsive networks that adapt to changing traffic patterns and improve resource allocation in real-time.

Authors in [50] proposes an attack detection method based on the invariant state set to ensure the reliability of the cyber attack detection algorithm in an SDN-based vehicle platoon system.

Authors in [124] proposes a security system architecture that divided into two parts: the control plane and the data plane. The control plane has two sub-parts, the Zone Controller and the Global Authority, which manage vehicles' and cloud providers' registration, authentication, and resource management using Vehicular Cloud Computing (VCC).

Authors in [125] proposes a framework that provides end-to-end security and privacy in C-V2X 5G, including an elliptic curve cryptographic authentication protocol and intrusion detection module based on tensor-based dimensionality reduction.

Authors in [119] proposes an SDN-based context-aware MDS with a control plane that secures the vehicle cluster, adjusts dynamic security parameters, and has local, regional, and global SDN controllers.

In [138], The optimization problem in an SDN-assisted MEC network is solved in three stages: initial offloading nodes selection, stateless Q-Learning for resource allocation, and the decision to offload as a potential game. Results show better performance compared to similar schemes.

In [126], consortium blockchain technology, smart contracts, and reputation-based data-sharing schemes are used to secure data sharing and storage in vehicular edge computing and networks. A three-weight subjective logic model is used for reputation management, with the blockchain consortium technology run on edge computing nodes for auditing purposes.

In [127], hierarchical blockchain-based authentication and access control are implemented on all nodes of the SDVN for data storage and sharing, with a distributed blockchain scheme per subnet for scalability. However, this increased CPU usage and latency have to be solved by optimization to find the optimal number of subnets.

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In [118], energy-efficient end-to-end security is proposed through RSU-based group authentication and a private collaborative intrusion detection system (IDS) based on collaborative learning between vehicles. This reduces communication and storage overhead while increasing efficiency and detecting intruders with 96.81 percent accuracy.

In [129], a platform is created to detect and respond quickly to DDoS attacks on SDN-based vehicular communications infrastructure, using PACKET_IN message anomaly detection algorithms, flow table statistics, and an SVM-based attack detection module. The experiment results showed the scheme's effectiveness, reducing response time and controller load during attack detection.

The DDoS attack detection on SDN-based vehicular communications differs even from DDoS attack detection on SDN-based IoT. The main difference between DDoS detection in SD-IoT and vehicular communication networks is the nature of the network traffic being analyzed. In SD-IoT, the focus is on the behavior of IoT devices, while in vehicular communication networks, the focus is on the behavior of vehicles and their associated infrastructure. Additionally, vehicular communication networks have unique characteristics, such as high mobility and real-time communication requirements, that must be considered when designing DDoS detection and mitigation solutions [171].

In [149], some function is implemented: (1)Multi-objective integer line programming model to select a Pareto optimal solution, which minimizes service migration costs. (2)Design efficient heuristics for CRM. (3) Using the Markov decision process (MDP) and reinforcement learning to choose a Pareto optimal solution for minimizing service migration costs.

In [95], a modified particle swarm optimization (MPSO-CO) algorithm to optimize load balancing in fog computing infrastructure. The simulation results show that the proposed solutions can effectively reduce latency, increase QoS, and improve stability and reliability in fog computing.

Authors in [172] proposes a VANET architecture called FCDVN-ML that combines SDN, fog computing, and machine learning to handle DDoS attacks. The system has three components: cloud computing for running ML algorithms, fog computing for executing attack detection rules, and a hierarchical firewall to block DDoS attacks.

Authors in [130] highlights the risks of security attacks in CoCA vehicular communications, such as taking over vehicle resources and jamming communication channels.

A study [128] tested LLDP poisoning attacks on four SDN controllers: Floodlight, POX, Open Daylight, and RYU. And then proposed LLDP authentication to overcome countermeasures.

Authors in [131] presents an SDN-assisted framework that uses Multigeneration Mixing (MGM) network coding for V2V communication and an authentication key request scheme for V2I communication.

Authors in [132] proposes using a Deep Q-Learning (DQL) based framework to detect and address malicious nodes in SDVN.

Authors in [90] proposed SDN-NEMO, an SDN-based Distributed Mobility Management (DMM) system for Network Mobility (NEMO). It utilizes an OpenFlow switch and an edge router called O-AR on the mobile network edge, with Central Location Management (CLM) on the SDN controller for location tracking and IP address mapping.

