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A Survey of VANET/V2X Routing from the Perspective of Non-Learning- and Learning-Based Approaches

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ABSTRACT Intelligent transportation systems (ITSs) have become increasingly popular because they support effective coordination in connected vehicles. ITSs present an integrated approach for exchanging relevant information in order to improve the safety, efficiency, and reliability of road transportation systems. A variant of mobile ad-hoc networks (MANETs) called vehicular ad-hoc networks (VANETs) are an integral component of ITSs. VANETs consist of interconnected vehicles with sensing abilities that exchange information related to traffic, positioning, weather, and emergency services. In general, vehicle-to-everything (V2X) refers to communications between any entity and a vehicle, where the entity may be a vehicle, a cloud-based network, a pedestrian, or equipment installed along a road. One of the crucial challenges in V2X is the reliable and timely circulation of information among vehicular nodes to allow drivers to make decisions that increase road safety. In this context, efficient V2X routing protocols play a key role in supporting reliability and safety, and enhancing the overall quality of service (QoS) in VANETs. However, VANETs have distinct characteristics, such as high vehicular node mobility, unsteady connectivity, rapid changes in network topology, and unbounded network size, that can significantly affect routing in the network. Various routing protocols for V2X communication exist in the open technical literature. In this survey, we categorize the routing mechanisms as non-learning- and learning-based approaches, and discuss existing V2X routing protocols and their contributions to and impacts on VANET performance. Here, the learning-based approach implies the use of machine learning algorithms. This survey also summarizes open challenges in designing effective V2X routing protocols and future research directions to consider when developing smart routing mechanisms for next-generation intelligent VANET technologies.

INDEX TERMS VANET, V2X, routing protocol, non-learning-based routing, learning-based routing.

I. INTRODUCTION

INTELLIGENT transportation systems (ITSs) aim to provide learning-based innovative services for transportation and traffic management and thus enable more coordinated, safer, and 'smarter' utilization of transport networks [1]–[3]. ITSs face numerous challenges related to the efficient handling of data communication in transportation systems. Over the last few years, immense progress has been reported in the area of network service provisioning to mobile users. Mobile ad-hoc networks (MANETs) address this by providing a promising wireless network topology with no administrator

involved in communication that has recently been widely extended to challenging communication scenarios like communication among flying drones and ad-hoc communications among mobile devices. MANETs consist of mobile and fixed nodes that follow specific protocols to communicate with each other. Vehicular ad-hoc networks (VANETs) [4]–[6] are a specific kind of MANET, that are linked with ITSs to provide traffic analysis, road safety, collision avoidance, emergency alerts, vehicle speed management, and automatic traffic signal enforcement [7]. Thus, VANETs are ad-hoc networks in which information can be communicated among

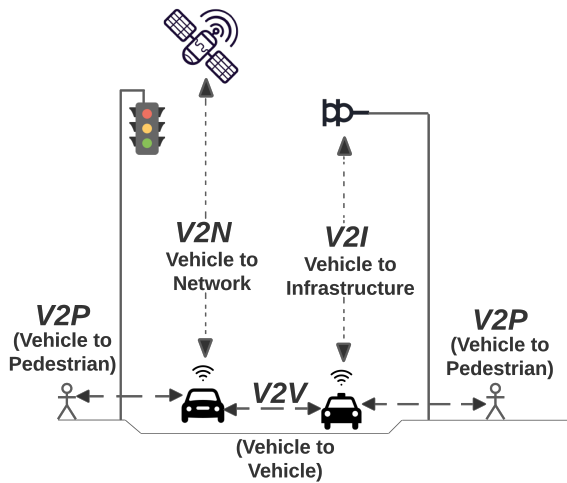


FIGURE 1. An illustration of V2X communications

vehicles. As is rightly mentioned in [8], VANETs are a key component of ITSs, which have been extensively investigated, notably for improving efficiency in traffic management, developing future smart cities, and addressing future transportation safety-related issues. Furthermore, VANETs can be deployed in military environments or remote areas, where network infrastructure cannot be installed.

In general, vehicle-to-everything (V2X) [20]–[22] refers to communications between any entity and a vehicle. Thus, V2X technology mainly covers vehicle-to-infrastructure (V2I), vehicle-to-vehicle (V2V), vehicle-to-network (V2N), and vehicle-to-pedestrian (V2P) communications. Fig. 1 shows an example of V2X communications. In VANETs, vehicles can convey information to other vehicles using V2V communications through which a vehicle communicates directly with another vehicle and shares information related to traffic conditions, such as traffic jams or accidents. V2I communications rely on the use of *road side units* (RSUs) [23], [24], which are generally special wireless devices that are mounted on the roadside. An RSU is a fixed piece of infrastructure that is connected to the Internet and can communicate with other RSUs and roaming vehicles, which transmit data to the nearest RSU. RSUs ensure reliability in data communications, and are thus helpful in many life-saving mishaps [25]. When RSUs are not directly in the range of vehicles, V2V communication is considered mandatory in VANETs [14]. In the case of V2N communications, vehicles access cloud-based services and 3G/4G cellular networks are used to deliver and receive messages for vehicle monitoring due to their enhanced coverage and high data transfer rates [26]. In V2P communications, the exchange of data is between a vehicle and a pedestrian. In the case of in-vehicle communications, communication occurs inside a vehicle for the detection and analysis of both drivers and vehicles to minimize accidents due to driver drowsiness or vehicle malfunctioning [27].

Routing is the mechanism used to select packets and transmit them on the least-cost path between the source and destination nodes. Thus, successful data transmission needs to be ensured by the routing protocol, which helps forward data packets to the intended destination. If transmission on the selected route fails, an appropriate recovery mechanism needs to be executed to retransmit the data [10]. In VANETs, vehicles are positioned on the road and act as mobile nodes in the network. In this context, ITSs are important, where routing can be intelligently handled, leading to efficient communications in VANETs. Thus, V2X routing protocols need to be designed to address challenges of VANET environments, such as rapid changes in network topology, high vehicle mobility, network heterogeneity, and variable network size. The physical layout of VANETs changes repeatedly due to the frequent movement of nodes, and route maintenance consequently becomes very challenging [28]. In addition, since vehicles move at high speeds, infrastructure-based networks can suffer from rapid handovers and radio signal fluctuations, leading to unreliable network connectivity [29]. Moreover, safety-related applications of ITSs depend on the aggregation of information from secured messages that are transmitted by vehicles in VANETs. For instance, safety messages could indicate the location, acceleration, speed, or braking state of a vehicle. The timely delivery of such information can help to avoid accidents [30]. Emergency and warning messages are exchanged by VANET nodes through unicast or multicast routing by following one of the V2X communication mechanisms, where routing can be delayed due to a limited number of cellular gateways or access points in road traffic environments [4].

Considering the aforementioned challenges associated with routing in V2X, it is essential to develop efficient routing mechanisms that transmit packets from the source to the destination by dynamically selecting a route containing a set of nodes such that the quality of service (QoS) criteria are satisfied in VANETs [31], [32]. The QoS criteria include the reliable and timely delivery of information and ITS applications [9], routing overhead, end-to-end delay, packet loss rate, network bandwidth, etc. Over the last few years, several works, such as [6], [33]–[49], have addressed the challenges of V2X routing and accordingly proposed routing protocols to improve road safety, security issues, and QoS by considering high mobility, irregular traffic patterns, frequent changes in network topology, and repeat exchanges of different types of information. These routing protocols focus on discovering and maintaining routes between two VANET nodes using non-learning- or learning-based approaches. Non-learning-based mechanisms do not use any machine learning scheme and generally follow threshold-based approaches. These routing protocols have simple designs and apply knowledge based on network topology, position, cluster, broadcasting status, and so on. Learning-based mechanisms, on the other hand, utilize machine learning algorithms to dynamically adapt to VANET environments by intelligently selecting routing paths. Machine learning algo-

TABLE 1. A classification of Existing Surveys on V2X Routing Protocols

Item	Year	Survey topic	Discussion of non-learning-based routing approaches	Discussion of learning-based routing approaches
[9]	2010	Unicast, multicast, geocast, mobicast, and broadcast routing protocols for VANETs	Yes	No
[10]	2014	Primary characteristics, strengths, and weaknesses of bio-inspired routing	No	Yes
[11]	2014	Clustering techniques and cluster-based routing protocols	Yes	No
[12]	2017	Different types of routing protocols in VANETs, and their advantages and disadvantages	Yes	No
[13]	2017	Challenges and potential applications of routing approaches, and privacy and security issues for VANETs	Yes	No
[14]	2019	Position-based routing protocols by using a taxonomy, and a FoG-oriented VANET framework to support the position-based routing	Yes	No
[15]	2019	The possibility of Sybil attack in position-based routing protocols in VANETs, and the exploration of the Greedy Perimeter Coordinator Routing	Yes	No
[16]	2020	Shortcomings of existing UAV-aided VANET routing protocols by analyzing their application areas, advantages, disadvantages, and future improvements	Yes	No
[17]	2021	A comparative investigation of existing reinforcement learning-based routing protocols, considering their working principles, applications, advantages, and disadvantages	No	Yes
[18]	2021	Different routing protocols and clustering algorithms for cluster head selection in VANETs	Yes	No
[19]	2021	Challenges of conventional mechanisms in vehicular networks and machine learning based approaches for the solutions for both network parts and communication in VANETS	No	No

gorithms can be effective tools to enhance trust, reliability, and route detection accuracy in V2X, as it is reported in several existing works [50]–[52]. In V2X, the decision-making for routing becomes intelligent [49] due to the incorporation of online learning approaches.

Why this survey: V2X communication poses some specific challenges, particularly because of the dynamic nature of the communication environment and fast-changing network states. Although the topic of V2X routing has been thoroughly studied and there already exist surveys on this area (summary in Table 1), many recent works, as stated above, have focused on applying artificial intelligence and machine learning techniques to explore the communication environment and choose routing paths. Such learning-based techniques sometimes augment existing non-learning-based techniques for V2X routing; however, many of them put the problem in a different dimension. Therefore, it would be interesting to explore such techniques and compare them with non-learning-based V2X routing techniques to get a clear understanding of the problem's dimension. Table 1 shows existing surveys that deal with V2X routing protocols and that there is currently no thorough survey of both non-learning- and learning-based V2X routing protocols. Existing non-learning- and learning based routing protocols in V2X have strengths and limitations that need to be properly identified in order to strengthen future designs of V2X routing mechanisms. Therefore, in this survey, we present an extensive study of the existing works that deal with the design and deployment of both non-learning- and learning-based routing protocols in V2X. Based on this study, we highlight

the impacts of these two types of routing approaches on overall network performance and their associated security and authentication issues. More specifically, the contributions of this survey are framed as follows:

- We study existing works that deal with non-learning-based routing protocols in V2X and highlight their contributions. The impacts of such routing protocols on VANET performance are discussed in light of high node mobility, high vehicle speed, QoS improvement, network topology, security and privacy, etc. The routing approaches' strengths and weaknesses are also highlighted.
- We review existing works that consider learning-based routing protocols in V2X. We present the impacts of these routing protocols on VANET performance in light of high vehicle speed, high node mobility, irregular vehicle density, QoS, security and privacy, dynamic network management, etc. We also discuss the contributions, strengths, and weaknesses of existing learning-based routing mechanisms.
- We highlight the findings from the extensive study of both non-learning- and learning-based V2X routing protocols and present a comparative study of a classification of directions in which the aforementioned two routing approaches are considered in the existing literature.
- We discuss the challenges of and future research directions for designing effective routing mechanisms that lead to smart and efficient routing protocols for V2X communications.

