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SDN-Based VANET Routing: A Comprehensive Survey on Architectures, Protocols, Analysis, and Future Challenges

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ABSTRACT As the automotive and telecommunication industries advance, more vehicles are becoming connected, leading to the realization of intelligent transportation systems (ITS). Vehicular ad-hoc network (VANET) supports various ITS services, including safety, convenience, and infotainment services for drivers and passengers. Generally, such services are realized through data sharing among vehicles and nearby infrastructures or vehicles over multi-hop data routing mechanisms. Vehicular data routing faces many challenges caused by vehicle dynamicity, intermittent connectivity, and diverse application requirements. Consequently, the software-defined networking (SDN) paradigm offers unique features such as programmability and flexibility to enhance vehicular network performance and management and meet the quality of services (QoS) requirements of various VANET services. Recently, VANET routing protocols have been improved using the multilevel knowledge and an up-to-date global view of traffic conditions offered by SDN technology. The primary objective of this study is to furnish comprehensive information regarding the current SDN-based VANET routing protocols, encompassing intricate details of their underlying mechanisms, forwarding algorithms, and architectural considerations. Each protocol will be thoroughly examined individually, elucidating its strengths, weaknesses, and proposed enhancements. Also, the software-defined vehicular network (SDVN) architectures are presented according to their operation modes and controlling degree. Then, the potential of SDN-based VANET is explored from the aspect of routing and the design requirements of routing protocols in SDVNs. SDVN routing algorithms are uniquely classified according to various criteria. In addition, a complete comparative analysis will be achieved to analyze the protocols regarding performance, optimization, and simulation results. Finally, the challenges and upcoming research directions for developing such protocols are widely stated here. By presenting such insights, this paper provides a comprehensive overview and inspires researchers to enhance existing protocols and explore novel solutions, thereby paving the way for innovation in this field.

INDEX TERMS Vehicular network, Energy, Vehicular ad-hoc network (VANET), Software defined network (SDN), Data routing, SDVN, IoV, V2V, V2I, V2X

I. INTRODUCTION

Nowadays, cities are becoming more crowded, with over 50% of the world population existing in urban cities, and this number is expected to rise. Despite the implementation of new traffic regulations and safety measures by governments, the rate of improvement in road safety remains low. Studies show that approximately 92% of road accidents are caused due to errors in human perception (such as drivers' negligence, inadequate surveillance, and distraction) or human decision-making (such as excessive speed, delayed reactions, and misjudgment of safety distance) [1]. Despite the advancements in in-vehicle safety technologies such as anti-locking braking

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systems (ABS), seat belts, airbags, and rear-view cameras, many people still lose their lives due to road traffic accidents yearly [2]. Most of these traffic accidents can be alleviated by realizing ITS, empowering many road traffic management and safety services [1], [2], [3].

Vehicular Ad-hoc Networks (VANETs) are a crucial component of ITS, and they are expected to significantly improve road safety and enhance the driving experience. VANETs are wireless networks formed spontaneously by vehicles to facilitate data exchange among vehicles, roadside units (RSUs), and pedestrians through message forwarding over multi-hop inter-vehicular communication. VANET can provide several safety-related applications that help prevent accidents and reduce traffic congestion. Also, it can support many infotainment services, such as weather conditions, video streaming, and nearby parking zones [4].

Based on the routing protocol, vehicles can form a mobile communication network, allowing various services to be deployed without using fixed networking infrastructures. Unfortunately, the self-organization and high node mobility make the network topology changes frequently, generating a challenging task regarding data delivery and service reliability [4]– [6]. Therefore, one of the main challenges of the VANET research community is the development of routing protocols with high adaptability to various VANET scenarios, intending to enhance the reliability and packet delivery ratio and decrease message delay [4]. In this context, conventional VANET routing protocols have utilized either network topology information or geographical vehicle distribution to decide the path from source to distention [2]. Accordingly, some routing protocols are proposed to address the unpredictable vehicle mobility and network fragmentation caused by uniform vehicles distribution [5]. Also, many routing protocols have been suggested to improve data routing decisions by gathering information about both network topology and vehicles' geographical locations. Consequently, the traditional routing protocols may not effectively handle the high mobility, intermittent connectivity, and resource constraints inherent in VANETs. As a result, there has been a growing interest in exploring the potential of emerging techniques and exploiting their abilities to address these challenges and enhance routing performance in vehicular communication [4].

Recently, researchers have focused on utilizing the software-defined networks (SDN) paradigm to improve data routing and increase data delivery rates. Due to its programmability and ability to provide global network management, SDN technology can address the multiple and unpredictable disconnections in VANET networks and deal with the future mobility of VANET nodes. Thus, SDN can give better scalability, programmability, and routing decisions than traditional networking systems. Utilizing SDN global network topology, network congestion, and infrastructure-less issues are reduced substantially [7] [8]. SDN can predict the vehicles' geographical location and future mobility and reduce the routing failure caused by continuous vehicle mobility [9]. Additionally, SDN can reduce the overhead of the entire network by minimizing the number of broadcasted control messages to find the routing paths [10].

By providing more details on the data routing under the SDN-based VANET model, this review aims to contribute to the understanding and advancement of this evolving research area by shedding light on the underlying mechanisms, algorithms, and architectural considerations of such protocols and discovering their robustness and limitations, and suggesting the appropriate improvements decisions. This is what will be presented in this review.

A. MOTIVATIONS

Nowadays, more motivation towards developing autonomous vehicles (AVs) is reinforced by the possibility of saving lives and reducing collisions and fatal accidents. Autonomous vehicles use embedded sensors with intelligent systems to observe their surroundings and control their movement autonomously. Unfortunately, wrong decisions may be made, mainly when undetected objects aren’t identified properly, especially when they depend entirely on the embedded sensors for decision-making without sharing the sensing data with neighboring vehicles, causing fallacious results and disastrous impacts. This critical dependence paves VANET developers and researchers to explore and devise novel methods to ensure high data reliability with minimal transmission delay. Using the current VANET infrastructure for enabling connected autonomous vehicles (CAVs) cannot meet the ambitions of deploying reliable services for such vehicles. SDN, as an emerging technology, can support CAVs with more programmability and manageability.

However, the subsequent inquiries need to be addressed carefully to ensure reliable deployment of SDN in the existing VANET infrastructure:

1. Can the VANET infrastructure solely improve the connectivity among autonomous vehicles?
2. What situations ensure the SDN role in VANET is helpful?
3. What is SDN's role in improving vehicular data delivery?
4. What are the merits and demerits of different SDN architectural designs in VANET infrastructure?
5. How can SDN realize highly reliable data routing solutions in a high-mobility environment?

Generally, conducting a thorough examination of current methods and proposals and identifying their limitations and shortcomings can facilitate the development of novel systems and solutions. So, this review will comprehensively study how SDN technology can enhance and optimize VANET routing.

The primary objective of this study is to furnish comprehensive information regarding the current SDN-based VANET routing protocols, encompassing details of their underlying mechanisms, forwarding algorithms, architectural considerations, and proposed improvements. In addition, full comparative analysis will be achieved to analyze the protocols regarding performance, optimization, and simulation results. Finally, the challenges and upcoming research directions for developing such protocols are widely stated here. By presenting such insights, this paper can inspire researchers to enhance existing protocols and explore state-of-the-art solutions, thereby paving the way for innovation in this field.

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TABLE 1
LIST OF ABBREVIATIONS

Acronym	Definition	Acronym	Definition	Acronym	Definition
ABS	Anti-locking braking systems	VANET	Vehicular Ad-hoc Network	OBU	On-board units
ITS	Intelligent Transportation System	MANET	Mobile Ad-Hoc Network	RSU	Roadside units
CAV	Connected autonomous vehicles	FANET	Flying Ad-Hoc Network	V2B	Vehicle-to-Barrier
V2I	Vehicle to Infrastructure	WSN	Wireless Sensor Networks	V2C	Vehicle-to-Cloud
V2V	Vehicle to Vehicle	I2I	Infrastructure-to-Infrastructure	V2U	Vehicle-to-UAV
UAV	Unmanned aerial vehicles	HRLLC	High-reliability low latency communications	QoS	Quality of Service
V2X	Vehicle-to-Everything	ETSI	European Telecommunication Standards Institute	QoE	Quality of Experience
V2P	Vehicle-to-Pedestrian	FCC	Federal Communication Commission	SCH	Service Channel
V2S	Vehicle-to-Sensor	MEC	Mobile edge computing	CCH	Control Channel
SDVN	Software Defined Vehicular Network	DSRC	Dedicated Short Range Communication	IoT	Internet of Things
SDN	Software Defined Network	WAVE	Wireless Access in Vehicular Environment	IoV	Internet of Vehicles

TABLE 2
COMPARISON OF SDVN-BASED VANET DATA ROUTING SURVEYS. THE SYMBOL ✓ INDICATES THAT THE TOPIC IS DISCUSSED; THE BLANK CELL INDICATES A TOPIC HAS NOT BEEN DISCUSSED, AND THE SYMBOL ∂ MEANS A TOPIC IS SLIGHTLY COVERED.

Year	Reference	Protocols Details	Protocols Taxonomy	Discussion of SDN Architectures	Discussion of role of SDN in data Routing	Data Routing Optimization Metrics	Protocols Application Area	Protocols Limitations	Protocols Robustness	Proposed Improvements	Comparison of Optimization Criteria	Analysis of performance evaluation	Simulation & Testbeds Tools	Future Challenges	New Trends and Upcoming Technologies	Main Topic
2022	**[11]**		✓					✓	✓					✓	∂	VANET/V2X routing using non-learning- and learning-based approaches
	[12]	✓									✓	✓	∂	✓	✓	Data dissemination techniques in VANET
2021	**[10]**		∂	✓	∂	✓		∂	∂		✓	∂		✓		SDVN architecture and routing techniques
	[13]	✓						✓	✓		✓	✓	∂		✓	QoS routing protocols in VANET.
	[14]	∂				✓		✓			∂	∂	∂	✓	✓	Technologies to solve routing problem in IoV
	[15]	✓						∂	∂		✓		✓			Cross layer routing methods in VANET
	[16]	✓						✓	✓		✓	✓			∂	Evaluation of VANET broadcasting routing
	[17]		✓					✓			✓	✓	✓	∂	✓	Cross-layer design and QOS routing in IoV
2020	**[18]**		∂	✓				✓	∂		✓	✓		✓	✓	Security and data routing in SDN-VANET
	[19]	∂	✓			✓		✓	✓			✓			✓	Position-based data routing in fog-based VANETs
	[20]	✓	✓					✓	✓		✓		∂	✓	✓	Location based routing protocols in VANET
2019	**[21]**			✓	∂		∂				✓		∂		✓	QoS and scalability of SDN-IoV routing protocols
	[22]	✓	✓		✓			✓	✓	✓		∂	✓	✓		Performance analysis of VANET routing protocols
	[23]	✓	✓			∂	∂		∂		✓			✓	∂	Challenges of data routing in IoV
2018	**[24]**	✓	✓					✓	✓		✓	✓		✓		VANET geographic routing protocols
	[25]	✓	✓					✓	✓		∂	∂				Comparative analysis of position based VANET routing
	[26]	✓	✓				∂	∂	∂		✓	✓				Data routing techniques in VANETs
2017	**[27]**	∂		✓				✓	✓		✓		∂	∂	✓	Challenges, applications and use cases of SDN in VANET
	[28]	✓	✓			∂		✓	✓		✓	∂	∂	✓		Single- and cross-layer VANET routing techniques
	[29]	✓	∂					∂	∂		✓	✓			∂	Position-based VANET routing protocols
2016	**[30]**		✓				∂	✓	✓		∂	∂	∂		✓	Heuristic-based VANET routing methods
	[31]	∂	✓				∂			∂	∂			✓		Architectures of routing protocols of VANET
2015-2012	**[32]**	✓	✓				✓	∂	∂		✓					Position-based routing protocols in VANET
	[33]	✓	✓			∂		∂	∂		✓	✓	✓			IoV data routing techniques and designs
	[34]	✓	✓					✓	✓		∂	✓	✓			Application oriented DTN VANET protocols
	[35]	✓	✓				✓	✓	✓			∂	∂	✓		Design and architecture of VANET routing
2023	**Our Survey**	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	**Comprehensive study about VANET data routing using SDN Technology.**

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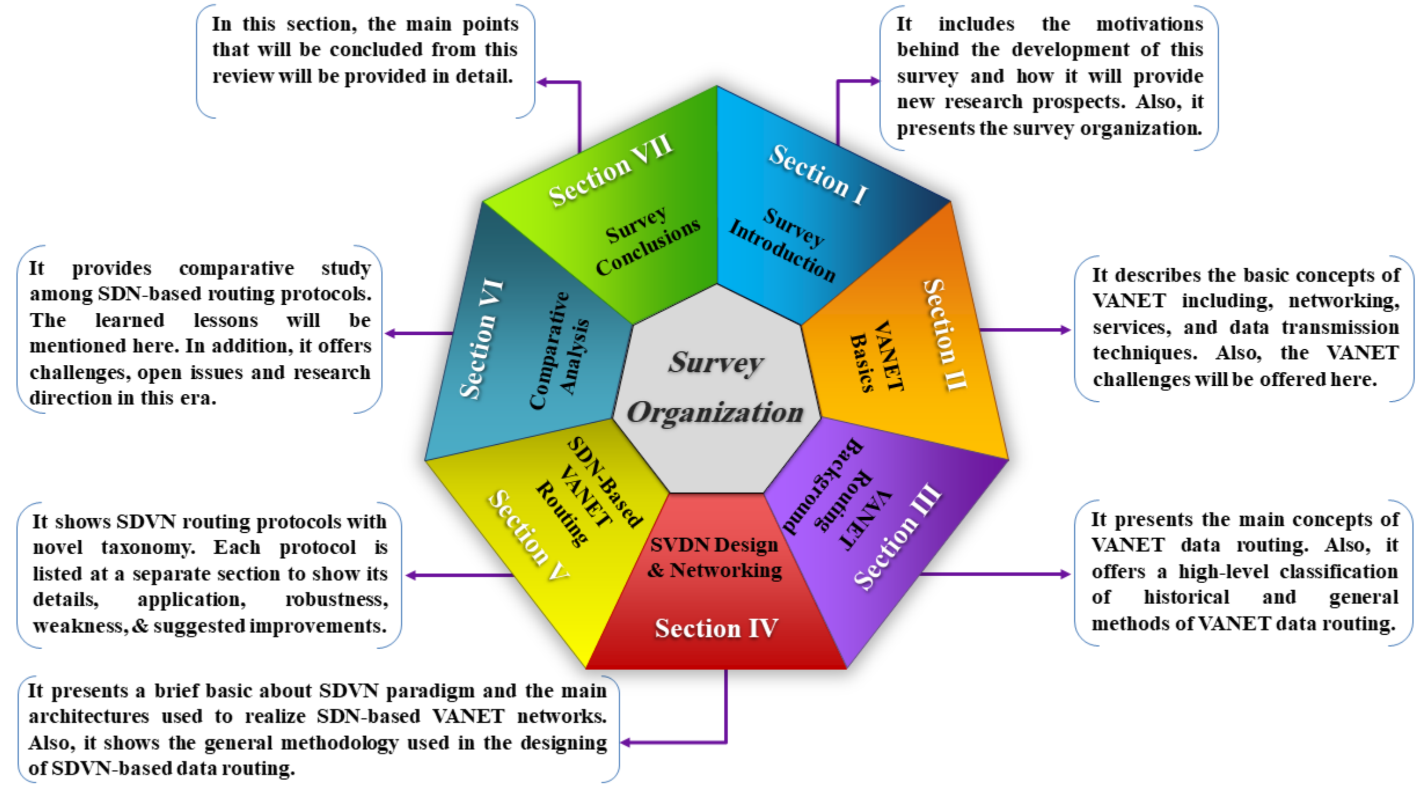

It includes the motivations behind the development of this survey and how it will provide new research prospects. Also, it presents the survey organization.

It describes the basic concepts of VANET including, networking, services, and data transmission techniques. Also, the VANET challenges will be offered here.

It presents the main concepts of VANET data routing. Also, it offers a high-level classification of historical and general methods of VANET data routing.

It presents a brief basic about SDVN paradigm and the main architectures used to realize SDN-based VANET networks. Also, it shows the general methodology used in the designing of SDVN-based data routing.

It shows SDVN routing protocols with novel taxonomy. Each protocol is listed at a separate section to show its details, application, robustness, weakness, & suggested improvements.

It provides comparative study among SDN-based routing protocols. The learned lessons will be mentioned here. In addition, it offers challenges, open issues and research direction in this era.

In this section, the main points that will be concluded from this review will be provided in detail.

FIGURE 1. Survey Structure.

B. RELATED WORKS

In the last decade, the number of surveys related to routing protocols in VANETs has increased incredibly. In this context, the researchers primarily focused on deterministic routing areas in their works, such as topology-based routing, positional routing, and secure routing methods. None has comprehensively studied SDN-based VANET data routing with complete performance analysis. However, table 1 presents the abbreviations list that was used throughout the survey. Table 2 compares previous surveys and our survey based on multiple comparison criteria such as technical details, SDN architecture, routing optimization metrics, proposals for future improvements, optimization criteria, and so on.

C. SURVEY STRUCTURE

Fig. 1 illustrates how the survey is organized, where the survey is structured into seven main sections; each one covers different aspects:

I. Section I, the introduction, explains why we conducted this work and how it can offer fresh research opportunities to researchers. Additionally, the structure of the survey is illustrated in this section.
II. Section II covers the fundamentals of VANET networks. It provides a comprehensive overview of VANET networking and data transmission techniques. Also, this section discusses various characteristics and challenges associated with VANETs.
III. VANET routing background: here, the main concepts and the high-level classification of VANET data routing will be detailed.
IV. SDN-based VANET design and networking: this section details the concepts and architectures of SDN-based VANETs to help grasp the next sections.
V. SDN-based VANET routing: SDN-based VANET routing protocols will be reviewed, showing their underlying mechanisms, forwarding algorithms, advantages, limitations, application area, and potential improvements.
VI. Comparative analysis: it includes a full comparisons among reviewed protocols. Open challenges and upcoming research directions will be provided here.
VII. Section VII will present the main conclusions.

D. CONTRIBUTIONS

In the last two decades, many surveys have been published to study VANET data routing from different aspects, such as routing mechanisms, forwarding techniques, or security methods. However, these studies still need to thoroughly explore the role of SDN in VANET data routing, which inspired us to conduct this comprehensive survey. First, an overview of how SDN can help VANET routing protocols is provided. Then, each routing protocol will be technically discussed, highlighting its underlying mechanism, architectural design, strengths, limitations, application area, and potential improvements. Finally, a comparative analysis with upcoming challenges will be presented. So, this survey extensively deliberates the SDVN data routing, aiming to provide new researchers with a deep understanding of the subject. However, this survey can contribute to the literature as follows:

1. A brief review of VANET from different aspects, such as data communication, services, and deployment challenges. In addition, the key concepts of VANET data routing and the conventional classification of such protocols are presented. A detailed discussion of metrics used to evaluate the performance of routing algorithms is also presented. This will be input to grasp the significance of SDN with VANET and its implication on the design of reliable protocols.
2. A full discussion about the SDVN architecture models and their role in VANET data routing. Also, the integration of SDN with VANET architecture will be covered here.
3. An in-depth discussion of the SDVN data routing with a comprehensive analysis and novel taxonomy of SDN-based VANET routing algorithms is presented. The aim is to qualitatively compare the different routing methods by evaluating their key features, characteristics, performance, simulation results, and limitations. In addition, the most appropriate areas of application and potential improvement will be identified separately for each protocol.
4. The open issues and upcoming research challenges with probable limits and solutions will be outlined and discussed. This discussion is very relevant not just for reviewed protocols but also for new challenges or optimization requirements. This research will aid decision-making by offering valuable insights into the most appropriate SDVN-based routing schemes.

II. VANET BASICS

A. VANET DEFINITION

VANETs are among the most studied areas in mobile ad hoc networks (MANETs). It is an efficient networking solution that allows vehicles to share data among themselves and with nearby infrastructure and pedestrians [2][3]. VANETs possess diverse attributes that differentiate them from MANETs, including but not limited to high node mobility, restricted mobility patterns, unpredictable network topology, and frequent battery recharging. In general, VANETs can be spontaneously established among mobile vehicles, either with or without the need for any pre-existing infrastructure. Infrastructure-independent VANETs, or self-organizing VANETs, operate without relying on existing infrastructure such as RSUs or fixed access points. One of the key characteristics of such VANETs is decentralized communication. Messages can propagate through the network by hopping from vehicle to vehicle, allowing the collaborating dissemination of critical information like emergency alerts or traffic updates. However, infrastructure-independent VANETs face many challenges. Maintaining continuous communication links can be difficult in sparse or highly dynamic scenarios, affecting communication reliability and data dissemination efficiency.

In contrast to infrastructure-independent VANETs, infrastructure-dependent VANETs are distinctively characterized by the significant presence of back-end infrastructure, particularly RSUs [36]. RSUs act as intermediary nodes that facilitate the connection of VANETs to external networks, including the Internet. Moreover, RSUs enable establishing a hybrid routing path that combines wired and wireless links to facilitate high-speed, large-capacity communication between VANET nodes. RSUs are deployed at intersections or some points along a road for different roles, such as data dissemination, decision-making, traffic data analysis, security management, and localization services [37].

To be part of VANET, vehicles must include OBUs (on-board units), the network devices fixed on vehicles to help them in wireless connectivity and localization services [12]. It can offer wireless communication over short distances using the IEEE 802.11p radio technology. Also, they can incorporate other network devices that employ different radio technologies, such as IEEE 802.11a/b/g/n, for data transmission purposes. In addition to wireless radio access, OBUs can help in channel congestion control, localization, data security, and message encoding [38]. Besides, vehicles use embedded sensors and multimedia devices to sense the surroundings and distinguish nearby objects to avoid crashes or unexpected breaks. Still, the sensing data must be shared with nearby vehicles and VANET infrastructure [39]. Recently, vehicles have embedded human-machine interfaces to make a cognitive VANET paradigm [40].

The VANET concept was initially introduced to deliver safety messages for drivers and passengers, providing information such as accident details, road safety messages, congestion information, and violation warnings to allow vehicles to make alternative decisions and save time in congested traffic. Also, VANETs are developed to provide entertainment and comfort services, such as video streaming, weather forecasts, music downloads, online gaming, and commercial advertisements, enabling travelers to plan their journeys more efficiently [41]. Utilizing real-time information, VANET will provide these services through direct or multi-hop communications [41].

B. VANET ARCHITECTURE

In VANETs, real-time messages can be transmitted over wireless communication through vehicles directly or by using other mediums such as handhelds, BSs, RSUs, drones, etc. Accordingly, VANET wireless communication can be achieved through various types of communication links (see Fig. 2) that can be classified according to the communicating systems into:

1. Vehicle-to-Vehicle (V2V): V2V links arise wirelessly between vehicles directly. These links are used mainly in infrastructure-independent VANETs to share vehicle safety-related messages. Also, it can be used for multi-hop communication in infrastructure-dependent VANETs.
2. Vehicle-to-infrastructure (V2I): V2I links will help vehicles share their data with VANET infrastructure. VANETs can utilize V2I to share messages and help vehicles access Internet services.
3. Infrastructure-to-infrastructure (I2I): I2I links exchange real-time data and traffic patterns among VANET infrastructures in particular areas, such as vehicle mobility patterns and traffic density data.
4. Vehicle-to-Pedestrian (V2P): Through V2P, vehicles will share data with nearby Pedestrians. V2P communications are essential in avoiding or minimizing accidents resulting from pedestrians' mental distractions or when people are in a position that is hidden from the driver's vision [42].

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5. Vehicle-to-Barrier (V2B): V2B links help to access data from the barriers installed on the roadside to evade run-off-road accidents [43].
6. Vehicle-to-Cloud (V2C): V2C helps direct communication between RSUs and cloud systems. It provides many services, such as decision-making, big data processing, and traffic density prediction [44].
7. Vehicle-to-UAV (V2U): In the future, UAVs will be a crucial part of ITS systems. Over V2U, the data are shared directly among the vehicles and UAVs over aerial communication [45].
8. Vehicle-to-Sensors (V2S): These links provide intra-vehicle communication between the vehicles and built-in sensors. It can be realized between OBUs and embedded or roadside sensors [46].

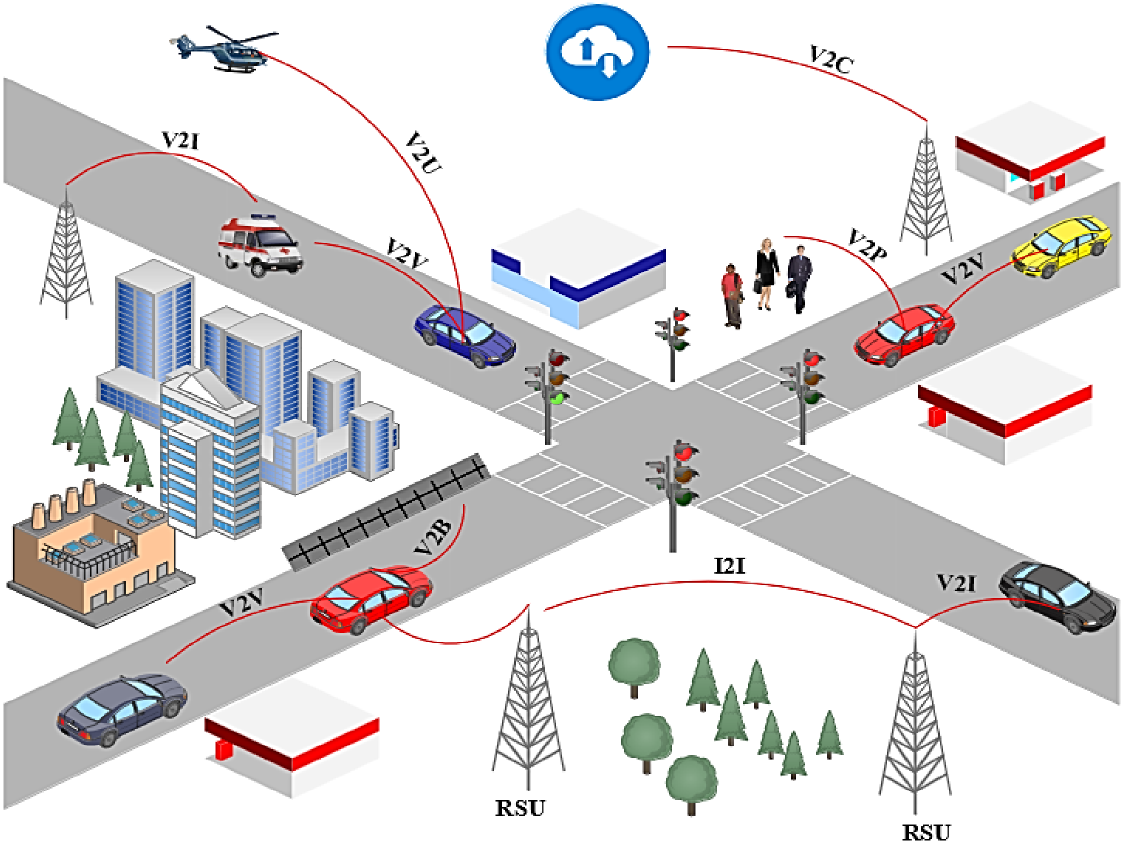

FIGURE 2. Basic VANET Communications

C. VANET COMMUNICATION

VANET have gained importance, leading to efforts by academic and government entities to establish standardized vehicular communication. In 1999, the US federal communications commission (FCC) initiated standardization by allocating 75 MHz of dedicated short-range communication (DSRC) spectrum for V2V and V2I communication. Similarly, in 2008, the European Telecommunications Standards Institute (ETSI) designated 30 MHz in the 6-sub-GHz band for VANET communications [47].

As shown in Fig. 3, the bandwidth for DSRC has been divided into seven channels, each with a 10 MHz. Six of them, known as service channels (SCH), are utilized for transmitting safety and non-safety-related packets. In contrast, the remaining channel, known as the control channel (CCH), is used to broadcast control data and critical safety services.

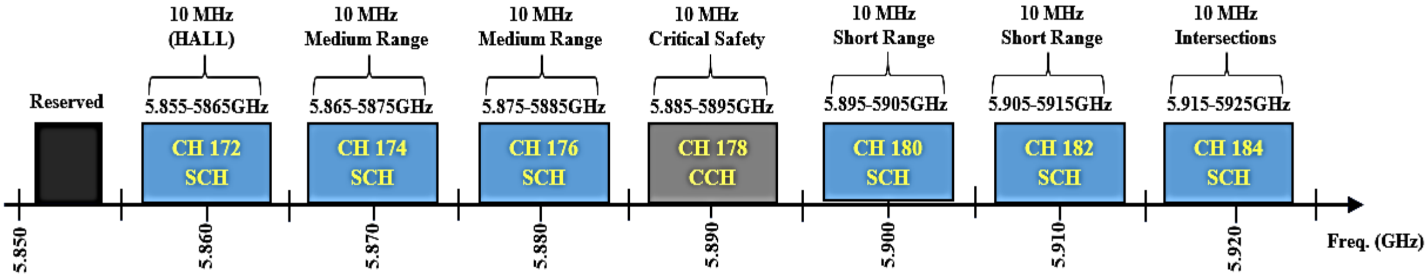

FIGURE 3. DSRC spectrum band channels.

To empower adaptability and flexibility, IEEE agreed with the DSRC standard and named it Wireless Access in Vehicular Environment (WAVE) in 2003, intending to enable direct vehicular communications up to a range of 1 km at regular road speeds [47]. Although DSRC/WAVE standards offer low transmission delay in a licensed bandwidth, the high node mobility and the dynamic nature of VANET can cause significant overhead and delay. All seven DSRC channels are used by vehicles regularly for their data exchange, which means that they must compete for access to these channels to send their packets. This competition can result in network congestion, increased packet latency, and reduced throughput, significantly degrading the overall QoS. [48]. The growing number of VANET services and the need for continuous and scalable communication have led to the exploration of various types of wireless communications, such as cellular communication (4G/LTE), ultra-reliable and low-latency communications (5G, mmWave, and THz channels), satellite communications, and cognitive radio systems [49][50][51].

D. DISTINGUISHED CHARACTERISTICS OF VANET

The design requirements of VANETs are distinct from other MANETs. To provide services effectively, the unique characteristics of VANET must be considered including:

1. Mobility variation: The VANET network comprises stationary entities such as RSUs and BSs, slow-moving vehicles, and high-speed vehicles. This variation in node mobility poses significant challenges to VANETs. For example, in high-mobility scenarios, the chance of successful communication between VANET nodes is slight, where the transmission range will be more limited [19]. In scenarios where the mobility of vehicles is moderate, communication can be negatively impacted by several factors, such as the Doppler effect, frequent link breakages, and increased latency. These challenges can decrease the communication quality and overall network performance [35]. Furthermore, several challenges arise when the environment becomes denser, such as more collided data, highly utilized bandwidth, channel fading, and signal interference. [52].
2. Movement restriction: In VANET, nodes mobility is influenced by the public transportation distribution, the nature of roads, traffic density, buildings, and other obstacles. However, this variation can result in some challenges for reliable data delivery [3].
3. Highly network disconnectivity: Traffic density may vary depending on the location and daytime, with higher densities at intersections, roads near offices and markets, and during the day. Low vehicle densities can lead to network fragmentation, hindering communication and packet delivery. Vehicles with high velocity can increase VANET dynamicity, causing network fragmentation into many disconnected fragments. Considering these factors when designing VANETs is essential to ensure continuous and effective communication [2].
4. Heterogeneity: VANET includes various entities regarding networking access, applications, and properties. The heterogeneity in hardware capabilities of VANET participants limits the performance of data processing and modeling. Besides, ever-increasing security and control access challenges have verified the possible effect of heterogeneous networks [38]. Besides, VANET applications are designed to serve various purposes, each with its own QoS requirements. For example, safety-related applications like collision alerts require low latency, typically less than 100ms. On the other hand, non-safety applications can tolerate more latency, up to 500ms. This heterogeneity of data flows must be considered while designing VANETs to ensure each application receives the appropriate QoS to work effectively [53].
5. Unlimited power and computation resources: The VANET network faces no power or storage restrictions. The embedded OBUs can utilize continuous and unrestricted power sources from vehicle batteries, thereby eliminating computation power-related issues. This enables the execution of various power-consuming methods, such as intelligent models and cryptography algorithms [51]. Also, it helps in increasing the network coverage by utilizing multiple antennas in VANET communications [54].
6. Unbounded network size: The VANET network can cover a single urban area, multiple urban areas, or even large cities, meaning its geographical scope can be unlimited. Ensuring that the network can handle increasing demands of data traffic and expand its coverage area while maintaining reliable communication is a crucial problem that requires to be addressed. [24]. However, the unbounded VANET network results in more issues, such as node management, data security and privacy, and vehicle tracking.
7. Spectrum Scarcity: Recent studies on DSRC-based VANET have identified reliability and scalability challenges when operating in large-scale, dense areas [28] [50]. The challenge of DSRC bandwidth scarcity comes from the increased demand for VANET services. However, cooperation with other network infrastructures may compensate for the bandwidth scarcity but bring additional challenges such as channel access, routing schemes, and data security [48].
8. Environmental Effect: Unlike MANETs, VANETs operate outdoors, where the surrounding environment can significantly impact electromagnetic signals [55]. Various obstructions, including buildings, vehicles, and trees, may interfere with VANET signals, leading to impairments such as multipath propagation, signal shadowing, and channel fading [56]. Additionally, weather conditions, such as rain, ice, and snow, can affect the conductivity of surfaces, resulting in altered reflection paths that may degrade VANET communication performance [57]. These conditions may also lead to flooded or snow-covered roads, negatively impacting node distribution. Also, the presence of sandy grains can cause high attenuation in microwave signals, potentially reducing the effectiveness of data transfer [58].
9. Data privacy: All VANET protocols have supposed the vehicles will be part of data communication over V2V multi-hop communications [24]. Due to data security and control access, all participating nodes need to be identified and known to VANET [59]. In this context, individuals may be

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reluctant to share information about their vehicles or intended destinations to avoid potential privacy breaches. As a result, addressing data privacy concerns in VANETs requires a balance between protecting personal information and respecting people's privacy preferences.