Authors in [99] proposes a scheduling scheme and determines the time interval for sending broadcast information from the RSU to the vehicle to maximize the communication success ratio and reduce overhead due to sending repeated messages from different RSUs to the exact vehicle. In the proposed scheme, information regarding vehicle identity, speed, and direction of movement is used by the Adaptive Broadcast Interval (ABI) Algorithm.

Authors in [89] proposes proactive mobility management using a vehicle trajectory prediction framework based on long short-term memory neural networks (LTSMs).

Authors in [88] presents a mobility-aware and QoS-driven (MobQoS) SDN framework with a QoS-driven route decision process and resource management based on Multi-Objective Evolutionary Algorithms on Decomposition (MOEA/D).

Authors in [87] proposes SDN-based mobility management (SDNVMM) to predict handovers, implement local caching schemes at road-side units (RSUs), and optimize the number of RSUs to save costs while maintaining QoS standards.

Authors in [79] discusses SDN-based intelligent handover and TDMA multichannel MAC (STMC-MAC) to optimize the vehicle handover process between RSUs.

Authors in [66] presents an SDN-based scheme to reduce latency and support seamless mobility in teleoperation. The scheme selects the network access point based on QoS criteria and reduces control signaling through a routing strategy.

Authors in [83] proposes a handover scheme that divides vehicles into clusters and uses MEC to control data reordering during handovers between clusters or eNodeBs.

Authors in [82] presents a centralized handover management framework called HUMOR and a machine learning-backed proactive handover algorithm called ABRAHAM, which uses multiple metrics to perform handovers.

SDN and machine learning can improve the efficiency and flexibility of wireless infrastructure in complex scenarios by configuring communication parameters based on learning and optimizing infrastructure performance according to [173].

In [103], the controller placement at the network's edge is carried out with multi-objective optimization: delay, load balancing, and path reliability—an algorithm based on multi-agent deep Q-learning networks (MADQN). In addition, to speed up the execution of this algorithm, a parallel process is running in the computing environment.

Authors in [158] tries to solve low latency data delivery and processing by making optimal data delivery and computing decisions based on a partially observable Markov decision process (POMDP).

In [152], a time-scale RAN slicing mechanism is used to optimize 5G communication services. Mathematical modeling is employed for Resource block (RB) allocation, utilizing a non-linear binary program and Markov decision process for global and individual allocation. Single-agent reinforcement learning is used for initial allocation, while multi-agent deep Q-learning is used for RB allocation and sharing between gNBs.

Authors in [146] proposes an intelligent SDN-based C-V2X network architecture that uses deep learning to offload traffic on network access points and vehicle communication devices. By embedding deep learning in the SDN controller, the scheme can handle complex situations in network infrastructure and maximize throughput while balancing the use of network access points and estimating vehicle trajectories.

A centralized and localized data congestion control strategy to overcome data congestion at crossroads is studied by [151].

The ML-CC strategy proposed in this paper is compared with CSMA/CA, D-FPAV, CABS, and NC-CC. The simulation results show that the proposed scheme reduces latency, increases throughput, and reduces packet loss ratio compared to other congestion control strategies. The deep learning-based tool to reduce the cost and optimize the performance of 5G-V2X infrastructure is explored in [145].

In [145] A deep learning-based tool called spatial-temporal residual network with permutation operator (PST-ResNet) is used to reduce the CAPEX and OPEX. Meanwhile, to optimize 5G-V2X performance related to multi-hop communication, cognitive radio, frequency spectrum usage, network coverage, routing, resource allocation, and interference management. A swarm intelligence-based optimization tool called subpopulation collaboration-based dynamic self-adaptation cuckoo search (SC-SDCS) can solve complex optimization problems for global optimization problems.

Integrating AI/ML with SDN in vehicular communications can significantly enhance performance, efficiency, and reliability. AI and ML algorithms enable the development of intelligent and responsive networks that can adapt to dynamic traffic patterns and optimize resource allocation in real time. Research findings show that these technologies can enhance security, detect and mitigate cyber-attacks, optimize network slicing, enable proactive mobility management, and improve handover processes [50], [95], [103], [124]–[126], [138], [145], [146], [149], [151], [152], [158], [172].

In the future, further exploration of AI and ML integration with SDN in vehicular communications can lead to more advanced and sophisticated solutions. Federated learning approaches can be explored to enable collaborative model training and information sharing between vehicles and infrastructure while ensuring privacy and security. Further research can focus on designing AI-based congestion control mechanisms, adaptive traffic management algorithms, and novel applications of reinforcement learning to enhance vehicular communication systems' efficiency and responsiveness.