Uniqueness of this survey: To the best of our knowledge,

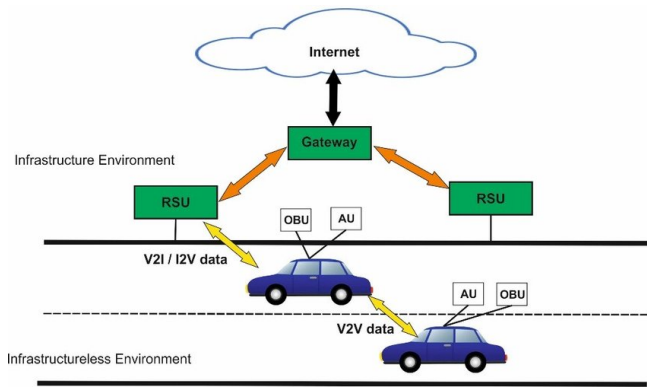


FIGURE 2. An illustration of VANET

the study of existing VANET/V2X routing protocols based on both learning- and non-learning-based approaches is what makes our survey unique. This survey clearly categorizes existing works based on the two aforesaid approaches and mentions their strengths and weaknesses.

Organization of this survey: The rest of this survey is organized as follows. Section II presents an overview of VANET/V2X, focusing on routing protocols. Section III provides a discussion on existing non-learning-based routing protocols. Section IV describes the existing works that consider learning-based V2X routing protocols and their impacts on network performance. In Section V, we present overall observations on existing non-learning- and learning-based V2X routing protocols. Section VI summarizes the challenges of and future research directions for designing efficient V2X routing protocols, and finally Section VII presents the conclusion of this survey.

II. VANET/V2X OVERVIEW

In this section, we present an overview of VANETs and highlight different types of VANET/V2X routing protocols. In V2X communications, one of the most challenging issues is VANET routing, where all the participants are vehicles having high mobility, long inter-vehicle distance, and high vehicle speed, and the vehicle density varies. Vehicles also have time-varying topology, trajectory-based predictable locations, low power consumption requirements, and frequent topology partitioning [53]. Therefore, we specifically focus on VANET routing in V2X communications. VANETs are decentralized, self-configuring, and cost-effective networks that are important for traffic management, disaster rescue operations, road safety, multimedia content sharing, commerce on wheels [54], etc.

VANETs are a type of ad-hoc network [13], i.e., an interim network that does not have any permanent infrastructure. Since VANETs are a sub-class of MANET architectures, they can be considered as multi-hop networks [11], [13]. They provide a quick and practical solution in emergencies, such as in the event of a disaster in which hydro poles, electrical services, and pre-established networks are damaged, caus-

ing the cellular network to fail. In this case, the disaster management team can create a simple ad-hoc network, like a VANET, for devices to communicate [55]. In addition, VANETs have been implemented to monitor traffic light behavior in the interest of curbing the risk on roads since road accidents are growing in number nowadays [56]. VANETs are characterized by:

- *High mobility:* In VANETs, vehicles can have high speeds, and making decisions on routing and security measures based on the position of a node is thus very tricky and challenging [28].
- *Unbounded network size:* The number of vehicles is unbounded, which leads to an uncontrolled network size in VANETs [12].
- *Rapid change of network topology:* Due to the continuous movement and high speeds of vehicles, the position of the vehicles changes repeatedly. As a result, the network topology changes rapidly and becomes unstable.
- *Frequent information exchange:* In VANETs, vehicles need to exchange information frequently with RSUs and other vehicles in order to control and manage routing and other functionalities. Thus, the frequent transmission of information must be efficiently handled.

Fig. 2 shows an example of a VANET that has two types of nodes: RSU and on-board unit (OBU). These nodes create an ad-hoc network and enable communications using single-hop and multi-hop links. The RSU [23], [24] is connected to the Internet and forms a fixed infrastructure that can communicate with other RSUs and roaming vehicles. RSUs provide distributed and cooperative applications in which they, other RSUs, and vehicles work together to process and share information in order to coordinate actions. An OBU [24] is a wave device that is mounted on-board a vehicle and exchanges and shares information with other OBUs and RSUs. An application unit (AU) [24] is a device within a vehicle, that uses applications provided by the end user. The AU device can be dedicated to safety applications or be a normal device like a personal digital assistant (PDA) that is capable of using the Internet. The AU is connected to the OBU using a wireless or wired connection and can reside with the OBU on a single physical unit.

A. TYPES OF COMMUNICATIONS

There are four types of communications in vehicular networks:

- 1) *Vehicle-to-vehicle communications:* When vehicles interact with each other, this is known as V2V communication. To decrease the number of car accidents, vehicles are designed to communicate with each other using V2V communications to share information about various life-saving road conditions [56].
- 2) *Vehicle-to-infrastructure communications:* When communication occurs between a vehicle and a fixed RSU, this is known as V2I communication [12]. The concept of V2I is not limited to life on land but also per-

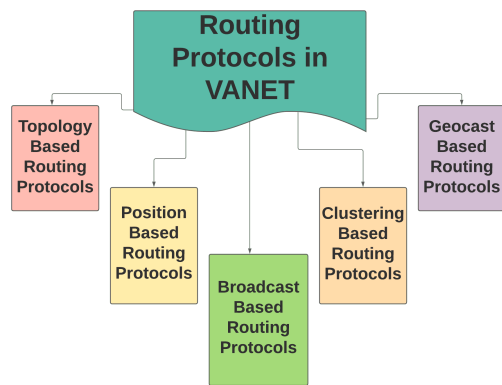


FIGURE 3. Classification of V2X routing protocols

tains to less-explored oceanic life [57]. Cyclones, ship accidents, accidental oil spills, and other dangerous situations can be prevented or mitigated by using V2I communication under water. V2I communications can help us know about life-threatening conditions prior to their occurrence such that we can be warned and fishermen can be notified in the event of emergencies.

- 3) *In-vehicle communications*: This type of communication happens inside a vehicle and is required to detect and analyze issues related to drivers and their vehicles in order to minimize accidents due to driver drowsiness, vehicle malfunctioning, etc.
- 4) *Vehicle-to-broadband cloud communications*: In the vehicle-to-broadband cloud communications, 3G/4G cellular networks are used to deliver and receive messages for vehicle monitoring and tracking due to their enhanced coverage, high data transfer rates, and reliability [26].

B. ROUTING PROTOCOLS IN VANETS / V2X COMMUNICATIONS

In VANETs / V2X communications, there are routing protocols designed to efficiently deliver messages [12]. Fig. 3 shows the different types of protocols used in VANETs / V2X communications. We have classified them on the basis of topology, position, cluster, geocast, and broadcast [12] [58] [11] [59]. These classifications are described below.

- **Topology-based protocols**: These protocols are based on the topology of the network. They maintain a routing table to store information related to the links on which data packets are sent from the source to destination vehicles. Existing algorithms attempt to minimize the control overhead in topology-based routing. However, in this routing mechanism, packets need more time to be delivered. Thus, topology-based protocols perform slower than other types of VANET routing protocols. Topology-based protocols are further classified into three types as follows.

- 1) *Proactive protocols*: Proactive protocols are table-driven routing protocols in which every node maintains a routing table. The routing table, which is updated every time there is a change in the topology of the network, contains information on neighboring nodes. Thus, route discovery takes the least amount of time.
- 2) *Reactive protocols*: Reactive protocols are on-demand routing protocols in which nodes do not maintain a routing table. A node obtains the route or path only when a message is to be delivered.
- 3) *Hybrid protocols*: Hybrid protocols combine proactive and reactive protocols. The network is divided into local and global regions. In the local region, proactive routing protocols are applied to reduce delay and overhead, whereas in the global region, reactive protocols are applied.

- **Position-based protocols**: This type of protocols is mostly adopted when the positions of the sender and receiver and the ideal path to the destination can be known with the help of the global positioning system (GPS). Position-based routing is also commonly known as geographic routing and does not require that a routing table be maintained.
- **Broadcast-based protocols**: This type of protocols is chosen when the vehicle that will receive the message is out of transmission range. Packet delivery is ensured by making use of flooding, where every node in the network receives the packet.
- **Cluster-based protocols**: In this type of protocols, vehicles are grouped into clusters, and every cluster has a leader that helps in bridging separate clusters. Leaders of two clusters communicate with each other and can make a decision on routing messages inside the clusters they control.
- **Geocast-based protocols**: This type of protocols is suited for multicast routing. Here, nodes have information about other nodes, and unlike in multicast routing, packets are delivered to a pre-known geographical region. The primary aim of these protocols is to guarantee the delivery of a message at a low cost. Routes do not need to be maintained, and route construction is also not required. Geocast-based routing protocols are effective when the reliable delivery of messages is a concern [54].

III. NON-LEARNING-BASED V2X ROUTING PROTOCOLS

In this section, we discuss existing works that consider non-learning-based V2X routing protocols and their impacts on network performance. Tables 14-16 present works that discuss non-learning-based V2X routing protocols and highlight their strengths and weaknesses. Fig. 4 shows the number of works published each year since 2008, that consider non-learning-based V2X routing.