10. Data security: Ensuring security in VANET is critical as a network breach can result in hackers taking control of vehicles, leading to traffic errors and fatal accidents [60]. To safeguard data transmission, packets must be protected from tampering to prevent eavesdropping and ensure the intended sender sent them. Generally, due to fundamental VANET characteristics, such as high topology changes, ensuring data security and non-repudiation pose significant challenges [61]. Key management is also challenging in vehicular communication. This can lead to a long list of revocable keys and significant overhead in revocation, especially when the number of nodes is extendable [59].
11. Data Inconsistency: Generally, VANETs have used data dissemination to inform nearby vehicles about traffic situations and road conditions. Most VANET protocols use global positioning system (GPS) for localization purposes. Unfortunately, GPS systems provide inaccurate position information where the buildings and covered tunnels can result in GPS signal blockage, leading to many technical challenges [62] [63]. As expected, the subsequent VANET applications require high-efficiency systems to analyze data and provide future decisions instantaneously.
12. Hard delay constraints. The importance of the delay constraint in VANETs depends on the application type and user requirements. Safety-critical applications demand low-latency communication, making delay a critical factor, while non-critical services can tolerate some delay. VANET often need to balance ensuring rapid communication for safety applications and efficient data delivery for other services.

III. VANET ROUTING BACKGROUND

This section provides background about the VANET routing concept, the main routing optimization parameters, and the existing metrics for evaluating VANET routing. This will help to understand the main ideas of VANET routing protocols before understanding the methodologies targeted in this study.

A. DEFINITION OF DATA ROUTING

A routing protocol is a set of guidelines that govern how nodes connect by selecting the best communication path between nodes, facilitating data exchange with minimal latency and maximal throughput. This is accomplished by following predefined rules and specified constraints in the protocol [22]. To enhance vehicular safety, the routing protocol must prioritize low latency and minimal packet loss when forwarding data packets. The primary challenge researchers have faced is designing an effective, reliable, and secure routing mechanism that can address the unique characteristics and limitations of VANETs with minimal overhead. This involves improving traditional routing protocols and adapting them in VANETs [22] [24].

Many researchers studied the feasibility of using different MANET routing protocols in vehicular communication, such as destination-sequenced-distance-vector (DSDV), dynamic-source-routing (DSR), optimized link state routing (OLSR), and ad-hoc-on-demand distance-vector (AODV). Due to VANETs characteristics, not all routing protocols designated for MANETs are appropriate for VANETs. Yet, some researchers have adapted MANET routing protocols to suit the distinct attributes of VANETs and developed routing protocols specifically for the vehicular environment [64] [65]. The performance analysis results show that these routing models cannot give efficient results when applied to VANETs data routing [66] [67].

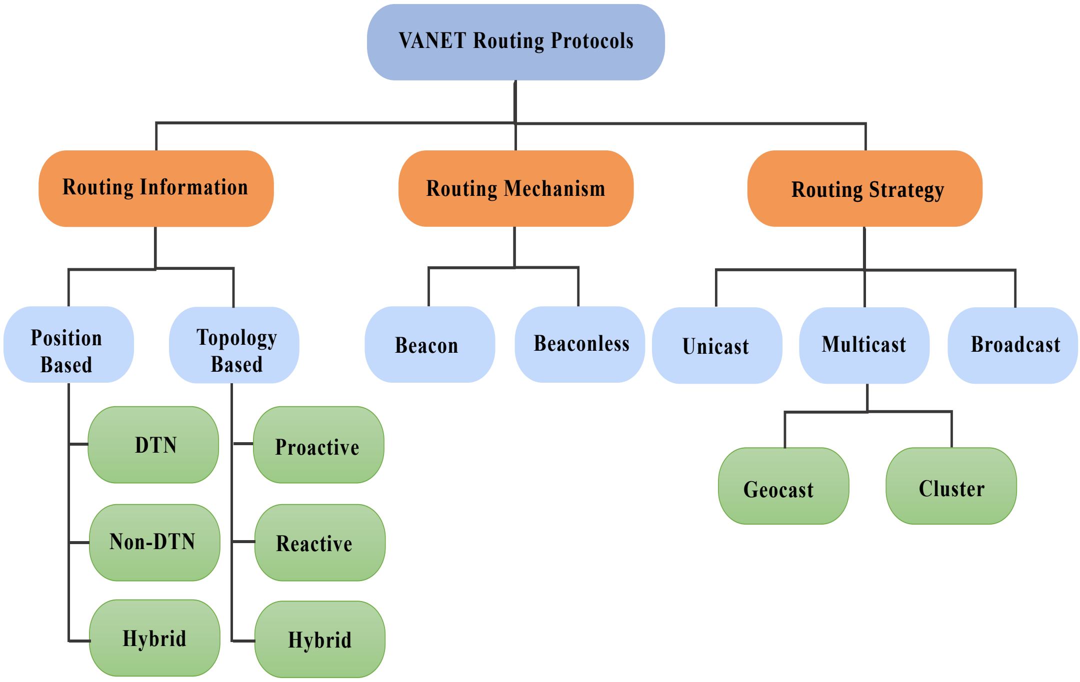

FIGURE 4. Taxonomy of conventional VANET data routing.

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B. CLASSIFICATION OF VANET DATA ROUTING

Due to the various architectures, requirements, and applications involved in VANETs, many routing algorithms have been developed. However, classifying VANET routing protocols can be complex, and researchers have used various methods and parameters to categorize them. In Fig. 4, we broadly classify VANET routing protocols into three main classes based on the VANET communication architecture:

I. Routing information-based routing protocols.
II. Routing mechanism-based routing protocols.
III. Transmission strategy-based routing protocols.

1) CLASSIFICATION BASED ON ROUTING INFORMATION

This class is based on how the routing information will be transmitted. These protocols can be further categorized into two sub-categories: topology-based, position-based, and hybrid routing protocols

Topology-based routing protocols rely on traditional MANET routing protocols, where information about links is maintained in a routing table and used as a basis to move packets from the source vehicle to the destination. In this method, each vehicle should know the network layout and use information about available vehicles and links in the VANET to make routing decisions [35]. Though these routing methods can search the best possible shortest routes, they have more limitations regarding scalability, overhead, and route discovery latency [66]. So, they may not be a proper choice for the high dynamic VANETs where the regular network fragmentation and partitioning demand frequent re-calculation of the topology information, which can lead to significant overhead [22]. Generally, these methods are divided into three categories [68] [66]: proactive, reactive, and hybrid routing protocols.

Proactive routing protocols, or table-driven protocols, enable nodes to have a routing table that stores route details of all other nodes in the network. It is essential to update the table regularly to keep it up-to-date with changes in the network topology and send it periodically to all neighbors [17]. Although these protocols have low latency, storing unexploited paths in the routing table at each node will cause high network overload and more consumed frequency, ultimately reducing overall system performance. Moreover, as the network grows, maintaining routing tables becomes increasingly complex [69]. Accordingly, these routing methods are not well-suited for VANETs as they are inefficiently responding to link failures [28] [69].

Reactive or on-demand routing protocols discover the route to a particular destination using information about other vehicles. It does not need to maintain information about the network topology [11]. When a route is unavailable, the sender node begins the path discovery process by requesting information from neighboring nodes in the network. Neighboring nodes with relevant information send a route reply packet back to the sender node, providing information about the path. Once the sender has received enough information to generate a path to the destination node, data transmission can begin along the established path [70]. Here, the flooding method will initiate more routing overhead, leading to network clogging [22]. Even though reactive routing protocols can save bandwidth with low memory requirements, they may have high latency and be unsuitable for security applications in VANET [35]. Due to the high response to link failures, these protocols are suitable for large-size and frequently changing VANETs [28] [71].

For optimal results, hybrid protocols combine proactive and reactive methods to reduce the overhead in proactive models and decrease the delay in reactive models [33]. Hybrid protocols divide the network into multiple zones to improve the reliability of the path discovery and maintenance processes. Despite their advantages, hybrid protocols are not better suited for high mobility and frequent changes in VANET topology [66] [72].

Conversely, position or geographic routing methods utilize nodes' geographical location instead of the IP addresses in the routing method. These protocols differ from topology-based routing because they do not maintain a routing table or share information about link states with neighboring nodes. Each vehicle must know its location and the location of its neighbors through GPS assistance or other location-determining methods [68]. This helps to transmit packets directly to the destination without performing the route discovery process or maintaining link state information and network topology status [19] [73]. Thus, they can be suitable and stable for high-mobility VANETs. Yet, the effectiveness of such protocols relies intensely on the accuracy and availability of location information, which can be affected by weather conditions and surrounding buildings [74]. Generally, geographic routing protocols can be categorized into delay tolerant networks (DTN), non-delay tolerant networks (Non-DTN), and hybrid routing methods.

DTN can address the technical issues arising from the lack of continuous network connectivity, such as VANET networks [75]. The DTN protocol employs the store, carry, and forward strategy, where each node stores data packets for a certain period before forwarding them to nearby access points for further forwarding [76]. This way, all nodes collaborate in delivering data packets, allowing the network to cope with high disconnectivity. However, when the vehicles maintain the packets if the connection with other vehicles is lost will result in increased packet delay [34].

Non-DTN protocols are designed for high-density VANETs with continuous connectivity, assuming a sufficient number of nodes are always present to facilitate successful communication [22]. These protocols utilize the basic greedy scheme, which allows a node to forward its message to the nearby neighbor toward the destination. However, this method may fail if there is no nearby neighbor to the destination other than the present node [77]. With the critical goals of these approaches to explore the shortest path toward the destination and reduce the required time for packet routing, the shortest path models may not constantly guarantee timely forwarding, particularly in sparse VANETs [22] [78].

To provide more adaptability, hybrid position-based routing protocols combine DTN and non-DTN routing algorithms to benefit from the ability of DTN routing protocols to maintain network connectivity and the minimum latency caused through data transmission using non-DTN protocols [22].

2) CLASSIFICATION BASED ON THE ROUTING MECHANISM

The classification of routing mechanisms may be based on whether they employ beacon messages as part of their routing protocols [28]. In a VANET, vehicles periodically broadcast beacons to announce their presence, share status information, and update their positions. Beacon-based routing protocols use beacon messages to exchange information among neighboring nodes and update their data before transmitting packets. These routing models are sender-based, where the sender can choose the optimal vehicle to forward data toward the destination using the information gathered by the beaconing system [79]. Unlike data packets, beacons are typically small and can easily pass through weakly connected links. However, the beacon overhead will mainly rise with higher traffic densities, causing channel congestion and beacon flooding challenges.

On the other side, beaconless-based protocols are receiver-based routing protocols. Unlike the previous class, this mechanism does not rely on exchanging beacon messages; instead, the receiving nodes choose whether to contribute to data routing. This approach reduces overhead and packet collision as long as the packet loss rate by eliminating the need for redundant beacons to flow over the network [80]. Nevertheless, the absence of the beacon messages means the nodes lack information about their neighbors and cannot directly know the next-hop relay in the routing path. This results in more delay as compared to beacon-based protocols. Besides, beaconless protocols are more susceptible to multipath formation, leading to redundant packets traveling in the network [79].

3) CLASSIFICATION BASED ON TRANSMISSION STRATEGY

Generally, the packets can be sent in four forms: unicast, broadcast, multicast, and geocast. Unicast routing protocols transfer the packet from the sender to a unique receiver over multi-hop transmission or carry-and-forward methods [81]. The carry-and-forward scheme involves the source vehicle carrying the packet as far as possible until it comes within the transmission range of a vehicle nearer to the destination [23]. Generally, most topology-based routing methods are unicast protocols. On the other hand, multicast routing schemes enable data routing from a single sender to many receivers within a particular geographic area. However, multicast routing schemes are divided into geocast and cluster routing methods [23].

Geocast-based routing protocols are position-based multicast routing methods that send messages from the source to all vehicles within a specific geographical zone of relevance (ZOR) [70]. The node membership is updated when outside the predefined geographical area, and here, it discards the packet [82]. However, by directing the packet flooding, the message overhead and channel congestion generated by broadcasted data can be minimized. Also, network partitioning and the existence of undetected vehicles may delay the appropriate message forwarding in geocasting mechanism [83].

Cluster-based routing protocols involve clustering techniques to group vehicular nodes with similar characteristics, such as traveling in the same direction with similar speeds. A cluster head (CH) is designated to manage the other nodes within the cluster that are referred to as cluster members (CM). The CH handles intra- and inter-cluster management and data routing tasks. While such protocols can improve scalability for large-scale VANETs, they may cause more delay and overhead in the presence of high mobility in VANET [84] [14].

Broadcast-based routing protocols are generally utilized to disseminate messages on road conditions, weather, and disasters, as well as for advertising and announcements [33]. These routing solutions employ a straightforward flooding scheme in which each vehicle resends the packet to other vehicles. This ensures the packets reach all destinations but causes a higher overhead [85]. Furthermore, further messages are broadcasted as node density increases, causing more collisions, increased bandwidth utilization, and reduced overall network reliability [83].

C. PERFORMANCE EVALUATION METRICS FOR ROUTING PROTOCOLS

In VANET, along with the common metrics designated to assess routing algorithms, such as end-to-end delay (E2E), packet loss ratio (PLR), and packet delivery ratio (PDR), there are many metrics that were considered in literature when evaluating VANET routing methods [86]. However, such metrics including:

1. End-to-End Delay (E2E): it is the time required for a packet to forward from its source until it reaches its destination [13].
2. Packet Delivery Ratio (PDR): PDR is determined by dividing the number of packets successfully delivered to the destination by the total number of packets sent by the source.
3. Packet Loss Ratio (PLR): PLR is the ratio of transmitted packets that fail to reach their intended destination due to faults in data transmission or network congestion.
4. Throughput: It measures the data transmission rate over a communication channel and is typically expressed as the average number of bits delivered per unit of time.
5. Jitter: It is a metric that quantifies the variance between the maximum and minimum delays experienced by packets traveling over a network. It is caused by variations in the queuing delay of consecutive packets, which can lead to differences in packets arrival time at the destination.
6. Routing overhead: The routing overhead refers to the additional data and control traffic generated by a routing protocol that is not part of the actual data being transmitted but is necessary for the routing process.
7. Bit Error Rate (BER): The number of bit errors divided by the total number of sent bits during a specified period.
8. Network load (NL): It is the proportion of nodes receiving a duplicate copy of a packet and total hello packets required for packet forwarding.
9. Normalized routing load (NRL): NRL expresses the proportion of routing packets to packets that deliver to their destination, with each hop counted distinctly [87].
10. Normalized overhead load (NOL): The fraction of routing packets to successfully reached packets, indicating the extra bandwidth used for routing packets [88].
11. Routing request ratio (RReq): This is obtained by dividing the number of routing requests transmitted by the source vehicle by the number of routing packets received by the receiver node [90].

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12. Average routing reply ratio (ARRr): The proportion of routing reply packets transferred from all nodes in the network that act as destinations of routing requests [89].
13. Average routing discovery time (ARDt): The period between transmitting a route request to a particular destination and getting a route reply from that destination [89].
14. Link failure (LF): This metric measures the average number of link failures during the routing process. A low LF value indicates the protocol successfully evades link failures [90].
15. Route lifetime: The average amount of time a discovered route remains valid, showing the efficiency of the routing method in maintaining stable and reliable routes [90].

D. OPTIMIZATION PARAMETERS USED IN VANET ROUTING PROTOCOL

In the literature, many optimization parameters were considered in designing and developing VANET routing methods. Unfortunately, even with many suggested VANET routing schemes, non-existing routing protocols satisfied all the optimization parameters [13], [28], [91], [92]. However, VANET heterogeneity and high diversity in node mobility, link disconnectivity, applications, and QoS needs are the main reasons behind such challenges. This subsection introduces the fundamental QoS parameters that enable the routing protocol to select the optimal relay node or the most efficient route toward the receiver [13].

1. Delay: The delay is the most critical parameter that routing protocols consider. Typically, it refers to four separate terms: access delay, transmission delay, propagation delay, and processing delay [41]. It is best to consider all these delays to reduce the total routing delay.
2. Communication distance: This parameter represents the physical distance between the current node and the next forwarding node [41].
3. Neighbor node discovery: A vehicle may have several one-hop neighbor vehicles within its communication range [85]. So, selecting the node with the most stable and reliable links is essential for efficient data routing. Generally, neighborhood discovery is achieved through beacon messages during route establishment. However, selecting the periodic interval for beaconing poses challenges, as small intervals increase control overhead, while large intervals provide stale information. To ensure timely and accurate network status updates, the routing protocol must select a suitable interval to address this tradeoff.
4. Link reliability: In vehicular communication, the measurement of link reliability is crucial for optimizing routing protocols to ensure data is transmitted reliably and efficiently [93].
5. Hop count (HC): By minimizing the number of hops, routing protocols can reduce the latency and increase the effectiveness of data transmission.
6. Vehicular traffic awareness: The VANET routing protocol should be adaptable and can provide high reliability in both urban and rural environments, even in sparse traffic. The rural area may sometimes have fewer vehicles without RSUs deployment. Here, fewer power constraints can be used by increasing communication ranges with higher transmission power to allow every node to reach its destination without the support of the RSUs. In contrast, the urban area is vast, crowded, and has a diverse range of vehicles. Therefore, the routing method must find a path that minimizes congestion in such environments. In this context, an adaptive routing scheme would be preferable to adjust its operation based on the traffic conditions in real-time.
7. Predictability: It is significant for the routing protocol to have the ability to predict the traffic density or next movement of the vehicle to take the necessary action and avoid packet loss and increased latency.
8. Dynamic and high mobility: The vehicle's mobility is restricted according to the road distributions and traffic rules. So, the consideration of node mobility has a high impact on the overall routing efficiency.
9. Scalability: Due to unpredictable network size, the routing protocol should be able to employ the increased number of routing requests and reduce resource consumption to guarantee optimal paths. Also, the routing algorithm should be able to address dynamic challenges, including broken links, network congestion, signal interference, and other factors [28].
10. Fault Tolerance: Due to rapidly changing topology, the vehicles are entering or leaving the network frequently. So, the routing protocol must be able to handle such changes by analyzing and predicting potential route failures in advance to prevent communication disruptions.
11. Multimodality: It is highly encouraged for routing algorithms to consider different specifications in making data routing decisions such as link status, vehicle kinematic information, traffic density, application category, and packet priority.
12. Security enhancement: Security in VANET routing is a critical aspect of ensuring the integrity, confidentiality, and availability of communication in these networks. VANETs are vulnerable to various security threats due to their dynamic and open nature, making secure routing protocols and mechanisms essential to prevent malicious nodes from entering the network and causing fatal results.
13. Context awareness: It is highly recommended to develop intelligent routing solutions to deal with unpredicted situations, like driver behavior, vehicle type, sudden route change, building distribution, and intersection status.
14. Resources utilization: The network resources are shared by multiple nodes simultaneously. Proper resource utilization ensures that resources are used judiciously and the system operates reliably and efficiently. The routing protocol must be aware of resource utilization and load balancing, efficiently using available network resources to ensure that data is transmitted without congestion and delays.
15. Energy optimization: Recently, electric and autonomous vehicles have been nominated as influential nodes in VANETs. Such nodes are restricted by their embedded battery energy. Energy-aware routing protocol aims to maximize the network lifetime, so it is preferred to take the node energy when developing new routing protocols.

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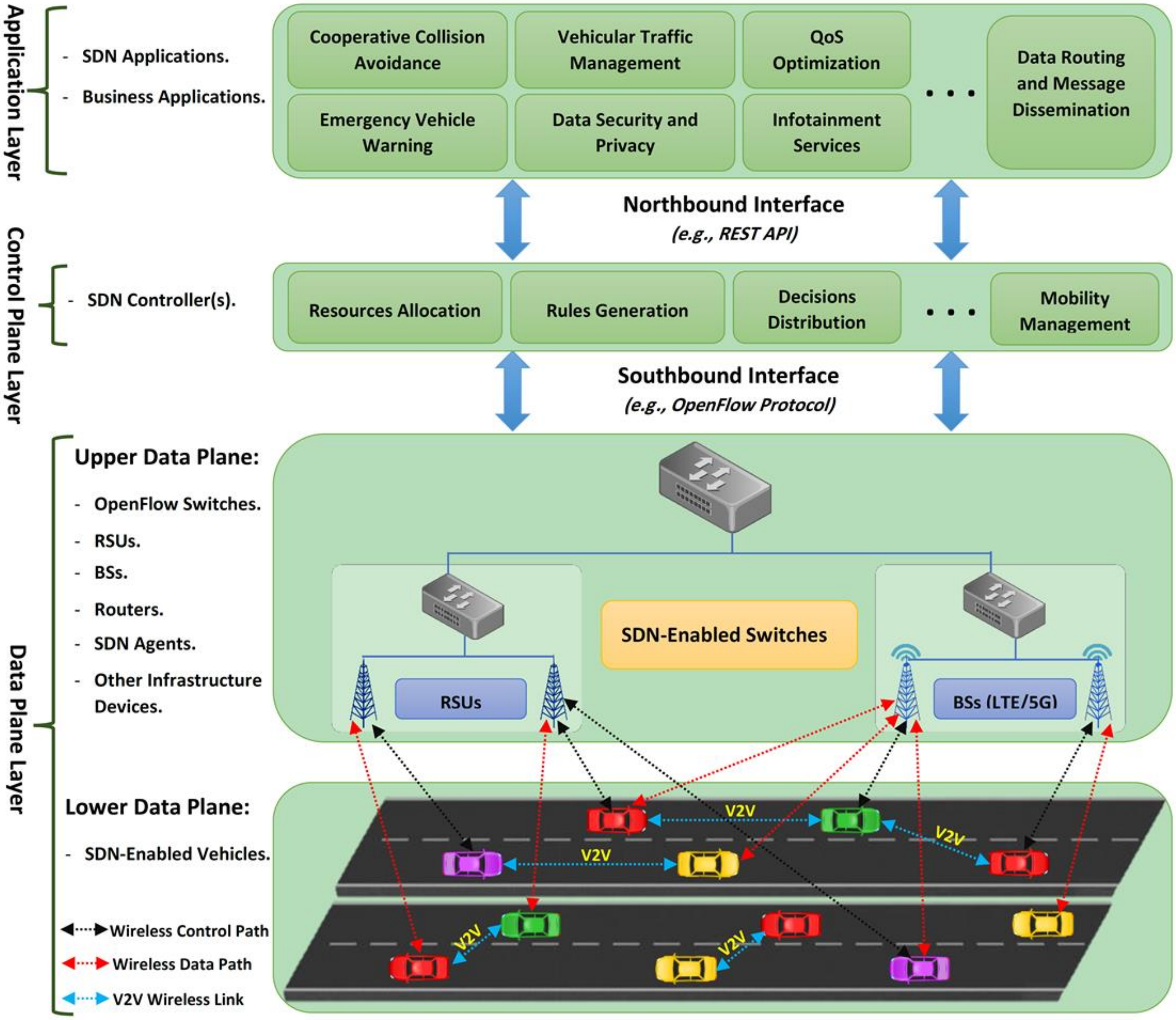

FIGURE 5. **Components of Software-Defined Vehicular Network.**

TABLE 3
COMPARISON OF TRADITIONAL VANET AND SDVN

Feature	Traditional VANET	SDVN Networks
Features	Complex network control. New protocol required to each problem	Control-data plane separation, programmability
Configuration	Error manual configuration	Automated configuration with centralized validation dynamic
Nature	They are static and inflexible networks	Programmable networks
Network Management	Difficult because changes are employed separately at each device	Easier with the help of controller(s)
Scope	They aren't used for new business due to little agility and flexibility	They help new business ventures through flexibility and agility.
Global Network View	Difficult	Central view at controller
Architecture	They have distributed control plane	They have a programmable centralized control plane
Resources Utilization	Less	High
Suitable Environment	They are suited to client-server architecture	SDN adapted to anywhere, anytime and any type of environment
HW/SW Support	They consist of hardware network devices	They are configured using open software
Scalability	Network scaling is unsustainable anymore due to high complexity	Easy salable due to agile centralized control
Dynamics	Become highly complex in multi-device and dynamic environment	Become accustomed to changing requirements
Research Perspective	Limits for new innovation in networking	Easy change in network
Performance	Relatively static configuration and limited information	Dynamic global control with cross layer information
Cost	High manageable cost	Less manageable costs

IV. SDN-BASED VANET NETWORKS

In this section, an overview of SDVN will be presented. Then, a general description of the SDVN architectures will be detailed, showing their structural design, advantages, and disadvantages.

A. SDVN BASIC DEFINITION

SDN is an emerging network paradigm that divides the network into two logical planes: control planes and data planes. This architecture is designed to provide flexibility,

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programmability, and reliability, making it easier for developers to deploy network applications. SDN network architecture is logically centralized, where the control units are distributed but work as a whole [94] [95]. In the context of VANET, SDN can be leveraged to address various challenges related to resource management and data routing, allowing reliable deployment of different VANET applications with better access decisions [10]. [7]. It can allocate resources to critical services and applications, ensuring they have sufficient bandwidth and low-latency connections. Also, the centralized controller can reconfigure network devices and routes in real time to respond to traffic patterns, network failures, or emerging events, making vehicular networks more agile and responsive [96].

As revealed in Fig. 5, the layered architecture of SDVN comprises three layers: a management layer, a control layer, and a data layer [10]. As compared with conventional network architecture, where all three layers are included in the same layer at each network device [27]. Table 3 presents the comparison of SDVN and VANET networks. However, the layered architecture of SDVN has the following layers and interfaces.

1. Management plane: This plane comprises various end-user applications for managing the network, enhancing its security, traffic flow, and overall performance [10]. These applications may include security tools, routing mechanisms, topology management, network monitoring utilities, balancing tools, and more. They use the northbound interface (NBI) to provide the SDN controller with logical commands to control forwarding device behavior.
2. Control plane: It is a core component of SDN, including the SDN controller and other modules like firewall, system status, failure control, and flow tables. It offers the necessary services and programming interfaces to function applications effectively, providing a comprehensive view of the whole network [97]. SDN controller is a virtual component that gathers information from data layer, such as vehicle location, velocity, and traffic load, and transmits it to the control plane for more processing [18].
3. Data plane: This layer comprises devices that forward data packets based on instructions received from the SDN controller [97]. The communication between the controller and data plane components is achieved through an open communication protocol called OpenFlow protocol that is responsible for securing the communication channel and sending rules and data associated with topology variations and communication formats [7]. In SDVN, OpenFlow-enabled switches consist of vehicles, RSUs, BSs, and other participant nodes.
4. Southbound interface (SBI): SBI is the communication interface between the controller and infrastructure devices at the data plane [97]. SBI uses OpenFlow protocol to provide API for data communication between OpenFlow controller and OpenFlow-enabled switches.
5. Northbound interface (NBI): NBI is the interface between the SDN applications plane and the SDN controller. The NBI interface provides an abstract view of the complete system. The NBI is not standardized yet [10]. Standardizing the NBI will bring benefits such as increased flexibility, reduced development effort, and improved compatibility across different SDN implementations.

B. SDVN ARCHITECTURE

First, SDN is planned for wire-based computer networks [27]. Implementing SDN in VANETs without any adaptation poses several challenges because of the inherent characteristics of VANET, such as a highly mobile network and a dynamic topology [18] [98]. The unique aspect of SDVN is that the data plane consists of vehicular devices, unlike static switches typically in traditional SDN networks [99]. However, depending on the control level of the SDN controller, SDVN architecture is classified into three types: centralized, hierarchical, and hybrid.

In centralized SDVN architecture, the control logic flow is managed by a central controller. The nodes in the data plane run actions based on flow rules delivered from the SDN controller, which prepares and distributes the rules to the intending vehicles. The vehicles then run actions based on the rules they receive [94]. The SDN controller gathers status messages from the data plane in a centralized control architecture, enabling it to create a global network topology and make informed decisions. However, network performance will suffer if the controller is a single point of failure and the vehicles cannot access the controller. Fig. 6(a) provides an overview of the architecture [10]. Scalability is also a challenge with this architecture. So, with the increase in vehicles, managing the growing number of received requests is a big challenge.

Hierarchical architecture is presented to address the challenges of centralized SDN architecture by helping to make decisions hierarchically. Here, the SDN controlling is clustered into multiple controllers on physically distributed servers [100]. The hierarchical SDVN architecture is designed to reduce the load on the controller by delegating flow decisions to the end nodes. Vehicles initially attempt to discover routes independently, and if unsuccessful, they can request assistance from the local controller (e.g., RSUs). If the local controller cannot find a route, the request is sent to the SDN controller to prepare and distribute flow rules. This approach is illustrated in Fig. 6(b), which shows a different process for interacting with the SDN controller compared to the centralized mode. With this approach, vehicles can still find routes independently or through the local controller even if the SDN controller is inaccessible or the network size increases. It can increase system flexibility and improve the overall system performance. Conversely, this SDN-controlling architecture requires more time for route discovery [101].

Finally, the hybrid SDN control architecture can address the problem of the long time required for route discovery in the hierarchal architecture model [10]. In this architecture, the control level can be adjusted to the network's specific needs. The controller can deploy all the flow rules or give some control to the end entities. For instance, the main SDN controller can control the RSUs centrally while allowing the vehicles in the data plane to operate hierarchically [102]. As illustrated in Fig. 6(c), the SDN controller helps the local SDN controller and the vehicles to deploy the control flow independently without access to the main SDN controller [98].

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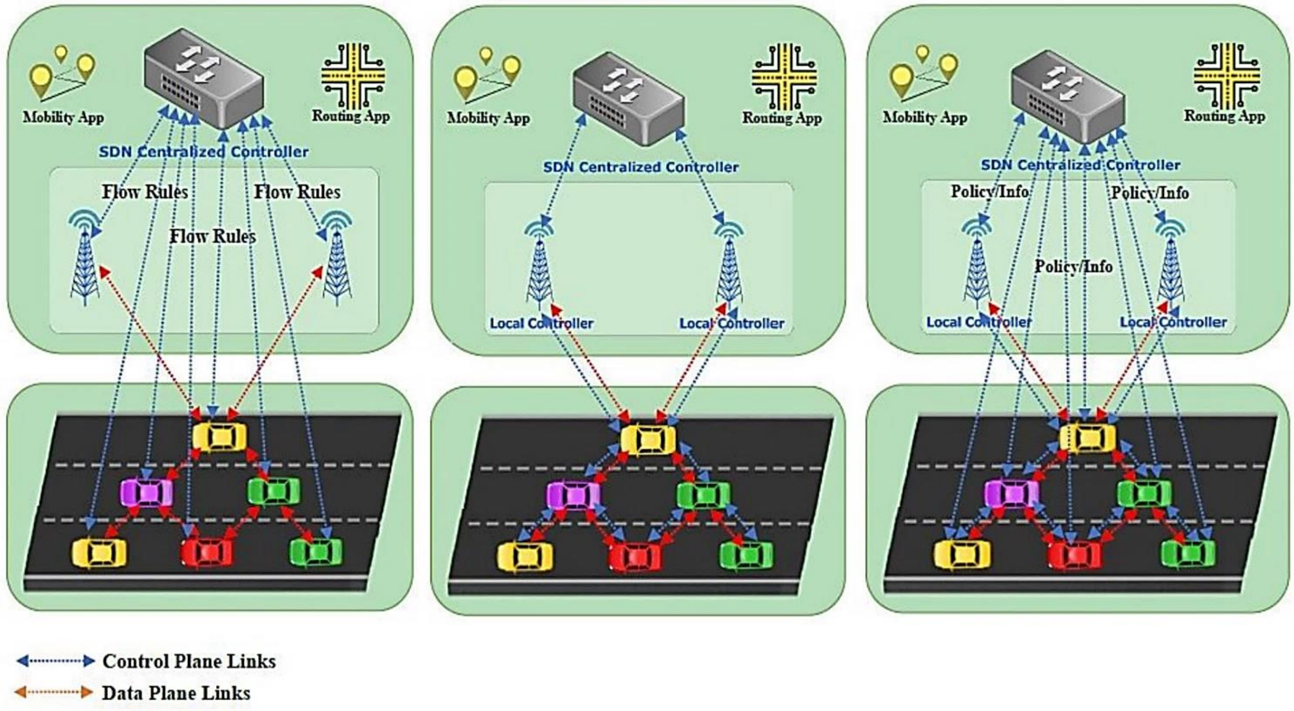

FIGURE 6. SDVN controlling architectures (a) Centralized architecture. (b) Hierarchal architecture. (c) Hybrid architecture.