5) SDN and Fog Computing

Authors in [101] uses SDN and fog computing to overcome problems in VANET infrastructure. Fog computing has advantages in providing computing and storage facilities close to the user to minimize latency [95]. Fog computing was easier to deploy and did not depend on telecommunication operators compared to MEC. On the other hand, it has lower capabilities than MEC [95], [174].

Authors in [140] proposed a real-time dynamic pricing model, a renewable energy management algorithm, and a centralized microgrid management algorithm for EV charging and discharging services.

Authors in [77] proposes a distributed fog-based station (FBS) controlled by SDN to overcome multiple time-constrained vehicular application scheduling.

Authors in [91] proposes a novel vehicular-network architecture based on SDN and fog computing to improve mobility management and reduce delays in communication. Meanwhile, Authors in [95] proposed a software-defined cloud/fog computing (SDCFN) architecture to distribute the load to more than one fog server.

Research findings highlight using SDN and fog computing to address various challenges in vehicular communications. Fog computing offers advantages in providing computing and storage resources close to users, reducing latency in vehicular applications [95]. It is considered easier to deploy than MEC and does not rely on telecommunication operators. However, fog computing may have lower capabilities than MEC in specific scenarios, making it essential to carefully evaluate the trade-offs between the two technologies based on specific use cases and requirements [95], [174].

In the future research can focus on enhancing the coordination and communication between fog nodes and cloud-based infrastructure. Moreover, developing adaptive algorithms and mechanisms that dynamically determine the optimal allocation of tasks between fog and cloud resources based on varying network conditions and application requirements can further enhance the performance and reliability of vehicular communications systems.

6) SDN and Cloud Computing

SDN and cloud computing integration have been proposed to support vehicular communications by providing a flexible, scalable, and cost-effective infrastructure. Cloud computing can offer on-demand computing and storage resources. The combination of SDN and cloud computing can enable seamless communication between vehicles, infrastructure, and cloud services and support emerging applications such as autonomous driving, intelligent transportation systems, and smart cities.

In [57], MEC-based and cloud VNF systems are implemented for collision avoidance and VRU safety.

In [144], cloud computing is combined with SDN in the form of the SDN-based vehicular cloud architecture (SVC) to increase software update flexibility.

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Study in [143] present a network model of the IoV that uses artificial intelligence and security management through dynamic key distribution and the SDN controller.

Authors in [140] proposes a system for EV charging and energy management in buildings using the cloud, fog computing, and SDN-based networks.

Study in [139] presents a charging optimization scheme using SDN and cloud computing that minimizes EV charging time and price through routing and scheduling algorithms.

The research findings indicate that integrating SDN and cloud computing in vehicular communications can bring several benefits, not only directly improving vehicular communication performance improvement but also creating services for vehicles such as security management [143], smart vehicle software update [144], and EV charging [139], [140].

In the future, further research can explore applying AI/ML algorithms in combination with SDN and cloud computing to enable predictive and adaptive decision-making in offloading traffic and processing on cloud computing.

7) SDN and ICN

In the previous sections, the challenges in vehicular communications can be overcome by developing a new RAT standard or utilizing computing technology and artificial intelligence. In this subsection, we will look at an alternative to overcome the existing challenges of vehicular communications by replacing a fundamental part of network communication, the TCP/IP protocol. The internet architecture needs to be fully scaled up to address the need for performance standards for communicating various applications.

ICN packet data is routed based on desired content instead of location-based addressing. In this scheme, the desired content is moved from the producer server to a node closer to the consumer accessing it through cache data. In ICN, packet data is routed based on desired content instead of location-based addressing. This scheme moves the desired cont1ent from the producer server to a node closer to the consumer accessing it in cache data. The integration of ICN technology with SDN has been proposed in several studies for a long time. For example, [175] proposed SDN-ICN integration architecture, deployment, and testing schemes. While in [176] ICN and NFV are proposed for network and cache slicing schema on a 5G network.

Moreover, recently network communication has changed from connection-oriented to content-oriented and then emerged the future information-centric network, including the content-centric network (CCN) and NDN. CCN architecture is implemented on edge computing to perform caching and distribution functions. Vehicular communications adopted this new network architecture, including NDN, to overcome the challenge and fulfill the application communication QoS needed [177]. For example, authors in [178] proposed caching and distribution of content on edge networks to overcome latency problems in HD map sharing for automated driving.