The authors of [60] propose a protocol in which common backbone vehicles are used for various types of traffic movement and interflow network coding to encode packets at the

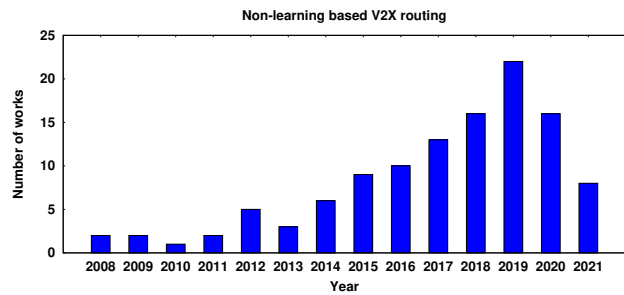


FIGURE 4. Number of works considering non-learning-based V2X routing

backbone vehicles. Here, vehicle movement and the quality of links are considered to form a backbone. A new class of routing protocols called road-based vehicular traffic (RBVT) protocols which perform better in city VANETs, is presented in [61]. In that work, reactive RBVT (RBVT-R) and proactive RBVT (RBVT-P) protocols were implemented and compared with MANET and VANET representative protocols. According to the simulation results, RBVT-R achieves a 40% increase in average delivery rate and RBVT-P achieves an 85% decrease in average delay compared to existing protocols. The protocols proposed in [62] have been implemented both in city and highway environments. The protocol performance analysis was performed considering different performance metrics. In [63], a routing algorithm based on Ad-hoc On-demand Distance Vector (AODV), which uses routing metrics including the length of each hop and the link remaining time, is proposed. The algorithm reduces routing overhead by using a receiver-based method. Moreover, a novel urban road scenario and mobility model are designed to describe car movement. In [64], the performances of the AODV and optimized link state routing (OLSR) VANET protocols are evaluated in VANET crossroad scenarios considering the end-to-end delay, packet delivery ratio (PDR), and throughput. Traffic lights affect VANET routing performance, and this was investigated in [65], which proposes shortest-path-based traffic-light aware routing (STAR). The way in which the packets are forwarded is determined by traffic patterns and traffic light signals on road intersections. STAR works over green light first forwarding where packets are forwarded along the path with green lights. V2I and V2V communications must cooperate to form V2X communications, which require a certain type of multi-hop routing design to enhance data delivery performance. By using a mathematical framework, the aforementioned issue is addressed in [66] for investigating the performance of data delivery in V2X networks. With theoretical analysis, the formulated global and distributed optimization problem helps improve latency and the data transfer rate. However, high node mobility and vehicle density are not highlighted.

A. TOPOLOGY MANAGEMENT AND HIGH NODE MOBILITY

Table 2 highlights the contributions of the works that consider high node mobility-based routing protocols in VANETs. In [33], traffic signals are used to address the issue of irregular vehicle distribution and network congestion at peak traffic hours. In that work, a routing protocol called greedy traffic light and queue aware (GTLQR), which takes into consideration of channel quality, street connectivity, relative distance, and queuing delay, is proposed to diminish packet loss and balance traffic loads among vehicles. The goal is to decrease the end-to-end delay pertaining to multi-hop routing while guaranteeing complete data packet delivery. In response to the problem of variable node mobility in VANETs, the work in [42] proposes an architecture in which dynamic moving zones are formed to facilitate the dissemination of information. This work deals with moving object modeling with databases.

The work in [67] proposes parking-area-assisted spider-web routing protocol (PASRP), which is a spider-web model for the transmission of data in urban VANETs. It is built on the basis of parking areas using digital maps and geographic information. In VANETs, there is restricted WiFi coverage, and the topology changes frequently due to highly irregular node mobility. The work in [68] defines the link state routing (LSR) optimization problem. Many protocols use the concept of flooding to know the destination position, which increases network overhead. If we consider less populated regions, the hop count would be increased due to repeated usage of recovery strategies. Lastly, hop-greedy routing protocol that selects the path with the lowest number of in-between intersection nodes while considering good connectivity is proposed in [54].

Man-made and natural obstacles, irregular node mobility, and variable topology cause repeat link disconnections in communications that are not in a line-of-sight configuration. However, three-dimensional (3D) movement can be used by unmanned aerial vehicles (UAVs) to improve routing in VANETs. As it is correctly stated in [16], UAVs can increase the line-of-sight probability and the efficiency of the store-carry-forward mechanism. Routing protocols designed for VANETs mostly address the issues of high node mobility and variable topology, which can lead to data loss, frequent link disconnections, and high end-to-end delays. Geography-based routing protocols are the most efficient of the existing protocols due to their low network overhead and the fact that they can control vehicular environments very well. The work in [69] demonstrates how high mobility, data loss, and link disconnections must be carefully dealt with when working with geographic routing protocols. That work proposes Beaconless Traffic-Aware Geographical Routing Protocol (BTA-GRP) that considers inter-vehicle distances, traffic density, and the direction of vehicles when selecting the next forwarding node and the corresponding route. Many existing research works consider variable node mobility; however, the data bit rate, efficient multi-hop data transmission, and

route length are important issues that need to be addressed efficiently in real VANET environments. In light of this, the work in [47] discusses challenges associated with VANET routing protocols on the basis of real-world experiments.

TABLE 2. Non-Learning-Based V2X Routing Considering High Node Mobility

Item	Contributions
[33]	With the help of traffic signals, the issue of irregular vehicle distribution is addressed along with network congestion at peak traffic hours
[42]	Dynamic moving zones are formed to facilitate dissemination of information, considering moving object modeling with databases
[67]	Based on a spider model, the proposed model is built on the basis of parking areas using digital maps and geographic information
[68]	Addresses the link state routing optimization
[54]	Selects the path with the least number of in-between intersection nodes
[16]	States that UAVs can increase line-of-sight probability and more efficient use of store-carry-forward mechanism
[69]	Considers distances, traffic density, and directions when selecting the next forwarding node and the corresponding route
[47]	Discusses VANET routing protocols' challenges on the basis of real-world experiments
[70]	Analyzes the link stability in route selection and formulated it as a least cost enabled flow problem
[43]	For video transmission, numerous independent routes are found instead of just one between the source and destination
[71]	Handles highly dynamic node mobility using an optimized mechanism
[72]	Designs a secure payment framework for Drive-thru Internet
[73]	Prioritizes node transmission using relay set
[74]	Parallel route is established to the destination to reduce losses in real time applications
[75]	The effects of node addition, deletion, and loss of link node due to mobility are considered

Dynamic node mobility is a challenging issue in multi-hop data transmission because the connecting links are not stable and the packets are thus not always delivered to the destination. Due to the absence of global information, conventional broadcasting methods cannot accurately determine link dynamics in VANETs. However, if global network information is available, link stability can be better scrutinized with the help of the software-defined vehicular network (SDVN). The authors of [70] analyzed link stability in route selection and formulated it as the least-cost-enabled flow problem. The time complexity is decreased by proposing an incremental packet allocation plan. Variable node mobility is the reason why video-on-demand (VOD) sessions cannot guarantee QoS. A fresh adaptive geographic routing plan is proposed in [43] to establish simplex VOD transfer in urban areas. That scheme involves finding numerous independent routes between the source and destination instead of just one. The number of routes is dependent on the size of the video file to be sent and the time interval over which the route is fixed.

Highly dynamic node mobility in VANETs is a serious issue, and thus a reliable and stable network connection is needed by existing secure payment solutions like drive-thru Internet. Moreover, service providers may fail to deliver proper services in order to keep messages confidential. The work in [71] takes this issue into account and addresses

highly dynamic node mobility in VANETs using an optimized mechanism. The work in [72] proposes a secure installment payment framework for drive-thru Internet in VANETs. VANETs are prone to errors, mainly because of high node mobility and frequent disconnections. Therefore, the work in [73] proposes an opportunistic routing (OR) protocol that can enhance the VANET's performance by prioritizing node transmission using a relay set. The source vehicle uses packet advancement, packet delivery possibility, and vehicle density to determine the vehicle for the next hop.

Communication link failure is very common in VANETs because of highly dynamic node mobility. The work in [74] proposes a mechanism in which a parallel route to the destination is established to reduce losses in real-time applications. The work in [75] proposes a dynamically evolving networking model that takes input of real vehicular traces to get results which can be more practical. The effects of node addition/deletion and loss of link nodes due to mobility are considered. A link compensation process and preferential attachment are also proposed to maintain an evolving network.

B. GEOGRAPHIC ROUTING

Recently, geographic routing protocols have been prioritized due to their scalability; however, some metrics, like vehicle mobility, bandwidth availability, and link quality, show trade-offs in them. The forwarding geographic routing strategy selects the nodes that are closest to the destination, which could be located near the border of the communication range, where the possibility of link breakage is aggravated. Continuously selecting these nodes without considering the available bandwidth results in more losses and high packet delays. The work in [76] addresses this by proposing a new fuzzy logic-based protocol. Successful VANET packet delivery is challenging because of high node mobility and frequent disconnections. Thus, the work in [77] proposes a spider geographic routing for urban VANETs. VANETs consider car nodes to be relays; however, VANET nodes are highly mobile, which makes it an ordeal to maintain persistent communication between neighboring nodes. The work in [78] proposes a protocol that helps to divide urban spaces into multiple zones, of which one with high geographical circumstances is selected to be the next zone, and relay node selection is applied to forward packets to the next zone.

In [34], geographical source routing is enhanced using an ant-based algorithm to discover the route with optimum network connectivity. Vehicles choose the path with the lowest total weight for the entire route. In [79], simulation platforms are used to compare position-based and geographical protocols with the integration of mobility models and realistic physical layer. Multipath routing and protocol tuning are also discussed to show their potential to increase the reliability of data transmissions. In [35], the authors propose a multilevel plot directed greedy opportunity routing protocol and investigate geographic routing protocols for multilevel VANET scenarios. Their results indicate that the possibility of connectivity is deteriorated in multilevel environments

due to the degradation of the wireless transmission range. In VANETs, one of the widely studied routing protocols is geographic routing, mainly due to the prevalence of wireless devices with GPS. Selecting the next relay node is a challenging task, and the work in [80] thus proposes path aware geographic perimeter stateless routing (GPSR) following an analysis of the shortcomings of GPSR.

TABLE 3. Non-Learning-Based V2X Routing Considering Geographic Routing

Item	Contributions
[76]	Selects nodes considering available bandwidth
[77]	Designs geographic routing based on a spider model for urban VANETs
[78]	Divides urban spaces into multiple zones, where relay node selection is applied to forward packets
[34]	An ant-based algorithm is used to discover the route with an optimum network connectivity
[79]	Presents a comparison between position and geographical protocols, with the integration of mobility models and realistic physical layer
[35]	Geographic routing protocols are investigated for multilevel VANET scenarios
[80]	Analyzes the shortcomings of geographic routing
[81]	Designs a beacon information independent routing that reduces the number of broadcasts and uses information collected from vehicles during previous attempts at route discoveries

Beacons are small HELLO messages that are periodically broadcast by every vehicle and are used by many VANET protocols to select the next neighbor. Since beacons have a smaller payload size than data messages do, they can easily be delivered over very weak links, which means protocols that rely on beacons can select routes with low signal strength. Most of the existing works incorporate a huge number of broadcasts for forwarding data packets, which results in wasted bandwidth. The authors of [81] propose beacon information independent routing (or geographic routing) that incorporates fewer broadcasts and intelligently uses information collected from vehicles during previous attempts to discover routes to the destination to forward data packets. Table 3 highlights the contributions of the works that consider geographic routing-based routing protocols in VANETs.

C. POSITION-BASED ROUTING

Table 4 highlights the contributions of the works that consider position-based routing protocols in VANETs. Existing topology-based works are not quite efficient due to high vehicle mobility, which is why the authors of [14] worked on position-based routing (PBR) protocols. The consideration of PBR in city environments and connectivity-aware routing protocols is highlighted in [14]. That work presents a fog-based VANET that supports PBR to use parked vehicles when utilizing road intersections to select a path. Vehicles in parking areas are also involved in packet transmission. PBR has been a conventional routing protocol of choice in VANETs; however, it does not ensure that there is a routing path between the source and destination before the transmission or provide details about connection duration. The work in [82] proposes connectivity-aware routing based

on infrastructure (iCAR-II), which helps in Internet service, mobile data offloading, and multihop vehicle applications. To construct a global network topology, iCAR-II predicts the connectivity of local networks and updates the location servers with real-time networking information.