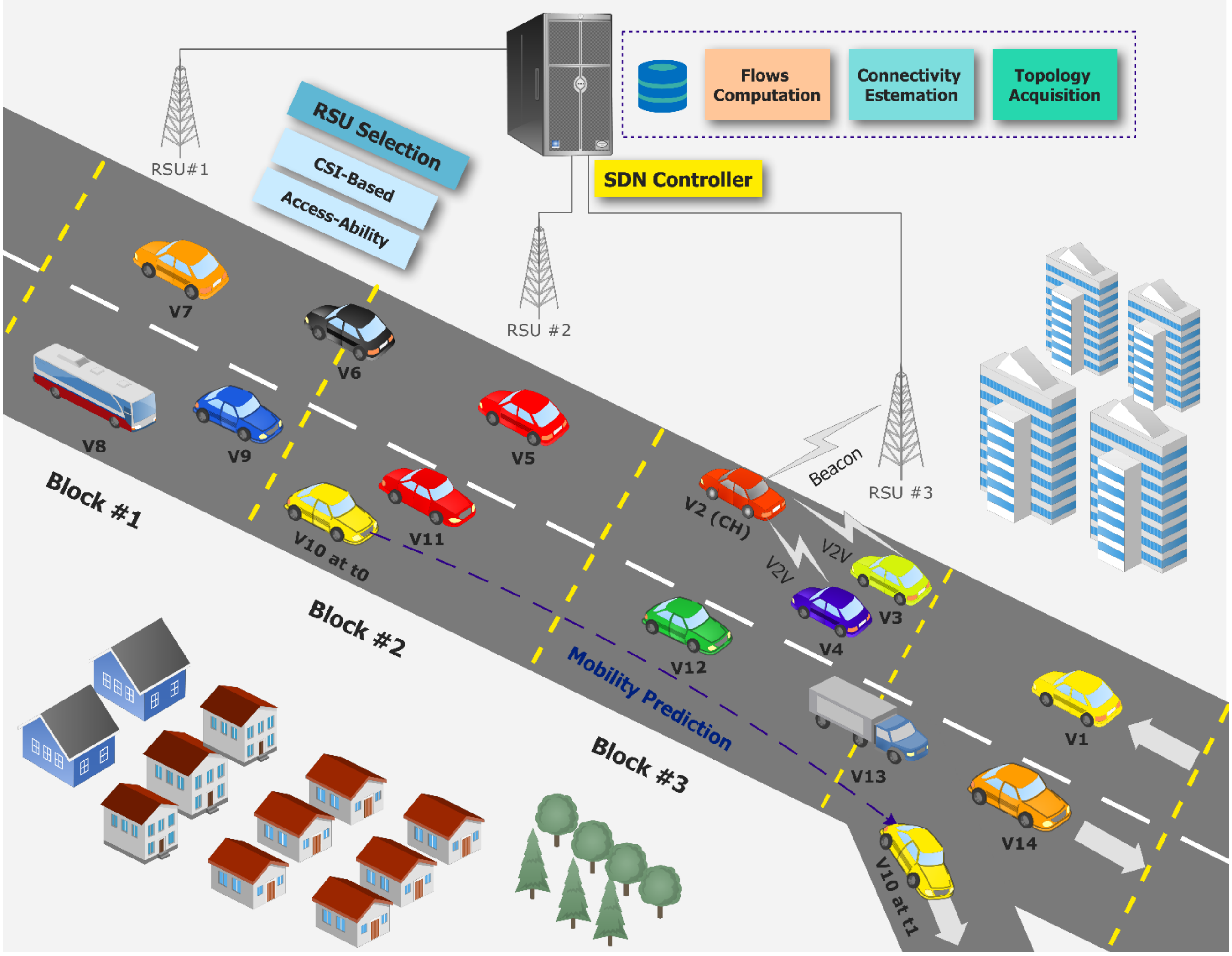

FIGURE 7. The basic principles of data routing in SDN-based VANETs.

V. SDN-BASED VANET ROUTING

A. BASIC PRINCIPLE OF ROUTING IN SDVNS

Vehicular networks typically use individual routing schemes to send/receive data with nearby infrastructure or other vehicles when located out of their transmission coverage range. In VANET, the traditional routing process involves exchanging node statuses, selecting routes, and maintaining/repairing routes.

However, the SDVN routing process is similar with more complexity, including further steps such as associating nodes, gathering network information, selecting a routing mode, calculating the flow table, and others [8]. Using multilevel knowledge and an up-to-date global overview of traffic conditions, data routing in SDVN will be more reliable [10]. In an SDVN, the controller manages routing and switching, while the vehicles will be used as data forwarding nodes [103]. The network is partitioned into multiple zones, and each zone can have its local controller that shares and updates the local topology with the central controller that will these data to build the global topology. However, before further discussing the existing SDVN routing schemes and revealing their classifications and challenges, the standard SDVN routing procedure will be presented first.

As revealed in Fig. 7, the vehicle associates with the most suitable RSU to receive its status beacon and routing query. The vehicle could select the optimal RSU to connect using various measurement means. For instance, a V6 vehicle can access RSU #1 and RSU #2, so it can select the appropriate RSU using either channel state information (CSI) or accessibility.

To control the network flow, the controller in each region must gather topology data to construct the network graph. This data can come from periodic beacon messages or prediction models. Periodic beacon messages include information such as velocity, location, direction, and cluster status. The status beacon can also contain relative mobility tables for neighboring vehicles [8]. Based on the SDVN architecture, the beacon messages can be transmitted to the local SDN controller or directly to the central controller. The controller can use this topology data to maintain traffic flow, react to routing queries, and deploy routing policy. The central or local controller will handle the routing process through various shortest-path algorithms. Link prediction models are an alternative to the periodic beacon mode. They help the SDN controller to build the network graph based on limited gathered data and mobility prediction-based links [104]. The controller can predict the next data transmission route using historical trajectory, the surrounding vehicles, and road traffic status, even if there are unstable links initially. As an example, in Figure 7, the controller can predict that V10 will move away from the coverage area of RSU2 due to a change in its direction.

SDVN allows two methods of route computation: centralized and hybrid. The former involves the controller finding the entire path from the sender to the receiver upon receiving a route query from the sender node. The latter, however, uses a combination of ad-hoc routing and controller-aided routing to determine the optimal path [105]. In SDVN hybrid mode, the controller creates the routing policy, which outlines the general routing behaviors and distributes rules to RSUs or vehicles. The intelligence of RSUs or vehicles is then used to forward messages. For hierarchical networks, the local controller, typically an RSU, will address routing queries within its coverage area. If a route cannot be found, the query broadcasts to other local controllers until one is found that can access the destination node. To manage local requests, node clustering is commonly employed [101] [8]. The controller will determine the members of each cluster independently [106]. Once vehicles receive the member list, the most stable one is chosen as CH based on different conditions, such as location and communication stability. The CH is responsible for data collection and managing local routing. Firstly, the CH gathers the status information of all cluster members and then relays that information to the controller.

Secondly, the CH may act as a local controller and oversee the intra-cluster routing. For instance, the V2 vehicle represents cluster heads with two vehicles as cluster members (V3 and V4). In an alternative hybrid mode, the controller can furnish vehicle flow rules for a limited period. This enables vehicles to determine optimal paths for routing data messages in a distributed manner based on the information received from the controller [107].

The SDN controller can create the network topology by considering the quality of the links. QoS metrics are utilized to determine the weight of a link, which is crucial in determining the shortest path for both static graphs and VANET communication. The shortest path techniques, such as Dijkstra [108], Eppstein’s K-shortest [109], and Bellman-Ford and Floyd algorithm [110], are employed to calculate the route using a static graph that is constructed from previous timeslot beacons.

To maintain high data delivery rates, the SDN controller can generate multiple paths per source-destination pair [108] [109]. This method is designed to mitigate the shortcomings of static graphs in dynamic VANET, where the validity of routes extracted from static graphs may need to be improved for transmitting data packets in real-time scenarios. Though the multi-path method can ensure the best performance regarding reliability and data rates, the controller overhead and highly consumed power will be a big challenge in such routing algorithms.

B. SDN-BASED VANET ROUTING PROTOCOLS

Using SDN in VANET routing can solve the problems of present infrastructure-less VANET routing methods [7]. Using SDN global network topology, packet drops, and congestion can be significantly reduced compared to conventional VANET networks [8]. SDVN helps predict the vehicles' location, reducing routing failure caused by continuous vehicle mobility [9]. Additionally, in SDVN, only some vehicles broadcast beacon messages to find the route from the source to a destination where the routing information does not need to be exchanged among vehicles [10]. Thus, SDN-based VANETs can also reduce the overhead of the whole network.

However, this section thoroughly discusses most SDVN routing algorithms and divides them into novelty based on different considerations, as shown in Fig 8.

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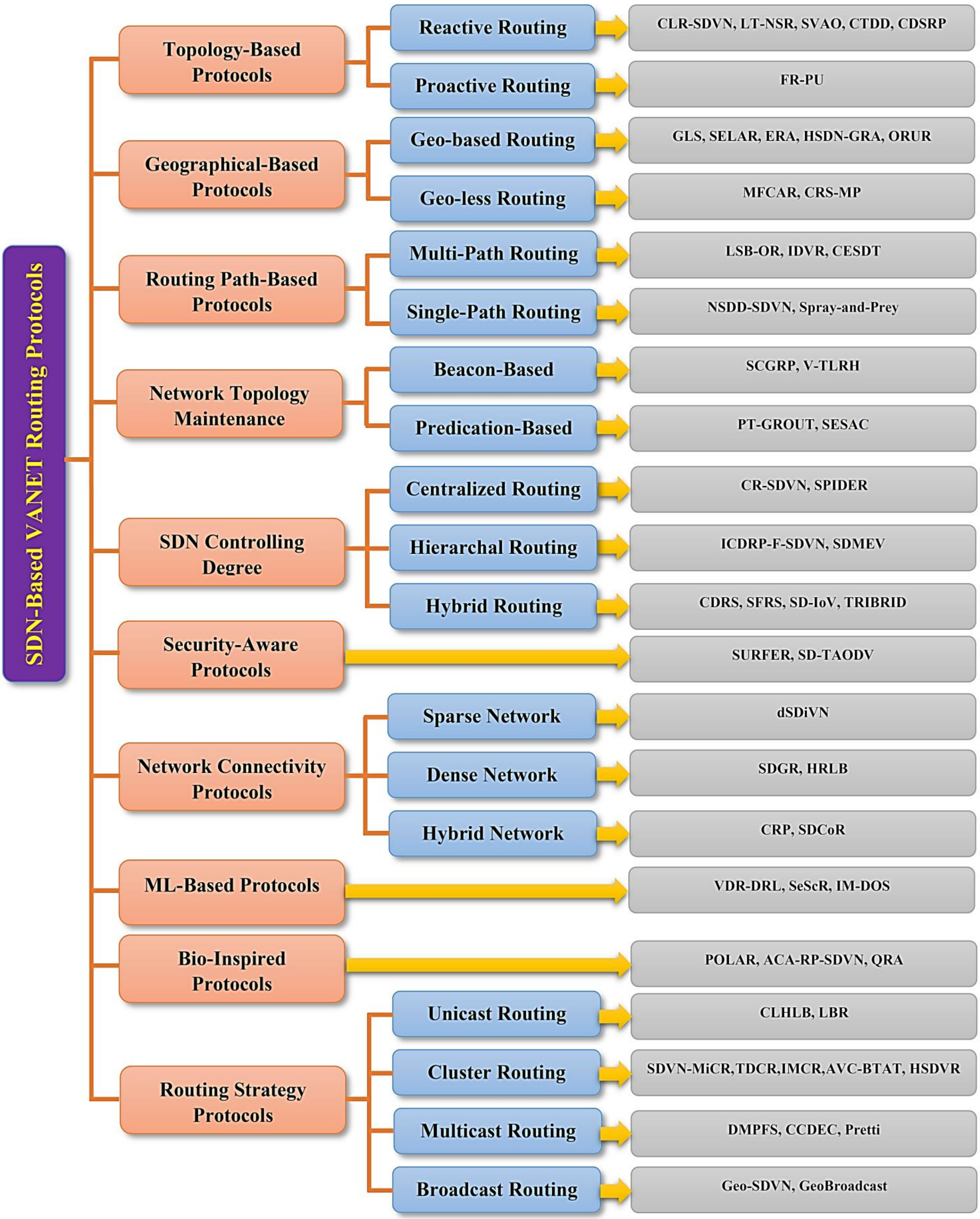

FIGURE 8. SDVN routing protocols taxonomy.

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1) INNOVATIVE CLUSTER-BASED DUAL-PHASE ROUTING PROTOCOL USING FOG COMPUTING AND SDVN (ICDRP-F-SDVN) [111]

ICDRP-F-SDVN is a cluster-based routing algorithm that combines fog computing and SDN to meet the requirements of smart vehicle communication. The protocol uses H-SDVN architecture where one central SDN controller is used for network management and fog node orchestration, and many SDN-RSUs controllers (RSUC) are linked to the fog servers. The area is partitioned into identical clusters based on predefined dimensions. The vehicle with the lowest mobility and the maximum residual distance is selected as the CH for that cluster. When the cluster member wants to send a packet, it first sends it to the CH node. The CH first checks its routing table to search if the destination is in the same cluster. If so, the CH will use the AODV protocol to deliver it. Otherwise, CH will send a routing request to the fog node to invoke the SDN for packet forwarding. If the SDN switch can access it, it will forward the packet to the fog node of the next cluster to deliver it to CH of the destination node. Otherwise, the routing request will be moved to the central controller, which will use the flooding technique to search the destination in all SDN switches. If none is responded to, the conventional AODV algorithm will be used as a fallback mechanism. The protocol also provides a mechanism to reduce the routing overhead by lowering the packet size and the number of exchanged hello messages. If a CM departs from the cluster, the CH will be informed by possessing the lifetimes of all the members and can recognize when they are leaving the cluster.

Advantages: The protocol ensures a high PDR by providing a fallback mechanism. The technique of optimizing overhead and mitigating broadcasts can conserve bandwidth.
Disadvantages: It is not a DTN routing protocol. Also, it neglects the link failure effect on the routing path.
Application Areas: It is most appropriate for urban zones with a suitable density of vehicles. Due to its various recovery options, it is also ideal for sparse zones.
Future Improvements: It may be more efficient if considering link prediction and store, carry, and forward (SCF) mechanism.

2) SDVN-ASSISTED MIGRATING CONSIGNMENT REGION (MICR) (SDVN-MICR) [112]

In [112], S. Prathiba et al. proposed the use of SDN and migrating consignment region (MiCR) model to deliver safety-messages to AVs on highways via 5G-V2X communication. The MiCR approach is based on federated K-means clustering and uses a three-tier architecture, including a centralized SDN controller, gNBs/edge server, and AVs layer. First, all AVs provide the edge server with information regarding their mobility. Then, the SDN controller processes the collected data using the federated K-means clustering algorithm to group AVs into consignment regions (CRs) based on their velocity and direction. The SDN controller selects a seed-AV (SAV) with maximum remaining energy and transmission range near the group's center. The SAV can reach all the other members in the cluster (MAVs) through a single V2V link. To reduce network traffic, the MiCR protocol includes *BreakCR*, *UpdateCR*, and *CombineCR* algorithms to keep clusters up-to-date and cope with the fast-moving nature of AVs. The *BreakCR* algorithm checks whether any AV in a CR is moved in the opposite direction of the CR or whether the range threshold has been surpassed. If the AV changes direction or the distance between it and the CR exceeds the threshold, the *UpdateCR* algorithm removes the AV from its current CR and adds it to a new CR that matches its direction and is closer in distance. The *CombineCR* algorithm merges CRs that share the same direction and velocity. In addition, the protocol offers a handoff strategy to transfer the feature set of a specific CR from one gNB to the next gNB.

Advantages: The protocol maintains the clusters continuously through many algorithms, ensuring high reliability and meaningfully decreasing the cost of cluster formation.
Disadvantages: Cluster maintenance will cause high computation overhead on the central SDN controller. Inter-clusters communication is not mentioned here.
Application Area: This protocol must be implemented in a secure, dense VANET network with 5G coverage.
Future Improvements: Trajectory prediction can increase cluster lifetime and decrease protocol computation overhead.

3) COOPERATIVE DATA ROUTING AND SCHEDULING SCHEME (CDRS) [113]

In [113], the authors proposed a cooperative data routing and scheduling mechanism, leveraging SDVN to optimize the delivery of infotainment packets with minimum latency and maximum throughput. As shown in Fig. 9, CDRS protocol uses H-SDVN architecture, with two tiers of control plane: the top tier located on the Internet and the lowest one at the RSU side. RSUs will collect network information by monitoring the broadcasted safety data and then send the collected information to the local controllers. The incremental and maximum weighted independent set (MWIS) method has been used to accomplish a computationally feasible solution while keeping near-optimal results. The incremental method prioritizes packet transmission based on their dwell times, traffic type, arrival time, and message type. It finds K shortest paths for each packet. Then, the feasible function is utilized to check the feasibility of each path in terms of link existence and potential conflicts. If a feasible path is found, the algorithm identifies the minimum delay possible for the packet over that path. The path with the lowest delay and satisfying all constraints is nominated as the optimal path for data routing, which is then inserted into the network graph.

Advantages: The consideration of packet dwell time can minimize the vehicle mobility effect. It improves PDR and minimizes packet collisions by simultaneously choosing the path for routing and scheduling the channel.
Disadvantages: Packet prioritizing without considering application type may lead to high packet loss and increased latency for safety-related packets.
Application Area: This protocol suits a secure, dense environment with multiple data access requests.
Future Improvements: Traffic prediction can help decide the future link dwell time changes. A routing recovery method is required in case of a link failure with the central controller.

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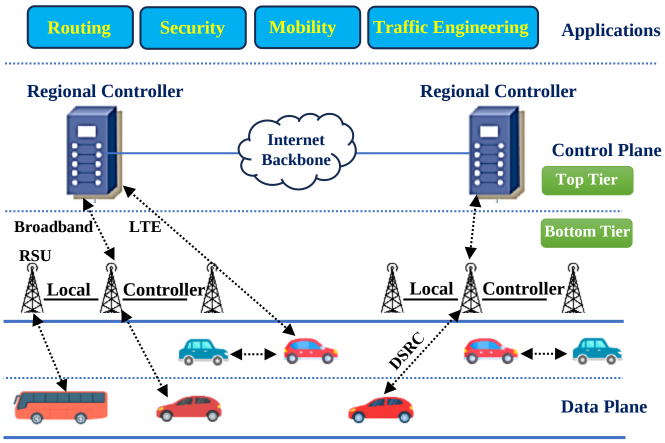

FIGURE 9. HD-SDVN system architecture is used in CDRS.

4) DELAY-EFFICIENT MULTICASTING BASED ON PARKED VEHICLES, FOG COMPUTING, AND SDVN (DMPFS) [114]

DMPFS protocol utilizes parked vehicles as stationary fog computing nodes with SDN to minimize transmission delay and improve link stability for multicast routing. Considering the type of vehicle that initiated the request, the incoming requests are prioritized into different categories: ambulance, police, firefighting, and regular requests. The protocol divides the area into several segments of fixed size. Each set of RSUs/BSs in a specific geographic area is controlled by a local SDN controller to make local routing decisions and network management. The local controllers then send their data to the central SDN controller. The protocol employs a joining/leaving method to determine whether to add or remove a vehicle from an active multicast session. The fog computing device periodically compares the velocity received from the beacon packets for all vehicles within its region to determine whether the vehicle is parked. DMPFS selects the optimal multicast path by considering several constraints, such as data size, resource congestion, link bandwidth, relay buffer, transmission rate, and network flooding. When a source node wants to multicast data, it sends a unicast request to the nearby RSU/BS, which forwards it to the local SDN controller. If all destination vehicles are within the controller coverage region, it builds the multicast tree and floods flow tables to all nodes in the tree. If some destinations are outside the coverage area, the request is directed to the central controller to search the optimal multicast routing.

Advantages: Requests classification and scheduling can achieve the QoS requirements. FC can assist with mobility and enhance location awareness in multicast routing.

Disadvantages: Vehicular density and node mobility are not considered in the routing decisions. The complexity and multiple constraints in the computing of optimal routing path may cause high data delivery latency.

Application Area: The protocol needs a fully covered area with high node density with some parked FC vehicles.

Future Improvements: Using ML methods for mobility prediction can enhance protocol operation. Also, data validity models can minimize the amount of data routed.

5) PREDICTION-BASED TEMPORAL GRAPH ROUTING ALGORITHM (PT-GROUT) [115]

PT-GROUT routing protocol aims to enhance routing performance and computation efficiency by integrating the hidden Markov model (HMM) and the temporal graph. The HMM technique is used to predict future routing information, which is then used as input for the optimal routing algorithm. The future temporal graph is built for the VANET network using historical routing statistics and localization data. When a packet is routed, a routing request is forwarded to the control plane to find the optimal routing path and sends it back to the requesting node. Then, the corresponding vehicles are updated and start in packet forwarding based on their flow tables. If vehicle density is too sparse, some BSs are chosen as relay nodes to participate in the routing process. Acknowledgement (ACK) messages are used to indicate data delivery. If a vehicle did not receive an ACK from the next-hop node after a predefined period, the vehicle encounters the failure and sends an error message to the controller to recalculate the forwarding path. If the controller cannot be reached, GPSR protocol is utilized for packet routing until they are received by a node that can access the controller.

Advantages: Incorporating temporal information in the graph ensures that the routing paths are more efficient and realistic. It provides computational efficiency with stable QoS.

Disadvantages: Using a centralized SDN will be the single point of failure; it may be overloaded with many routing requests.

Application Areas: It is best to deploy in an urban area with well-distributed roads and a suitable vehicular density.

Future improvements: It can provide further efficiency if it considers the link lifetime in routing decisions. Vehicular density prediction can also improve its efficiency.

6) SOCIAL COMPUTING INSPIRED PREDICTIVE ROUTING (SPIDER) [116]

SPIDER is a centralized SDVN-based routing protocol with the aim to provide low-latency, reliable data routing in a dynamic VANET environment. As shown in Fig 10, the protocol consists of three components: context feature mining, one-shot prediction, and social-based optimization routing. Context feature mining is designated to decide vehicle similarity using multiple factors such as direction, acceleration, speed, and movement angle. The one-shot prediction algorithm is used to predict link lifetime based on the contextual features known from the nodes. The expected link lifetime is then used in the social-based optimization routing model called time-constrained influence maximization (Trim) model, which uses social computing techniques to identify relay vehicles with high data-spreading capabilities. When a vehicle wants to send data to another vehicle, it forwards a routing request to the nearby controller with the destination vehicle information. The controller will find the best path and send it back to the requesting node to initiate multi-hop data routing along the path based on the flow table. The optimal path is calculated using several metrics, including delay, jitter, congestion, and PDR.

Advantages: The consideration of driver behavior in the routing decision makes it more proper for real-life operation.

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Disadvantages: The whole network is affected if the centralized SDN controller fails for any reason. Unsecured data transmission can produce unreliable outcomes.

Application Area: This algorithm necessitates a secure and well-distributed urban environment for complete functionality.

Future Improvements: The protocol scalability and efficiency can be improved by introducing traffic density prediction along the practical zone and implementing routing recovery and flooding mitigation mechanisms.

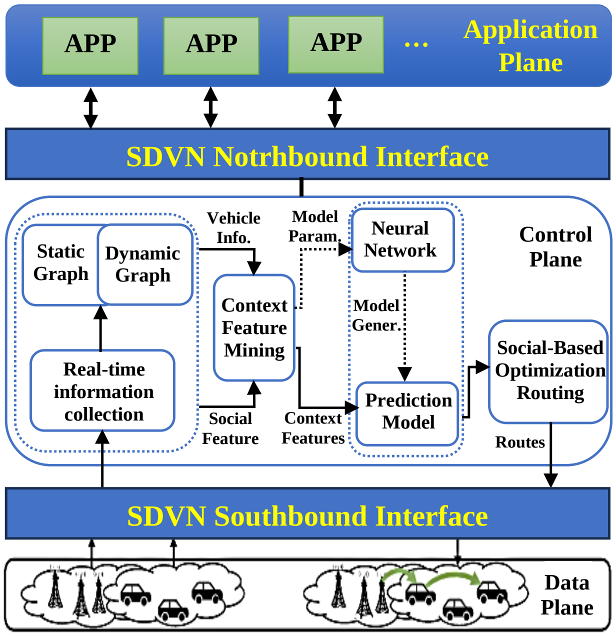

FIGURE 10. SPIDER protocol architecture.

7) GREEDY ROUTING WITH LINK STABILITY (GLS) [117]

GLS is a link stability-constraint, intelligent fuzzy-based routing algorithm for urban VANETs, focusing on finding a path with maximum stability and minimum latency. GLS protocol is a semi-centralized, intersection-and hierarchical-based approach. The central controller handles a routing table that maintains the priorities of packets routed from one area to another. It selects the optimal path according to link stability, where the selected relay node is a neighbor geographically closer to the destination and has a stable link with the present node. To initiate packet transmission, the SDN controller performs two algorithms: area selection (AS) and relay selection (RS) algorithms. In AS, the controller uses fuzzy logic to determine a consecutive sequence of areas that will be utilized for data forwarding, considering the area capacity, packet success rate, and the distance between areas. Then, using the RS algorithm, the protocol will use the real-time traffic pattern to determine the best path over the selected areas. Finally, the computed path is issued to the source vehicle for packet forwarding to the next selected hop until the packet reaches the destination. To adapt to changes in network topology, the protocol uses a reinforcement learning (RL) model to dynamically update the routing table and adjust routing policies based on past routing experiences.

Advantages: Focusing on intersections is a practical way to improve connectivity between road segments. Also, using RL can avoid redundant exploration when choosing the next step.

Disadvantages: Even if it realizes a substantial performance improvement, the protocol complexity will increase with the rise in the network size.

Application Area: It is best for deployment in secure and well-developed urban regions with less complex road structures.

Future Improvements: Traffic density prediction can help in avoiding sudden disconnection. Also, area segmenting with a scoring strategy can enhance the performance.

8) SDN EMPOWERED LOCATION AWARE ROUTING (SELAR) [118]

SELAR is a location-aware multipath routing protocol using 5G and fog computing, along with the SDN paradigm, to improve data transmission and recover connection failures. To minimize energy consumption, the protocol disables redundant devices during off-peak hours, where the path satisfying all constraints and minimizing the number of active networking devices will be selected as the optimal one. Based on data size and path capacity, the protocol can transfer the data over a single path or divide the data into multiple fragments and transfer those fragments over multiple routes. The procedure stays active until all data requests are achieved. Then, it updates the status of each device, the path, and the number of activated networking devices for each data demand. The controller uses path quality and vehicle mobility patterns to decide whether a link will be lost and whether that link can be recovered. It classifies the connection loss as severe or temporary failure. In the case of temporary failure, the failed vehicle waits for the link to recover. In severe failure, the nodes terminate monitoring of the present forwarding table and execute their routing rule before the disconnection. The forecast-based selective routing method (FSR) is introduced, based on multiple parameters, to predict the routing failures in advance.

Advantages: Energy-ware consideration can be a practical approach for satisfying green VANET. The use of the FSR with SDN can minimize delay and increase performance.

Disadvantages: The switching off for multiple nodes may conflict with VANET's unpredictable network size nature, where there may be a sudden extensive increase in the data demands, hence decreasing scalability.

Application Area: This protocol requires complete coverage of urban areas to work properly.

Future improvements: Security challenges should be improved. Traffic density prediction can help proactively determine the required active nodes (e.g., RSUs).

9) PENICILLIUM REPRODUCTION-BASED ONLINE LEARNING ADAPTIVE ROUTING SCHEME (POLAR) [119]

POLAR is an adaptive routing approach for hybrid SDVNs, employing online sequential learning and swarm intelligence. The local SDN controllers are deployed to process global information and dynamically choose the best routing strategy based on real-time traffic conditions and road network layouts. Depending on the traffic scenario, it can switch between multiple routing strategies such as AODV, OLSR, GPSR, DSR, and DSDV. A Geohash technique is used to divide the large zone into multiple grids. A penicillium reproduction algorithm (PRA) enhances the learning efficiency of an online sequential extreme learning machine. This model is then sent to local controllers for

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regional management. To map traffic patterns to an ideal routing method, a data processing module is introduced that extracts geographical features and traffic patterns, such as node density, road capacity, and maximum road speed, and labels these data sets for learning decision-making models in the SDN controller. Based on this model, the controller determines the performance metrics of various routing schemes to select the best one.

Advantages: Using real-time vehicular data with traffic patterns can increase protocol adaptability. Multi-learning features will help in making more optimal routing decisions.
Disadvantages: Multi-hop V2V communication is not discussed here.
Application Area: This protocol must be implemented in a well-organized urban area with different traffic patterns.
Future improvements: Neighbor quality, link lifetime, and communication stability must be considered in low-level routing decision selection.

10) SECURE SDN-BASED ROUTING PROTOCOL (SURFER) [120]

K. Mershad presented a secure IoV routing scheme in [120], which uses SDN controlling with blockchain technique for packet routing securely. The protocol is an improved version of the author's previous protocol (ROAMER) [121], which utilized RSUs for geographical routing and the store, carry, and forward (SCF) mechanism. The protocol has two sub-routing mechanisms: SURFER-1, which uses SDN to improve data transmission over the ROAMER routing technique, and SURFER-2, which deploys SDN across the entire IoV. To secure both the routing actions and data transactions, a blockchain model is integrated with the high-performance blockchain consensus (HPBC) method. For each geographical zone, RSUs are clustered, with each cluster being controlled by an SDN controller. Some of the RSUs are selected to form a blockchain network to maintain the transactions using two blockchains: a routing blockchain and a message blockchain. Each RSU holds a table of nearby vehicles, while the controller of each RSU cluster records and updates a table of RSUs that are managed by it. When a node needs to send a message to another one, initially, it checks if the destination is within its routing table. If not, the packet is transferred to the nearest RSU. If the destination is within the RSU vicinity, the RSU will forward the packet using geographic routing or SCF methods. If not, the RSU will create a multicast request for all nearby RSUs. If no reply, the request is forwarded to the SDN controller to check if it can access the destination and create flow rules accordingly. In SURFER-2, an optimized objective function is introduced to search for the best routing path with maximum network connectivity, less latency, and minimum network traffic.
Advantages: The performance analysis in both urban and highway presented the scheme's efficiency in terms of E2E delay and PDR, along with scalable security solutions.
Disadvantages: The higher network traffic overhead is observed here. SURFER-1 efficiency may be unreliable with no constraints in the next relay selection.
Application Area: Due to the DTN mechanism, the protocol can be deployed in urban and highway situations.
Future Improvements: An intelligent model is preferred to determine the optimal sub-protocol based on network traffic.

11) CONTEXT-AWARE COOPERATIVE DATA SHARING IN EDGE COMPUTING ASSISTED 5G-VANET (CCDEC) [122]

In [122], Luo et. al proposed a context-aware protocol for cooperative data sharing in the mobile edge computing (MEC)-based SDVN network. The 5G network will provide Internet connectivity and be used as an interface to collect contextual information from mobile vehicles. Besides, the DSRC technique will enable cooperative data sharing among nearby vehicles. The architecture of the protocol is shown in Fig 11. CCDEC protocol uses graph theory with a balanced, greedy algorithm to distribute content more evenly. The protocol operates in three phases. In the first phase, vehicles exchange beacon messages to help them sense contextual information, such as cached and required data items, as well as neighboring nodes and channel capacity. In the second phase, all vehicles communicate with the BS to share contextual information via the cellular link. In the third phase, after deciding the set of vehicles to send and the set of data items that must be sent for each sender, the selected senders will use V2I or V2V communication for content transfer.

Advantages: Using conflict graphs, decreasing the search area, and managing the restrictions is possible. Contextual information can improve the protocol's adaptability.
Disadvantages: The protocol did not consider nodes' mobility and network dynamicity, where all the nodes are supposed to be in the same neighborhood in a time interval.
Application Area: This protocol must be deployed in a highly covered area by the cellular network and VANET.
Future improvements: Expanding the scope of application scenarios to include multiple channel access is beneficial. For more reliability, it is best to integrate computation offloading.