The proposed architecture in [142] called Software-Defined Vehicle Named Data Networking (SDVNDN) has components for efficient caching, content naming, intelligent forwarding, push-based forwarding, intrinsic data security, congestion control, topology indicator, content prefix management, and state information monitoring.

Authors in [179] and [136] both studies the implementation of NDN to improve communication performance in cooperative vehicle infrastructure systems and vehicular networks, respectively.

NDN is also combined with SDN in [136] and [142] to optimize communication performance in vehicular networks.

The research findings suggest that ICN, such as CCN and NDN, can provide a potential solution to overcome the challenges in vehicular communications by replacing the traditional TCP/IP protocol. ICN facilitating efficient content distribution through caching. The integration of ICN technology with SDN has been proposed in several studies to enhance network management and content delivery in vehicular communications [136], [142], [175]–[179].

In the future, further research can focus on enhancing and optimizing the implementation of ICN, particularly NDN, in vehicular communications. This includes developing more efficient caching and content distribution strategies to improve real-time data sharing for various applications. Additionally, efforts can be directed toward improving the intrinsic data security and congestion control mechanisms in ICN-based vehicular communication systems.

C. SDN INTEGRATION INTO MAC AND PHY LAYER

SDN implementation can significantly improve the performance of vehicular communications by enabling more efficient and intelligent handover processes between RSUs and managing communication resources at the SDN-based MAC and PHY layers.

Authors in [79] discusses the STMC-MAC, an SDN-based intelligent handover, and TDMA multichannel MAC to optimize the handover process between RSUs. Each vehicle will get access from multiple RSUs at one time. Furthermore, the SDN controller forecasts which RSU will provide communication access for a vehicle in the next road segment.

Authors in [116] presents a MAC layer architecture and design that works with principles similar to SDN, named Carrier Sense Multiple Access/Contention Queue (CSMA/CQ). The scheme increases throughput efficiency by 30% compared to the IEEE 802.11 standard and separates control and data transmission channels.

Authors in [137] proposed "sdnMAC", a hierarchical network architecture to manage communication resources at SDN-based MAC and PHY layers. The SDN controller manages the RSUs and sets time slots for vehicles. The RSUs detect collisions and convey mobility and density information to the controller. The framework was tested for setting communication parameters (frequency hopping, transmission power control, adaptive modulation & coding).

It improved QoS and adaptive routing at the MAC and NET layers.

From all the information above, integrating SDN into the MAC and PHY layer of vehicular communication offers substantial benefits. This integration enhances the MAC and PHY layer's adaptability and responsiveness by enabling dynamic configuration and management of communication parameters based on real-time network conditions. SDN's centralized control facilitates efficient resource allocation, reduces collisions, and optimizes communication, resulting in improved QoS, reduced latency, and enhanced overall network performance [116], [137].

Future research can explore advanced SDN-based MAC and PHY layer architectures to address challenges like high mobility and dynamic communication environments in vehicular networks. Emphasizing intelligent handover mechanisms, resource allocation, and adaptive routing algorithms can improve QoS and communication efficiency.

D. SDN AND CROSS-LAYER DESIGN

Cross-layer design remains relevant and valuable in vehicular communications, even with the availability of SDN as a promising solution. While SDN offers centralized network management and dynamic resource allocation, the cross-layer design complements these capabilities by facilitating efficient communication and optimization across different protocol layers [94], [180].

When combined, SDN and cross-layer design offer additional network performance advantages. However, the paradigm shift in network architecture induced by the adoption of SDN and cross-layer design has given rise to a variety of issues [180].

The cross-layer design in vehicular networks allows the use of metrics from different layers to create optimum routing paths. The SDN-based hierarchical network architecture in [94] uses three parameters from different layers in its implementation.

The movement of nodes in a VANET requires the cross-layer design to utilize information from the PHY and MAC layers to achieve better QoS [100].

Authors in [141] proposed a framework called "Cross-Flow," which integrates SDN and SDR and enables the SDN controller to control MAC and PHY layer parameters.

Authors in [137] proposed sdnMAC, a hierarchical network architecture to manage communication resources at the MAC and PHY layers.

Study in [79] discusses an SDN-based intelligent handover for optimizing vehicle handover between RSUs.

Authors in [116] proposed a MAC layer architecture based on SDN principles, named CSMA/CQ, which increases throughput efficiency.