TABLE 4. Non-Learning-Based V2X Routing Considering Position-Based Routing

Item	Contributions
[14]	Fog-based VANET supporting PBR is presented to use parked vehicles for utilizing road intersections to select a path
[82]	Proposes connectivity aware routing, which helps in internet services, mobile data offloading, and multihop vehicle applications
[83]	Attempts to find the links with the highest packet reception possibility to be used as relay links
[84]	Proposes a location prediction technique to improve the routing performance by reducing the location errors
[85]	Designs vehicles' movements prediction-based routing
[86]	Presents a comparison and analysis to identify the most acceptable topology-based routing protocols in VANETs
[87]	Uses the ant colony algorithm such that a road is found with an optimal connection

In 3D VANETs, dynamic vehicles and path loss gradually uplift the possibility of link interruptions that deteriorate packet reception probability. In [83], a packet reception reliable routing protocol is proposed to improve link reliability. The work attempts to find the links with the highest packet reception possibility to use them as relay links. In position-based routing protocols, VANETs use positions acquired from satellite systems, like GPS, Compass and Galileo, and global navigation satellites. However, they are prone to technical and environmental issues that affect routing performance. Thus, the work in [84] proposes a location prediction technique that uses a Kalman filter to improve routing performance by reducing location errors. According to [85], routing protocols based on position are considered to be more reasonable while comparing with other VANET routing protocols. That work proposes a movement-prediction-based joint routing and hierarchical location based service. The primary objective of the survey in [86] is to identify the most acceptable topology-based routing protocols in a dynamic mobile VANET environment. The work in [87] proposes a position-based routing protocol that is an improvised global state routing protocol. The protocol uses the ant colony algorithm in an enhanced manner such that a road is found with an optimal connection in the network.

D. SOFTWARE-DEFINED NETWORKING-BASED APPROACHES

Software-defined networking (SDN) provides a global network topology and can introduce programmability to VANETs. Thus, SDN-based architectures can manage highly complex and dynamic VANETs by decoupling the control plane from the data plane. An SDN-enabled connectivity-aware geographical routing protocol (SCGRP) is introduced in [88] for optimal data transmission. VANET nodes are highly dynamic, and consequently, there are frequent link disconnections that lead to high end-to-end delays. Thus,

selecting a stable route is a key concern in VANETs. In [89], a routing protocol based on SDN is proposed for stable route discovery between the source and the destination. The SDN main controller (MC) finds the global network view, whereas numerous local controllers take charge of localized views of multiple zones under the MC. In [41], the authors propose a routing protocol called ROAMER that combines geographic and carry-and-forward protocols and uses RSUs to route messages in VANETs. ROAMER was later upgraded to shift routing operations that use a distributed SDN architecture as well as blockchain system in RSU networks in order to route packets securely and efficiently [41].

TABLE 5. Non-Learning-Based V2X Routing Considering SDN-based Approaches

Item	Contributions
[88]	Proposes a SDN-enabled connectivity aware geographical routing for optimal data transmission
[89]	Maintains a stable route discovery between the source and destination
[41]	Proposes a distributed SDN architecture with blockchain system in RSU networks in order to route packets securely and efficiently
[90]	Presents a concise summary of VANET structures with details on the SDN control
[38]	The large region is divided into numerous small grids based on the geographical location to find a set of grids having good connectivity

Vehicular communications have improved due to the introduction of SDN in VANETs. In [90], a concise summary of VANET structures is provided, with details of the SDN control. This survey also discusses the issues that must be addressed and the technologies that are required to design a robust protocol by maintaining latency, connectivity, and safety bounds in VANETs. The majority of existing VANET routing protocols take a distributed approach that leads to a local optimum and results in network congestion; SDN is thus quite popular because of its centralized control. In [38], a hierarchical geography-based SDVN routing protocol is proposed. First, the large region is divided into numerous small grids based on geographical location to find a set of grids that have good connectivity. Then, the path cost function is constructed with load balancing. Table 5 highlights the contributions of the works that consider SDN-based routing protocols in VANETs.

E. CLUSTER-BASED APPROACHES

Table 6 highlights the contributions of the works that consider cluster-based routing protocols in VANETs. In [91], every vehicle estimates a trustworthy low-overhead path using a cluster-based QoS algorithm known as the cluster-based adept cooperative algorithm. It helps maintain long-lived routes for which the most sustainable path is adaptively selected on the basis of signal strength, beacon, and node mobility. It reduces control message overhead and the routing table recalculation process. When transmitting data in VANETs, reliability cannot be guaranteed because of highly dynamic node mobility. Vehicle density is generally higher

at junctions than on straight roads, and thus the packet loss rate tends to increase as the velocity of a vehicle increases in junctions. Vehicular routing assisted by clustering is introduced in [92] for network scalability. The moving clusters enhance the connection establishment time and message delivery ratio. To optimize network performance, VANET routing protocols used clustering and multipoint relaying (MPR) until it was discovered that MPR, which was initially designed for open areas, does not really benefit from road section configurations. The authors of [93] propose a chain branch leaf clustering scheme to enhance broadcast traffic and help with routing actions.

VANETs are used for gathering and distributing safety-related information in order to reduce road accidents. It is in this context that the work in [94] proposes an adapted routing protocol for road safety in hybrid VANETs. An important contribution of that work is the introduction of a rider optimization algorithm to select neighbor nodes in order to ensure network lifetime as well as lossless connections. This protocol enhances road safety by forwarding valid data from the source to the destination. Attack detection using cluster-based data compilation is considered in [95], with the decisions related to message delivery executed at the cluster head. As it is discussed in [15], malicious nodes can be very dangerous and may send a substantial number of data packets to vehicles or RSUs. To address this issue, the authors of [95] propose a stream position performance analysis (SPPA) approach that considers distributed denial of service (DDOS) to monitor the position of the sender field station. SPPA tests the trustworthiness of data packets that are used for decision-making.

TABLE 6. Non-Learning-Based V2X Routing Considering Cluster-Based Approaches

Item	Contributions
[91]	Maintains long-lived routes where the most sustainable path is adaptively selected on the basis of signal strength, beacon, and node mobility
[92]	The network is divided into clusters which move along with vehicles for supporting data dissemination at road junctions
[93]	The proposed clustering scheme enhances the broadcast traffic
[94]	Introduces a rider optimization algorithm to select neighbor nodes in order to ensure network lifetime
[95]	Considers DDOS attack to monitor the position of the sender field station, where the trustworthiness of data packets is tested
[96]	Designs a centralized clustering approach with a data transmission optimization method for cellular-V2X hybrid vehicular networks

VANETs have three possible architectures, namely, pure ad-hoc, hybrid, and wireless local area network. There are several real-life traffic scenarios that need to be tackled during the design of a routing protocol in VANETs. Sybil attacks are crucial attacks in VANETs, as it is discussed in [15], [95], [97], and thus need to be handled efficiently to improve security aspects in VANETs. The works [15], [97] clearly describe how Sybil attacks can affect VANET routing protocols and briefly mention prevention mechanisms. The work in [98] reviews communication models, like RSU,

cluster-based, and V2V communications. According to its authors, the topic will forever be research-oriented and will be further enhanced in the future. Cluster-based approaches have the ability to use web signals to disseminate messages among vehicles. The probable distribution of V2V packet delays is analytically derived in [99] assuming bi-directional highways. The interesting thing in this work is that it discusses how related works miscalculated the maximum distance between two UAVs, which are aircraft that operate without the involvement of a human pilot on board. In [96], a cluster-based routing mechanism is proposed, that is based on SDN-enabled short-range communication and cellular-V2X hybrid vehicular networks. In [96], a heuristic algorithm is designed, that involves a two-stage approach in which the aggregated data can be delivered via cellular networks or V2V transmissions. However, the centralized one-hop based approach can suffer from transmission bottleneck and network delay.

F. NAMED DATA NETWORK-BASED APPROACH

In VANETs, named data networks (NDNs) use content-centered mechanisms to name content instead of the host, which is associated with a broadcast problem. The work in [100] addresses this by proposing a Bayesian receiver forwarding decision to resolve the broadcast problem. Vehicles receiving interest packets make forwarding decisions with the help of Bayesian decision theory pertaining to present network conditions, which are determined by interacting with neighbors. Sometimes drivers in vehicles want to acquire data whose location is unknown. NDN, which focuses on delivering mechanisms on the basis of the content of the message rather than the host address of the data, can be helpful in addressing this issue. In [101], an RSU assisted NDN mechanism is proposed that shows improved network connectivity in VANETs. Table 7 highlights the contributions of the works that consider NDN-based routing protocols in VANETs.

TABLE 7. Non-Learning-Based V2X Routing Considering Named Data Network Based Approaches

Item	Contributions
[100]	Vehicles receiving interest packets make forwarding decisions with the help of Bayesian decision theory
[101]	An RSU assisted NDN mechanism is proposed

G. INTERSECTION-BASED DISTRIBUTION ROUTING

VANETs are affected by traffic lights, road intersections, and variable traffic conditions. The authors of [102] take these issues into account and propose an intersection-based distribution routing (IDR) concept. Vehicles are supposed to stop at intersections because of traffic lights, and thus an intersection vehicle fog (IVF) approach is proposed in which the stopped vehicles form a dynamic collection or vehicle fog. To avoid rerouting, the IVF approach adjusts the routing

direction in real time on the basis of destination. When the IVF approach makes a routing decision, the IDR model uses ant colony optimization (ACO), which is discussed in [34], to identify the optimal routing path. In that case, the connectivity for multi-hop links between the intersections is based on traffic conditions.

H. IMPROVING QOS

Table 8 highlights the contributions of the works that target the improvement of QoS in V2X routing protocols. In VANETs, multi-hop communication is an ordeal, particularly due to irregular topology and frequent disconnections. To resolve this issue, the work in [103] considers multi-constrained QoS and interestingly proposes an optimized cost model to solve routing problems like road congestion, collisions, quality of the network, QoS, cost, etc. An optimum route is found using a mean computing Jaya algorithm and it is observed that this mechanism performs better than existing ones in terms of cost and convergence analysis. The work in [104] addresses the issues of large VANET network size, irregular topology, and frequent disconnections by proposing adaptive QoS-based VANET routing, which adaptively chooses the intersections through which data packets reach their destinations. The proposed scheme improves QoS on the basis of delay, connection probability, and PDR. In that work, an ACO-based algorithm is proposed to reduce routing search time and the impact of network congestion. Video content streaming between vehicles is possible in VANETs, but because of frequent disconnections, dynamic node mobility, and spaced vehicle distribution, video data packets are transferred via multiple discovered routes in order to increase the chances of error-free packet delivery. The work in [105] discusses packet loss ratio minimization by optimally distributing video packets on multiple routes. In that work, video playback and reconstruction are achieved while also ensuring QoS.