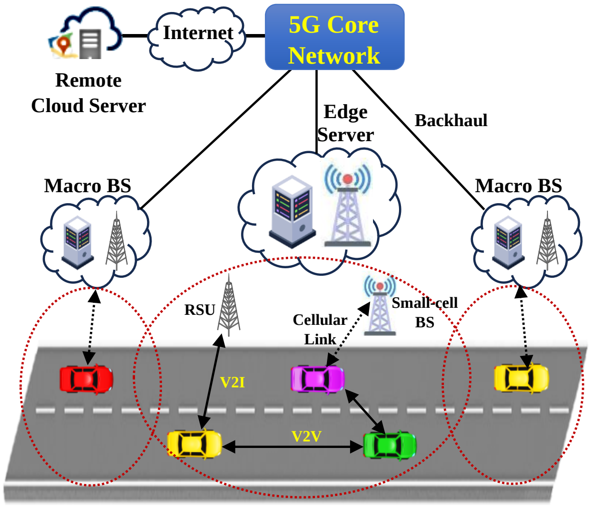

FIGURE 11. The CCDEC protocol architecture.

12) SDN AND FOG COMPUTING-BASED SWITCHABLE ROUTING (SFSR) [123]

SFRS protocol combines SDN and fog computing technology to facilitate data routing over more stable links. Using the information received by periodic beacons, the SDN-enabled RSU controllers (RSUCs) will make a local routing decision. Wireless switches are deployed at every junction to facilitate packet transmission through VANET communication. Fog nodes collect information periodically and calculate the weight of each road edge based on constraints such as road length, Euclidean distance between intersections, delay, node density, and stability. This information is delivered to the local RSUC to measure streets suitability and select proper paths under different situations. For data routing, when a new data flow reaches the switch, it sends a request to the controller, which uses its global view of the network status to calculate the optimal greedy routing path. Then, the decision rules are sent to switches over DSRC or Internet communication. If the stability period of the path streets is larger than the time required for data transmission, packets are sent via VANET. Otherwise, packets are sent via the Internet when the vehicle density is low. In that time, the controller examines streets that previously lacked sufficient vehicle density. If data transmission is possible, the controller determines a new VANET path. Otherwise, the CSF strategy is used for data transmission if data routing is impossible via VANET and the Internet.

Advantages: Roadside switches can increase reliability and ensure high PDR even with low vehicular density.
Disadvantages: The protocol is unsuitable for less-infrastructure VANETs such as highways. Roadside switches increase security vulnerabilities and deployment costs.
Application Area: The suitable area should have well-organized roads with pre-installed required infrastructure.
Future improvements: Future vehicle mobility and link lifetime analysis are good options for protocol improvement in scalability and adaptability.

13) EFFICIENT ROUTING ALGORITHM (ERA) [124]

An ERA is a routing protocol designed for the MEC- SDN-based IoV paradigm to predict the shortest, stable path by forecasting the nodes' trajectory using an artificial neural network (ANN). The control plane includes a centralized SDN controller and multiple edge servers that collect real-time messages from the vehicles for future position prediction locally. Each edge server contains multiple modules. The input manager (IM) module is designated to retrieve and process vehicle information. The synchronizer module will synchronize the data into a distributed local table, including the real-time node status pattern. Finally, the routing module (RM) will generate the routing path by considering the information received from other modules. After getting all available routing paths, the RM module will order the paths in ascending order using the number of hops. The path with a greater lifetime is chosen for data routing. Once the optimal path is selected, the flow rules are forwarded to the corresponding nodes and RSUs in the chosen route. If the destination vehicle is out of the edge coverage area, the request is forwarded to the SDN controller, which will use the global network topology to calculate the optimal routing path.
Advantages: Introducing edge controllers can minimize the SDN controller burden by reducing the number of requests sent from nodes to the SDN controller.
Disadvantages: using centralized SDN architecture will cause a single point of failure. The SDN is not fully utilized here, where most routing decisions are made in EC.
Application Area: it is suitable in a fully connected secure environment with an average number of requests.
Future improvements: Computation offloading can help when the local EC is overloaded with increased requests.

14) INFLUENCE MAXIMIZATION-BASED DYNAMIC FORWARDING NODE SELECTION SCHEME IN SDVN (IM-DOS) [125]

In [125], Zhao et al. proposed the IM-DOS routing protocol, which integrates social communication with data routing in SDVN networks, considering timeliness and dynamics among nodes to ensure stable routing paths among adjacent nodes. The protocol consists of three algorithms: a link lifetime prediction algorithm, a subgraph generation algorithm, and a forwarding algorithm. The link duration prediction method uses dynamic parameters such as distance, speed, acceleration, location, and direction to predict the link's lifetime. Then, based on the predicted lifetime and single-hop delay, the subgraph generation algorithm removes some invalid links in the entire graph. The last algorithm calculates the optimal path using the time-constrained influence maximization method inspired by social computing, where the nodes with the maximum influence in terms of link timeliness and transmission probability are selected as relay nodes. Finally, the controller will forward the routing path to the requesting node, and each node participating in the route to update its routing table and forward the packets.

Advantages: Link duration prediction can improve protocol reliability and decrease packet loss ratio.
Disadvantages: Although some redundant nodes are eliminated by subgraph generation, it did not consider the routing recovery during data transmission and future hops.
Application Area: The performance evaluation shows that the protocol can improve the performance of multi-hop data transmission in highly dynamic SDVN environments.
Future Improvements: Considering the vehicle density, the protocol efficiency can be improved significantly.

15) HYBRID SOFTWARE-DEFINED NETWORKING GEOGRAPHIC ROUTING APPROACH (HSDN-GRA) [126]

HSDN-GRA is a clustering-based geographical routing protocol. The protocol utilizes a multi-criteria approach to select the most reliable relays while ensuring connection availability, including the contact interval between nodes, the available load of each node, and the log of encountered communication errors embedded in each cluster head. It comprises five algorithms: contact duration and free load calculation algorithm, cluster head election algorithm, log update algorithm, geographic routing algorithm, and data dissemination algorithm. The protocol incorporates a multi-agent method, where each vehicle has two independent agents: a controller agent and a data transfer agent. The first agent runs the routing and network control plane, while the second agent follows the rules given by the first agent for data transfer. The node with the highest load is designated as a cluster head that will maintain an error log that records communication anomalies during the routing process. For data routing, first, the controller agent of the sender vehicle will check the error log to check the link failure with the destination node. If so, the controller sends the information with the respective

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packet to the data agent. Then, a reply message is transmitted when the data agent successfully relays the packet. The absence of a reply message will trigger the update of the communication anomaly log of each vehicle.

Advantages: The duration of inter-vehicle contacts allows for taking proactive measures to prevent early link failures. Also, the use of an error log can help avoid unstable links.
Disadvantages: Obtaining the quantitative values of multiple criteria in selecting the next relay will lead to more delay with high overload on the cluster head.
Application Area: it is suitable in dense environments with low to medium vehicle mobility.
Future improvements: The protocol must be simulated using a powerful network simulator. Cluster size optimization and routing maintenance can increase protocol efficiency.

16) ANT COLONY ALGORITHM-BASED ROUTING PROTOCOL IN SDVN (ACA-RP-SDVN) [127]

In [127], Kong et al. designed a routing algorithm for SDN-based urban vehicular networks, which employs the ant colony algorithm to determine the best routing path. The algorithm deploys forward ants to discover the complete routing path from the source to the destination. Besides, the backward ants are forwarded to update the path pheromone. The area is divided into multiple sections. Each section is managed by a local SDN controller located at the intersection to provide routing and management rules. Instead of searching for the routing path between the source and destination vehicles, the protocol explores the route between two vertex intersections, as revealed in Fig 12. When a routing request is received, the local controller checks if the destination IP address is within the control area. If so, it generates a path based on the topology location information and selects nearby intersections for data forwarding. When the destination is outside the control area, the request is relayed to the main controller, which will use an ant colony algorithm to find an inter-area routing link based on the destination location. Finally, the computed path is sent to the local controller to initiate the routing process.

Advantages: The issue of reaching a local maximum in the ant optimization algorithm is addressed by incorporating the global network topology of SDN.
Disadvantages: The route optimality may not be guaranteed since the best relay is defined based on a heuristic method, and ant colony optimization can be computationally intensive.
Application Area: It requires uniform-distributed transportation roads with high vehicle availability.
Future improvements: For more reliability, load balancing can enhance the protocol efficiency and minimize traffic load.

17) TRAFFIC DIFFERENTIATED CLUSTERING ROUTING (TDCR) [128]

In [128], Qi et al. introduced a TDCR scheme for data collecting and routing in a hybrid SDVN architecture to minimize cellular bandwidth cost and guarantee QoS over a centralized one-hop clustering method. The vehicles with the same mobility pattern are grouped into a particular cluster. The head of each cluster is determined through link lifetime and location to the nearest RSU. The cluster head aggregates the packets of its cluster and drops identical or invalid packets. After that, a two-stage heuristic method is used to determine the transmission mode through cellular or DSRC communication technology.

Advantages: Ensuring QoS is achieved through the formation of clusters while communication costs are minimized by balancing the tradeoff between data latency and cost.
Disadvantages: Free vehicles (non-clustering) cannot access the controller. The protocol did not mention any routing recovery and maintenance mechanism.
Application Area: It is suitable on straight roads with high cellular and DSRC infrastructure coverage.
Future improvements: Link lifetime prediction can enhance the clustering process. Adopting a robust routing maintenance model can improve protocol efficiency.

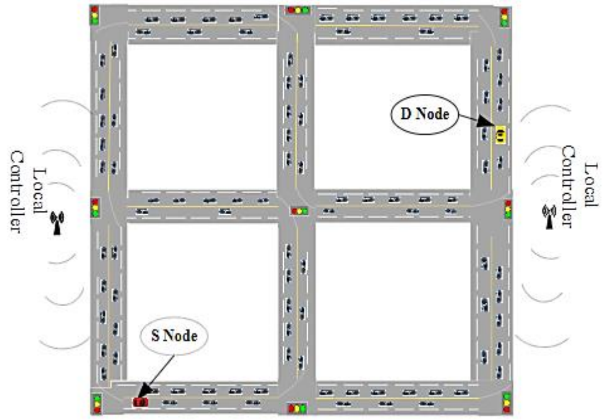

FIGURE 12. The ACA-RP-SDVN protocol [127].

18) SDN-ENABLED SPECTRAL CLUSTERING-BASED OPTIMIZED ROUTING (SESCR) [129]

Nahar et al. [129] leveraged spectral clustering and deep learning to maintain cluster stability and path selection in SDVN networks and reduce the impact of arbitrary node distribution. A Laplacian graph is used to categorize vehicles into clusters based on eigenvalues. Initially, each vehicle analyzes the mobility data of neighboring vehicles and computes its cluster head eligibility score (CES), considering the velocity difference, the Euclidean distance, the adjacency value, and the weight matrix values. Afterward, vehicles share their CES with their neighboring vehicles. Once all CESs have been received, the node with the maximum CES is chosen as the CH. After forming clusters, SDN utilizes the deep deterministic policy gradient (DDPG) algorithm to identify the best path to the destination vehicle based on the quality of available routes. The learning process continues at each forwarding node until the packet delivers its target.
Advantages: Deep learning can take sensory information as input from the practical area to provide output with approximations, thereby minimizing latency and overhead.
Disadvantages: Using a single cluster head can cause a single point of failure. The nodes' capability and buffer size are neglected when selected as cluster heads.
Application Area: Due to the focus on the performance analysis of protocol in urban traffic circumstances, the protocol can be deployed in such an environment.

Future Improvements: The protocol can be optimized by utilizing link reliability and mobility prediction techniques.

19) THREE-LEVEL ROUTING HIERARCHY BASED ON SDVN AND MOBILE EDGE COMPUTING (V-TLRH) [130]

In [130], Ji et al. proposed a three-level routing hierarchy in an SDN-MEC-VANET architecture. The edge devices are distributed in network segments, and the vehicles periodically send status information to the closest edge device. When an edge device receives a beacon from a vehicle without an associated edge device, it updates its management table and sends a message to that vehicle to update the domain in its beacon packet and notifies other vehicles and edge devices that it has found the target edge device for access. Meanwhile, the SDN controller is informed to record each edge device's access status. The protocol architecture is shown in Fig. 13. The protocol supports three levels for data transmission. Level I is used if the source node has a forwarding entry to the destination to transmit data directly to the destination. Level II is utilized when a vehicle is associated with an edge device but has no route to the target destination. So, it uploads a request to its edge device to search for a path to the destination. If found, the edge device uses the Dijkstra algorithm to calculate the shortest path and distribute the routing path to the source vehicle and all participating nodes. Level III is used if the edge device of the requester vehicle cannot access the destination. In this case, the routing request is forwarded to the SDN controller to calculate the route over multiple edge nodes. The controller chooses the edge-based route and informs the edge devices to participate in data transmission along the path. Then, the destination edge will use the Dijkstra algorithm to find the shortest path toward the intending vehicle. V-TLRH uses vehicle mobility information to calculate the working duration of potential links, where the link with longer durations is preferred for data transmission.

Advantages: The MEC can function autonomously when a controller fails, enhancing system resilience.

Disadvantages: The protocol supposes the ability of MEC to make routing decisions without intelligibility. The Dijkstra algorithm may result in a high delay in routing calculation.

Application Area: The protocol can be suitable for secure VANETs with high node-infrastructure connectivity.

Future Improvements: Providing the protocol with load-balancing technique can increase the efficiency of edge servers.

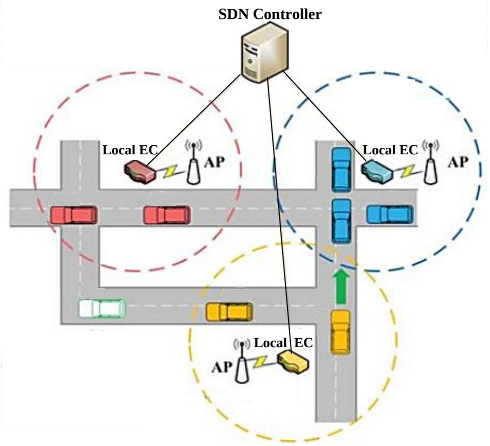

FIGURE 13. The architecture of V-TLRH protocol.

20) SDN-BASED MULTI-ACCESS EDGE COMPUTING FRAMEWORK FOR THE VEHICULAR NETWORKS (SDMEV) [99]

In [99], Nkenyereye et al. presented an SDN-MEC-based data routing scheme for VANET communications. The network architecture consists of four layers: the forwarding layer, the control layer, the MEC layer, and the access layer. Within the MEC layer, RSUs are deployed inside eNB to form eNB-RSU. The eNB-RSUCs act as local controllers that manage the network and provide the best communication modes to nodes at the network edge. The eNB-RSUCs also have a communication decision module that monitors link status and implements routing decisions. If the eNB-RSUC fails to create routing rules, the SDN controller generates new rules and updates the forwarding devices' flow tables. The SDMEV framework employs two algorithms: choose neighboring vehicles that receive in-vehicle messages over V2V or V2I links and update the forwarding device flow tables. Vehicular nodes in each MEC group are communicated with eNB-RSU via an LTE network. Then, the clusters are formed based on periodic Hello messages. The fuzzy logic model selects the head of each MEC based on vehicle location, velocity, and SNIR metric. The CH requests in-vehicle wireless access to collect data and service-based IVI messages from cluster members. If the message belongs to the warning category, it sends it to neighboring vehicles via V2V communication. For vehicles that cannot comply with V2V, V2I communication over LTE is used to disseminate the warning message. The CH forwards the packets to the eNB-RSU to request flow entries if they are not predefined. If the eNB-RSUC fails to create routing rules, it transfers the request to the central controller to generate new rules for forwarding packets to vehicles. If there is signal interference among neighboring vehicles, the controller states the flow decisions and sends to a node located near the RSU to forward the data to the destination.

Advantages: The protocol can achieve high PDR and low E2E and computation latency compared to the baselines.

Disadvantages: The protocol neglected the impact of vehicle mobility and network sparsity on routing decisions. Due to multi-layer architecture, it suffers high complexity.

Application Area: It can be adopted in high-density VANET where the node distribution is sufficient for clustering.

Future Improvements: Considering link reliability and node mobility can improve routing decisions and increase protocol effectiveness.

21) TRIBRID ROUTING PROTOCOL [131]

In [131], Liyanage et al. developed a link connectivity-aware SDN-based routing protocol to determine the shortest and most stable paths between source and destination nodes. The routing framework comprises centralized and distributed routing mechanisms. The routing scheme can handle routing requests in unicast, broadcast, or SCF methods. In network uncertainties, the broadcasting-based technique is integrated with unicast routing. The broadcasting mechanism finds an agent node based on the last known location of the destination node to replace it in centralized routing. Once a node with a stable path is found, packets are forwarded to it via unicast, after that, the agent node

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will broadcast the packets to the estimated destination location. For sparse network conditions, the model seeks to use the SCF technique to deliver packets. The routing scheme follows an incremental algorithm with a bidirectional shortest path algorithm to discover the shortest paths and check for stability and latency. When the packet reaches the starting node of the link, the path with the minimum residual lifetime is selected to transmit packets until the feasibility criteria are met, depending on link lifetime, effective velocity, and transmission time.

Advantages: The protocol can deal with VANET issues, such as obsolete or network information unavailability by applying SCF and broadcasting techniques.
Disadvantages: Due to the broadcasting technique, network congestion will increase. There is no mechanism to show the role of SDN in knowing the black hauls in the network.
Application Area: Due to its dealing with different conditions, it can be adopted in different VANET situations.
Future Improvements: Using vehicle mobility prediction models can help predict the future network state and proactively select the best routing mechanism.

22) SDN-ENABLED ROUTING FOR INTERNET OF VEHICLES IN ROAD-AWARE APPROACH (SD-IOV) [132]

SD-IoV is a road-aware SDN-based routing scheme with the aim to send data over the shortest and most reliable path. It leverages the cellular links to share control messages between the controller and vehicles. Edge controllers are deployed to periodically gather real-time vehicle information and analyze it to remove redundant data and forward only necessary information to the controller. Whenever a vehicle needs to transmit data, it inspects its routing table for the destination address. If the destination is found, the vehicle uses a greedy method to forward the data to its destination. Otherwise, a request is moved to the edge controller and then to the SDN controller to compute the routing path and deliver it. First, the SDN controller searches all routes with the help of hop count, direction, and relative speed; then, it selects one path as optimal if it has a vehicle density between 25-80%. After that, the computed routing path is delivered to the source vehicle to initiate the data transmission. The routing recovery is invoked when the link expires before the data is fully transferred. When the edge control receives a failure report, it checks the type of failure and forwards a new route if it is within its coverage area or requests a new routing from the controller.

Advantages: The cellular network can offload the VANET from massive data transmission while ensuring its accessibility with minimum delay requirements.
Disadvantages: Using cellular networks will bring more challenges, such as resource access and data security.
Application Area: it is suitable in well-distributed urban areas with uniform roads.
Future improvements: Trajectory prediction can help in protocol optimization. Adopting secure SDVN architecture can be a good choice for protocol improvement.

23) Quality of Service Aware Routing Algorithm (QRA) [133]

QRA is a multi-metric geographical routing protocol that can determine reliable and connected routing paths using connectivity probability and signal-to-noise-plus-interference ratio (SINR) metrics in the SDN-IoV paradigm. When the local controller receives a data routing request, it will check if a route to the destination already exists and is updatable. If so, it will send the path to the participating nodes. If not, QRA initiates the route discovery process by sending route discovery packets and recording each traveled segment's intersection identifier and SINR value. Then, using a modified laying chicken algorithm, the best path is selected over the closest intersection to the destination with the highest vehicular density and greediness factor. The RSU computes a greediness factor based on the closeness of neighboring intersections to the destination intersection. The route establishment process is re-initiated if no route meets the SINR metric.

Advantages: It aims to identify the most reliable and connected routing paths that ensure high QoS, considering reliability and connectivity as key factors.
Disadvantages: QRA efficiency is exposed in high-mobility networks. The overhead is high in a sparse traffic scenario.
Application Area: The protocol is appropriate for urban VANET services that need stable data transmission.
Future Improvements: The protocol can be improved by utilizing more constraints on the routing selection such as vehicle load and link duration.

24) VANET DATA ROUTING BASED ON DEEP REINFORCEMENT LEARNING (VDR-DRL) [134]

In [134]**,** Yang et al. suggested a data routing and distribution method based on a deep reinforcement learning model. The vehicular area is divided into multiple segments, with a cluster head selected for each segment. The SDN controller uses the neural episodic control method to select edge cluster head nodes and the Q-learning algorithm to choose a gateway cluster head vehicle from multiple edge heads. Each agent selects the next-hop relay as its action, and the hops number and signal quality between the node and the RSU determines the reward. LTE-based V2I data transmission is used to distribute data to the gateway cluster heads, while DSRC is used for V2V data transmission. In the beginning, vehicles send their status information with signal quality factors to RSUs to compute the SINR of each node. These data are then sent to the SDN controller to choose heads nodes based on vehicle distribution, velocity, and channel conditions.

Advantages: Using multiple nodes as cluster heads can increase communication reliability, especially with the dynamicity of the VANET network.
Disadvantages: The protocol neglects the effect of vehicle mobility when selecting the cluster heads.
Application Area: It can be deployed in a secure environment with fully covered by an LTE network.
Future Improvements: Using routing recovery schemes can help with protocol improvements. Also, it requires to be tested and compared with well-known VANET protocols.

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25) CROSS-LAYER ROUTING HANDOFF MECHANISM WITH LOAD BALANCING IN SDVN (CLHLB) [135]

In [135], Gao et al. proposed a path connectivity-based cross-layer unicast geographic routing handoff method using SDVN to ensure efficient data delivery at different traffic densities. The cooperation between the V2V cross-layer and V2I routing occurs based on the number of backbone paths whose connectivity probability exceeds a threshold. If the connectivity probability is below the threshold, V2I routing is used; otherwise, the system switches to V2V cross-layer routing mode. When a node has data to transfer, it first checks if the destination is a neighboring node. If it is, the source vehicle directly transmits the packet to the destination. Otherwise, the routing request is transferred to the central controller to calculate the optimal path. Using the path cost function, the controller selects the most optimal routing path based on the total rate of all next-hop nodes and the total load of all relay nodes on a backbone path. The vehicles with the highest transmission rate are selected as the relay nodes on the candidate backbone path. After choosing the relay nodes, the central controller issues the routing flows to the source, destination, and relay nodes on the chosen path. To avoid the ping-pong effect, only the transmission rate of neighbor nodes closer to the destination is compared.

Advantages: Using the degree of road density in routing decisions can improve protocol efficiency and increase its chance of application in real-time VANETs.
Disadvantages: The protocol did not include mechanisms for computing road density. Also, the lack of a routing recovery mechanism will increase the routing overhead and delay.
Application Area: It is suitable to apply in a secure, fully covered VANET environment.
Future Improvements: Using mobility prediction and link lifetime estimation can improve the protocol's effectiveness.

26) MULTI-FLOW CONGESTION-AWARE ROUTING (MFCAR) [136]

MFCAR protocol utilizes a hierarchal SDVN with graph theory to find relay nodes with low congestion and short paths in the VANET network. Each vehicle can exchange network control messages with the nearly SDN edge controller through a 5G-NR interface. Each vehicle maintains a list of neighboring vehicles and shares the list information with nearby SDN controllers using delta compression. For data routing, first, the source vehicle requests the SDN edge controller for data routing. If the destination vehicle is within the coverage area of the SDN edge controller, it determines the best route and adjusts the forwarding tables of all vehicles along the path. If not, the central SDN controller is requested to find the optimal route. SDN controller employs a uniform-cost search algorithm to compute the optimal path based on congestion insensitivity and QoS requirements. Starting from the source node, the node with the minimum objective function value is chosen as the next relay until the destination is reached. Then, the SDN controller updates the forwarding tables and network topology image to reflect the effect of the recently assigned flow on network congestion. When the flow ends, the SDN controller removes its impact from the network connectivity graph.

Advantages: It allows for fine-tuning the optimality of V2V routes between path length and congestion rate. Only updates to the neighboring table are sent to the central controller, resulting in bandwidth savings.
Disadvantages: it requires high computation for routing decisions. The lack of link reliability and vehicle mobility may challenge the application of the protocol.
Application Area: It is suitable to apply in urban areas with good DSRC and cellular communication coverage.
Future Improvements: The congestion insensitivity value can be dynamically adjusted based on the QoS needs and current vehicular situations.

27) NETWORK SELECTION AND DATA DISSEMINATION IN HETEROGENEOUS-SDVN NETWORKS (NSDD-SDVN) [137]

In [137], Chahal et al. introduced an NSDD-SDVN protocol for distributing vehicular data over multiple network interfaces. For network selection, a two-stage single-leader multiple-follower Stackelberg game theory is employed using the application requirements and network parameters such as bandwidth, cost, delay, throughput, and signal range as selection constraints. As illustrated in Fig. 14, the network selection involves a network detection manager, a priority manager, a network filter, and a network selection manager. For data dissemination, the protocol selects the path with the maximum link duration value as the optimal one. When a node needs to route a packet, it forwards a routing request to the RSU. If the RSU has an entry to the destination in its flow table, it transfers a reply packet to the source node; otherwise, it transmits a request packet to the central controller. If the source node is outside the coverage area of the local controller, it sends a hello packet to its neighbors, then it computes the link duration for each neighbor and selects the one with the maximum value for data transmission.

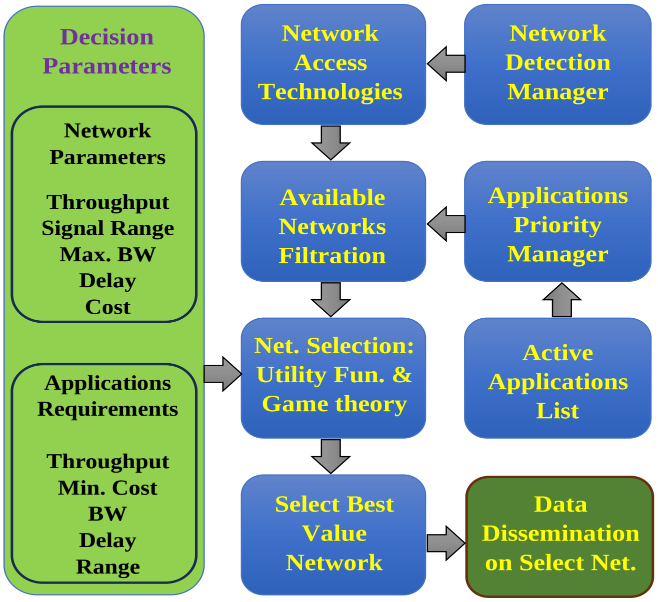

FIGURE 14. The flow work of NSDD-SDVN protocol.

Advantages: Using application requirements with network parameters can lead to efficient data delivery and maintain high QoS for different VANET services.

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Disadvantages: The calculation of the utility function requires high computational power, which may impact the network efficiency. Also, the data dissemination process is done hierarchically, which can cause delays in the system.
Application Area: Due to the lack of routing maintenance and recovery, it can apply with high vehicular density.
Future improvements: The improvement can be achieved by providing an efficient handover technique to allow the data to be transmitted seamlessly over multiple interfaces.

28) CENTRALIZED ROUTING SCHEME WITH MOBILITY PREDICTION (CRS-MP) [138]

CRS-MP is a centralized unicast geo-less routing scheme that calculates the best routing path based on the global SDVN topology image and mobility prediction. The local SDN controller uses a back-propagation neural network (BANN) for mobility prediction. Based on the estimated node mobility, the protocol will make routing decisions and assign the transmission method over V2I or V2V data transmission. For data routing, the source vehicle sends routing requests containing the IP addresses of both the sender and receiver vehicle to the RSU/BS. The RSU/BS will make routing decisions when both the communicating vehicles are in their transmission range. Otherwise, the request will be forwarded to the local SDN controller to make routing decisions. The SDN controller will use the road segment identification of the communicating nodes to instruct the particular RSU/BS to select the transmission method for each node using a bipartite matching scheme. If the source and destination vehicles are moved in different RSU communication ranges, I2I communication will be used. Finally, if both the communicating nodes are out of the transmission range of any RSU, multi-hop transmissions over BSs are used, with BSs acting as intermediate relay nodes.

Advantages: Different V2V and V2I data transmission channels and vehicle mobility prediction can enhance QoS and decrease bandwidth utilization issues.
Disadvantages: Cellular networks will increase resource access and data security challenges.
Application Area: Using DSRC and LTE, the protocol can adapt to urban and highway environments.
Future improvements: Using edge computing can be a good choice for protocol optimization. Also, adopting link reliability when selecting the next hop relay can be a good choice.

29) CROSS-LAYER SDVN ROUTING PROTOCOL (CLR-SDVN) [139]

In [139], You et al. introduced an SDN-based cross-layer routing strategy to find the optimal path in an urban environment by leveraging the global network topology, channel status, link lifetime, and vehicle mobility pattern. The network comprises three core systems: the main SDN controller, local controllers, and forwarding nodes. The local controller (e.g., RSUs) stores information about the local network topology of its coverage area by maintaining a database of vehicle state information. Utilizing cloud computing technology, the databases of all RSUs are combined in a global network state vector. For data routing, the source vehicle first transmits a request message to the nearest RSU. The RSU will check its database to see if it has an entry for the destination node. If so, it will compute the routing path using the local network topology image. Otherwise, the request will be forwarded to the main controller to search for the optimal routing path. After that, the reply packet is delivered to all vehicles on the routing path through local controllers, limited by a specific period and a maximum number of hops. The protocol has routing recovery and maintenance mechanisms, where the path is checked for repair upon link damage, and the routing discovery process is restarted if repair is impossible.

Advantages: A reliable routing path is obtained with multiple considerations such as channel conditions, link stability, vehicle velocity, and location.
Disadvantages: With high density, the main SDN controller is burdened by the numerous steps required for route calculation.
Application Area: it is suitable in an urban city with uniform roads and high availability of cellular infrastructure.
Future improvements: Using data offloading techniques with edge computing can decrease the computation overhead and delay on SDN controllers.

30) INFLUENCE MAXIMIZATION-BASED CLUSTER ROUTING ALGORITHM FOR SDVN (IMCR) [140]

In [140], Wang et al. presented a double-head clustering algorithm for influence maximization in a hierarchal SDVN network to reduce overhead and improve transmission efficiency. Adjacent vehicles are divided into logical clusters. The vehicle with the most influential role on all other vehicles is designated as the primary cluster head which is responsible for collecting members' mobility information and sending it to the SDN controller. If the primary cluster head is left, the backup cluster head immediately takes over to eliminate the issue of a single point of failure. The influence maximization strategy is invoked to select the new backup cluster head. Both cluster heads update information with each other so that the backup head can act as the primary one if necessary. SDN controller will exchange the flow table and relevant vehicle information with the cluster heads only if the vehicles are in two clusters. When a vehicle that does not belong to any cluster needs to communicate with a specific cluster, it communicates directly with the local controller to find the path toward the destination. The controller replies with the flow table to the requesting node and sends it to the cluster head of destination node to initiate data packet exchange by following the flow table.

Advantages: The selection of double cluster heads can better solve problems such as the method of re-affiliation of cluster and packet loss rate, especially when the existing CH fails.
Disadvantages: The periodic execution of the clustering process results in high control overhead. SDN's role in data routing and vehicle mobility is not considered sufficiently.
Application Area: it is preferable to be applied in dense environments with restricted vehicle mobility.
Future Improvements: Using more constraints on cluster management can increase cluster stability.

31) HETEROGENEOUS SDVN-BASED COOPERATIVE TEMPORAL DATA DISSEMINATION (CTDD) [141]

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In [141], Die et al. introduced a CTDD protocol for data routing in a heterogeneous, decentralized SDVN architecture, considering the temporal details of data, the heterogeneity of network interfaces, and the delay limitations on service requests. For each service, the protocol achieves scheduling decision that includes broadcast rules, bandwidth allocation strategies, and routing paths. The network interfaces modify their operation rules once they get the SDN control message. Accordingly, a priority-based task assignment algorithm dynamically distributes the transmission tasks of each request over multiple interfaces. When the vehicle enters the transmission range of a network interface, it sends a service request and mobility pattern to nearby RSU/BS, which sends it to the SDN controller for further processing. Based on node mobility and the distribution of network interfaces, the controller decides the set of interfaces for each vehicle and determines the set of data units to be routed over each one. Schedulable requests that can efficiently decrease bandwidth utilization and be satisfied before their delay requirements are selected. Then, a priority function will prioritize the requests based on allocation ratio, service limit, and data productivity. Finally, the routing decision and data flows are delivered to the corresponding vehicles to initiate data delivery.

Advantages: The utilization of request scheduling along with data routing allows for the efficient allocation of data delivery tasks with less waiting time.
Disadvantages: The protocol results in high computation overhead and latency due to multi-constraint data scheduling.
Application Area: Due to network-wide information from various network interfaces, it can be deployed in urban covered by multiple network infrastructures.
Future Improvements: The protocol neglected the security issues associated with heterogonous VANETs. Also, multi-hop V2V data transmission is not considered here.