Cross-layer design plays a crucial role in vehicular communication by enabling the seamless integration of information and optimization across different protocol layers. This approach enhances communication efficiency, adaptability, and QoS provisioning in dynamic vehicular environments [79], [94], [100], [137], [141], [180].

In the future, researchers can explore standards and develop guidelines for implementing SDN-based cross-layer design in vehicular communications to ensure interoperability and compatibility across different network environments.

E. SDN AND COMMUNICATION PROTOCOL MODIFICATION

Authors in [86] proposed enhanced handover schemes by integrating SDN with Random access channel (RACH)-less and Make before the break (MBB) handover schemes on C-V2X communication. The purpose of this scheme is to shorten the handover execution time. This scheme can be implemented by redesigning the signaling protocol. The new signaling protocol design has a scheme: (1) Unification of lower layers signaling messages for handovers and signaling messages for SDN network path updates. (2)Transmitting cell timing information messages between cell radio temporary identification between the base station (BS) and SDN controller. The implementation of the scheme in this study was successful in reducing handover execution time and maintaining reasonable signaling overhead.'

Authors in [84] proposes a methodology to minimize handover duration using the faster X2 interface for inter-system handover. The simulation results show a better handover preparation and completion time than previous studies.

The integration of SDN with modified handover schemes, as demonstrated in [86], and the utilization of faster interfaces for handovers in [84] collectively underscore the correlation between SDN, protocol modification, and improved performance in vehicular communication, specifically in reducing handover execution times.

In the future, researchers can further explore and develop advanced SDN-based communication protocols that optimize various aspects of vehicular communications. Additionally, efforts can be made to standardize SDN-based communication protocols to ensure compatibility and interoperability among different vehicular network environments.

VI. OPEN AND FUTURE RESEARCH DIRECTION

The literature review highlights significant advancements in implementing SDN for vehicular communications. These developments must consider performance requirement standards and vehicular communications use cases. Key enabling technologies like NFV, MEC, network slicing, AI/ML, fog computing, and cloud computing contribute to high-performance, reliable, and scalable vehicular communications beyond RAT-only implementation. SDN is suggested to be applied alongside various enabling technologies to tackle vehicular communications challenges.

SDN and other enabling technologies address performance standards, such as latency, mobility, reliability, throughput, security, and maintaining low communication overhead. By improving network architecture, routing, SDN controllers, and data planes, vehicular communications performance can

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be supported. Scalability, single points of failure, load balancing, reducing latency, and protocol overhead are challenges addressed by SDN controllers in vehicular communications. E-HSDV, multiple controllers, and local controllers near RSUs show promising results in resolving these issues, but further study is needed.

Distinctive characteristics of VANETs, such as high node mobility and heterogeneity, present challenges for SDN routing performance in vehicular communications. Scalable and flexible cluster-based dual-phase routing methods benefit from fog computing, but more effective routing protocols must be developed to support VANETs' dynamic topology and high node mobility. Several routing schemes have been proposed, including HSDN-GRA, ROAMER, SURFER, ORUR, MFCAR, and RL-SDVN, addressing load balancing, congestion-aware routing, and latency issues.

Challenges in SDVN architecture, such as scalability, network dependability, and effective communication, have been addressed by proposed hierarchical SDVN architectures like E-HSDV and others. Researchers can focus on creating resilient SDVN designs that adapt to changing network conditions. Technologies like NFV, VNF, MEC, and network slicing can improve vehicular communications, but challenges related to reliability, latency, QoS awareness, and resource efficiency remain.

AI, ML, and different algorithms in vehicular communications can address security, mobility management, congestion control, and optimization issues. However, challenges in obtaining accurate data for ML models and algorithms and the scalability of proposed methods to large-scale vehicular networks persist.

Fog computing can improve vehicular communications, but issues such as resource availability and capabilities compared to MEC must be resolved. Research may focus on developing novel algorithms to overcome these drawbacks and evaluating the effectiveness of fog computing in real-world contexts.

Integrating cloud computing with vehicular communications faces challenges like network latency, bandwidth limitations, security, privacy, and cost-effectiveness. Researchers can focus on creating practical algorithms and protocols that minimize latency and ensure data confidentiality and privacy.

The MAC layer implementation based on SDN has shown promise in enhancing vehicular communications performance. The reliability and scalability of these strategies across expansive vehicular networks should be explored.

SDN and cross-layer architecture can significantly increase performance for vehicular communications. However, using these technologies has caused a paradigm shift in network architecture, giving rise to several issues. Implementing cross-layer mechanisms introduces additional complexity, requiring careful consideration of protocol interactions and dependencies.