In [106], the authors propose a spider-web-based transmission mechanism that combines electronic maps and geographic information systems (GISs) to deal with emergency data in VANETs. When transmitting emergency data, confirmed spiders and request spiders are used to obtain the transmission path between the source and destination in order to improve packet delivery and average transmission delay. Speed and QoS are the two main characteristics of VANETs. The work in [107] studies the proactive fisheye source VANET protocol on the basis of speed, altitude, QoS, etc., in real traffic scenarios.

To effectively predict link reliability between vehicles and design a routing protocol that reliably meets QoS requirements, the work in [112] analyzes the reasons behind communication link instability and discusses vehicle motion characteristics. In that work, a time-based link duration model is shown to help find the optimal end-to-end path during rapid topology changes. 5th Generation (5G)-enabled VANETs help enable time-sensitive services with a designated QoS and better bandwidth usage. A review of

TABLE 8. Non-Learning-Based V2X Routing Considering the Improvement of QoS

Item	Contributions
[103]	Proposes an optimized cost model to solve routing problems like road congestion, collision, quality of network, QoS, cost, etc.
[104]	Adaptively chooses intersections through which data packets reach their destinations and improves the QoS on the basis of delay, connection probability, and PDR
[105]	Discusses the packet loss ratio minimization by optimally distributing video packets on multiple routes
[106]	Proposes a spider web based transmission mechanism to deal with emergency data in VANETs
[107]	Studies the proactive Fisheye source VANET protocol considering speed, altitude, QoS, etc., in a real traffic scenario
[108]	The reliability is ensured by selecting trustworthy and compatible routes with the minimum additional communications
[109]	The proposed routing approach leads to the reduction of the latency, enhancement of the delivery ratio, and minimization of the network overhead
[110]	Maintains a QoS guaranteed routing following a stable matching based routing approach that minimizes the end-to-end delay by using the best forwarder device
[111]	Discusses route discovery in V2X communications and highlights that DSDV must be preferred to AODV when V2X communications are performed

various management protocols is presented in [113], along with issues pertaining to 5G networks. In that work, a brief description of existing VANET models, applications, classifications, benefits, and drawbacks are also presented.

The connected dominating set is employed in [114] to broadcast video content and design an efficient routing protocol in VANETs in order to provide high-quality video streaming at various rates in urban environments. Interleaving is applied to spread loss bursts and reduce the impact of loss distributions. Single-packet losses are also taken into consideration, and a store-carry-forward protocol is used to retransmit packets stored in local buffers. In [108], routing reliability is ensured by selecting trustworthy and compatible routes considering minimum additional communications. Two very important goals are tackled by [109]: latency reduction delivery ratio enhancement, and the minimization of network overhead. The authors of [109] propose a routing protocol for urban environments that shows promising success ratios, negligible communication overheads, and low delivery delays. In [115], two new AODV-based protocols are designed to broadcast and filter route reply (RREP) messages and improve network performance. AODV is studied in [116] for 5G VANET routing optimization.

When there are rapid topology variations and frequent loss of links between vehicles, it is challenging to achieve QoS while delivering emergency messages. This issue is addressed in [110] by designing QoS guaranteed routing in device-to-device (D2D) assisted cellular-V2X (C-V2X) communications for emergency message dissemination. The proposed mechanism follows a stable matching-based routing approach that minimizes end-to-end delay by using the best forwarder device. If the requested data is not found in the neighbor device, a 5G base station is requested through a pedestrian. Due to the 5G-based environment, the time com-

plexity of the proposed mechanism is crucial and thus needs to be analyzed. In V2X communications, route discovery can be done using reactive or proactive approaches, which are compared in [111]. The results of that work highlight that destination-sequenced distance-vector routing (DSDV) must be preferred over AODV when V2X communications are in the participating candidates. However, DSDV cannot be used directly; it is feasible only as a starting point to develop other exclusive routing protocols.

I. HIGH VEHICULAR SPEED

In VANETs, maintaining end-to-end connections is indeed difficult, and thus the store-and-forward concept, which depends solely on node cooperation, is used for vehicular communications. The authors of [53] propose a hidden Markov model for predictive VANET routing that monitors vehicle movements to enhance transmission performance. The model predicts the future location of vehicles by considering where a vehicle regularly visits or who a vehicle regularly contacts, i.e., historical data is considered. To enhance the reliability and efficiency of path selection, a routing protocol is designed in [117] that considers speed, traffic loads, the number of nodes, and error rate. Channel parameters are also considered to increase reliability. VANET nodes are highly dynamic, and thus dynamic link stability is a challenging issue. V2V works without RSUs or gateways, but the possibility of successful link establishment gradually decreases as the number of red traffic lights, crossroads, sparsely distributed vehicles, and variations in vehicle speeds increases. RSUs are considered in [118] for ensuring route establishment and broadcast control route requests in sparse VANETs with crossed road layouts. RSUs also help with route discovery in gateway zones when the next hop for relaying route request packets is absent. Since there are chances of link failure, handoff overhead, and link re-establishment because RSUs are static and vehicles are dynamic. Thus, relying solely on RSU forwarding is not effective. To minimize the loss of buffered packets along the route and maintain a stable link, a local route repair mechanism that incorporates RSUs is designed in [118].

The work in [119] proposes a scheme in which short video recordings can be sent to any city infrastructure through VANETs, which helps provide quick emergency services. In this work, a multimedia multimetric map-aware routing protocol is proposed to send video complaint using VANETs in smart cities. Due to technological developments, the most commonly used single-hop multicast communications are gradually being overpowered by multi-hop unicast communications in VANETs. The work in [120] addresses this by using a predicted value for calculating route lifetime, and the prediction scheme is implemented using AODV routing. Self-organization in wireless multi-hop networks leads to inefficient and unreliable decision schemes for data routing. To address this, the authors of [121] propose the Manhattan mobility model, which integrates RSUs into both wired and wireless models for transmitting data and optimizing route

TABLE 9. Non-Learning-Based V2X Routing Considering High Vehicular Speed

Item	Contributions
[53]	Proposes a hidden Markov model for predictive VANET routing that monitors vehicle movement behaviors to enhance transmission performance
[117]	Enhances the reliability and efficiency in path selection considering the speed, traffic loads, number of nodes, and error rate
[118]	Proposes a local route repair mechanism, and ensures route establishment and broadcasting control route requests in sparse VANETs with crossed road layout
[119]	Designs a multimedia multimetric map-aware routing protocol to send video-complaining messages using VANETs in smart cities
[120]	Predicts route lifetime and the prediction scheme is implemented in AODV routing
[121]	Utilizes the Manhattan Mobility Model to integrate RSUs into both wired and wireless models for transmitting data and optimizing route decisions
[122]	Proposes Harris Hawks Optimization based approach to select two instead of multiple hops to assure stability of route and high data transmission success rate

decisions. Irregular vehicle mobility is analyzed using motion information, and a greedy algorithm that incorporates wired RSUs is used for wireless vehicle communication. The work in [122] proposes an Harris hawks optimization-based algorithm to select two rather than multiple hops and thereby ensure route stability and a high data transmission success rate. Table 9 highlights the contributions of the works that consider high vehicular speed.

J. HYBRID PROTOCOL

The authors of [123] propose direction-based cache agent location-aided routing, which is a hybrid routing protocol. In that work, geocast and position-based routing are combined, which significantly improves the routing performance of VANETs. Data delivery performance in V2X communications is addressed in [124] by developing a mathematical framework that considers throughput and latency. Moreover, an optimization problem is formulated for maximizing throughput and latency for hybrid V2I-V2V networks. An algorithm is proposed in [124] that uses a multi-hop routing approach to select the optimized path to maximize the weighted sum of throughput and latency. The solution provided in [124] achieves low latency and high throughput; however, the frequent change of topology in V2X is not highlighted.

K. MAINTAINING SECURITY AND PRIVACY

As per [125], VANETs protect nodes from outside observers by using unidentified routing protocols; however, existing protocols depend on unnecessary traffic or encryption, which makes them highly costly and unable to provide complete sender, receiver, route, and data privacy. The work in [125] proposes a cost-effective and efficient location-based routing protocol to address this. Multilateral security is guaranteed by using public key infrastructures (PKIs) and digital signatures. In [126], DDOS attacks are prominently discussed and a secured minimum delay routing protocol is proposed.

TABLE 10. Non-Learning-Based V2X Routing Considering Security and Privacy

Item	Contributions
[125]	Designs a location-based, cost effective, and unidentified efficient routing protocol to protect nodes from outside observers
[126]	Handles DoS attacks by proposing a secured minimum delay routing protocol
[127]	Designs an anonymous onion-based routing protocol introducing dynamic relay groups to maintain privacy in VANETs
[39]	Proposes a routing protocol exploiting handshake-less communications, a competent collision resolution mechanism, and ACK decoupling
[40]	Derives an optimal incentive for the PSP with the use of contact theory
[15]	Explores position based routing protocols getting attacked by Sybil vehicles, and consequently GPCR is proposed

In [127], a novel anonymous onion-based routing protocol introduces dynamic relay groups, which maintains privacy in VANETs. In this work, groups are formed of the vehicles around specific locations, and the vehicles are used for cryptographic onion relay. This protocol keeps the source, destination, route, and real vehicle identity anonymous. To ensure privacy in VANETs, the authors of [39] propose an efficient routing protocol that exploits handshake-less communications, a competent collision resolution mechanism, and acknowledgment (ACK) decoupling. Real-world experiments, computer simulations, and theoretical modeling are used to analyze the mechanism. Security and a global consensus are very much needed to cope with the increased use of cryptocurrencies for real-time payments. Payment channel networks present a promising solution to cryptocurrencies. In that work, transactions are offloaded from blockchain and then directly handled using a minimum-involvement-required payment channel. Despite their importance for successfully dealing with path-based transactions, incentive mechanisms pertaining to payment service providers (PSPs) have not been efficiently studied. PayGo, a routing protocol that is proposed in [40], does not find the best path in terms of budget, but derives an optimal incentive for the PSP using contact theory. The PSP is induced by PayGo to make a deal with counterparties that guarantee throughput and penalize payment latency.

VANETs are vulnerable to several types of malicious attacks, such as Sybil attacks [15], which are able to disrupt the normal functioning of most VANET protocols and are not easily detectable. In Sybil attacks, a legitimate vehicle with ill intentions (Sybil vehicle) gets into the network and mischievously launches virtual camouflaged vehicles to affect the VANET routing mechanism. In [15], the authors explore position-based routing protocols that are attacked by Sybil vehicles and consequently propose greedy perimeter coordinator routing (GPCR). Table 10 highlights the contributions of the works that consider security and privacy in V2X routing protocols.