32) LINK STABILITY BASED OPTIMIZED ROUTING PROTOCOL (LSB-OR) [142]

LSB-OR is a distributed SDN-based routing protocol that selects the optimal routing path by considering both the shortest and most stable links. The source vehicle divides the data into multiple units and sends them through multiple shortest paths identified by the SDN controller under link stability constraint. The protocol employs an incremental packet allocation scheme, which explores nodes from both source and destination nodes until a middle one is found. The protocol then extracts the bottleneck link of the path to estimate the remaining link lifetimes and find the link with the lowest rate before assessing the stability of the path. If the bottleneck link fulfills the link capacity limitation, then all links in the path successfully satisfy the link capacity limit. The protocol then checks the next higher path until all data units are assigned or the maximum acceptable paths are analyzed. If multiple paths exist with the same number of hops, the protocol chooses the path with less mobility. When the requested vehicle gets the flow rules, it extracts the path information and inserts it in the buffered packet to send to the next hop. All participating nodes test the validity of the received path and store the path in their flow tables if positive. If there is a route breakdown, the vehicle requests the controller for the routing re-initiation process.

Advantages: The established routes are stable, ensuring reliable packet delivery.
Disadvantages: It does not consider scalability and traffic heterogeneity which may result in higher overhead and latency.
Application Area: Given network-wide information, the protocol can be deployed in highly-density environment.
Future Improvements: Adopting reliable vehicular density prediction model can improve routing stability.

33) LINK AVAILABLE TIME PREDICTION-BASED BACKUP CACHING AND ROUTING (LBR) [143]

In [143], X. Yan et al. presented the LBR routing algorithm, which aims to improve the performance of flow delivery and data routing performance in high-speed V2I networks. The LBR architecture comprises two planes: the SDN control plane, which utilizes an SDN controller to manage and control the entire VANET network, and the data plane, which includes various radio access networks and basic infrastructure like RSUs, BSs, and vehicles (see Fig. 15). SDN controller includes many modules which enable it to obtain the vehicle information and predict the link lifetime for each vehicle based on its mobility information. The topology management module will gather the status information of vehicular nodes and connected RSUs. The link availability prediction module will utilize up-to-date status information to calculate the duration of available links. The information awareness module is integrated with the data forwarding function in RSUs to collect a dataset about network metrics, channel metrics, and vehicle mobility information. Finally, the data forwarding module updates flow rules and routing decisions based on flow tables in RSUs.

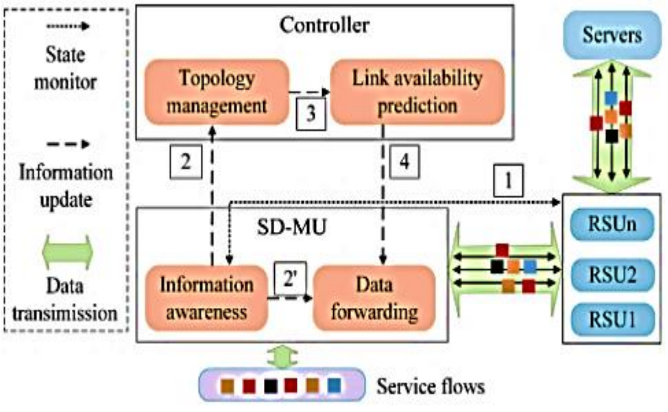

FIGURE 15. Data transmission in LBR protocol [143].

Advantages: Considering link duration prediction improves the rate at which flows are delivered.
Disadvantages: LBR did not give any flexibility in the multi-hop V2V data routing, where it merely applied in high-speed V2I communication.
Application Area: Considering high-speed mobility with link duration prediction can maintain protocol efficiency in a highway environment.

Future Improvements: ML-based solutions for link duration prediction can provide more efficiency—the need to develop it to allow multi-hop V2V communication in urban areas.

34) SOFTWARE-DEFINED COGNITIVE ROUTING FOR THE INTERNET OF VEHICLES (SDCoR) [144]

In [144], Cheng et al. introduced the SDCoR routing protocol, which utilizes reinforcement learning technology in SDN-based IoV network to deploy different routing protocols in various traffic scenarios. The protocol is based on a software-defined cognitive IoV network architecture. The SDN controller comprises three modules for sensing and learning purposes: the sensing module, the learning module, and the routing decision module. By sensing the current environment, Q-learning-enabled cognitive data forwarding is implemented in the SDN controller to learn the best routing strategy that can achieve efficient routing performance in a current environment based on the nodes' velocity and vehicular density. The protocol defines a set of actions, including GPSR and AODV protocols. The Q-learning reward function employs two routing performance metrics: PDR and E2E.

Advantages: Instead of following a specific routing strategy, this protocol switches between multiple strategies based on traffic situations.

Disadvantages: This scheme can only select between two routing protocols, and the rise in routing requests may lead to a high computation overhead on the SDN controller.

Application Area: It is preferable to be applied in a vehicular environment suited for GPSR and AODV protocols.

Future Improvements: The actions can be improved by integrating more routing strategies. Defining reward functions with more specifications, such as link lifetime and routing overhead, can increase protocol efficiency.

35) GEOCAST PROTOCOL FOR SOFTWARE-DEFINED VEHICULAR NETWORKS (GEO-SDVN) [145]

In [145], Sousa et al. suggested a geocast routing algorithm that utilizes LTE and WAVE standards to optimize data routing in a specific geographic area. The SDN controller is logically centralized and does not depend on the existence of RSUs. Vehicles communicate with each other over WAVE standard and share packets with the SDN controller using LTE. Each vehicle has a flow table with two matching fields: vehicle ID and a geocast ID that identifies the corresponding vehicle geographical zone. To send a message, the vehicle checks its routing table first, if it has an entry in its table, it uses the corresponding flow for routing the message to its nearby nodes using a one-hop broadcast. If not, a table-miss message is sent to the SDN controller to compute the routing path. If the response is positive, it performs the action provided in the reply message. If not, it discards the packet. First, the controller computes the minimum connected dominating set (MCDS) of the graph in the region of interest. Vehicles in the MCDS will broadcast the packet to all vehicles in the next hop list, while vehicles not in the MCDS will discard the packet. The next hop nodes are determined using a depth-first search starting from the sender vehicle. In the low-density scenario, the controller detects each connected sub-region and chooses a vehicle from each sub-region to act as a region head to broadcast the message in its connected sub-region via a V2V link and send it to the controller using LTE links. When the controller gets the message, it retransmits it to all region heads to deliver it to all vehicles within their sub-regions.

Advantages: It can decrease the latency and overhead by minimizing the number of broadcasting vehicles.

Disadvantages: The protocol creates high overhead on network resources. WAVE standard may cope with high channel congestion, especially in high-density environments.

Application Area: The protocol can be deployed in different urban areas with moderate vehicular density.

Future Improvements: Intelligent models can optimize the number of recipient nodes, resulting in optimization the delay and routing overhead.

36) HIERARCHICAL ROUTING SCHEME WITH LOAD BALANCING (HRLB) [101]

In [101], Gao et al. suggested an SDN-aided hierarchical routing method to determine the optimal path based on the traffic density and the node transfer probability from one grid to another. First, the central SDN controller will use vehicle status patterns to build a global network connectivity graph. When a source node has data to be sent, it first checks for a matching routing entry in its table. The data is sent directly using that routing rule if a match is present. Otherwise, the routing request is uploaded to the central controller to find the optimal routing path using three algorithms: grid selection, path selection, and relay node selection (see Fig. 16). Initially, the area is segmented into smaller grids, and the well-connected grids are identified using traffic density and historical transfer probability. Next, a path cost function is used to determine the two routes with the least cost, considering path length, traffic density, nearby node distance, and network load. Finally, for load balancing, the relay nodes with low traffic loads are selected on both paths by considering the remaining buffer and distance to the receiver node. Once the routing path is received, the node starts data routing while the controller monitors the route load status. If the load is more than 70%, the controller instructs the node to use the second link. If not, the SCF method is used.

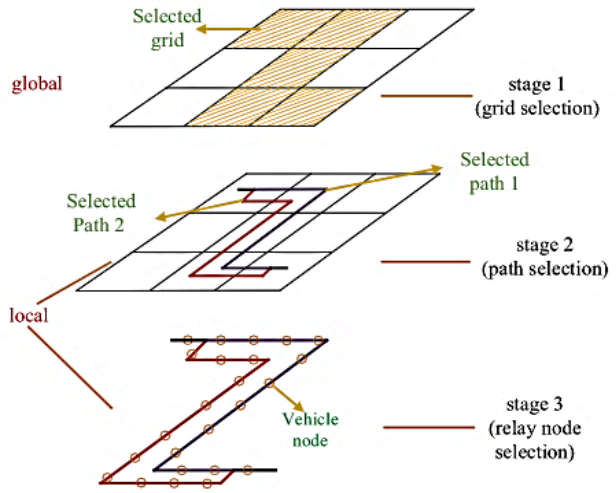

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FIGURE 16. Data transmission in HRLB protocol [101].

Advantages: It can reduce latency and overhead by avoiding new routing discovery. Network congestion will be reduced by using a backup route instead of computing a new one.

Disadvantages: The distance of the SDN controller from vehicular nodes makes finding efficient routes for time-sensitive applications difficult.

Application Area: It is suitable in urban areas with high vehicle connectivity.

Future Improvements: Studying the routing with high node mobility may require some improvements, such as using mobility prediction models to know the future grid of nodes.

37) SDN-ENABLED SOCIAL-AWARE CLUSTERING (SESAC) [146]

W. Qi et al. [146] introduced an SDN-aided social-aware clustering-based routing protocol for 5G-VANETs. The social pattern prediction model is utilized to enhance cluster stability. The nodes' mobility is modeled as a discrete time-homogeneous semi-Markov model, with the social pattern being presented as a set of road segments and corresponding sojourn times that the node will follow the next time. At first, the road is divided into rectangular areas, and vehicles are grouped based on location. The vehicles record the road segments they travel through and transmit it to the nearby BS. The SDN controller groups nodes with similar routes into clusters and selects cluster heads according to the distance with other nodes, relative velocity, and vehicle attributes. The data exchange between cluster members is performed via V2V links, and the cluster head sends the aggregated data to the BS, which includes control messages and flow rules dissemination.

Advantages: Vehicle clustering can reduce network congestion and improve PDR. Using vehicle patterns and social awareness can increase clusters' lifetime.

Disadvantages: Many issues are not addressed here, such as security issues, connection loss with the central controller, and the impact on vehicle mobility.

Application Area: Particularly, the protocol can work more effectively in work environments with regular vehicle traffic, such as universities or government complexes.

Future Improvements: Mobility prediction models can help know future nodes' mobility and lead to stable clusters.

38) LIFETIME-BASED NETWORK STATE ROUTING (LT-NSR) [147]

LT-NSR protocol employs MEC in SDVN to enable traffic offloading from the cellular network to V2V communication in highway VANETs. The protocol deploys the control plane of SDN within the MEC architecture, introducing the SDNi-MEC server. This server has a context database that maintains vehicles context information, such as position, velocity, and neighboring vehicles. Initially, when the source node intends to transmit packets, it forwards a data request to the SDNi-MEC server. Then, it checks whether a V2V routing path exists between the communicating nodes that have already communicated over the cellular links. If multiple V2V routing paths are available, the V2V routing path with the highest lifetime links is selected as the optimal path. Finally, the peered vehicles will be informed to use V2V data routing instead of cellular communication. V2V offloading continues until the lifetime of the path expires or when the path is disrupted due to vehicle mobility. Once V2V routing is completed, the communicating vehicles must return to cellular communication. If the vehicle detects a broken link before the data delivery is complete, it sends a repair message to the SDNi-MEC server to fix the failure. To recover the path failure, a lifetime-based path recovery mechanism has been presented to replace the drive-away vehicle with another neighboring vehicle that can directly communicate with the intended vehicle. If not, a packet is dropped, and the vehicles must revert to the cellular data routing from the V2V links.

Advantages: The protocol can maintain high network connectivity and data transmission using dual networking infrastructures for data routing.

Disadvantages: The multiple switching between cellular and VANET channels can lead to high packet loss and latency.

Application Area: It is suitable in highway environments where the number of cellular users seems small.

Future Improvements: Mobility prediction can help produce proactive handover. QoS-based offloading decisions can balance the networking load of both networks.

39) COGNITIVE ROUTING PROTOCOL FOR SOFTWARE-DEFINED VEHICULAR NETWORKS (CR-SDVN) [148]

Ghafoor et al. introduced the CR-SDVN routing protocol to find stable routing paths using cognitive radio technology and hierarchal SDVN architecture to select the channel and relay node efficiently. The protocol allows data transmission only when the source and destination agree on the transmission range over a common idle channel. The method is divided into two phases: the registering phase and the route prediction phase. In the registering phase, a subset of RSUs is selected as local controllers, arranged in a tree structure according to transmission delay, propagation delay, number of hops, and expected number of reachable vehicles. In the route prediction phase, the vehicle uploads the routing request to the local controller, which tries to reply with the optimal path to the source node. If no path is available, the request is sent to the central controller to find the best routing path. If the source vehicle is out of range of any local controller, it transmits beacon messages to locate the next-hop relay towards the nearest controller. The source vehicle computes the link duration prediction for each neighboring vehicle to identify the optimal relay node with minimum value to establish a path to the local controller responsible for data routing. The number of users on the road is predicted using the energy detector scheme in the spectrum sensing mechanism.

Advantages: The selection process of local controllers can reduce the main controller burden. A cognitive radio system can overcome the issues of bandwidth scarcity in SDVN.

Disadvantages: Multi-hop communication is not discussed here. All data transfer will be based on controllers that may result in high overload with increased routing requests.

Application Area: The protocol can give good results when used in minimum building environments with low crowds.

Future Improvements: It requires some routing technique as a backup in case of a link failure with the central controller.

40) FLEXIBLE ROUTE AND PROACTIVE UPDATING ROUTING PROTOCOL (FR-PU) [149]

In [149], Yang et al. introduced the FR-PU routing mechanism for data routing in SDVN framework efficiently by considering multiple link factors with a proactive update scheme to improve network performance and continually monitor the route path. It uses the Dijkstra algorithm to identify stable and short path links. The protocol includes two schemes: FR and PU. The FR scheme determines an effective route by considering the relative distance between communicating nodes, link stability rate, and successful reception ability. The PU scheme enables the SDN controller to monitor and analyze the entire application duration to mitigate the impact of continuous vehicle mobility. Accordingly, the protocol will constantly update the routes in response to vehicle motion changes. The controller measures the predicted expiration of the computed route path and sends it to the source vehicle. This route is only valid for the current data transmission. The new routing request needs to be invoked to generate a new route version for the next generated packet. Upon identifying abrupt changes in vehicle mobility, the controller recalculates the optimal paths for all unexpired routes using the same algorithm. If the original path fails, the controller sends an updated report to the source node to update its cached route table.

Advantages: The PU mechanism will minimize the effect of abrupt mobility changes in the vehicles by allowing the SDN controller to take responsibility for the application duration.
Disadvantage: Computing proactive routing paths can bring more delay and SDN overhead. Node mobility makes the computing of proactive routing paths worthless.
Application Area: It is best for the FR-PU protocol to be deployed in a secure urban environment.
Future Improvements: Mobility prediction models can enhance the efficiency of the proactive routing computation.

41) OPTIMAL RESOURCE UTILIZATION ROUTING SCHEME (ORUR) [150]

The ORUR protocol utilizes a cloud-enabled SDN model to select optimal routing paths and mitigate congestion of V2V communications by balancing the load of communication paths across the entire urban road network. The SDN controller keeps track of existing data communication paths by monitoring real-time connectivity and transmission delays on road segments. When a vehicle needs traffic data, it sends a request packet to the SDN controller to find the best path for data forwarding. If the data is available in the cloud database, it is sent to the vehicle through LTE downlink. Otherwise, the SDN controller uses the WAVE network to compute the optimal routing path based on a list of road segments to be followed. The vehicle then adds the optimal path to the header of each data packet and sends it to the destination using V2V communication. Once the data is delivered, the vehicle sends a finish message to the SDN controller. If no optimal path is available over the LTE or WAVE network, the SDN controller obtains the data from the source via an LTE link and sends it to the destination via LTE.

Advantages: This method includes a load balancing and congestion prevention routing system.
Disadvantages: Cloud-enabled SDN can cause high latency in routing computing. Network connectivity and delayed transmission monitoring cause high complexity and overload.
Application Area: It is suited to be deployed in an urban city with multiple road sections and high vehicular density.
Future Improvements: Vehicular density estimation may provide efficient results rather than network monitoring.

42) SDN-ENABLED CONNECTIVITY-AWARE GEOGRAPHICAL ROUTING PROTOCOL (SCGRP) [151]

The SCGRP protocol employs a cloud-based SDN controller to choose the most efficient path for packet forwarding. The SDN controller uses an updatable network topology to predict the connectivity and link duration between communicating nodes. When a source node has data to be sent, it first checks its routing table to see if it has a routing path to the destination vehicle. If a routing path exists, the data packet is forwarded accordingly. If not, it requests the SDN controller for a routing rule. SDN controller calculates a forwarding region around the source node, and selects the next hop relay within this region, considering multiple metrics that are traffic density, distance, velocity, and link duration. Considering the speed difference between the source and potential next-hop nodes, the SDN controller will prioritize nodes with lesser speed differences to find a stable routing path with maximum link duration. After that, the calculated path is sent back to the source node to start the data delivery process. Finally, if there is no connection with the SDN controller, the data packet will be flooded to all nearby vehicles.

Advantages: Using vehicle distance, velocity difference, and link duration in routing decisions can decrease packet loss rate.
Disadvantages: The protocol did not consider the junction while messages were broadcasting/beaconing.
Application Area: The protocol can be applied in an urban city with moderate vehicular density.
Future Improvements: Data security must be adopted, especially when using cellular networks for data delivery.

43) SOFTWARE-DEFINED TRUST-BASED AD-HOC ON-DEMAND DISTANCE VECTOR ROUTING (SD-TAODV) [152]

In [152], Zhang et al. proposed the SD-TAODV routing algorithm to enhance the security and throughput of the SDN-based VANET. Along with data routing, the SDN controller is also responsible for trust management in VANETs. The SDN controller computes the routing path and updates it if a better path with a higher trust value is found. To build the network topology, the SDN controller broadcasts topology request messages to record the trust value of nodes. SDN controller will evaluate the node trust value of each vehicle through forwarding ratio and node trust computation methods. The packets are divided into control packets (Trusted-RREQ, Trusted-RREP) and data packets. If a node receives a T-RREQ packet from a neighbor, it checks if it has already received the request and then checks its routing table for a new route to the destination. If a new route exists, it updates its routing table and sends a T-RREP packet back to the source. Otherwise, it broadcasts the T-RREQ packet to its neighbors. If a node gets multiple T-RREQ messages, it selects the path with the better trust value from its routing table. The destination vehicle sends a T-RREP message

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back to the source via the relay nodes, and the forwarding paths are established when the T-RREP message passes through the relay nodes. After receiving the T-RREP message, the source transmits the packets following the designated forwarding path.

Advantages: It reduces routing overhead by updating the routing path only when receiving a new path with the best trust.
Disadvantages: The protocol performance can be affected regarding latency as it still relies on the conventional AODV algorithm with minor adjustments.
Operational Environment: It can be applied in dense environments with moderate vehicle distribution.
Future Improvements: An efficient method to detect black hole nodes through modifying routing requests and reply packets in AODV can be one of the required improvements.

44) ADAPTIVE VEHICLE CLUSTERING & BEAMFORMED TRANSMISSION FOR AGGREGATED TRAFFIC (AVC-BTAT) [153]

AVC-BTAT is an adaptive clustering routing protocol for 5G-VANET with the aim to improve network management and handle the growing traffic by predicting the arriving road traffic. Using SDN global information, the vehicles are clustered based on their mobility and real-time road conditions. The cluster head is selected according to three metrics including angle of arrival (AoA), received signal strength (RSS), and inter-vehicular distance. Also, the backup head is selected to ensure communication continuity. As shown in Fig. 17, the SDN controller controls BSs/RSUs using high-capacity fiber optic links. To obtain the cell load conditions, each BS maintains a local database (LDB) that stores information about the vehicles in its cell, including clustering information, vehicle locations, traffic requirements, and transmission schemes. The information from multiple LDBs is combined to form a global database (GDB), which the SDN controller uses to design network policies and update local application modules. The protocol proposes an adaptive transmission scheme with selective modulation and power control to improve the trunk link capacity. So, if the traffic exceeds the trunk-link capacity, the cluster head removes some vehicles with high traffic requirements to guarantee communication quality. Here, cooperative communication is used by sharing antennas with the cluster head as virtual antenna arrays to enhance the quality of communication and reduce traffic distribution delay. Adaptive beamforming is also suggested to enhance coverage range by using a wider beam for complete cluster coverage and a narrow beam to reduce interference and improve the trunk link throughput rate when multiple clusters coexist.

Advantages: Using a dual cluster head and dynamic beamforming coverage improves trunk link communication quality and clusters' network robustness.
Disadvantages: Protocol complexity can lead to high latency in dense VANET. Using cooperative communication can lead to increased latency and cluster head management overhead.
Operational Environment: It is preferable to be deployed in an urban city with high cellular communication coverage.
Future Improvements: Mobility prediction consideration can enhance AoA and decrease beamforming search latency.

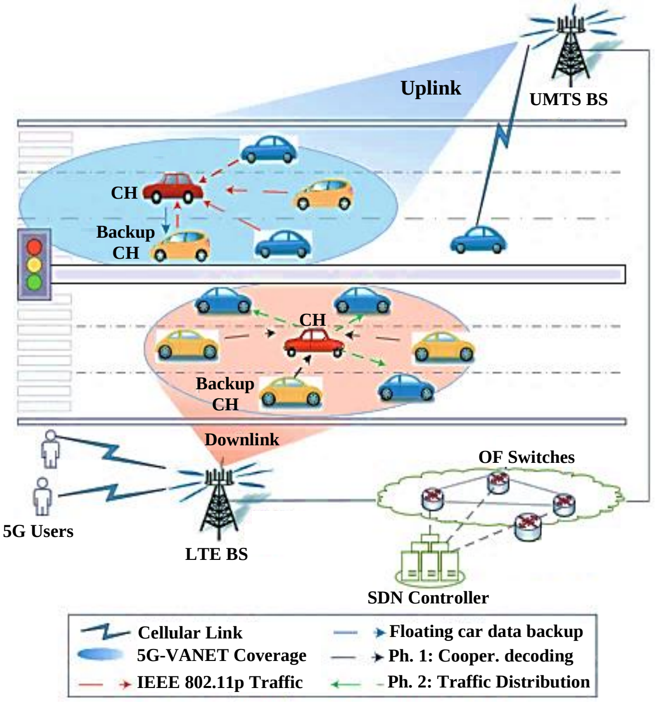

FIGURE 17. The system architecture of AVC-BTAT protocol [153].

45) SDN-BASED GEOGRAPHIC ROUTING PROTOCOL (SDGR) [154]

SDGR leverages the node location, vehicle density, and digital maps to find the shortest routing paths using Dijkstra's algorithm. Considering the road dimensions, the central SDN controller uses periodic beacon messages to calculate the traffic density for each road. SDGR protocol consists of two main algorithms: forwarding path algorithm and packet forwarding algorithm. The former algorithm calculates the shortest path with higher forwarding progress and vehicle density, based on network state vector and digital map. In the packet forwarding algorithm, the SDN controller creates a subgraph for the source and destination nodes to select the best next-hop relays. There are two packet forwarding modes: forthright and junction modes. The forthright mode delivers data packets based on the next hop position, velocity, and direction. In contrast, the junction mode uses a congestion detection mechanism to address the load balance problem in intersections where the nodes with lower buffer limits are used to ensure smooth traffic flow. Finally, the SDN controller sends this path to the source vehicle to help it deliver packets to the destination vehicle.

Advantages: Junction forwarding positively impacts the traffic signal in road junctions. Packet latency will be reduced by using digital map information to elect the hop node.
Disadvantages: Overhead minimizing mechanism is not adopted here. Placing the central controller far away from the end vehicles leads to an increase in route discovery time.
Operational Environment: It is good that it is applied in a well-defined transportation area so that it is possible to build sub-graphs by SDN controller.

Future Improvements: More analysis is required to show its efficiency with different transportation layouts and situations.

46) DISTRIBUTED SOFTWARE-DEFINED INFRASTRUCTURE LESS VEHICULAR NETWORK-BASED ROUTING (DSDiVN) [155]

In [155], Alioua et al. introduced dSDiVN, a distributed multi-hop SDN-based architecture for data routing in infrastructure-less VANETs. The approach assigns a dedicated mobile SDN controller for each zone partition. Based on IEEE 802.11p, the SDN controllers will obtain a global view of the network state. The road is segmented into fixed-size fragments, representing virtual cluster. The vehicle with the most extended lifetime is selected as the cluster head. Once elected, each cluster head activates its local mobile controller to manage a backup candidate list to prepare for potential failure and establish a recovery controller. The knowledge base of each local controller is compressed and backed up on the recovery controller to help the recovery controller to continue services if a mobile controller fails. Once activated, the recovery controller uses the knowledge base replication to respond to routing requests immediately.

Advantages: Through zone partitioning and distributed controllers, it can improve scalability, ensure a reasonable delay, and provide better support for delay-sensitive services.
Disadvantages: It did not show the backup controller election. A high number of hops causes a longer flow setup time.
Operational Environment: It can be applied in urban, less-infrastructure VANET environments.
Future Improvements: The protocol requires more attention toward the minimization of routing overhead and quality of neighbors when selecting the next hop relay node.

47) HIERARCHICAL SOFTWARE-DEFINED VEHICULAR ROUTING (HSDVR) [156]

Correia et al. [156] proposed a cluster-based routing strategy to address the issue of connectivity loss with the SDN controller and provide virtual infrastructure. There are two types of SDN controllers: the local controller and the primary controller. If there is no connection with the primary SDN controller, the local SDN controller will take on the role of the primary controller and handle the network in its domain until the primary controller reconnects. For data routing, the source vehicle checks whether it already has a path to the destination in the routing table. If so, it redirects the packets towards the destination. Otherwise, it broadcasts the request path message to neighboring nodes. When a vehicle receives a routing request message, it checks if it has a route to the destination. If it has, then it checks if it is a controller. If yes, then it sends the request path to the requesting vehicles. Otherwise, if it is not a controller but has a route, it sends a route update request to the local controller to update it and then forwards the updated path to the requested vehicle. If there is no route and the receiving vehicle is not a controller, the local controller forwards the message to the primary controller to find the path toward the destination node.

Advantages: Using a filtering technique to determine the next relay will reduce transmission overhead. The route can be found if the connection with the central controller is lost.
Disadvantages: Due to local routing computation, the computational complexity and overhead will be increased.
Application Area: The protocol is unsuitable for sparse VANET, so it is good to be deployed in dense urban areas.
Future Improvements: Using RSU for local computation and vehicle information management will reduce the workload of the local domain controller.

48) SDN-BASED ON-DEMAND ROUTING PROTOCOL (SVAO) [110]

In [110], Baihong et al. proposed the SVAO routing protocol to utilize SDN to enhance the efficiency of data routing in the VANET network. The system separates the SDN architecture into local and global control systems. Local SDN controllers are installed at every crossroad to collect the vehicles' information and perform local routing decisions. The global SDN controller utilizes a centralized level with an improved AODV method to calculate the optimal route among several road segments along which a message should be forwarded. Initially, the source vehicle sends a route request message to the local controller. If the destination is found within the local scope, the local controller will send the route information to the source; otherwise, it will request the next controller level to inquire about the destination vehicle information. If none in the current SDN controlling level can access the destination vehicle, the request will be repeated until the destination vehicle is located. If none of the local controllers can access the destination vehicle, the global level will request to calculate the position of the route to find the final route among the road segments. After selecting the forwarding road segments, the corresponding local controllers will be informed to search the shortest transmission path and the forwarding nodes that participate in the routing path by utilizing the Bellman-Ford algorithm. The candidate path will be selected according to the link stability, the relative velocity, and the number of nodes.

Advantages: Employing hierarchical SDN controlling can alleviate the burden of the central controller.
Disadvantages: In a high-speed scenario, the performance degrades rapidly. Also, the assumption that all roads are one-way is impractical.
Application Area: The protocol requires well-distributed urban, so it is only suitable for denser traffic situations.
Future Improvements: using mobility prediction can enhance the protocol efficiency by helping to determine the next intersection before data transmission.

49) INTERSECTION DYNAMIC VANET ROUTING (IDVR) [157]

IDVR is an intersection-based geographical routing protocol that utilizes a centralized SDN architecture to enhance route stability and minimize delay. The controller gathers real-time traffic information and selects one vehicle as an intersection cluster head (ICH) for each intersection according to the maximum lifetime until it exits the cluster zone. When a packet reaches an intersection, the protocol applies recursively between the current and desired destination intersections. For each intersection, the protocol computes the threshold point distance, which represents the final point of the handover process to be invoked. Besides,

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the SDN controller periodically calculates the average throughput for each road segment. When packets arrive at the ICH, it uses Dijkstra's algorithm to search the shortest route based on the current location, destination location, and the maximum of the minimum average throughput among the set of candidate shortest routes. When the current ICH reaches a threshold point, a new ICH should be elected, and all data should propagate to the new ICH. When no vehicles are in the cluster zone, the current ICH follows the SCF rule until it reaches another ICH closer to the destination intersection.

Advantages: The protocol can ensure high reliability by utilizing intersections with a minimum number of segments.
Disadvantages: Routing re-calculation at each intersection will cause high latency due to multiple routing computations.
Application Area: It is suitable for urban environments.
Future Improvements: The performance can be improved by considering multi-constraints such as communication ability and resource computing.

50) COST-EFFICIENT SENSORY DATA TRANSMISSION IN HETEROGENEOUS SDVN NETWORKS (CESDT) [158]

He et al. [158] proposed a CESDT protocol to minimize communication costs and bandwidth requirements by utilizing various wireless resources and scheduling the data over them. The protocol uses cloud-based SDN as a resource manager to centrally manage all network resources. It is based on the vehicle trajectory prediction to estimate network availability and required bandwidth. Based on the bandwidth requirements, the SDN controller selects the optimal network interface from all available candidates and determines the optimal routing path over single or multi-hop transmission links. The single-hop communication is modeled using a network availability matrix, while a time-dependent graph models the multi-hop routing. For multi-hop data routing, it employs a polynomial time approximation scheme to select the optimal shortest path among several paths that can fulfill the application requirement in a time-dependent manner. To find the optimal single-hop routing paths, the protocol uses a greedy approximation algorithm, where all available network interfaces are initially selected and then gradually removed one by one in each iteration until the bandwidth requirement is slightly above the specified limit.

Advantages: The communication cost can be minimized by directing the data over various communication interfaces.
Disadvantages: Large-scale networks may not achieve optimality due to using greedy methods in route selection.
Application Area: Due to its interoperability, it can be useful in an environment covered by multiple network infrastructures.
Future Improvements: Using link lifetime and routing duration can improve protocol reliability and scalability.

51) PREDICTIVE TIME-DEPENDENT MULTICAST ROUTING PROTOCOL (PRETTI) [159]

In [159], He et al. developed a multicast routing protocol to make efficient multicast scheduling decisions and reduce network delay and communication costs. Communication overhead is reduced by leveraging vehicle trajectory prediction, which models the predicted topology change with a time-dependent graph (TD-G). The protocol determines whether there is a time-dependent path (TD-P) between two nodes and stores all reachable nodes in a set. To select the best routing path with the minimum total cost from the set of available paths, the protocol employs the time-dependent shortest path (TD-SP) algorithm that identifies the earliest reachable path and then updates it if a shorter path exists.

Advantages: Using trajectory prediction and a time-dependent graph, the routing overhead and network cost can be decreased.
Disadvantages: The protocol complexity is relatively high, making it less suitable for denser networks.
Application Area: Due to protocol complexity, it is preferred to be applied in a moderate-density vehicular environment.
Future Improvements: Considering multiple constraints, such as vehicle mobility, context features, and link lifetime can improve the performance of data multicasting.

52) COOPERATIVE DATA SCHEDULING-ROUTING PROTOCOL IN HYBRID SDVN (CDSRP) [160]

In [160], Liu et al. proposed a centralized cooperative data dissemination scheme by utilizing a hybrid of I2V and V2V communications. The protocol employs a hierarchal SDVN infrastructure where the local controllers are embedded in RSUs. The local controller performs both data routing and scheduling decisions by selecting the communicating vehicles and instructing them on which channel to tune and which data to share. Data routing decisions consider both communication constraints and application requirements, providing a higher priority to vehicles with shorter remaining dwell times in the service region. The communication process is divided into three phases: first, all vehicles use V2V mode to broadcast beacon messages to identify a list of neighbors; second, all vehicles switch to I2V mode to inform the RSU of their current neighbors and their cached and requested data items; third, for data delivery, each vehicle uses either I2V or V2V mode. Here, the vehicles on the I2V channel can receive data items from the RSU, while other vehicles can simultaneously communicate over the V2V channel.