In this part of this section, we highlight some important findings from this survey:

- SDN support is essential for vehicular communications, enabling centralized network management, dynamic resource allocation, and real-time responsiveness. Without SDN, vehicular networks would face challenges in handling the dynamic nature of communication, leading to suboptimal routing, increased latency, and potential breakdowns, which could obstruct the deployment of safety-critical applications and progress toward more efficient and safer transportation systems.
- C-V2X will likely win the competition among RATs in vehicular communication due to its advantages and the automotive industry's adoption rate. C-V2X leverages existing cellular infrastructure and supports efficient communication with low latency, high reliability, and scalability. This makes it suitable for safety-critical applications and future autonomous driving, leading to a more interconnected and intelligent transportation ecosystem. Industries are expected to primarily support and adopt C-V2X for its scalability and wide application range, driven by significant momentum and support from major players in the automotive and telecommunications sectors. As C-V2X becomes dominant, it will foster cooperation among vehicles and infrastructure, enhancing road safety, traffic efficiency, and overall transportation.
- With the coexistence option between RATs, communication standard developers and chip manufacturers for RATs can continue their work. It is possible to create an integrated vehicular communications infrastructure that brings out the advantages of each RATs and covers the weaknesses of each RATs. SDN can act as an orchestrator in this integrated vehicular communications infrastructure.
- The drawback of SDN lies in potential single points of failure, security vulnerabilities, and scalability challenges due to the centralization of network control and the dependency of SDN infrastructure on its controller. Programmable data planes Programming Protocol-Independent Packet Processors P4 are essential in mitigating SDN's drawbacks by reducing the dependence on SDN controllers and enabling fine-grained control over packet processing. Programmable data planes allow for optimized data forwarding, reduced bottlenecks, and improve overall network performance, making vehicular communications more reliable and efficient while minimizing the impact of the SDN controller as a single point of failure.
- The ICN-based intent-centric approach is well-suited for vehicular communication, as it allows for efficient content caching and distribution of common information that AV and ITS operations need. The ICN implementation can reduce latency and enhance communication performance. By integrating ICN with SDN, vehicles can benefit from optimized caching and forwarding strategies, improved content distribution, intelligent interest handling, and intrinsic data security. SDN's cen-

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tralized control and real-time responsiveness, along with ICN's content-oriented routing, create a combination that can address the challenges of vehicular communication and provide better communication performance.

With the very dynamic character of vehicular communications, the application of SDN technology that can provide the ability to monitor the global condition of communication network infrastructure and to be able to perform on-the-fly configuration and communication parameter adjustments is highly recommended. In the last part of this section, we summarize our recommendations for future research directions and areas that require future investigation:

- Linking each SDVN research to the distinctive characteristics and use cases of vehicular communications.
- Implement programmability on the SDN data plane to improve SDVN performance and reliability by creating an intelligent data plane that more independent of the control plane, for example, by combining open-switch and P4 programming language.
- Implement th SDVN experiment on a hardware testbed to bring up test results in a more realistic environment.
- Proposed SDN based adaptive power transmission and receive antenna algorithms to solve blocking problem in dense VANETs condition.
- Explore communications standards other than IEEE 802.11 and C-V2X to see the potential for their application in the future, like 6G, LiFi, and satellite.

VII. CONCLUSION

This paper surveys SDN integration with other enabling technologies applied to vehicular communications. We present a performance comparison and coexistence of RAT IEEE 802.11 and C-V2X. We also summarize the SDN application on the various V2X use cases and the SDN application to solve specific problems in vehicular communications. Finally, we indicates several potential exciting directions for future works in SDN-enabled vehicular communications. The main contribution of this survey paper is to comprehensively discuss SDN support in vehicular communications based on the distinctive characteristics of vehicular communications, from standard RATs to various specific challenges that exist in vehicular communications. Studies on architectural enhancements and SDN components to support vehicular communications are also discussed, and what is not less important is the integration of SDN with various vehicular communications addressed comprehensively. With all these discussions, this survey paper is the most comprehensive SDVN survey up to the time of publication of this article. And the implication is this survey paper can be used as a reference for all researchers interested in SDN and vehicular communications research.

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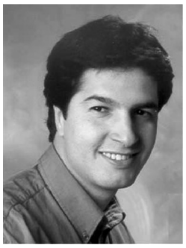

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