L. FAULT DETECTION

VANET routing protocols must receive valid information from neighboring vehicles as beacons; if an OBU is soft faulty, it will reduce system performance. Thus, a fresh self-soft fault observation routing protocol is proposed in [128] to send data to the destination without delays and detect soft faulty vehicles. A vehicle is assumed to know whether or not decisions made by neighboring vehicles are faulty and whether or not neighboring vehicles should be excluded from the routing process. Data forwarding is done via fault-free vehicles on almost completely connected paths, and the best path at every junction is selected by fetching the path values through which data is forwarded. False alarm and fault detection rates are used to test the performance of the fault detection method.

M. PROBABILISTIC ROUTING

An efficient VANET routing protocol shows good performance in terms of packet loss, end-to-end delays, etc. In the interest of achieving these promising results, the work in [37] proposes a probabilistic multimetric routing protocol (ProMRP) that is especially designed for VANETs. It uses probability to estimate the percentage of packets successfully delivered to the destination on the basis of four metrics, namely, distance to the destination, position of a node, available bandwidth, and density of the nodes. An improved version of ProMRP is also proposed that helps to estimate the node's current position before sending the data instead of utilizing the last known position from the previous beacon message.

Considering the intersection-based routing mechanism, a microscopic scheme is proposed in [129], where intersecting nodes help maintain and update records by collecting data from passing vehicles. Vehicles' current positions are recorded to compute the connectivity probability and estimate the delivery delay. Both microscopic and individual data are used for enhancing the accuracy of the results. To decrease the complexity associated with position estimation, vehicles are arranged in a queue. In this context, the network overhead is also low because there is no generation of dedicated control packets in the proposed scheme. Table 11 highlights the contributions of the works that consider probabilistic routing in VANETs.

TABLE 11. Non-Learning-Based V2X Routing Considering Probabilistic Routing

Item	Contributions
[37]	Uses the probability to estimate the percentage of successful packet delivery to the destination and estimates the current node positions before sending the data
[129]	Intersecting nodes help maintain and update records by taking data from every passing vehicle, and the delivery delay and vehicles' current positions are recorded to compute the connectivity probability

N. UAV IN VANETS

With the introduction of flying VANETs (FANETs), cost-effective UAVs can be used to accomplish complex missions in the sky [130]. In FANETs, the reliability of information exchange is still in its initial stages. UAVs stand apart from traditional networks as they are deployed in the sky and the mobility model adopted is determined by the nature of the mission. A comprehensive study that critically compares FANETs and considers architecture, constraints, mobility models, simulation tools, routing techniques, and future challenges is presented in [130].

O. HANDLING OF CONGESTION AND SHADOWING EFFECTS

One of the most crucial challenges in VANETs is addressing the end-to-end delay problem. This problem can be exacerbated by congestion in the network. Greedy-based techniques are generally used in this context, but they result in the local maximum problem and data congestion, which lead to even higher end-to-end delays. The work in [131] proposes a mechanism that helps to evaluate the end-to-end delay of the entire path before messages are sent. To this end, stable backbones are built on road segments and connected via bridge nodes at intersections. Road segments are assigned weights by the bridge nodes on the basis of delay and connectivity-related information. The routes with the lowest average weights are then selected to forward data packets.

The time delay and the quality of the communication link must be considered when designing VANET routing mechanisms. Yet, many communication protocol theories ignore obstacles, such as buildings and trees, that are bound to be present in an urban environment. These obstacles can cause signal fading or completely block signals. The vehicles parked on roadsides can be considered relays to reduce shadowing effects. The work in [36] proposes a parked vehicle relay routing algorithm to improve vehicular communications in VANET routing.

P. NETWORK OVERHEAD

The work in [132] compares proactive, reactive, and hybrid routing protocols on the basis of behavior and performance in urban environments. It also studies the performance of User Datagram Protocol (UDP) and Transmission Control Protocol (TCP) with variable car density. It was observed that the proactive OLSR protocol has the least network overhead, the reactive AODV protocol performs best in terms of transfer rate at the TCP level, and the hybrid zone routing protocol (ZRP) has the lowest latency and increases the delay rate. A novel routing protocol is proposed in [133] to reduce the network overhead generated due to the periodic exchange of beacon messages when routing. To achieve this, two-directional antennas are used to decrease the size, rather than the number, of beacons. Greedy forwarding is modified at road segments to calculate the distance between the packet sender and the direct neighbors instead of using their present

geographical locations. Table 12 highlights the contributions of the works that consider network overhead in V2X routing.

TABLE 12. Non-Learning-Based V2X Routing Considering Network Overhead

Item	Contributions
[132]	Presents a comparison between proactive, reactive, and hybrid routing protocols on the basis of their performances in urban environments
[133]	Reduces the generated network overhead due to periodic beacon message exchange in routing

Q. NETWORK CONNECTIVITY

Guaranteeing connectivity in VANETs is challenging because of topological aspects that depend on the flow of vehicles, which is dynamic. The utilization of fixed infrastructures could be a promising option, although the costs involved are prohibitive. In urban cities, metropolitan buses can be used as the backbone (metropolitan VANETs). The work in [134] addresses this by proposing a live mobile ad-hoc backbone that can increase network connectivity and provide an effective infrastructure for VANETs. Statistical analysis shows that the proposed backbone can ensure good connectivity in the network. A new routing protocol is also designed in that work to have the proposed backbone exploit intrinsic connectivity. This protocol can improve network performance by giving priority to nodes during the route discovery process.

To choose the next forwarding street, routing protocols generally consider the density or number of vehicles. However, unequal spatial vehicle distributions significantly change the connectivity for multi-level or single-level streets. The authors of [135] propose a connectivity-aware routing protocol based on spatial distribution that helps to divide streets into multiple segments and gather vehicle numbers and positions in every segment in order to monitor the connectivity quality of the segments. Table 13 presents the contributions of the works that consider network connectivity in V2X routing.

TABLE 13. Non-Learning-Based V2X Routing Considering Connectivity in the Network

Item	Contributions
[134]	Designs a live mobile adhoc backbone and routing protocol to increase the network connectivity and provide an effective infrastructure for VANETs
[135]	Proposes a connectivity-aware routing based on spatial distribution that helps divide streets into more than one segments and gathers vehicle numbers and positions at every segment in order to monitor the connectivity quality of the segments

R. 3D VANET SCENARIOS

Traditional VANET routing protocols assume planar scenarios but are actually applied in 3D. Many routing issues for 3D VANET scenarios are addressed in [136]. More specifically, that work analyzes the features of 3D urban road networks

and develops 3D routing protocols. It also proposes an improved two-part 3D oriented routing protocol, the first part of which draws attention to issues in simple 3D city structures and the second part of which addresses complex 3D city structures.

IV. LEARNING-BASED V2X ROUTING PROTOCOLS

In this section, we discuss the existing works that consider learning-based V2X routing protocols and their impacts on network performance. Tables 22 and 23 present the works and highlight their strengths and weaknesses. Fig. 5 shows the number of existing works that consider learning-based V2X routing, where machine learning has been employed since 2009.

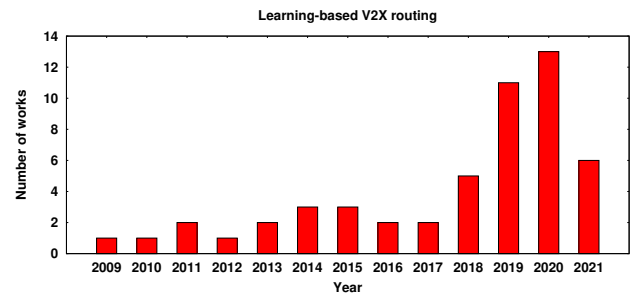


FIGURE 5. Number of works considering learning-based V2X routing

A. IRREGULAR VEHICLE DENSITY

Vehicle density and traffic are irregularly distributed in metropolitan cities. Moreover, man-made constructions can block vehicular traffic, which makes designing protocols for VANETs challenging. In [48], a Q-learning-based routing protocol, known as Q-learning-based RSU-aided traffic-aware routing (QTAR), is introduced for urban VANETs. VANETs connect highly mobile vehicles with dynamic inter-vehicle spacing and fluctuating vehicle density on roads. These characteristics affect VANET performance; however, if the mobility of vehicles can be predicted, continuous service becomes possible. In [6], the authors propose a central routing scheme that can predict mobility using a software network controller that is powered by artificial intelligence. Moreover, it is difficult to provide trustworthy multi-hop communications because of vehicle movement, a shortage of wireless channels, and the lossy attributes of wireless channels. The work in [137] thus investigates a VANET routing protocol that employs the Q-learning algorithm with a fuzzy constraint that is portable and can learn optimal routes on the basis of AODV.

Due to unstable link connections, reliable communication between vehicular nodes is still not achievable. The work in [138] proposes a reinforcement learning-based routing protocol for clustered electric vehicle (EV)-VANETs, that uses a K-harmonic means algorithm to upgrade the cluster structure's stability. Distributed ITSs require that information be stored independent of fixed infrastructure like