Advantages: Using dwell time-driven priority can ensure a high packet delivery ratio in a vehicular environment.
Disadvantages: The limitation of RSU to broadcast a single data unit at every scheduling period will cause high latency and decrease the overall QoS.
Application Area: It is best to be deployed in urban VANET with a reasonable number of vehicles.
Future Improvements: MIMO technology and full-duplex communication can increase its efficiency and delivery rate.

53) CENTRALIZED ROUTING PROTOCOL (CRP) [108]

CRP routing protocol uses a centralized SDN model for data routing efficiently while minimizing routing overhead. The protocol presented the minimum optimistic time (MOT) algorithm to handle changes in network density by allowing the protocol to switch between multi-hop forwarding and SCF models according to the current network density. Using global network information, the MOT algorithm can estimate the minimum time required for any vehicle to transmit a packet to

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another one along the best route. When a vehicle receives or generates a packet, its routing client application checks its routing table for a path to the destination. If a path exists, the packet is sent along that path. If no path exists, a route query message is sent to the SDN controller, which uses the MOT algorithm to determine the shortest route from the current vehicle to the destination vehicle. Based on the global network image and digital map, the SDN controller computes the optimal route and sends it back to the requesting node to start the data routing process.

Advantages: The switch between multi-hop forwarding and CSF models can ensure high network performance.
Disadvantages: Using Wi-Max with Wi-Fi can bring more security and bandwidth utilization issues.
Application Area: The protocol requires a digital map with special in-vehicle embedded interfaces.
Future Improvements: H-SDVN architecture can help in fault tolerance and reduce the overload on the central controller.

54) EFFICIENT MULTIPLE-COPY ROUTING IN SDVN (SPRAY-AND-PREY) [107]

In [107], Ming et al. proposed an SDN-based multiple-copy protocol to improve the delivery rate and minimize network resource costs. A graph-based utility function is leveraged to determine the best carriers based on global network topology, the distance to the destination, and the number of hops. The protocol uses the Dijkstra algorithm to find the minimum communication hops from any carrier to the destination. When two carriers have the same distance, the one with a larger angle with existing copies is chosen. In the spray phase, the source node duplicates a fixed number of messages and transmits them to one-hop neighbor carriers. The controller then uses the prey algorithm to choose the next carriers. The prey phase continues until the destination receives the message, and then the controller clears all other copies. A cooperative elimination scheme removes duplicates with poor utility and reduces delivery delays.

Advantages: By spraying multiple copies of packets, PDR will be high. Using distance/angle in the utility function can reduce the latency and the number of sprayed copies.
Disadvantages: It did not consider nodes' mobility and low-density situations.
Application Area: The protocol requires a highly dense vehicular environment to ensure many carriers.
Future Improvements: The protocol requires an efficient algorithm to minimize the number of sprayed messages and communication overhead.

55) SDN-BASED GEOGRAPHICAL BROADCASTING ROUTING PROTOCOL (GEOBROADCAST) [9]

GeoBroadcast is designed to broadcast messages under SDN supervision within a specific geographical region. For data routing, the vehicles will send their messages to the nearest RSU. If a flow entry is found in the RSU flow table, the RSU will use the cached flow rule for data routing. If not, a packet-in message is sent to the SDN controller to retrieve the geographical information of the destination and find all RSUs within the destination geographical area. The shortest routing paths to the searched RSUs are computed and sent to the corresponding RSUs. Finally, these RSUs will broadcast the message among the vehicles within their broadcast area. To prevent duplicate packets from being sent to two RSUs within the transmission range of the source vehicle, a sequence number is used to identify duplicate packets. The controller processes only one packet and adds a drop rule to one of the RSU flow tables. The Floodlight OpenFlow controller is used as the SDN controller, including multiple modules such as topology management, RSU location management, and GeoBroadcast routing.

Advantages: Geographical-based message broadcasting can reduce communication overhead.
Disadvantages: The protocol did not consider the need for V2V data transmission in less-infrastructure VANETs. Also, message reliability and validation are not considered here.
Application Area: With I2I links, the protocol can provide good results in a fully covered area with enough RSUs.
Future Improvements. Routing maintenance and recovery models are suitable solutions to improve protocol reliability.

VI. COMPARATIVE ANALYSIS AND DISCUSSION

This section provides a qualitative comparison of SDN-assisted VANET routing protocols based on their state-of-the-art ideas, features, optimization principles, performance evaluation techniques, and results analysis. The comparison is presented in Tables 4, 5, 6, 7, and 8. Table 4 summarizes the protocols based on various parameters and factors. Table 5 outlines the key features of the protocols, including their performance objectives, innovative ideas, and emerging techniques used. Table 6 lists the performance metrics and evaluation techniques for assessing the discussed protocols. Table 7 presents the optimization parameters used in the existing routing protocols, while Table 8 compares the protocols based on their performance evaluation and result analysis techniques. The tables provide researchers with a valuable resource for selecting an appropriate protocol or designing a new one. The following subsection thoroughly discusses the comparable factors and special features.

A. DISCUSSION ON GENERAL CHARACTERISTICS OF PROTOCOLS

Table 4 compares the reviewed routing protocols based on their operational characteristics related to various QoS parameters, performance measurements, and techniques. In addition to the tabulated data, a qualitative comparison is mentioned here.

Routing protocols, such as SPIDER, CLHLB, HRLB, and SCGRP, utilize a centralized SDN controller to provide per-flow routes to vehicles based on the computation of the global topology controller. While these protocols can maintain more efficient routes with a high PDR, the central controller's burden and route computation latency present significant challenges. On the other hand, several protocols, such as DMPFS, OCDEC, SDMEV, and QRA, adopt hierarchical SDN controlling to compute routing paths locally. These schemes ensure low latency of local routing paths and efficient load balancing. Still, their applicability in real-time is doubtful due to low data delivery and high latency of global routing paths. To address these issues, hybrid SDN control is used in many protocols, such as POLAR, TDCR, SeScR, and LSB-OR, to move the local routing computation from the central controller to local controllers and vehicles. This approach can minimize routing latency and communication overhead. However, computing routing paths locally with local view controlling can decrease protocol reliability, especially when using cached routing paths.

In most protocols, such as ICDRP-F-SDVN, GLS, POLAR, and V-TLRH, the controller finds just one path for data transmission. This single-path approach is simple and suitable for low-traffic or sparse networks. The dynamic nature of VANET can cause links to be temporary, which may not provide enough time to transmit the necessary data. This can lead to increased latency and decreased throughput. To address this issue, some schemes, such as SELAR, TRIBRID, and Pretti, establish multiple routes to ensure high PDR and less latency. However, multiple paths can cause high network congestion, especially in dense VANET.

Existing SDVN routing schemes use either a beacon-based method or a prediction-based method to maintain the dynamic topology of the network. Beacon-based protocols like SDVN-MiCR, SURFER, SFRS, SDMV, and CRS-MP use regular beacons to update the network topology. In contrast, prediction-based protocols, such as CDRS, V-TLRH, CESDT, and Pretti, use historical data to predict link status and reduce the number of beacons sent to the controller. While beacon-based methods can cause high uplink overhead, they maintain efficient routes and high data delivery. Prediction-based methods, conversely, are more scalable with minimum network overhead in dense networks. However, complex prediction algorithms can cause high latency and controller overhead.

SDVN routing protocols, such as POLAR, IM-DOS, HSDN-GRA, and MFCAR, provide unicast routing paths from source to destination, which can offer high data delivery with minimum network overhead in multi-hop communication. However, the computation of routing paths is restricted to SDN controllers, and vehicles cannot participate in routing computation. This limitation can result in a high packet loss rate in sparse or less-infrastructure VANETs. In contrast, some routing protocols, such as CDRS, SDMEV, and ORUR, allow vehicles to search for routing paths toward the destination using packet broadcasting. While this approach increases network overhead, it can ensure a high packet delivery ratio, especially when routing flows are not received, or the communication link with the SDN controller is unavailable or disconnected. Some protocols, such as SCGRP, SD-TAODV, dsDiVN, and HSDVR, use adaptive modes for data transmission to improve routing efficiency. However, such schemes require more tools for communication management and decision-making. TRIBRID is an example of a routing scheme that uses the SCF mode to improve PDR and minimize network overhead.

Many VANET applications realize this by broadcasting safety messages to nodes within the communication range using V2I links. Several SDVN routing protocols have been suggested to compute V2I routing paths and ensure high PDR, including DMPFS, STDD, LBR, and ORUR. Conversely, other protocols such as POLAR, ACA-RP-SDVN, HRLB, and QRA focus on using SDN programmability to establish multi-hop V2V routing protocols for vehicles to share their data. However, using SDVN routing protocols to find the optimal route for a particular communication model (e.g., V2I or V2V) is a weakness. Adopting both models in data routing, as in PT-GROUT, CCDEC, SFRS, and SDMEV protocols, can ensure high PDR and improve scalability, but it may increase complexity and controller overhead.

Many existing SDVN routing protocols, such as IM-DOS, TDCR, LSB-OR, and SDGR, use static shortest path algorithms, such as Dijkstra's algorithm, to determine the shortest routes. Generally, in SDVNs, the links between communicating vehicles are valid for a short time, rendering such algorithms for static networks inadequate. Consequently, solving the routing problem becomes equivalent to finding the fastest route in a dynamic temporal graph. The researchers have explored the routing paths problem in temporal graphs, as in the PT-GROUT, CDRS, SPIDER, and SeScR, which primarily focus on refining the online query effectiveness of network pre-computations.

Numerous approaches have been proposed to decrease the number of control messages exchanged with the SDN controller, which are required to convey mobility and status information of vehicles or clusters. The increased number of exchanged packets generates high uplink/downlink communication overhead, and concerns regarding data security and node privacy can further raise the number of control messages and packet size. Vehicle trajectory prediction has been identified as the upper solution for decreasing overhead in protocols such as SDVN-MiCR, SPIDER, LSB-OR, and VDR-DRL. This approach significantly reduces the amount of beacon status while the controller constructs the network graph based on gathered beacons and mobility predictions. Vehicle clustering has also been applied in many protocols, such as TDCR, IMCR, HSDVR, and AVG-BTAT routing methods, to minimize the overhead by allowing only the cluster head to communicate with the controller. However, the size of beacon packets is not adequately reduced as the cluster status messages are still being sent. Protocols that use vehicle clustering and mobility prediction can be classified as having the lowest communication overhead. Conversely, protocols that use broadcasting and data dissemination, such as SDMEV, LBR, Spray-and-Prey, and GeoBroadcast protocols, are classified as having high communication overhead where many control packets are broadcasted to find next-hop nodes.

To cater to the requirements of SDVNs, routing schemes need to tackle not only the problem of broadcast storms in congested networks but also the challenges of routing in intermittently connected networks. As a result, some works focused on routing for both scenarios, such as POLAR, SURFER, and CLHLB, instead of solely dense networks, as seen in DMPFS, ERA, and CRP. However, only a few studies are designed for sparse scenarios, such as LBR, LT-NSR, and dSDiVN.

VANET allow vehicles to connect with RSUs to obtain real-time traffic data, warning reports, and entertainment data. Some proposed protocols, such as CDRS, DMPFS, CTDD, and NSDD-SDVN routing protocols, consider packet parameters, such as type, required bandwidth, and maximum latency, in routing decisions. The priority of some packets over others can ensure a high PDR. However, the vast majority of SDVN protocols do not consider message priorities. Protocols such as SFRS, SD-IoV, CRS-MP, and IMCR prioritize access to entertainment data at the expense of essential data, such as safety messages and weather warning reports.

SDVN routing protocols need to consider the required computation power and implementation complexity. Some protocols such as PT-GROUT, SDVN-MiCR, SPIDER, and IM-DOS protocols have addressed these issues through prediction-based routing schemes. However, running intelligent or time-constraint routing can also be complex due to the high computation requirements in a controller. On the other hand, cluster-based routing schemes are generally less complex, as the SDN role is limited to forming clusters and performing inter-clustering routing. Examples of such protocols include TDCR, IMCR, ORUR, and dsDiVN. When comparing the complexity of protocols, factors such as run-time assumptions, optimization criteria, and coverage area should be considered.

The reviewed routing algorithms can be categorized according to their ability to handle increasing routing queries in the network. Centralized routing schemes such as SELAR, IM-DOS, VDR-DRL, and Geo-SDVN protocols are not scalable due to the heavy computation required by the central controller. This makes them unsuitable for large-scale networks. In contrast, hybrid routing schemes such as CDRS, POLAR, SFRS, and TDCR are designed to be scalable with a hierarchical SDN architecture. Vehicle clustering is one of the scalable solutions.

Vehicular communications require reliable data transmission between fixed RSUs and mobile vehicles or between them. The reviewed SDVN routing protocols have introduced various schemes to ensure reliable data delivery. For routing protocols, the communication reliability is evaluated based on the recovery strategy, packet drop ratio, link duration, and forwarding mechanism. SDN accomplishes this by using a linear graph with weighted vertices and branches as the probabilistic model. For instance, SCGRP, SPIDER, and CDRS routing protocols have used link lifetime to ensure reliability on multi-hop data routing. However, given VANET mobility, such a method may be insufficient since vehicle mobility may cause link breakage. Conversely, other protocols use acknowledgment messages to guarantee the delivery of a message packet exactly once while detecting errors or packet loss. Reliable protocols typically incur more overhead than unreliable protocols, resulting in slower and less scalable operations.

VANETs provide many applications with specific constraints and QoS requirements, such as delay, bandwidth, and transmission rate. However, most of the reviewed protocols did not consider the application type in their forwarding decisions, potentially leading to suboptimal results where diverse application requirements are not adequately addressed, as is the case with protocols like SPIDER, ERA, SeScR, CLHLB, HSDVR, and Spray-and-Prey. Some protocols focused solely on routing safety messages, such as ICDRP-F-SDVN, DMPFS, SDMEV, and GeoBroadcast, or only on infotainment data, such as the CDRS protocol. So, prioritizing some applications over others may negatively impact transfer balance, resulting in poor quality of experience (QoE). Conversely, some routing protocols addressed data transfer for both types of applications, with some prioritizing critical applications over entertainment applications, such as HSDN-GRA, TDCR, CTDD, and CRP. Others only mentioned the ability to send packets of both types without specifying the data transmission and queue management mechanism, as in the QRA, CLR-SDVN, and IMCR protocols.

B. DISCUSSION ON PERFORMANCE AND INNOVATIVE IDEAS

Incorporating multi-constraints with context awareness into routing decisions makes the protocol more practical and appropriate for real-world applications. For instance, while protocols developed for highway scenarios may be able to avoid considering traffic distribution, those developed for urban scenarios must consider several road segments and intersections distribution. Besides, the protocols with more complex mechanisms tend to utilize more control messages, which can result in more controller burden. Therefore, performance metrics are chosen and evaluated accordingly depending on the objective. In the same context, even though emerging technologies can enhance the reliability and scalability of routing protocols, they require more technology access and management costs with more security challenges. In general, the protocols that adopt centralized SDN have the highest delay and the least scalability. Nevertheless, protocols that are specifically designed for urban environments are expected to exhibit lower delays and improved connectivity in high-density scenarios. Some protocols prioritize the optimization of traffic load and computation overhead, while others attempt to achieve optimal control by distributing the SDN controllers hierarchically. However, the following discussion focuses on innovative ideas, emerging techniques, and performance objectives. The strengths and weaknesses of creative ideas, key features, and performance criteria are also discussed technically here.

ICDRP-F-SDVN [111] aims to maximize throughput and reduce communication overhead using fog computing and vehicle clustering in SDVN data routing. The protocol was evaluated through simulation and compared with other methods using five metrics: throughput, E2E delay, packet handling, control messages overhead, and cluster head switching. However, the protocol does not consider high vehicle mobility and network sparsity in its performance.

SDVN-MiCR [112] protocol aims to deliver vehicular data with low delay and high reliability in highway situations by reducing channel congestion caused by the high rate of data dissemination. The protocol was tested through real-time simulation, demonstrating its superiority in communication overhead, PDR, latency, and collision rate. Although the protocol outperforms current protocols by 18.3% in terms of PDR and latency, it did not consider the effect of mobility on routing decisions.

The CDRS [113] aims to enhance packet delivery by minimizing average service time and preventing conflicts during data transmission. The protocol was evaluated in different scenarios with various metrics including packet drop ratio, deadline missed ratio, PDR, service delay, computational time, and solution quality. Although the protocol targets infotainment applications, it was not tested with real-time infotainment applications. Besides, the computation time may become challenging in dense environments where the number of vehicles exceeds the predefined threshold of 25 vehicles per controller.

DMPFS [114] employs stationary vehicles as fog nodes to participate in multicasting data routing. However, the real-world environment may not guarantee a consistent number of vehicles to be as fog nodes, resulting in an inability to ensure the high reliability and scalability of data routing. Moreover, packet categorization and zone segmentation techniques minimize overhead and time complexity, but these methods introduce controller computation overhead issues. The protocol is evaluated using PDR, E2E delay, and communication overhead across varying mobility rates. Nevertheless, the protocol performance does not evaluate with no or few parked vehicles on the roadside.

PT-GROUT [115] protocol employs temporal graphs for routing decisions with high efficiency in routing computation and time expense for the routing process. The protocol is assessed using various performance metrics including computation cost, PDR, delivery delay, and jitter. The algorithm consistently outperforms others in high-traffic density situations. However, under low-density scenarios, the four metrics evaluated for Dijkstra's algorithm may resemble those of PT-GROUT. Additionally, as the number of vehicles increases, the SDN controller workload will rise due to the more extensive computations required for temporal graph processing. SPIDER [116] is a predictive routing scheme, inspired by social computing to enable efficient and reliable data exchange in dynamic vehicular networks. The protocol is evaluated using average delay, jitter, network congestion, average calculation time, and PDR metrics. However, it is essential to consider multiple factors in routing decisions such as high mobility and controller overload. GLS [117] considers historical routing experiences and real-time mobility patterns to identify routes with high link stability and short delays. The protocol performance is evaluated using three variations: GLS-no-update, GLS-update, and GLS with various metrics, including PDR, average delay, path length, and communication overhead. The GLS form performs better in providing efficient and stable transmission than other variations. However, the protocol efficiency decreases with increased transmission distance or reduced node count. SELAR [118] employs SDN to manage the load of fog nodes and reduce energy consumption in 5G-VANET networks. The novelty stems from its adaptive control paradigm that optimizes traffic load and determines active networking devices. The effectiveness of the protocol is evaluated using simulation-based experiments. However, the protocol performance has not been evaluated using primary QoS metrics, such as PDR, delay, and throughput. Also, the protocol applicability in dense environments may experience high delay and packet loss. POLAR [119] leverages edge computing, swarm intelligence, and machine learning models to select the optimal routing strategy with better PDR and E2E delay across several VANET scenarios. The protocol's strength lies in its adaptability, as it can switch between several routing protocols based on real-time conditions. The protocol is compared with classical routing strategies, including AODV, OLSR, GPSR, DSR, and DSDV, using PDR and E2E delay as comparison parameters. Although the protocol maintains high QoS regarding PDR and E2E delay, the simulation has not considered extreme traffic conditions like highway roads and sparse networks. SURFER [120] combines blockchain technology with SDN to enhance the reliability and security of data routing in IoV. Simulation results in urban and rural situations have demonstrated the protocol efficiency regarding E2E delay, PDR, routing overhead, and traffic load. Following this analysis, when the number of packets increases significantly, the packet drop rate will be high where the packets need to stay more times in the waiting queues at relay nodes. Besides, the blockchain technology will produce additional packets with larger sizes due to encryption processes.

CCDEC [122] is an SDN-based context-aware data cooperative dissemination strategy. The protocol performance is evaluated and compared to other protocols using multiple metrics, including protocol overhead, channel capacity gain, delay, and data delivery ratio. The communication quality and efficiency may be questionable due to the assumption of communication ability only between neighboring vehicles with LoS. SFSR [123] protocol aims to reduce packet loss rate through switching messages transmission over the VANET infrastructure and Internet network via roadside fog switches placed at intersections. However, deploying fog systems to participate in V2V data routing will increase deployment costs and system complexity. The protocol is simulated and evaluated regarding PDR, packet loss ratio, E2E delay, and routing overhead. However, various considerations, such as vehicle mobility and traffic features, are not adequately evaluated. ERA [124] protocol leverages machine learning and edge computing techniques to improve data routing in the SDN-IoV network. Based on the traffic conditions and vehicle mobility information, the vehicle location can be accurately predicted. Although ERA outperforms other protocols in terms of PDR, other QoS metrics, such as E2E delay and throughput, are not considered. However, the protocol efficiency may be affected in the sparse network where insufficient mobility information will cause to inaccurate prediction model. IM-DOS [125] uses social computing and a link lifetime prediction model to select the optimal relay for broadcasting safety messages in the SDN framework. The simulations demonstrated the scheme's efficiency regarding E2E delay, PDR, and package utilization. Yet, the results become more inconsistent as the vehicle number increases and the coverage area enlarges. Besides, the scheme does not consider backup transmission during the transmission process and upcoming hops.

HSDN-GRA [126] addresses the connectivity issue in VANET through clustering techniques and multi-constraints relay selection. The protocol is evaluated using the JADE multi-agent platform, measuring routing overhead, packet drop rate, and throughput. However, for more accurate results, the protocol performance must be evaluated under real-time traffic situations using network simulation software such as NS3 and OPNET. ACA-RP-SDVN [127] employs an ant colony strategy for data

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routing in dynamic urban situations, alleviating the concern of low success rates and poor routing performance. Although the ant colony scheme can improve the data routing by continuously adapting routing tables with channel congestion, their applicability in VANETs can be inefficient. Nonetheless, experimental results demonstrate that the method outperforms AODV and GPSR protocols regarding routing lifetime, routing change rate, and communication performance. However, the protocol did not consider network dynamicity and node mobility. TDCR [128] aims to meet QoS requirements for delay-sensitive services in terms of delivery rate and E2E delay through DSRC and C-V2X hybrid communication. The protocol is simulated and evaluated regarding routing overhead, hops count, average delay, and bandwidth cost. The simulations demonstrated that the protocol accomplishes low latency for delay-sensitive applications and low bandwidth cost for high data-rate ones. However, the assumption that there are always enough vehicles within the DSRC range cannot be achieved in most realistic environments. SeScR [129] employs the spectral clustering technique with a deep learning model to improve cluster stability and routing reliability. Extensive analysis has been performed to ensure protocol efficiency against other clustering-based schemes regarding cluster stability, lifetime, and association time restrictions. Also, it is compared with SDN- and ML-based schemes using throughput, latency, and computation delay. However, it didn’t consider road conditions and vehicle parameters in cluster formation and routing decisions. V-TLRH [130] uses a three-level routing hierarchy to improve routing performance and data delivery in a dynamic VANET network. The results analysis shows the protocol can perform well under different network scenarios, such as network change and node mobility. It has a higher PDR and reasonable delay than other approaches in different VANET scenarios. However, the performance testing did not consider the complexity, load distribution, and synchronization of multiple edge servers.

SDMEV [99] protocol utilizes edge storage and computation abilities to minimize packet latency and loss rate for SDN-enabled V2X communication. Performance analysis shows that the data routing over SDMEV can satisfy the delay requirements for V2X services. However, the results indicate that vehicles far from the congestion area can receive messages in over 1 second, which may be insignificant in some situations. Moreover, the controller will suffer a high burden in generating forwarding rules and knowing the actions that must be employed on the vehicles. TRIBRID [131] aims to find stable and shortest routes for packet routing with minimum latency. It utilizes the centralized and distributed routing models for unicast, broadcast, and SCF data delivery. The protocol efficiency is analyzed and verified using PDR, latency, routing overhead, and hop number. However, the impact of node mobility is not considered in the performance analysis. SD-IoV [132] utilizes edge-enabled SDVN technology to minimize routing overhead and improve scalability in highly dynamic VANETs. The results analysis showed a significant improvement in PDR, E2E delay, and routing overhead. Also, the edge controllers can minimize link failure in the network. However, the E2E delay may increase with the high changes in vehicle mobility.

QRA [133] utilizes the connectivity rate, road traffic information, and SINR metric to determine the optimal path for message routing over reliable and stable path in urban vehicular environments. The performance evaluation is realized through mathematical simulation and compared with other strategies in terms of PDR, average delay, routing overhead, and controller overhead. However, the protocol does not consider the hops count, which may result in undesirable delays in vehicular data transmission. VDR-DRL [134] combines SDN and DRL techniques to select edge and gateway head nodes. Numerical analysis shows that the scheme can enhance data throughput for different vehicle densities and velocity ranges. However, the dual cluster head selection may increase controller overhead and packet latency. Furthermore, the protocol must be evaluated and analyzed using various conventional QoS metrics. CLHLB [135] combines V2I and V2V cross-layer routing to deliver packets with high efficiency at different traffic densities using path connectivity probability. Simulation results demonstrated a significant gain in PDR and average delay compared with many routing strategies. However, the protocol may experience increased latency due to the gradual increase in multi-hops in the final routing path. MFCAR [136] leverages the management capabilities of SDN to decide the best routing paths using cellular and Wi-Fi standards. The numerical analysis demonstrates that the protocol outperforms Dijkstra's algorithm regarding PDR, throughput, and average delay. However, the simulations were carried out with fixed geographical positions of communicating vehicles, which may not fit the nature of VANET networks. Additionally, the protocol needs to be compared with the most studied routing algorithms, such as AODV and GPSR.

NSDD-SDVN [137] utilizes multiple wireless interfaces to enable efficient data transfer under different application requirements. The SDN controller will select the network interface using a two-stage Stackelberg game theory method. The numerical analysis demonstrates the protocol's efficiency regarding average delay, PDR, throughput, and routing overhead. However, the multi-metrics used in the utility function may result in high computational power and increased delay. CRS-MP [138] leverages the ANN technique to predict mobility patterns and anticipate the nodes' arrival rate in the network. The protocol is simulated and compared with other existing routing methods regarding transmission delay with varying vehicle velocity. However, the protocol's performance is not analyzed when the connection is loss with the controller or in the node sparsity scenario. CLR-SDVN [139] can generate optimal routing paths over the most stable links in urban inter-vehicle networks using cross-layer parameters such as forwarding probability, bandwidth availability, and link lifetime. The overall evaluation of the protocol is demonstrated and compared with other protocols in terms of routing overhead, E2E delay, packet drop ratio, and average throughput. However, the performance analysis did not address high mobility and low vehicle density situations. IMCR [140] aims to reduce overhead and improve transmission efficiency by applying an SDN-powered influence maximization algorithm to select double-head clusters. The protocol is compared under three structures: no cluster, single-

CH, and double-CH. However, the protocol complexity needs to be analyzed with the ordinary situations of VANETs.

CTDD [141] routing strategy enables unified management of heterogeneous network resources, capitalizing the number of routing quires completed within a delay constraint. The protocol considers the properties of temporal data, the wireless interface heterogeneity, and the delay constraints. Although the simulation results demonstrated the superiority of the algorithm over other competitors, the impact of increased data requests in high-density VANETs and the impact of service requests from other nearby network interfaces were not considered. LSB-OR [142] introduces an optimization-based routing algorithm with a source routing-based forwarding initiation strategy to efficiently deliver and cache flow information in the appropriate nodes using route validity times. The protocol is evaluated using various metrics such as time complexity, accuracy, PDR, latency, and overhead. Although the protocol has a very low processing delay, it may negatively impact packet reception due to its failure to consider node density and controller overhead.

LBR [143] aims to avoid re-routing waste in high-speed SDVN networks by accelerating forwarding rules through a link lifetime prediction method. The simulation is set to a high-speed train network with the cellular network as roadside infrastructure. The analysis demonstrated that the protocol outperforms the GPSR-L protocol with successful data delivery. SDCoR [144] uses RL with SDN to adaptively select the best routing strategy in IoV under different traffic situations. Although the analysis has demonstrated that the protocol can achieve better PDR than AODV and GPSR strategies, the method's effectiveness must be verified with other QoS metrics, such as E2E delay and throughput. Also, the overhead of the SDN controller will increase intensely with the increased number of routing requests.

Geo-SDVN [145] uses an SDVN architecture without depending on the existence of RSUs for data transmission. Accordingly, it can reduce the cost of infrastructure deployment and improve node accessibility. The protocol was evaluated using mathematical model methods in terms of PDR, average delay, and transmission overhead. However, the performance was not analyzed in various VANET scenarios with varying node mobility. HRLB [101] uses a three-level hierarchical routing approach with load balancing to maintain high PDR in real-time situations. However, this approach may increase routing overhead and latency, especially in non-uniform transportation areas. The evaluation of the algorithm is verified through simulation using PDR, throughput, average delay, and average hop count metrics. Generally, the protocol needs to consider vehicle mobility and density in performance analysis to achieve the best results.

SESAC [146] combines a social-aware clustering technique with a 5G network to improve cluster stability, prevent congestion, and reduce packet loss. The protocol is simulated and evaluated regarding cluster lifetime and clustering overhead. However, the analysis does not include other critical QoS metrics, such as PDR, delay, and throughput. LT-NSR [147] finds the routes with the longest lifetime based on the current traffic status and vehicle context information using over cellular and V2V communications. Even though such a method can improve PDR and reliability, the average delay will increase due to multiple offloading between network architectures. The numerical simulation uses multiple metrics, including offloading fraction rate, throughput, link average lifetime, and delivered data volume. Even though the protocol can achieve high throughput when the density of the nodes is average, its efficiency will decrease in low- or high-density situations. CR-SDVN [148] uses SDN to select the most stable vehicle routing path over cognitive vehicular networks. The algorithm is simulated and compared with other counterparts using PDR, E2E delay, and routing overhead for performance analysis. Even with extensive simulation, the impact of the increased rate of routing requests for the primary users was not realized. FR-PU [149] studied the effect of sudden changes in vehicle motion on data routing by using vehicle mobility information. It aims to find the reliable, shortest paths before data transmission proactively. Numerical results indicated the protocol can be more efficient and reliable than AODV and OLSR protocols based on E2E delay, PDR, and routing overhead. The protocol performs satisfactorily even at high vehicle mobility and extended application duration. However, the protocol performance will degrade when no nearby vehicles are available when the primary relay changes motion or direction.

ORUR [150] leverages cloud-based SDN technology to optimize bandwidth utilization and channel congestion through data transmission over multiple road segments. The protocol utilizes edge servers to minimize latency and reduce bandwidth usage from multiple cloud access. The protocol evaluation requires additional analysis in terms of delay and PDR. SCGRP [151] aims to reduce transmission delay and overhead over SDN-based vehicular communication. The protocol is evaluated using PDR, E2E delay, NRL, and hop counts ratio. However, the protocol performance will decrease with high node mobility or sparse networks. SD-TAODV [152] is an AODV-based secure routing protocol. To minimize routing overhead, the controller calculates the routing path and updates it only if a new path with a higher trust value is presented. The numerical analysis shows the protocol can outperform the traditional AODV algorithm regarding throughput and routing overhead. However, the E2E delay is higher than that of AODV due to using the traditional AODV protocol with minor modifications. Also, the controller overhead will increase in dense VANETs where the trust model requires more computations. AVC-BTAT [153] utilizes an adaptive transmission method with selective modulation and power control to improve the data delivery over the trunk link between the cluster head and BS and minimize packet delay during transmission over V2I links. The analysis demonstrated the protocol efficiency in supporting high mobility VANET by improving cluster stability and QoS performance regarding BER, SNR, and throughput. However, node mobility may pose more challenges in real-time applications.

SDGR [154] utilizes node position, traffic density, and digital map to determine the optimal routing paths and avoid connectivity issues such as local maximum and sparse disconnections. The protocol was compared to AODV and GPSR protocols regarding PDR and delay, using a moderate

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number of vehicles (50 to 200). However, further analysis and evidence are needed to confirm its suitability for sparse VANETs. dSDiVN [155] deploys mobile SDN controllers to fill the gap of the lack of SDN in infrastructure-less VANET areas. Even though the protocol shows high reliability in mathematical simulation, further experimentation is needed to confirm the protocol's efficiency regarding latency, throughput, and routing overhead. HSDVR [156] uses a clustering technique to address the potential disconnections with the main SDN controller. The protocol is simulated and evaluated in an urban scenario using several metrics, including PDR, E2E delay, throughput, and routing overhead. However, further evaluations are needed to verify the protocol's reliability in various situations, such as partial RSU distribution and correlated mobility patterns. SVAO [110] leverages SDN to improve transmission efficiency by utilizing a two-level design to find the road segments and routing path along which a packet should be forwarded. The protocol is evaluated through simulations and compared to OLSR, DSR, DSDV, and DB routing protocols. It considers the influence of node density and velocity on the data transmission rate and average delay. However, due to a slight change made to traditional AODV, the protocol generates many control packets in the event of a link failure as the network density increases.

IDVR [157] utilizes a centralized SDN to collect real-time traffic knowledge and select the optimal routing path from a set of candidate shortest paths. The protocol is evaluated and compared to other protocols, including IRTIV, VDLA, and GPCR, using E2E delay and throughput metrics. However, the computation of multiple paths may lead to high overhead on the SDN controller, which requires further optimization. CESDT [158] leverages service bandwidth requirements to schedule and route transmission requests over multiple paths of various network interfaces in heterogeneous vehicular networks. To evaluate its performance, a prototype urban traffic monitoring application is developed that collects overall traffic conditions from crowd-sourced taxi traces in Shenzhen, China. The protocol is evaluated using PDR and compared to OLSR and GPSR. Other QoS metrics were not considered in evaluating the protocol's effectiveness. Besides, data offloading over multiple interfaces may cause more delays and complexity. Pretti [159] applies SDN and trajectory prediction to minimize communication costs and ensure message delivery for multicast data routing. Extensive experiments are conducted using different traffic scenarios. While the evaluation demonstrates the protocol's effectiveness in various scenarios in terms of latency and PDR, there is room for improvement regarding message validity and node mobility considerations.

CDSRP [160] presented an SDN-based scheduling and routing algorithm for data dissemination over hybrid I2V and V2V communication links. The protocol is simulated, and its performance is evaluated under various traffic situations using various metrics such as scalability gain, broadcast productivity, gains distribution, delivery rate, and latency. However, further examination at the MAC layer is needed to validate the model in real-time VANET situations. CRP [108] protocol represents one of the early works that deal with SDN in VANET routing. The algorithm leverages global network information to determine the routing path with minimum delay and low overhead in dynamic network density. While this model increases protocol adaptability with various scenarios in VANETs, the calculation of the next hop may generate high delay and controller overhead. The protocol is evaluated regarding PDR, E2E delay, and routing overhead. However, the impact of high mobility on routing computation was not considered in the performance analysis.

Spray-and-Prey [107] protocol utilizes centralized SDN to generate multiple copies of data in the network. The network overhead and buffer expenses are minimized by removing other copies in the network when a single copy reaches the intended destination. While this protocol reduces packet latency and network resource costs, the delay and bandwidth utilization will increase with the number of nodes. GeoBroadcast [9] implements a module to automatically control the geographical places of RSUs to be used as a basis for data forwarding. The performance analysis showed its efficiency in reducing the controller overhead and bandwidth consumption with minimum delay. However, the protocol did not analyze the key challenges of VANET, such as high mobility and low density.

However, Fig. 18 presents the statistical analysis of standard metrics used for performance evaluation in the reviewed works. It is observed that most of the works use metrics such as E2E delay, PDR, throughput, overhead, and network load to analyze the routing protocols.

Moreover, a statistical study on the optimization parameters used to improve the reviewed works in this survey has been conducted. As depicted in Figure 19, delay minimization is the most significant parameter for routing protocol optimization, owing to the critical importance of delivering data packets with the least possible delay for safety-related services. Routing protocols such as SPIDER, CDRS, TDCR, CLR-SDVN, Pretti, and CDSRP prioritize delay optimization.

Furthermore, protocols such as PT-GROUT, POLAR, ERA, CRS-MP, and VDR-DRL consider communication distance a key parameter due to its impact on link reliability and data delivery. So, the optimal selection of the next relay can minimize packet loss and increase reliability. However, the protocols considering this optimization parameter use several parameters and constraints, such as node mobility, communication distance, and buffer size. DMPFS, CCDEC, SeScR, SD-IoV, and HRLB are examples of such protocols.

Regarding overhead control, the reviewed algorithms can be divided into two classes. Some protocols aim to optimize the overhead of the SDN controller through hierarchical control architecture or load balancing, such as ICDRP-F-SDVN, TRIBRID, SVAO, SURFER, SDVN-GRA, CTDD, and ORUR protocols. Others optimize the overhead by utilizing mobility prediction to minimize the number of exchanged beacons, such as IM-DOS, SPIDER, ERA, SD-IoV, and SESAC protocols.

However, other optimization parameters have received less attention from researchers due to the difficulty of modeling these parameters or the lack of sufficient data from the network infrastructure. Therefore, it is necessary to intensify efforts to optimize protocols with more parameters to create more reliable protocols that can adapt to different network situations and communication requirements.

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TABLE 4.
Characteristics of SDVN routing schemes. The symbols “SP”, “MP”, “U”, “MC”, “B”, “L”, “M”, “H”, “D”, S”, ✓, “-“and × indicate single path, multi-path, unicast, multicast, broadcast, low, medium, and high, dense, sparse, included, un-included, and un-mentioned respectively.

Protocol	Year	Category	SDN Architecture	Data Transmission Paths	Network Topology Maintenance	Transmission Mode	Communication Model	Routing Algorithm	Communication overhead	Network Connectivity	Message priority	Complexity	Scalability	Communication Reliability	Applications Data
ICDRP-F-SDVN	2022	Hierarchal SDN	Hybrid	SP	Adaptive Beacon	U/B	V2V	Greedy, AODV	M	D	×	M	H	H	Safety
SDVN-MiCR		Cluster	Centralized	SP	Beacon	B	V2I, V2V	N/A	L	D	×	M	M	L	Safety
CDRS		Hybrid SDN	Hybrid	SP	Beacon	U/B	V2V/V2I	Graph based	M	-	✓	H	H	M	Infotainment
DMPFS		Multicast	Distributed	SP	Beacon	MC	V2I	N/A	H	D	✓	H	L	M	Safety
PT-GROUT	2021	Predication	H-SDVN	SP	Beacon	U	V2V, V2I	earliest-arrival	L	D	×	H	H	H	Safety
SPIDER		Centralized SDN	Centralized	SP	Beacon	U	V2V	Graph-Based	H	-	×	H	H	H	N/A
GLS		Geo-Based	Centralized	SP	Beacon	U	V2V	Greedy	H	D	✓	M	L	H	N/A
SELAR		Geo-Based	Centralized	MP	Beacon	U/B	V2V	N/A	H	-	×	L	L	H	Both
POLAR		Bio-inspired	Hybrid	SP	Beacon	U	V2V	Multiple	H	S	×	H	H	L	N/A
SURFER		Secure	Distributed	MP	Beacon	U	V2V, V2I	N/A	M	S	×	M	H	M	N/A
CCDEC		Multicast	Hierarchal	SP	Beacon	MC	V2V, V2I	Greedy	H	D	×	H	H	H	N/A
SFRS	2020	Hybrid SDN	Hybrid	SP	Beacon	U	V2V, V2I	Greedy	H	D	×	L	M	H	Both
ERA		Geo-Based	Centralized	SP	Beacon	U	V2V	N/A	H	D	×	M	L	H	N/A
IM-DOS		ML-Based	Centralized	MP	Beacon	U	V2V	Dijkstra	M	D	×	H	L	H	N/A
HSDN-GRA		Geo-Based	hybrid	SP	Beacon	U	V2V	N/A	H	D	×	M	M	H	Both
ACA-RP-SDVN		Bio-Inspired	Distributed	SP	Beacon	U	V2V	Greedy	L	D	×	H	H	L	Safety
TDCR		Cluster	Hybrid	SP	Beacon	U	V2V, V2I	Dijkstra	M	D	×	M	M	H	Both
SeScR		ML-Based	Hybrid	MP	Beacon	U	V2V	Graph-Based	L	D	×	H	H	N	N/A
V-TLRH		Beacon-Based	Centralized	SP	Adaptive Beacon	U	V2I	Dijkstra	M	D	×	M	L	L	N/A
SDMEV		Hierarchal SDN	Distributed	SP	Beacon	B	V2V, V2I	N/A	L	D	×	H	M	L	Safety
TRIBRID	2019	Hybrid SDN	Distributed	MP	Beacon	U/B	V2V	Bi-SPF, SCF	L	S	×	H	H	M	N/A
SD-IoV		Hybrid SDN	centralized	SP	Semi Beacon	U	V2V	Greedy	L	D	×	M	L	H	Both
QRA		Bio-Inspired	distributed	MP	Beacon	U	V2V	Greedy	M	D	×	M	M	H	Both
VDR-DRL		ML-based	centralized	SP	Beacon	U	V2I, V2V	Greedy	M	-	×	H	L	L	N/A
CLHLB		Unicast	Centralized	MP	Beacon	U	V2V, V2I	N/A	M	S	×	L	H	M	N/A
MFCAR		Geo-less	Hierarchy	SP	Beacon	U	V2V, V2I	uniform search	L	D	×	M	L	M	Both
NSDD-SDVN		Single path	distributed	SP	N/A	U	V2V	N/A	M	D	✓	L	H	L	Both
CRS-MP		Geo-less	Centralized	SP	Beacon	U	V2V, V2I	N/A	L	D	✓	M	L	L	Safety
CLR-SDVN		Reactive	Distributed	SP	Beacon	U	V2V	N/A	H	D	✓	M	H	H	Both
IMCR		Cluster	Distributed	SP	Semi-Beacon	U	V2V	N/A	L	D	×	M	H	L	Both
CTDD		Reactive	Centralized	MP	Beacon	B	V2I	N/A	M	D	✓	M	L	L	Both
LSB-OR		MP	Hybrid	MP	Beacon	U	V2V	Dijkstra	M	D	×	M	H	H	Safety
LBR	2018	Unicast	Centralized	SP	Beacon	U	V2I	N/A	L	S	×	M	L	M	N/A
SDCoR		Hybrid Conn.	Centralized	SP	Beacon	U	V2V, V2I	AODV, GPSR	L	S	×	M	L	M	N/A
Geo-SDVN		Broadcast	Centralized	SP	Beacon	B	V2V	depthfirst search	H	S	×	M	L	L	Safety
HRLB		Dense Network	Centralized	MP	Beacon	U	V2V	N/A	M	S	×	H	L	M	N/A
SESAC		Predication	Centralized	SP	Beacon	U	V2V, V2I	N/A	L	D	×	H	L	L	N/A
LT-NSR		Reactive	Centralized	SP	Beacon	U	V2V	N/A	M	S	×	L	H	H	N/A
CR-SDVN		Centralized	Distributed	SP	Beacon	U	V2V, V2I	N/A	M	D	×	M	H	H	Both
FR-PU		Proactive	Centralized	SP	Beacon	U	V2V	MFR	H	D	×	L	L	L	Safety
ORUR		Geo-Based	Centralized	SP	Beacon	B	V2I	N/A	H	D	×	L	L	L	Safety
SCGRP	2017	Beacon-Based	Centralized	SP	Beacon	U/B	V2V	N/A	H	D	×	L	L	M	N/A
SD-TAODV		Secure	Centralized	SP	Beacon	U/B	V2V	AODV	H	D	×	M	L	L	N/A
AVC-BTAT		Cluster	Centralized	SP	Beacon	U	V2V, V2I	N/A	L	-	×	H	M	H	N/A
SDGR		Dense Conn.	Centralized	SP	Beacon	U	V2V	Dijkstra	H	D	×	M	L	L	N/A
dSDiVN		Sparse Conn.	Distributed	SP	Beacon	U/B	V2V	N/A	H	S	×	M	H	H	Safety
HSDVR		Cluster	Hierarchal	SP	Beacon	U/B	V2V, V2I	N/A	L	D	×	M	H	L	N/A
SVAO		Reactive	Distributed	SP	Beacon	U	V2V	Bellman–Ford	M	D	×	L	M	L	N/A
IDVR		Multiple paths	Centralized	MP	beacon	U	V2V	Dijkstra	M	D	×	M	L	L	N/A
CESDT	2016	MP	Centralized	MP	Predication	U	V2V	Exhaust. search	L	-	×	M	L	M	N/A
Pretti		Multicast	Centralized	MP	Predication	MC	V2V	Time-based path	L	D	×	H	L	L	Safety
CDSRP		Reactive	Distributed	SP	Beacon	U/B	V2V, V2I	Greedy	L	D	✓	L	H	L	Safety
CRP	2015	Hybrid Conn.	Centralized	SP	Beacon	U	V2V	Dijkstra	H	D	×	L	L	L	Both
Spray-and-Prey		SP	Centralized	SP	Beacon	B	V2V	Dijkstra	H	D	×	L	L	L	N/A
GeoBroadcast		Broadcast	Centralized	SP	Beacon	B	V2I	N/A	M	-	×	L	L	L	Safety

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TABLE 5.
SUMMARY OF KEY FEATURES OF SDVN ROUTING PROTOCOLS.

Protocol	Performance Objective	Innovative Idea	Supported Techniques
ICDRP-F-SDVN	Maximize throughput and minimize latency with the number of control messages.	Using FC with SDN for VANET data routing. Develop communication overhead minimization mechanism.	Fog Computing
SDVN-MiCR	Data Routing with high reliability and low delay in highway scenarios.	Using federated K-means algorithm to create continuous clusters.	5G, Federated K-means
CDRS	Maximize PDR with least average service time and congestion degree.	Combination of routing and scheduling in one optimization model.	N/A
DMPFS	Reduce multicast routing delay and bandwidth utilization.	Use parked vehicles as fog node.	Fog Computing
PT-GROUT	Guarantee the quality and efficiency of routing computation. Minimize the time of routing computation.	Using temporal graphs for finding routing decisions.	N/A
SPIDER	Provide stable routing paths in SDVNs with latency minimization.	Find the similarities among vehicles using SC and one-shot prediction	Social computing (SC)
GLS	Find a stable route that maintain short delay along with high PDR.	Considering both histrionics routing experiences and real-time traffic conditions in data routing.	RL
SELAR	Reduce energy consumption and satisfy BW and delay constraints.	Energy optimization through switching off the unused RSUs nodes.	5G, Fog Computing
POLAR	improved PDR and E2E delay in various VANET scenarios.	Using PRA with hybrid SDVN to select the best routing model.	5G, MEC, PRA
SURFER	Capitalize the efficiency and security of data routing in IoV.	Using blockchain with SDN in securing IoV data routing.	Blockchain
CCDEC	High scalability and fully utilization of the allocated computing resources.	SDVN based cooperative data sharing model in 5G-VANET along with the integration of MEC capabilities	MEC, 5G
SFRS	Improve data transmission with decrease packet loss rate.	Using roadside switches to make a switchable routing decision.	Fog Computing
ERA	Reduce the control message overhead with PDR improvement	Using multiple MEC to reduce the overhead on SDN controller.	MEC, ANN
IM-DOS	Find the most reachable path with less congestion, and high PDR	Using IMN concept in social computing to select the optimal routes.	MLP, Social computing
HSDN-GRA	Overcome the lack of connectivity by choose the optimal relays based on multi-constraints.	Consider link reliability, load balancing, and communication error logs in optimal relays selection.	N/A
ACA-RP-SDVN	Select the optimal intersection-based route toward the destination.	Using ant colony to search the optimal route toward the destination.	Ant colony
TDCR	Optimize QoS and make a tradeoff between cellular bandwidth cost and E2E delay.	Using heuristic algorithm to find the optimal solution of a tradeoff between cellular bandwidth & multi-hop E2E delay.	C-V2X
SeScR	Enhance cluster stability and route selection method.	SDN enabled spectral clustering-based routing using DDPG.	DRL
V-TLRH	Perform fast & uninterrupted data routing in SDVN-MEC architecture.	Using MEC for data routing independently in SDN-MEC-VANET.	MEC
SDMEV	Meet the latency requirements settled by 3GPP for V2X services in C-V2X communication	Using clustering technique in SDN-MEC framework for data routing.	Fuzzy, MEC
TRIBRID	Finding stable and shortest routes to deliver a given set of packets with minimum latency.	Comprising both centralized and distributed routing models for unicast, broadcast, and SCF data delivery.	N/A
SD-IoV	Select stable communication links and overcome mobility issues.	Using average number of hops, link connectivity, and vehicles direction/velocity in data routing decisions.	MEC
QRA	Using the most reliable and connected paths.	Using LCA to find optimal route based on QoS parameters	LCA
VDR-DRL	Improve the efficiency and throughput of VANET network.	Using DRL to select two CHs, one for delivering RSU data using V2I and another one for V2V data distribution.	DRL
CLHLB	Find excellent transmission performance at various vehicle densities.	Mutual cooperation of V2I routing and V2V cross-layer routing.	N/A
MFCAR	Choose short and uncongested V2V paths for data routing.	Adapting congestion insensitivity parameter in data routing.	N/A
NSDD-SDVN	Find stable routing paths under various application requirements.	Using two-stage Stackelberg game theory to find stable links.	Game-theory
CRS-MP	Minimize the overall delay in comparison with V2I and V2V mode.	Using BANN for mobility predication in distributed SDN architecture.	ANN
CLR-SDVN	Provide stable communication with spectrum scarcity and recurrently connected networks.	The path is selected using forwarding probability, existing BW, and link duration.	N/A
IMCR	Reduce the signal processing overhead with QoS improvement.	Using influence maximization algorithm for double HCs selection.	N/A
CTDD	Maximize the number of routing requests completing within less delay.	Adopting priority-based scheduling with data routing in SDVN.	N/A
LSB-OR	Find multiple shortest, stable paths to deliver a given packets number.	Use source routing-based FI operation with modified flowmod message.	N/A
LBR	Avoid re-routing waste by accelerating the forwarding rules when a link is interrupted.	Using link available time prediction for data routing in high-speed SDVN-I2V communications.	N/A
SDCoR	Achieve the good routing performance of IoV based on various network scenarios in the space-time dimension.	Using RL with SDN controller to select the optimal routing protocol suited for vehicular environment adaptively.	RL
GEO-SDVN	Increase nodes accessibility and connectivity with increasing the PDR.	Minimize RSUs number with transmission power consideration.	N/A
HRLB	Find optimal, stable routing with load balancing in SDVN.	Create of two parallel routing paths: main and backup route.	N/A
SESAC	Improve cluster stability and increase CH lifetime.	Using a social pattern prediction model to predict vehicles' future routes and the corresponding sojourn time on each segment.	5G
LT-NSR	Find V2V routing path that has the longest life time based on the current network topology.	Using MEC with SDVN to provide central routing method using cellular and V2V communications.	MEC
CR-SDVN	Select the best routing path that maximizes the path duration among all the paths.	Combine a radio cognitive capability with a routing technique by using the SDN-based VANET approach.	Cognitive Radio
FR-PU	Find a reliable shortest path with continuously routes maintaining.	Using vehicle's mobility to find the routing paths duration proactively.	N/A
ORUR	Selecting a shortest routing path with load balancing over the whole urban road segments.	SDVN-Cloud-based routing model with consideration of other already used routing paths in VANET.	Cloud
SCGRP	Selection the optimal forwarding node with longer link life time.	Utilize digital map with SDN global view to route the packets on a more connected shortest routing path.	N/A
SD-TAODV	Improve the VANET performance and data security.	Using trust model with routing process to enhance data security.	N/A
AVC-BTAT	The signaling overhead of a VANET is significantly reduced along with improved communication quality.	Selective modulation and power control is used to improve the capacity of CH-BS link.	5G, MIMO
SDGR	Provide optimal routing paths and avoid local maximum and sparse connectivity problems.	Next hop packet decision is taken by vehicles. Provide Congestion detection mechanism for balancing load.	N/A
dSDiVN	Bridge the gap of no SDN-based architecture in infrastructure-less VANET zones	A distributed SDN-based clustered architecture for infrastructure-less VANETs with mobile multi-controllers.	N/A
HSDVR	Improve the QoS performance in the situation of loss of connection.	Using clustering technique to provide connectivity re-establishment when disconnection occurs.	N/A
SVAO	Enhance VANET data transmission efficiency with link reliability.	Using hierarchical query strategy to reduce the query time.	N/A
IDVR	Increase network efficiency, by increasing the throughput, and decreasing end-to-end delay.	Find optimal route using nodes' location, and the maximum of the minimum throughput among the shortest paths.	N/A
CESDT	Ensure a low overhead by finding optimal network interfaces satisfying services bandwidth requirements.	Scheduling and routing transmission requests over multiple-paths of various network interfaces.	N/A
Pretti	Minimize communication cost and guarantee data delivery threshold for multicast VANETs.	Generate a time dependent shortest path tree to model the connection of every multicast node with the source.	N/A
CDSRP	Maximize the number of vehicles that can be served over I2V or V2V.	Online scheduling with hybrid data routing using I2V and V2V links.	N/A
CRP	Optimize the packet delivery delay and minimize routing overhead	Using MOT algorithm to measure the minimum time for any vehicle to transmit a packet to another one.	N/A
Spray-and-Prey	Spray multiple-copies of message to increase the PDR.	Use spray and prey method for packet forwarding to next relay based.	N/A
GeoBroadcast	Minimizing controller overhead and network bandwidth consumption.	Automatically manage the GPS location of RSUs to use in data routing.	N/A

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TABLE **6.**
COMPARISON OF PERFORMANCE METRICS AND TECHNIQUES USED IN SDVN ROUTING PROTOCOLS. THE SYMBOL ✓ INDICATES THAT THE METRIC IS INCLUDED; THE BLANK SPACE INDICATES THE METRIC HAS NOT BEEN INCLUDED.

Protocol	**End-to-End Delay**	**Packet Delivery Ratio**	**Packet Loss Ratio**	**Throughput**	**Bit Error Rate**	**Jitter**	**Routing Overhead**	**Connectivity Probability**	**Network Load**	**Normalized Routing Load**	**Average Routing Reply Ratio**	**Average Routing Discovery Time**	**Routing Request Ratio**	**Link Failure**	**Percentage Idle Time**	**Route Lifetime**	**Availability of Recovery Process**	**Routing Maintenance**	**DTN Support**	**Scoring Technique**	**Flooding Mitigation Concern**	**QoS Support**	**AI Adoption**
ICDRP-F-SDVN	✓	✓		✓			✓										✓	✓					
SDVN-MiCR	✓	✓	✓				✓		✓								✓	✓			✓		✓
CDRS	✓	✓	✓									✓		✓	✓	✓							
DMPFS	✓	✓					✓			✓								✓				✓	
PT-GROUT	✓	✓				✓		✓		✓		✓	✓				✓			✓		✓	✓
SPIDER	✓	✓				✓								✓		✓						✓	✓
GLS	✓	✓					✓							✓						✓			✓
SELAR									✓					✓		✓	✓	✓					
POLAR	✓	✓						✓														✓	✓
SURFER	✓	✓					✓				✓	✓	✓						✓				
CCDEC	✓						✓				✓												
SFRS	✓	✓	✓				✓		✓				✓	✓			✓		✓	✓			
ERA		✓						✓	✓				✓	✓		✓							✓
IM-DOS		✓							✓	✓				✓		✓							✓
HSDN-GRA		✓	✓	✓			✓			✓													✓
ACA-RP-SDVN	✓											✓	✓										✓
TDCR	✓			✓			✓		✓	✓											✓	✓	
SeScR	✓			✓			✓														✓		✓
V-TLRH		✓									✓	✓										✓	
SDMEV	✓	✓		✓					✓														✓
TRIBRID	✓	✓					✓	✓								✓	✓	✓	✓				
SD-IoV	✓	✓					✓	✓						✓		✓		✓		✓			
QRA	✓	✓					✓		✓											✓		✓	✓
VDR-DRL				✓			✓	✓															✓
CLHLB	✓	✓						✓												✓			
MFCAR	✓	✓		✓																		✓	
NSDD-SDV	✓	✓		✓			✓		✓	✓												✓	✓
CRS-MP	✓							✓												✓			✓
CLR-SDVN	✓		✓	✓			✓							✓		✓	✓	✓				✓	
IMCR	✓		✓				✓																
CTDD	✓									✓	✓		✓										
LSB-OR	✓	✓					✓					✓				✓						✓	
LBR		✓						✓								✓						✓	
SDCoR		✓																				✓	✓
GEO-SDVN		✓					✓											✓					
HRLB	✓	✓		✓			✓							✓			✓	✓	✓	✓		✓	
SESAC		✓					✓			✓													✓
LT-NSR		✓		✓					✓	✓				✓		✓		✓					
CR-SDVN	✓	✓					✓												✓				
FR-PU	✓	✓					✓							✓		✓		✓					
ORUR	✓											✓	✓					✓				✓	
SCGRP	✓	✓	✓							✓				✓			✓						
SD-TAODV	✓			✓			✓																
AVC-BTAT				✓	✓		✓		✓									✓				✓	
SDGR	✓	✓						✓												✓			
dSDiVN	✓	✓						✓	✓		✓	✓	✓	✓			✓	✓		✓			
HSDVR	✓	✓		✓			✓		✓									✓			✓		
SVAO	✓	✓																					
IDVR	✓			✓			✓												✓	✓		✓	
CESDT	✓	✓		✓			✓		✓												✓	✓	
Pretti	✓								✓													✓	✓
CDSRP	✓	✓		✓				✓	✓												✓		
CRP	✓	✓					✓												✓				
Spray-&-Prey	✓	✓								✓													
GeoBroadcast		✓					✓		✓												✓		

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TABLE **7.**
OPTIMIZATION PARAMETERS USED IN THE EXISTING ROUTING PROTOCOLS FOR SDN-BASED VANETS. THE SYMBOL ✓ INDICATES THAT THE PARAMETER IS INCLUDED; THE BLANK SPACE INDICATES THE PARAMETER HAS NOT BEEN INCLUDED.

Protocol	Delay Optimization	Quality of Neighbors	Link Reliability	Hop Count Accountability	Vehicles Clustering	Zone Segmentation	RSU Needs Consideration	Road intersection consideration	Communication Distance Consider	Localization Inf. Requirements	Traffic Density Awareness	Mobility Predication Consideration	Security Consideration	Vehicles Mobility Concern	Increased Requests Efficiency	Fault Tolerance	Traffic Condition Adaptability	Multi-Constraints Decisions	Context Awareness	Overhead Control	Node Energy Awareness	Load Balancing
DRP-F-SDVN	✓	✓			✓	✓	✓		✓	✓						✓				✓		
SDVN-MiCR	✓			✓	✓				✓	✓				✓	✓					✓		
CDRS	✓						✓								✓	✓		✓				✓
DMPFS	✓	✓				✓	✓			✓					✓	✓		✓	✓	✓		
PT-GROUT	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		✓				✓				
SPIDER	✓	✓	✓						✓	✓		✓		✓				✓	✓		✓	
GLS	✓	✓	✓			✓		✓	✓	✓	✓			✓				✓				
SELAR		✓	✓						✓	✓				✓		✓		✓			✓	✓
POLAR	✓					✓	✓	✓	✓	✓	✓			✓			✓	✓	✓			
SURFER	✓						✓			✓			✓									✓
CCDEC		✓					✓			✓									✓	✓	✓	✓
SFRS	✓						✓	✓	✓	✓	✓					✓						
ERA			✓	✓			✓		✓	✓		✓		✓			✓		✓			
IM-DOS	✓	✓	✓	✓			✓		✓	✓				✓					✓			
HSDN-GRA		✓	✓		✓				✓	✓				✓	✓			✓		✓		✓
ACA-RP-SDVN	✓					✓	✓	✓			✓											
TDCR	✓	✓		✓	✓				✓					✓	✓			✓		✓		
SeScR	✓	✓			✓		✓		✓	✓				✓				✓		✓		
V-TLRH			✓			✓	✓			✓				✓								
SDMEV	✓				✓	✓	✓			✓					✓							
TRIBRID	✓		✓	✓			✓		✓	✓	✓			✓		✓	✓	✓				
SD-IoV	✓	✓	✓	✓		✓	✓	✓	✓	✓		✓		✓				✓		✓		
QRA	✓	✓				✓	✓	✓	✓	✓					✓		✓	✓		✓		
VDR-DRL			✓	✓	✓	✓	✓	✓	✓	✓												
CLHLB	✓	✓					✓			✓	✓						✓	✓	✓			✓
MFCAR	✓	✓		✓														✓				
NSDD-SDVN			✓				✓		✓		✓						✓		✓	✓		✓
CRS-MP	✓					✓	✓	✓	✓			✓					✓					
CLR-SDVN	✓	✓	✓	✓		✓	✓		✓	✓						✓		✓				
IMCR	✓	✓			✓															✓		
CTDD	✓						✓			✓					✓	✓						✓
LSB-OR	✓	✓	✓	✓		✓				✓										✓		
LBR	✓		✓				✓		✓	✓				✓								
SDCoR										✓	✓			✓			✓		✓			
GEO-SDVN	✓					✓				✓	✓									✓		
HRLB		✓		✓		✓			✓	✓	✓				✓		✓			✓		✓
SESAC		✓			✓	✓			✓	✓									✓	✓		
LT-NSR		✓	✓			✓			✓	✓				✓		✓			✓			✓
CR-SDVN	✓			✓			✓		✓	✓										✓		
FR-PU		✓		✓				✓	✓	✓				✓		✓		✓				
ORUR	✓			✓		✓	✓	✓		✓	✓											✓
SCGRP		✓		✓			✓	✓	✓	✓	✓			✓		✓	✓	✓				
SD-TAODV				✓									✓									
AVC-BTAT	✓				✓	✓			✓	✓										✓		
SDGR	✓			✓		✓	✓	✓	✓	✓	✓			✓			✓	✓	✓			✓
dSDiVN	✓				✓	✓				✓	✓					✓						
HSDVR	✓				✓		✓													✓		
SVAO	✓					✓	✓	✓	✓	✓												
IDVR	✓			✓		✓		✓		✓										✓		
CESDT	✓	✓										✓								✓		✓
Pretti	✓	✓										✓							✓			
CDSRP	✓	✓					✓		✓	✓					✓					✓		
CRP	✓								✓	✓	✓							✓		✓		
Spray-&-Prey				✓					✓	✓					✓			✓				
GeoBroadcast				✓			✓			✓					✓					✓		✓

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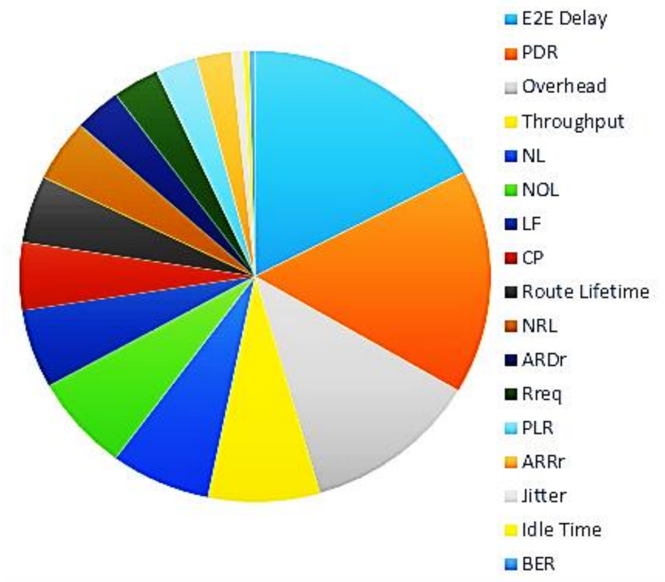

FIGURE 18. The statistical analysis of standard QoS metrics used for performance evaluation in the reviewed protocols.

B. EVALUATION TOOLS AND TESTBEDS USED IN RESULTS ANALYSIS.

Now, we focus on the simulation tools used to analyze the effectiveness of the techniques reviewed in section V. Table 8 compares the reviewed protocols regarding performance evaluation and analysis techniques employed. Since the VANET routing protocols are a highly interdisciplinary field, they require flexible tools for performance evaluation. These tools should be adaptable to various domains, including network design, communication strategies, optimization theory, and emerging fields like ML, stochastic geometry, and game theory [161].

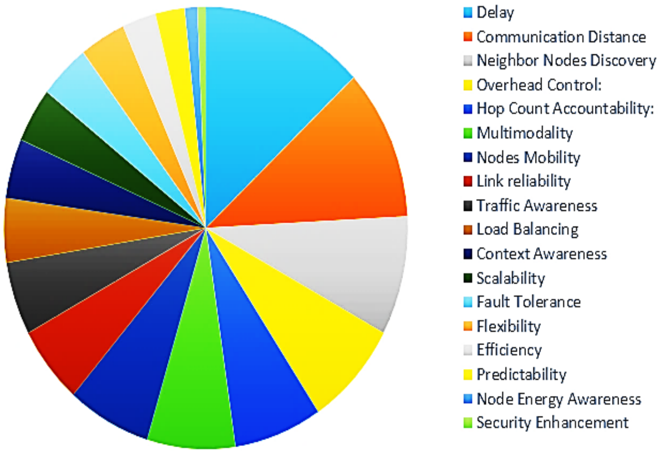

FIGURE 19. Optimization parameters used in reviewed SDVN routing protocols.

Network simulators help researchers investigate a network's operation under varying situations that might be challenging or expensive to realize using real systems and entities, specifically in the context of VANETs. So, they are mainly focused on testing new protocols or proposing modifications to current ones in a controlled and repeatable fashion [162]. Compared to the time and expense of establishing a complete real-time testbed, network simulators are moderately fast and affordable. Consequently, conducting extensive real-world experiments with SDVN routing is inherently challenging and severely limited due to various factors, including cost, regulations, time limitations, and the necessity of open space [163], [164]. As a result, researchers rely heavily on simulators and emulators to assess the effectiveness of their routing algorithms by utilizing comparable or identical traffic scenarios and management levels. Unfortunately, only a limited number of simulators offer support for SDN in the VANET environment [164]. For example, NetSim ver.11 has a module that supports the use of SDN in implementing VANET protocols [163], [164]. Regarding the Veins simulator, due to its compatibility and OpenFlow module integration, numerous papers have employed it in the context of SDVN [165]. Eclipse MOSAIC is a powerful tool combining multiple simulators in a single package to model and evaluate ITS solutions. However, we have not found substantial research on using this simulator for SDVN routing [162]. Also, no research is related to using the VENTOS simulator in SDVN routing [166]. Furthermore, there is no mention of SDN support in the documentation of VANETsim simulator that comes with built-in modules. So, it poses a challenge in extending the simulator to accommodate emerging technologies [167].