TABLE 14. Non-Learning-Based V2X Routing Protocols

Item	Strengths	Weaknesses
Xia <i>et al.</i> [33]	(1) High packet delivery ratio, (2) Low end-to-end delay	(1) High mobility, (2) Irregular topology
Goudarzi <i>et al.</i> [34]	(1) Control overhead is decreased, (2) Low end-to-end delay, (3) Ant-based broadcast mechanism, (4) Does not need road side unit (RSU) or traffic sensors	Less optimized route discovery in irregular traffic conditions
Ledy <i>et al.</i> [79]	(1) Explanations to contradictory results which are found in other related works are given, (2) Positional and geographical based protocols are compared with details	Absence of realistic simulation
Lin <i>et al.</i> [42]	(1) Vehicles communicate with each other to create dynamic moving zones in order to facilitate information circulation, (2) Introduces indexing techniques and moving object modeling, (3) Simulation studies are conducted on real road maps	(1) Impacts of high and irregular traffic are not highlighted, (2) Lack of discussion on security and privacy issues
Liu <i>et al.</i> [67]	(1) PASRP helps in obtaining the transferral path and a higher packet delivery ratio, (2) Greedy forwarding strategy and multi-priority mechanism for scheduling help in managing and forwarding packets to lessen mean end-to-end delay, (3) PASRP considers the real Washington D.C. map and also outperforms existing protocols (4) Dynamic node mobility	(1) Irregular vehicle distribution, (2) Less trustworthy transferral of data in emergency conditions
Toutouh <i>et al.</i> [68]	(1) Better quality of service (QoS), (2) A real VANET scenario on the basis of city of Malaga has been used to evaluate the performance of the network	(1) Dynamic node mobility, (2) Irregular topology, (3) No administration.
Haghighi <i>et al.</i> [127]	(1) The protocol keeps the source, destination, route, and real vehicle identity anonymous, (2) Does not rely on RSUs, (3) Multi-path forwarding is used, where multiple copies of the transmitted message are sent through network layers	Lack of privacy in backbone nodes that play a key role in providing connectivity status around an intersection
Sahu <i>et al.</i> [54]	(1) Backbone nodes have been introduced, which play a key role in providing connectivity details around an intersection, (2) High packet delivery ratio, (3) Short end-to-end delay	(1) High vehicle mobility, (2) Frequent disconnections in the network
Nazib <i>et al.</i> [16]	Survey on various UAV assisted routing protocols have been compared based on working formula, design principles, benefits, disadvantages, applications, future scopes, and improvement areas	Lack of insights on irregular node mobility and variable topology
Gnanasekar <i>et al.</i> [103]	(1) Cost model accounting for road congestion, collision, quality of the network, and Quality of Service (QoS) cost was proposed, (2) Fuzzification of QoS factor was involved in the work, (3) The routing cost is minimized	(1) Lack of details of the impact of variable topology and frequent disconnections in the network
Ferronato <i>et al.</i> [132]	(1) Performances of three position based routing protocols are compared, (2) Consideration of varying cars density	The overhead of the network and routing protocol implementation are not highlighted in details
Din <i>et al.</i> [69]	(1) Consideration of dense urban as well as sparsely distributed traffic, (2) Helps in addressing time delay, packet drops, and disconnecting link issues, (3) Fast routing path connectivity	(1) Lack of details on irregular node mobility, (2) Routing overhead is not highlighted
Sun <i>et al.</i> [102]	(1) Due to high routing path connectivity, the model needs packet forwarding only, which reduces transmission delay and increases transmission ratio, (2) The routing direction is adjusted on the basis of real-time destination to avoid rerouting	Variable traffic conditions of the overall network are not detailed
Ullah <i>et al.</i> [14]	(1) Good packet delivery ratio, (2) Less end-to-end delay, (3) Less transmission time, (4) Less communication cost	Lack on details of variable topology and protocol overhead
Nzouonta <i>et al.</i> [61]	(1) Better in urban environments, (2) More average delivery rate and low average delay than other competing protocols	Overheads of routing and rerouting are not highlighted
Xu <i>et al.</i> [83]	(1) Better packet delivery ratio, (2) End-to-end delay is low	(1) Difficult distribution of nodes, (2) Critical path loss
Silva <i>et al.</i> [80]	(1) Packet routing loops have been discarded to avoid the delivery of similar packets to the same neighbor node, (2) Line-breakage, which is caused due to road accidents and dead-end roads, can be avoided, (3) Low packet loss rate, (4) Low end-to-end delay	Lack of overhead analysis due to the introduction of additional tables
Zhu <i>et al.</i> [136]	(1) High packet delivery ratio, (2) Low hop count, (3) Low end-to-end delay	Non consideration of 3-D VANET application environment
Mezher <i>et al.</i> [119]	(1) Variable node mobility and interfering buildings are considered, (2) Video messages are proposed as an alternative to text messages to report road accidents	Less efficient management of road accidents
Li <i>et al.</i> [104]	Local QoS models for estimating real time as well as completing QoS for urban roads	(1) Handling variable network conditions is not highlighted, (2) Impact of irregular topology
Sudheera <i>et al.</i> [70]	(1) Flow instantiation (FI) based source routing for software-defined vehicular network (SDVN) analyzes link stability in route selection, (2) Incremental packet allocation plan decreases time complexity, (3) Multiple shortest paths	Impact of variable node mobility
Zhu <i>et al.</i> [35]	(1) A good delivery ratio, (2) The proposed scheme reduces average hop count	Lack of analysis of complex node distribution and transference conditions in multi-level VANET environments
Salkuyeh <i>et al.</i> [43]	(1) Packet loss ratio is decreased, (2) Freezing delay is improved, (3) Estimation of connectivity possibility to select the best-connected route	Routing overhead with variable node mobility
Sun <i>et al.</i> [36]	(1) Good communication quality, (2) High success rate, (3) Low delay	Overhead of routing and rerouting
Cárdenas <i>et al.</i> [37]	(1) Low packet loss rate, (2) Low end-to-end delay	(1) Impact of short communication link lifetime, (2) Lack of details of variable topology under different network conditions

TABLE 15. Non-Learning-Based V2X Routing Protocols (Continue...)

Item	Strengths	Weaknesses
Togou <i>et al.</i> [131]	(1) High probability of connectivity, (2) Low end-to-end delay, (3) High packet delivery ratio, (4) Low control overhead	Impact of high node mobility and irregular traffic are not highlighted
Gao <i>et al.</i> [38]	Advantageous in terms of throughput, average delay, average hop count and delivery ratio	(1) Impact of scattered connectivity, (2) Lack of details related to the handling of network congestion in various network scenarios
Ghafoor <i>et al.</i> [89]	(1) Improves end-to-end delay, (2) Message delivery ratio is high, (3) Low network overhead	Lack of details on the overhead of the software-defined based architecture
Al-Kharasani <i>et al.</i> [91]	(1) Helps maintain long-lived routes, (2) Control message overhead is reduced, (3) Recalculation process of routing tables	Details of node mobility and traffic overhead are not highlighted
Rivoirard <i>et al.</i> [93]	(1) Decreases routing traffic due to formation as well as retransmission of control messages on topology, (2) Helps in overall network stability	Lack of details of the impact of different network conditions
Alsharif <i>et al.</i> [82]	(1) Dynamically selects paths with a lower delivery delay and guaranteed connectivity, (2) High packet delivery ratio, (3) Less end-to-end delay	(1) Impacts of high variable node mobility and dynamic topology are not detailed, (2) Lack of reliability
Alzamzami <i>et al.</i> [76]	(1) High packet-delivery ratio, (2) Low end-to-end delay, (3) Takes a combination of multiple metrics taking into account the vehicle position, link quality, direction, and attainable throughput for selecting the fittest next-hop when forwarding the packets	(1) Discussion on non-availability of bandwidth, (2) Lack of variable node mobility under various network conditions
Abbasi <i>et al.</i> [39]	(1) Less end-to-end delay, (2) High packet delivery ratio, (3) Trustworthy message transfer in multi-hop communications	(1) Details of protocol overhead are not highlighted, (2) Lack of details on irregular vehicle density
Gao <i>et al.</i> [121]	(1) Real-time planning is improved, (2) Network transmission performance is improved, (3) Packet delivery ratio is high, (4) Reduced end-to-end time delay	(1) Issues of handling unstable networks are not highlighted, (2) Lack on a discussion of the protocol overhead with the availability of bandwidth
Tiennoy <i>et al.</i> [101]	(1) Assures enhanced network connectivity, (2) Latency is reduced under different vehicular transmission ranges and vehicle densities, (3) Use of real-world dataset	Lack of discussion on the protocol overhead under highly dynamic and irregular node mobility
Chen <i>et al.</i> [77]	(1) Improvement in packet delivery ratio, (2) Reduction in mean transmission delay, (3) Considers frequent link disconnections and node mobility	(1) Overhead of selective forwarding scheme is not highlighted, (2) Security and privacy issues
Yao <i>et al.</i> [53]	(1) High packet delivery ratio, (2) Low end-to-end delay, (3) Improves buffer occupancy, (4) Less traffic overhead, (5) Packet delivery possibility can be predicted, (6) Seamless handoff between vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) is enabled so vehicle density or node mobility will not affect the performance	(1) Details on handling irregular vehicle density are not highlighted, (2) Lack of discussion on long-term route selection
Wu <i>et al.</i> [60]	(1) High packet delivery ratio, (2) Low network overhead, (3) Low end-to-end delay, (4) Common backbone vehicles are used for various traffic flows, (5) Reliably connected backbone	(1) Lack of details on the performance analysis under variable node mobility, (2) Impact of different network scenarios is not highlighted
Qiu <i>et al.</i> [106]	(1) To improve packet delivery ratio as well as average transmission delay, confirmed spiders and request spiders are used for obtaining the transmission path between the source and destination, (2) To lessen end-to-end delay, restricted greedy forwarding process is combined with dynamic multi priority message queue management process on the basis of position prediction, (3) Convergence rate is minimized	(1) Computational complexity, (2) Security and reliability issues
Mershad <i>et al.</i> [41]	(1) Distributed SDN architecture as well as blockchain system in RSU network to securely and efficiently route packets, (2) More flexibility, scalability	(1) Details on the overhead of the SDN framework are not highlighted, (2) Implementation complexity
Raja <i>et al.</i> [94]	(1) High packet delivery ratio, (2) High throughput, (3) Low routing overhead, (4) Low energy consumption, (5) Low end-to-to delay (6) High network lifetime	Uncertain agreement between energy consumption and transmission delay
Gurumoorthi <i>et al.</i> [123]	(1) Advantages of both geocast and position based routing, (2) Improvement of average end-to-end delay, hop count, packet delivery ratio, and retransmission ratio	(1) Lack of details on security and authentication issues, (2) Impact of high node mobility in different network conditions
Gurumoorthi <i>et al.</i> [62]	(1) City and highway environments have been used to deploy and implement the mechanisms (2) Low average hop count, (3) High Throughput	(1) Low packet delivery ratio, (2) High end-to-end delay, (3) High packet loss ratio
Jaiswal <i>et al.</i> [84]	(1) High packet delivery ratio, (2) Less end-to-end delay, (3) High throughput, (4) Location error due to considerations of GPS and such other systems is minimized	Positions acquired from satellite system are prone to technical and environmental issues which affect the routing performance
Kulla <i>et al.</i> [120]	(1) Successful packet delivery ratio is increased, (2) Throughput is improved, (3) The lifetime of links is considered to find the predicted route with the highest stability on the basis of relative speed	Lack of analysis with different routing mechanisms
Lee <i>et al.</i> [78]	(1) Helps divide urban spaces into multiple zones where one zone, with high geographical circumstances, is selected to be the next zone and relay node selection is applied to forward packets to the next zone, (2) Relay node selection algorithm is applied to forward packets to the next zone	Impact of the relaying mechanism on the network and routing overhead is not highlighted
Kumar <i>et al.</i> [81]	(1) Reduced number of broadcasts for data forwarding, (2) High successful packet delivery ratio, (3) Low end-to-end delay	(1) Bandwidth management issues, (2) Impact of highly dynamic node mobility is not highlighted

TABLE 16. Non-Learning-Based V2X Routing Protocols (Continue...)