Fig. 20 illustrates a statistical analysis of the most utilized simulation tools and testbeds employed to assess SDVN data routing. The graph highlights that most researchers rely on the NS3 simulator to validate their proposals. Besides, Python, OMNET++, and Matlab were the secondary options for most researchers to test their protocols.

In terms of testbeds, only a few studies utilized them to explore the application of SDVN data routing [164]. Testbeds integrate various SDN features to enable researchers to test protocols under authentic conditions and obtain experiment results. However, there are several limitations to conducting such realistic experiments in SDVN models, which include:

1. Security challenges of deploying protocols.
2. Weather situations.
3. Communication channels issues.
4. The cost of used infrastructures.
5. Network infrastructure adaptability and compatibility.
6. The challenge of retrieving data from the network.

Therefore, tackling all these problems and obstacles is essential when utilizing realistic experiments. Another approach is to create alternative simulation tools that enable researchers to effectively assess various VANET scenarios and SDN programmability. Such tools must simulate mobility patterns and networking protocols with more realistic parameters to reach good results.

Several mobility simulators are available for evaluating and modeling traffic systems, including SUMO [168], VISSIM [169], SimMobility [170], and PARAMICS [171]. SUMO, an open-source traffic simulation application, has gained popularity in recent decades. Given its high efficiency and compatibility, SUMO is widely used in traffic modeling in VANET routing works. It can model various types of vehicles, public transport, and even pedestrians in traffic systems. Additionally, it provides accurate vehicle traces in any map imported into the system, such as open street maps.

TABLE **8.**
COMPARISON OF PERFORMANCE EVALUATION AND RESULT ANALYSIS TECHNIQUES.

Protocol	**Simulator**	**Simulation Time (Sec)**	**Simulation Area (km^2)**	**Scenario Area**	**Number of Vehicles**	**Nodes Velocity (km/h)**	**Communication Range (m)**	**Payload (Bytes)**	**Compared Routing Protocols**
ICDRP-F-SDVN	NS3, Sumo, RYU	180	4 x 4	Both	10-100	20-50	250	512	IDVR, VDLA, MoZo, IRTIV, GPCR, CORA, BRAVE, CBDRP
SDVN-MiCR	NS3, Sumo	6000	2.5 x 0.5	Highway	100-800	20-150	400	512	ABGR, TB-EM, BBPSO, DCRB.
CDRS	Matlab, Sumo, C++, NS3	200	N/A	Urban	5-25	0-40	200	32, 56	SPA, LSP, FCFS, MRF, CDD
DMPFS	Omnet ++, Sumo, Veins	900	N/A	Urban	6000	20-80	N/A	N/A	DTMR, MABC
PT-GROUT	NS3, Sumo, Python	300	2.6 × 1.4	Urban	100-500	0-60	500	1024	PRHMM, Dijkstra, HRLB,
SPIDER	Sumo, Python	100	120x100	Urban.	200-600	1-60	250	1024/256	TSD, IM-DOS, CT, Greedy algorithm.
GLS	Sumo	500	3 x 3	Urban.	800-2400	0-80	300	N/A	HRLB, QGrid
SELAR	Python, Mininet.	N/A	0.1 x 0.1	Urban.	5-100	N/A	N/A	N/A	N/A
POLAR	NS3, Sumo,	N/A	1.5 x 1.5	Urban	50-250	30-90	250	512	AODV, OLSR, GPSR, DSR, OLAR, DSDV
SURFER	NS3, Sumo,	1000	18.6 x 11.4	Urban	5k-50k	30-150	300	1-50	QRA, SD-IoV
CCDEC	NS3, Sumo	N/A	N/A	Urban	45-400	N/A	100	N/A	PMC, N-HOP, Random Greedy
SFRS	NS2, Sumo	300	3 x 2	urban	50-150	N/A	250	512	AODV, GPSR, IGR, SFIR.
ERA	Mininet, Sumo, Python	500	3 x 3.5	urban	200	20-90	200	512	AODV, GPSR, SDGR
IM-DOS	Python, Sumo	N/A	3 x 1.5	Urban	200-600	1-60	250	N/A	Dijkstra, TDS
HSDN-GRA	Matlab	80	1.5 x 1.5	Urban	10-50	0-100	150	N/A	MA-DSDV, PSO-C-MA-DSDV
ACA-RP-SDVN	Matlab	50	0.5 x 3.5	Urban	10-40	20-80	150	N/A	AODV, GPSR
TDCR	C++	N/A	2 x 0.04	Urban	N/A	60-100	200	512	N/A
SeScR	OMNeT++, Sumo	600	10 x 10	Urban	25-200	0-108	300	512	DMMCA, DDRL, DABFS, MFCAR, RSAR
V-TLRH	NS3, Sumo	N/A	0.5 x 0.5	Urban	30-90	20-80	150	1000	Pro-AODV, IGPSR, IR
SDMEV	OMNeT++, Veins, Sumo	400	5 x 5	Urban	100-500	40-110	N/A	N/A	GPSR, HDSV, SDVN
TRIBRID	NS3, Sumo	400	1.5 x 1.5	Urban	20-100	N/A	200	1500	SHORTEST, ROMSGP, SCF
SD-IoV	Mininet, Sumo	1200	3 x 3	Urban	20-200	0-90	N/A	512	SCGRP, HRAR
QRA	NS3, Sumo	500	9.2 x 5.7	Urban	50-550	0-50	350	512	GPSR, CRP
VDR-DRL	N/A	N/A	N/A	Urban	100-500	60-100	250	N/A	N/A
CLHLB	NS3	50	2 x 2	Urban	80-200	0-40	300	1024	GPSR, CLWPR, IAR
MFCAR	NS3, Sumo	N/A	1 x 1	Urban	150-400	30-50	N/A	1024	Dijkstra
NSDD-SDVN	NS3, Sumo	200	2 x 2	Urban	100-500	18-90	350	1024	HSDV, GPSR
CRS-MP	N/A	N/A	N/A	Urban	40-120	50-120	200	5 MB	SCGRP, HRAR
CLR-SDVN	OPNET	300	10 x 50	Urban	15-70	15-25	500	1024	AODV, SVAO, SDGR
IMCR	CodeBlocks, Sumo	100	1.6 x 1.9	Urban	10-280	N/A	N/A	N/A	Clusterless, Single CH.
CTDD	C, Matlab, Sumo	N/A	6 x 6	Urban	1800	N/A	N/A	N/A	EDF, PSU
LSB-OR	NS3, Sumo	500	1.5 x 1.5	Urban	20-100	16-125	200	1500	AODV, ROMSGP
LBR	N/A	N/A	N/A	Railway	N/A	300	200	N/A	GPSR-L
SDCoR	Omnet, sumo, C++, python	360	2.5 x 2.5	Urban	N/A	N/A	400	512	AODV, GPSR
GEO-SDVN	Omnet++, Sumo, Veins	120	5.06 x 5.06	City	50-300	0-50	300	N/A	Flooding, IVG
HRLB	NS3	1200	3 x 3	City	280	0-85	500	1024	GPSR,GPSR-MALA, RPGR,VDLA, SCGRP
SESAC	N/A	N/A	N/A	Urban	10- 40	20-50	350	N/A	LID, MPBC
LT-NSR	NS3	300	5 x 0.2	Highway	20-50	60-120	300	N/A	GD-NSR
CR-SDVN	NS2	N/A	N/A	Urban	5-30	N/A	250	64	HSDV, EPDM-R
FR-PU	NS3	150	1 x 1	Urban	40	0-55	200	512	AODV, OLSR, FR
ORUR	Omnet++, Sumo	180	N/A	Urban	1000	N/A	175	1000	GeoSpray, AQRV, Vela
SCGRP	Mininet, Sumo	400	2.5 x 2	Urban	50-500	10-100	250	512	CRP
SD-TAODV	Opnet	900	5 x 5	Urban	25	N/A	N/A	N/A	AODV
AVC-BTAT	Matlab	N/A	N/A	Urban	6	N/A	N/A	512	N/A
SDGR	NS2, Sumo	N/A	1.5 x 1.5	Urban	50-200	N/A	200	512	AODV, GPSR
dSDiVN	NS3, Sumo	120	1 x 1	Urban	200	30-100	300	N/A	N/A
HSDVR	NS3, Sumo	150	N/A	Urban	25-150	N/A	200	1024	AODV, DSDV, GPSR
SVAO	NS3, Sumo	N/A	2 x 0.04	Urban	N/A	30-110	N/A	1000	OLSR, DSR, DSDV, DB
IDVR	Sumo, Matlab	1000	4 x 4	Urban	100-500	10-60	250	512	VDLA, IRTIV, GPCR
CESDT	Python, NS3.	N/A	N/A	Urban	28000	0-80	250	N/A	OLSR, GPSR
Pretti	NS3, Python, Sumo	N/A	5 x 5	Urban	100	N/A	N/A	N/A	MAODV
CDSRP	CSIM19	N/A	N/A	Urban	N/A	80-120	300	N/A	MRF, FCFS
CRP	NS3, Sumo	150	1 x 1	Urban	10-100	10-100	N/A	1024	AODV, OLSR, GPSR
Spray-&-Prey	NS3, Sumo	N/A	1 x 1	Urban	20	0-70	250	N/A	Epidemic, Spray-and-Wait, Geo-Spray
GeoBroadcast	Opnet, NS3	N/A	2.5 x 2.5	Urban	100	N/A	200	120	N/A

The selection of the simulation area can significantly impact the evaluated results and performance analysis. For instance, when a large area is chosen, the vehicles may move far apart, which can hinder the presence of next-hop nodes near the data carrier. To tackle this issue, some studies, such as GLS, SURFER, CTDD, CDRS, and CLHLB have increased the number of nodes or reduced the default speed in the simulation experiment. This may lead to questionable results, as adjusting to the environment requires working with various scenarios. Moreover, specific protocols did not mention the simulation area in their analysis, including CDRS, DMPFS, CCDEC, LBR, and HSDVR. On the other hand, selecting a small area can reduce the computational overhead caused by the simulator and provide better outcomes for routing data in

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urban areas. However, the results may not be reliable for real-time data transmission where the area of protocol deployment is increased. These protocols include SELAR, MFCAR, FR-PU, SDGR, and dSDiVN. Furthermore, most of the reviewed algorithms consider urban scenarios for performance analysis. Nevertheless, urban areas' population, traffic density, road distribution, and communication requirements vary due to geographical features. Nonetheless, some protocols that have considered the features of the geographical area and parameters include SPIDER, CESDT, HRLB, and CLR-SDVN. Also, only three protocols have been evaluated in the highway scenario, namely SDVN-MiCR, LBR, and LT-NSR protocols. Finally, the protocols should be compared with similar routing mechanisms for performance analysis and efficiency validation. Fig. 21 depicts a statistical analysis of the most used protocols for comparison. However, no specific routing protocols can be deemed as a reference for analyzing the performance of all SDVN routing algorithms. GPSR, AODV, and OLSR protocols are the main benchmarks for the performance analysis of many reviewed works. TDCR, AVC-BTAT, and dSDiVN did not compare with other works.

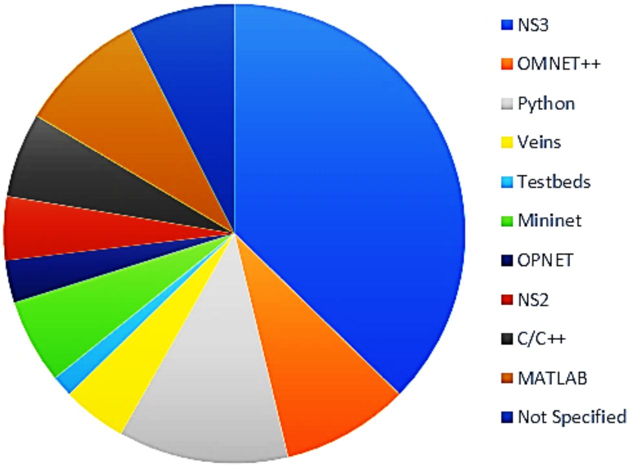

FIGURE 20. Simulation tools used in reviewed works.

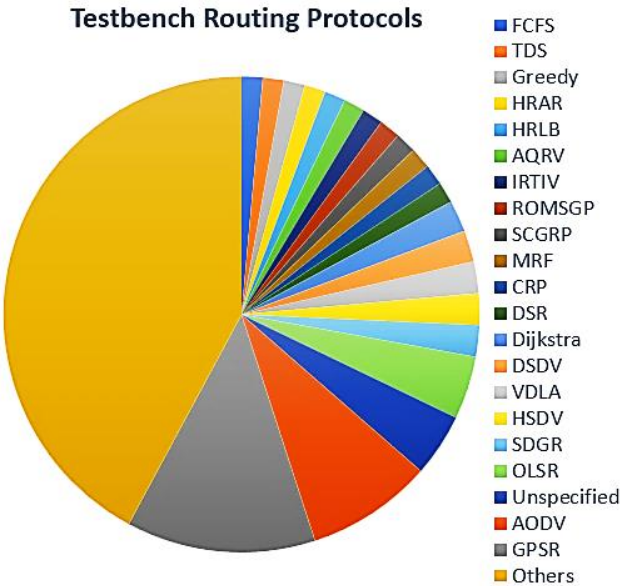

FIGURE 21. Testbench protocols used in reviewed works.

VIII. OPEN ISSUES AND FUTURE CHALLENGES

The former sections have summarized most SDVN routing protocols and comprehensively analyzed their performance regarding delivery guarantees, routing efficiency, and other factors. Despite the efforts to develop SDVN routing protocols, several gaps should be resolved. The incorporation of SDN and VANETs is still in its early stages, and many issues need to be refined. These issues must be thoroughly investigated to ensure flexible and robust usage of SDN in VANET routing with efficient allocation of physical resources. Therefore, there is still a performance gap between the current routing approaches and the ideal ones that can fully leverage the advantages of SDN. Table 9 presents upcoming research directions, investigated problems, recommended solutions, and suggested references to supplement this study. So, the open issues and future challenges are outlined here:

1) Lack of high mobility consideration: While SDN offers flexible and programmable network control, its suitability for VANETs is still at a primary stage. The rapid changes in topology make it challenging to gather network information correctly. As a result, an efficient solution is necessary to maintain high performance in highly dynamic VANET and decrease latency in the network. Nonetheless, many routing schemes have been developed to address the issue of rapid network topology updates [172] [173]. To ensure efficient routing and traffic management, it is critical to maintain a reliable and updatable global topology view at the SDN controller. In recent years, the fog and edge computing techniques have been introduced to support the global controller. In addition, proactive mobility management algorithms and hybrid SDN architecture can assist in delegating partial load for mobility management, resulting in new mobility management techniques.
2) Management of flow rule policies: In SDN, the data forwarding rules comprise general rules. The improvement of the flow rule policies is necessary to maintain seamless services. For instance, the real-time data are uploaded to BSs/RSUs for processing using general flow policies rather than specific policies related to data forwarding. BSs/RSUs generate local data routing policies using their local network topology information. Once data is processed, BSs/RSUs forward it to the central controller over the SBI interface.
3) Lack of research in dedicated trajectory prediction methods: Trajectory prediction refers to the estimation of the future state of a vehicle based on its current state. Conventional trajectory prediction models typically rely on different models of motion analysis, such as the Markov chain, kinematic model, constant speed mobility model, and others using extensive historical data from the vehicle and neighboring nodes [8]. In SDN, limiting the collected data is essential to avoid overwhelming the controller. So, it is optimal to utilize limited available vehicle mobility information to predict the vehicle trajectory within a limited period to satisfy the SDVNs routing requirements.

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TABLE 9.
OPEN RESEARCH CHALLENGES OF SDN-BASED VANET DATA ROUTING

Challenge	Problem (s)	Proposed Solutions	Recommended References
Lack of High Mobility Consideration	• High network delay. • More communication breakage. • Late provided services.	• Proactive mobility management with hybrid control plane switches. • Using proper ML algorithms to create vehicles mobility predication systems.	[194]–[197]
Management of Flow rule Policies	• Fault routing decisions. • Network congestion	• Utilizing logical & decentralized controller architecture. • Flow rules minimization algorithms	[142] [198]–[200]
Lack of Research in Dedicated Trajectory Prediction Algorithm	• Controller overload. • High bandwidth utilization	• Apply limited vehicle status data to predict vehicle trajectory in a short time horizon. RL is good choice.	[174], [175], [201], [202]
Further Reduction of Communication Overhead	• High latency. • More packet loss ratio • Network congestion	• Vehicle trajectory predication models. • Using multi-networking interfaces for data propagation. • MEC & clustering technique in SDVN.	[203], [204]
Lack of Study in Routing Algorithms in Controller	• Expired routes. • Unreliable routing decisions.	• Dynamic timetable-dependent routing approach	[175], [198], [205].
Lack of applying AI in Routing Management in Controller	• Computational complexity, • More real-time data preprocessing.	• Constructing the routing metric, routing policy or per-flow QoS parameters from the historical and real-time data.	[134], [175], [200]
Recovery Mechanism of Failed Routing Instructions	• Increased packet delivery delay. • High data loss, • Extra control packets.	• Avoid failed links using ML methods to select the links with most appropriate connectivity.	[206], [207]
Lack of Research in Multicast Routing	• Less safety. • Late warning messages delivery	• Orchestrate the multicast decisions within the global-view SDN.	[16] [208], [209]
Lack of Considering Security in Routing:	• SDN overload. • Severe accidents • More malicious packets.	• Preventive measures and mechanisms are required to keep the network safe from malicious nodes/activities. • Blockchain-based security systems.	[176], [178], [210]–[212]
Scalability of SDVN:	• SDN controller overhead. • High latency. • Limitation of provided services.	• Utilizing logical/decentralized controller architecture. • Integration of fog and edge computing to mitigate the controller overloading. • Using UAV as flying standby SDN controller in high-traffic or dense areas.	[174], [175], [179], [201], [203]
Controller Bottleneck Consideration	• Controller overhead. • High latency. • Limited services.	• Decentralized architectures such as hybrid SDN. • Traffic prediction models can be used to predict the vehicular traffic. Based on traffic density, logical controllers can be allocated to avoid controller bottleneck.	[179], [213], [214]
Further Reduction of Communication Latency	• Late services. • Invalid data. • More accidents and traffic issues.	• Coexistence of multiple networking interfaces. • Adopting 5G-URLLC facility.	[113] [215]–[218]
Lack of Real-world Implementation	• Unreliable results. • Unpredicted outcomes.	• Developing testbeds to verify SDVN-based routing in various traffic scenarios.	[161], [163], [164], [181], [199]
The Lack of Mechanism of Multiple Controller Placement	• Complex management. • High costs. • More latency	• Developing reward-based cooperation models to utilize BSs or RSUs as SDN controller. • RL-based SDN controllers' localization.	[183], [184], [219]–[222]
Lack of Infrastructural and Economic Considerations	• Increased costs. • Unreliable deployment	• Complete study about real-time traffic to identify its requirements and estimate the available resources, and thus plan the eventual applications and services that can be supported in real-time.	[223], [224]
Lack of Optimal Localization Mechanisms	• Un-updateable network topology • Fault routing decisions. • Unreliable data delivery.	• Using video-based positioning system and cooperative localization system can mitigate some faults outcomes in GPS.	[185]–[188], [225], [226]
Lack of weather effect consideration	• Low vehicles mobility. • Degrade radio signal propagation • Weakness of communication between SDN and vehicles.	• Development a mechanical system that can cope with these conditions. • Using short P2P communications among SDN controller and vehicles and among vehicles themselves.	[190], [227], [228]
Further Reduction of computation load	• Controller bottleneck. • High costs. • More consumed power.	• Using edge and fog computing for SDN computation offloading.	[191], [192], [229], [230]
Integration of other techniques	• Resources Provisioning. • Costly. • Security issues.	• Complete investigation to evaluate the deployment feasibility, efficiency, security and privacy vulnerabilities of the cooperation of SDVN with other techniques.	[191], [223], [231]
Deficiency of Simulation Platform	• Poor evaluations and analysis • Unreliable assessments.	• Proof of concept studies to prove the feasibility of SDN in VANET routing. • Development ML-based assessment systems to deal with the expected challenges in SDVN-based data routing.	[162], [163]
Lack of Standardization:	• Limited communication between vehicles and SDN controllers. • Mutual exclusiveness occurs	• Developing tools/protocols to deal with communication, data processing, and encoding standards required for SDVN.	[193], [232], [233]

4) Further reduction of communication overhead: Beacons and data packets transmitted to/from the controller result in high communication overhead. Predicting the vehicle trajectory in the controller is the most effective solution to reduce this overhead. In this scenario, the number of status messages is significantly minimized, and the controller constructs the network graph using the received beacons and link estimates. Numerous relevant studies have utilized clustering techniques to minimize the overhead [174]. Future research should empower the controller to allocate routing queries to local controllers with many routing metrics or explicit routing strategies based on the network situation to reduce communication overhead further. Developing intelligent schemes to evaluate the trade-off between centralized and distributed routing is worthwhile, such as adaptively switching the SDVN routing method under different network conditions [130].
5) Lack of research in forwarding algorithms in controllers: Many current studies utilize the static shortest path strategy, such as Dijkstra's algorithm, to find the optimal routing paths. Still, in VANETs, most links between nodes have a limited validity period, rendering conventional shortest-path schemes unsuitable for static networks. This results in the routing problem being converted to finding the best path in a dynamic timetable graph [115], [148]. In an SDVN, the controller may have to manage millions of routing queries concurrently, making it crucial for route planning algorithms to be efficient enough to fulfill networking requirements. However, the current algorithms rely on pre-computed network data, which is unattainable in dynamic SDVNs. Therefore, to achieve an effective timetable-dependent routing scheme, it is essential to adopt road route planning algorithms or develop an alternate method as a future research direction.
6) Lack of AI in routing management: There is a lack of research on utilizing AI to improve the routing performance of SDVNs. Specifically, increasing data traffic presents a highly promising method to address the dynamic and large-scale nature of SDVNs. For instance, statistical learning, neural networks, or deep learning could be utilized to create the routing metric, routing policy, or even per-flow QoS parameters based on historical and real-time data. Despite the potential benefits of AI in SDVNs, new challenges may arise, such as computational complexity, learning and manned strategies, and pre-processing real-time data [175].
7) The need for a recovery strategy of failed routing: In real-world scenarios, computed routes may become unusable if a link breaks due to node dynamicity. Unfortunately, current works do not provide effective recovery mechanisms from route failures. The most straightforward approach to repair a failed route is to initiate local recovery requests or send the routing query to the controller for a new route. Accordingly, the E2E delay will be more with high data loss rate. Additionally, the monitoring of link status can help in re-routing data through previously recognized paths, which may minimize the delay. Generally, neither approach is a feasible solution for entirely resolving the failure. So, future failures can be prevented by tracing back and determining the underlying cause. By incorporating historical data and current link status into machine learning methods, the links with the most appropriate connectivity can be selected for data routing.
8) The need for multicast routing: Most current studies concentrate on delivering unicast routing. Nevertheless, multicasting is an essential routing method for many critical VANET applications, such as collision avoidance and platooning driving. Coordinating multicast requests within the global view controller is crucial for effective one-to-many data delivery.
9) Security consideration: Security is a critical concern in VANET communications where it directly impacts the safety of in-car travelers, vehicles, pedestrians, and others. SDVNs, with the presence of a controller, can be less vulnerable to cyber-attacks than other types of wireless vehicular paradigms. Most researchers have prioritized the confidentiality and integrity requirements for the network and SDN controller access. Consequently, any false information can result in low delivery rates and high latency. However, many cyber-attacks, such as GPS spoofing, Denial of Service (DoS) attacks, tunneling attacks, and gray hole attacks, can significantly impact the SDVN efficiency [176], [177]. Furthermore, the integration with other technologies such as cloud/fog computing and 5G networks will lead to more security risks [178]. In general, security for SDVN routing has not been extensively studied. So, it is crucial to develop preventive measures and strategies to safeguard the network against malicious access and ensure the security of both the SDN controller and communication data.
10) Network scalability: The majority of SDVN routing protocols are not scalable, as they are typically designed for urban or highway scenarios [179]. It is preferable for the routing protocol to be scalable to handle the unexpected increasing in the number of nodes and support reliable services in various network situations. However, the scalability of SDVN networks can be improved by adopting logical and decentralized controller architecture. For instance, a logical controller must be assigned in a scenario with varying vehicular density to ensure the best data delivery in high-traffic scenarios. Besides, the integration of fog and edge systems can help in the minimization of the controller overload. For instance, standby offloading resources such as drones and parked or low-mobility vehicles can reduce the load on resident controllers. Also, the traffic prediction algorithms can be utilized to predict traffic density and load balancing to enhance scalability in scenarios with many nodes managed by a single controller.

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11) Controller bottleneck consideration: The increasing volume and complexity of traffic patterns generated by vehicles may overwhelm the SDN controller. In such a situation, the SDN controller becomes a limiting factor in terms of processing capacity, communication bandwidth, or overall performance. One of the best solutions is to explore distributed control strategies to delegate decision-making processes to edge devices or distributed controllers to enhance reliability and reduce the load on the central controller. This can help improve performance and ensure the system can handle a higher density of vehicles [179]. Besides, the complex routing mechanisms and intelligent decision-making processes can also contribute to controller bottlenecks, particularly when utilizing historical and real-time data [175]. So, the controller bottleneck should be considered in upcoming SDN-based data routing work.
12) Further reduction of communication latency: Achieving low latency is crucial for effective vehicular communication. Several studies have been proposed to leverage cloud/edge computing techniques to provide caching services and address the various routing needs [44] [99]. Due to various factors, such as information collection, channel conditions analysis, computational workload, and vehicles tracking techniques, the network complexity will increase with more latency [180]. Some studies have suggested using multiple interfaces like DSRC and C-V2X communications to minimize latency. Frequent handovers caused by high-density vehicle traffic can delay transmission and degrade performance. So, to improve latency, the optimization of average delay from different angles, such as data processing, routing establishment, flow rule propagation, and failure recovery is important.
13) Lack of real-world implementations: Despite the numerous theoretical concepts and ideas proposed in the literature, they have yet to be validated through real-world implementations. As an exception, in [164], Secinti et al. provided a testbed for SDVN using Raspberry Pi for both RSU and vehicles that are Wi-Fi enabled. In [181], Sadio et al. proposed a more advanced testbed for SDVN with multiple controllers, including the Twinand Wi-5 controllers. Four Zodiac FX switches are used to build the SDN backbone. To implement SDVN in the real world, a comprehensive assessment of the vehicular network is required to identify which control layer component can be added or removed from the infrastructure plane to leverage SDVN's benefits fully. In the future, greater emphasis should be placed on developing real-world implementations and simulation tools to evaluate the performance of SDVN systems. This will help determine which control layer component should be decoupled from the infrastructure plane.
14) The consideration of multiple controller placement: Several SDVN routing protocols have proposed using numerous controllers to maintain the proper functioning of the network in the event of a single controller failure. To optimize the number of controllers, it is essential to determine the best locations for placing them. With SDVN, the controller placement problem becomes more complex as new candidates, such as BSs and RSUs, can be considered potential controllers [182]. One potential solution to address the challenges of controller placement is to develop reward-based cooperation solutions that utilize BSs or RSUs as SDN controllers. Machine learning algorithms such as reinforcement learning (RL) can be employed to determine the optimal localization of SDN controllers, including the number and distribution of controllers [183]. However, none of the SDVN routing proposals address this issue which is still doubtful and needs more research effort.
15) Lack of infrastructural and economic considerations: Although the cellular infrastructure is already in place and can provide extensive coverage areas with high throughput and capacity, there are still financial barriers to achieving uninterrupted SDN services via such networks [184]. The main costs are associated with the deployment of SDN controllers and the need for new applications and technologies, such as edge services and cybersecurity models. Accordingly, the development of an effective economic model can enhance the integration of SDN and nearby infrastructures. Besides, studying vehicle traffic in real-time is crucial for determining the hardware and software requirements and planning the services that can be deployed.
16) Lack of optimal localization mechanisms: All the reviewed protocols rely on the GPS to collect vehicle coordinates and for localization purposes. However, vehicles have high speeds and different mobility patterns, requiring exact localization at small intervals. In many communication protocols, the GPS update time is 1 second, which is ineffective for accurate vehicle localization [185]. The imprecise vehicle localization resulting from the 1-second GPS update time can lead to more challenges and incorrect routing decisions. However, various models have been proposed to determine the precise position of vehicles. A cooperative localization system can help mitigate faults resulting from GPS imprecision [186]. Also, a video-based positioning system and distance estimation are samples of optional solutions here [187]–[189]. Unfortunately, none of these models have been utilized and tested with SDVN data routing.
17) Lack of weather affects consideration: Adverse weather conditions, such as heavy rainfall, high winds, and snowfall, can affect vehicle mobility and traffic density, causing a high impact on signal propagation and data transmission [190] [185]. Developing a mechanical system that can effectively cope with such conditions can improve data routing performance. Also, establishing short P2P communications among controllers and vehicles, as well as among vehicles themselves, can help minimize the impact of weather changes on data routing.

18) Further reduction of computation load: The deployment of SDVN in real-time environments, particularly in dense traffic, can result in a significant computation load where a larger number of requests will be generated which leads to potential performance issues [191], [192]. Therefore, offloading computation workloads to the vehicles or edge servers can accelerate the computation and save energy. However, the scheduling of offloading workloads in SDVN routing is still challenging and needs more investigation. Besides, the development of big data processing techniques can help in the mitigation of such challenges.
19) Integration of other techniques: The cooperation of SDVN with other technologies, such as cloud/edge computing, and blockchain techniques, can enhance communication reliability and overall QoS in various VANET scenarios. However, a comprehensive investigation is necessary to assess the feasibility and effectiveness of such techniques in SDVN models. Such integration can also introduce new security and privacy vulnerabilities, which must be investigated.
20) Deficiency of simulation platforms: VANET and SDVN networking models have different properties, including signal coding, MAC, security requirements, and congestion handling. Therefore, it is essential to establish a general simulation platform that includes typical vehicular network scenarios to facilitate fair evaluations and comparisons of SDVN routing solutions. Researchers often use different network simulation tools and mobility models to evaluate proposed solutions. However, many simulators do not support SDVN modules, and most lack integration with emerging technologies, critical attributes for SDVN routing design. Significant improvements are necessary to meet SDVN routing requirements, including developing new modules and simulation tools [163]. Further, simulators should include mobility models that mimic real vehicle mobility to establish a realistic simulation situation.
21) Lack of standardization: Interworking gaps among heterogeneous networks are challenging in SDVN networking. As the future of SDVN is not restricted to communication among vehicles, it will include new technologies and entities with several features from different manufacturers. Defining the boundaries of how far one can integrate SDN into VANET is yet to be established. As a result, mutual exclusiveness can occur, leading to communication failures between vehicles. Standardizing technologies can be a solution to overcome this issue [193]. Besides, A standardized and vendor-agnostic SBI can facilitate interoperability between different SDN controllers and network devices [172]. Developing ML-based assessment solutions can aid in proving the feasibility of SDN in VANET environments. These solutions can provide insights and suggestions to address some of the expected challenges and issues in SDVN.

VIII. CONCLUSIONS

SDN, as an emerging technology, can potentially resolve several problems in vehicular networks. Its implementation in VANETs has increased considerable interest from the academic world and industry. First, we provide full details about VANET networks, including their architecture, communications, and challenges. Next, a general description of traditional routing protocols used in VANET is provided. More specifically, this research paper offers a thorough review of the presenting SDVN architecture and routing schemes, along with related information on data routing under SDVN. This survey has provided a comprehensive examination of SDN-based VANET routing protocols, shedding light on their underlying mechanisms, forwarding algorithms, and architectural considerations. The survey explored each protocol individually, highlighting their robustness, limitations, and suggested improvements. SDVN-enabled routing protocols have been divided into various categories based on their modes of operation, routing mechanisms, transmission modes, and others. By comparing and analyzing various optimization criteria, performance evaluation techniques, and simulation tools, this survey has contributed to a better understanding of the current state of SDN-based VANET routing protocols. Lastly, the research identifies the challenges of SDVN and provides future directions for researchers interested in SDVN architecture or data routing. Overall, this survey not only provides a comprehensive overview of SDN-based VANET routing protocols but also serves as a platform for researchers to build upon and innovate. It lays the foundation for further exploration, enabling the development of more efficient, reliable, and scalable routing solutions in the dynamic and challenging vehicular ad hoc network environment.

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