Item	Strengths	Weaknesses
Wang <i>et al.</i> [63]	(1) Routing overhead is reduced using a receiver-based method, (2) Uses routing metric that includes length of each hop and link remaining time	(1) Impact on routing link stability, (2) Detailed analysis under irregular and highly dynamic node mobility is not highlighted
Duduku <i>et al.</i> [126]	(1) Distributed denial and denial of service attacks have been prominently discussed, (2) Discussion on cost-effectiveness	Routing overhead and irregular node mobility issues
Sood <i>et al.</i> [15]	Greedy Perimeter Coordinator Routing (GPCR) was proposed, and it was concluded that GPCR is prone to Sybil attacks	Lack of details on the performance analysis under different network scenarios
Marchang <i>et al.</i> [118]	(1) Analysis of RSU dependent data forwarding and route discovery, (2) To avoid the loss of buffered packets on the route, local route repair was attempted with the assistance of RSUs	Impact of the absence of link stability is not detailed
Zahedi <i>et al.</i> [133]	(1) Two directional antennas were used for decreasing the size of beacons without affecting their count, (2) Greedy forwarding was modified at road segments in order to calculate the distance in between the packet sender and the direct neighbors	Lack of details on the selection of antennas in varying signal strength and network scenarios
Elshaikh <i>et al.</i> [71]	(1) The enhancement of AODV using Taguchi method has improved VANET performance, (2) Packet delivery ratio has increased, (3) Less end-to-end delay	Overhead analysis and the real-life implementation details are not highlighted
Ganesh <i>et al.</i> [74]	Parallel route is established to the designated destination for reducing losses in real-time applications	Lack of details on the routing overhead
Bhoi <i>et al.</i> [128]	(1) Decisions by neighbor vehicles help to overcome faulty paths in the routing, (2) Data forwarding is done via fault-free vehicles in the almost completely connected path and the best path at every junction is selected by fetching path values through which data is forwarded, (3) False alarm and fault detection rates are used to test the performance of the fault detection method	(1) Impact of wrong decisions by neighbor vehicles is not highlighted, (2) Lack of details of the impact of irregular and high node mobility on the proposed protocol
Song <i>et al.</i> [72]	Ensures payment confidentiality vouchers, periodic reconciliation, payment in installments and offline signature verification	(1) Impact of protocol overhead on the network performance is not highlighted, (2) Lack of discussion of irregular node mobility in different network conditions
Li <i>et al.</i> [114]	(1) Connected dominating set was employed to broadcast video content, (2) Three statuses were added to avoid repeated calculations of the connected dominating set, (3) To reduce the impact of packet losses, interleaving was employed for spreading outburst losses, (4) Store-carry-forward protocol is used for retransmitting stored packets in local buffer	(1) Impact of store-carry-forward mechanism on the network performance is not highlighted, (2) Protocol overhead
Kumbhar <i>et al.</i> [108]	The reliability in routing is ensured by selecting trustworthy and compatible routes considering the minimum additional communications in the network	Lack of details of the impact of irregular and high node mobility
Hossain <i>et al.</i> [122]	(1) Stability of route, (2) High data transmission success rate	(1) Lack of details of the impact of network congestion, (2) Security and privacy issues
Hawbani <i>et al.</i> [109]	(1) Reduction of the latency, (2) Enhancement of successful delivery ratio, (3) Minimization of the network overhead	(1) Lack of details of the impact of high-speed vehicles, (2) Issues of adaptability in different network scenarios
Aravindhan <i>et al.</i> [87]	(1) An improvised Global State Routing protocol, (2) Ant colony algorithm is used in an enhanced manner such that a road is found with an optimal connection in the network	(1) Network overhead, (2) Lack of convergence analysis
Rajhi <i>et al.</i> [86]	Identifies the best possible topology-based routing protocols in a mobile and dynamic environment in VANETs	Lack of details of high-speed mobility and adaptability in frequently changing network topology
Qi <i>et al.</i> [96]	(1) Proposes SDN-enabled clustering routing for cellular-V2X hybrid vehicular networks, (2) A heuristic algorithm is designed	The centralized one-hop based approach can suffer from the transmission bottleneck and network delay
Alghamdi <i>et al.</i> [110]	(1) Designs a QoS guaranteed routing in D2D communication assisted C-V2X, (2) Emergency message dissemination is considered, (3) Minimizes the end-to-end delay by using the best forwarder device, (4) Uses 5G base stations	The time complexity of the proposed mechanism needs to be analyzed
Priya <i>et al.</i> [111]	Highlights the advantages of DSDV over AODV when V2X communications are considered	(1) The time complexity of the proposed mechanism needs to be analyzed, (2) Variable network conditions are not highlighted
Li <i>et al.</i> [124]	(1) Data delivery performance in V2X communications is dealt with using a mathematical framework, (2) An optimization problem is formulated for maximizing the throughput and latency	The frequent change of topology is not highlighted

TABLE 17. Learning-Based V2X Routing Considering Irregular Vehicle Density

Item	Contributions
[48]	Proposes a Q-learning based RSU-aided traffic-aware routing for urban VANETs
[6]	Designs an artificial intelligence based central routing scheme that predicts mobility using a software network controller
[137]	Designs a VANET routing protocol based on Q-learning algorithm using a fuzzy constraint, which is portable and learns optimal routes on the basis of AODV
[52]	Based on the vehicle variable ratio, V2X communication capabilities and predictive rerouting mechanism are analyzed

RSUs. Therefore, [46] proposes a protocol to collect data in VANETs by considering vehicle velocity and bandwidth efficiency. The work in [139] addresses VANET data aggregation and proposes an adaptive forwarding delay control system that is based on a distributed learning. The proposed scheme dynamically changes the speed of the nearby sensors' reports to improve their chances of connecting with each other, which leads to efficient aggregation of data. The vehicle variable ratio analysis in [52] focuses on analyzing V2X communication capabilities and addresses how well the predictive rerouting algorithm performs when many vehicles (a high percentage of them) do not get to communicate due to traffic density. The existing V2X communication channel does not include crucial properties like suspicious message transfers and latencies. Table 17 highlights the contributions of the works that consider irregular vehicle density in V2X routing.

B. UNCERTAIN NODE MOBILITY

Aside from vehicle mobility, we see that route length, data transmission rate, and data transmission efficiency in multi-hop environments also play a vital role in performance of VANETs. The work in [47] discusses issues in VANET routing and proposes a routing protocol that has the ability to learn the best suited transmission parameters from interactions with the environment. The proposed approach specifically takes into account the data transmission rate, route length, and vehicle movement. In [45], the bus rapid transit (BRT) system is proposed, whose buses have regular mobility patterns. It has the capability to tackle uncontrolled node mobility and select the most suitable routing paths to deliver data. It uses knowledge of the predictable and periodic movements of buses to learn the temporal distance to transmit every piece of data to RSUs using a dedicated bus-based foundation. The authors of [140] propose a superior form of BRT and use simulations to show the performance improvement achieved.

Machine learning (ML) approaches are quite beneficial, and the work in [141] thus proposes a trustworthy best-path prediction mechanism that has a fog node-based architecture and a longer compatibility time. The proposal achieves a packet delivery ratio of 16%, 99% accuracy, and longer connectivity than existing comparable solutions. The work in [142] considers the City section, INVENT, and Manhattan

TABLE 18. Learning-Based V2X Routing Considering Uncertain Node Mobility

Item	Contributions
[47]	The proposed routing protocol has the ability to learn the best suited transmission parameters from interactions with the environment
[45]	Uses knowledge of predictable and periodic movement of buses to learn the temporal distance to transmit every data to RSUs
[140]	Proposes a better form of BRT which results in overall performance improvement of bus-based routing
[51]	A group-based routing approach is proposed for detecting the position in 3D for beam selection in mmWave-based V2X transmissions

mobility models to learn about vehicle mobility and analyze the impact of mobility on VANET performance. The performance of these models is recorded and correlated using suitable mobility metrics, as they play a very important role in network design. Furthermore, reinforcement learning is used to meet the requirements of VANETs. The authors of [51] consider beam alignment difficulties and routing stability issues in millimeter Wave (mmWave)-based V2X transmissions, and accordingly propose a scheme for detecting the position of vehicles in 3D for beam selection or alignment purposes. A group-based routing approach is followed to choose a secure path that can achieve trustworthy data transmissions. Table 18 highlights the contributions of the works that consider uncertain node mobility in V2X routing.

C. UAV IN VANETS

In [143], an adaptive UAV-assisted VANET routing protocol is proposed that is based on geographic routing and a Q-learning mechanism. In that work, the global route in the aerial routing module is calculated using the depth-first search (DFS) and fuzzy-logic algorithms and considers UAV-collected information, such as the global road condition, that is forwarded to vehicles on the ground.

D. ENERGY EFFICIENCY AND SECURITY

The work in [144] considers energy efficiency, reliability, and connectivity in data transmission and designs a new routing protocol that combines multicopy, connection lifetime prediction, and a forwarding scheme with link state information. Security issues in VANETs are considered in several existing works since ITS services are adversely affected by malicious vehicles. A secure intelligent routing protocol is proposed in [145] to send data via the quickest path through authenticated vehicles. The authors show system performance is improved when the selection of authenticated vehicles using the quickest path keeps the network free from malevolent attacks. The proposed mechanism considers safe message transmission, delay, link connectivity, and vehicle position models. In [146], an approach is proposed that uses a hash function and a digital signature to ensure security in implementations of VANET routing protocols. Table 19 highlights the contributions of the works that consider energy efficiency

and security in V2X routing.

TABLE 19. Learning-Based V2X Routing Considering Energy Efficiency and Security

Item	Contributions
[144]	Considers the energy efficiency, reliability, and connectivity in data transmission to combine multicopy, connection lifetime prediction, and a forwarding scheme together with link state information
[145]	Considers vehicle position models, where the system performance is enhanced, and the selection of authenticated vehicles using the quickest path keeps the network free from malevolent attacks
[146]	Uses hash function and digital signature to ensure security in VANET routing protocol implementations

E. SDN-BASED APPROACHES, TOPOLOGY, AND TRAFFIC MANAGEMENT

Dynamic topology, variable bandwidth, and network changes make it harder for VANETs to support stable data transmission at any moment in time. Hybrid routing algorithms have been used to tackle this issue; however, they are known to cause the blind path problem. The authors of [147] use a reinforcement learning-based hybrid routing algorithm to track the available paths and their status online. VANETs can manage traffic in real time and send emergency messages to base stations, and are thus an emerging part of wireless networks. All vehicles behave as sensor nodes to collect information from their surroundings and send it to base stations. In [148], artificial neural networks (ANNs) are used to test VANETs' packet loss and throughput performance. The M-estimators performance function is used instead of the conventional mean squared error performance function. The work in [44] proposes a framework known as road data enrichment that collects data from different sources to elevate ITS services, including traffic event detection and vehicle routing. The Twitter MAPS of location-based social media data is presented for route services, while Twitter incidents (T-incidents) and low-budget learning-based road detection incidents are built with the help of variable data fusion for event services.

TABLE 20. Learning-Based V2X Routing Considering SDN-Based Approaches, Topology, and Traffic Management

Item	Contributions
[147]	Proposes a reinforcement learning-based hybrid routing algorithm to track the available routing paths online along with their status
[148]	VANETs' packet loss and throughput performance are analyzed by an ANN-based learning approach
[44]	Proposes a framework that takes data from different data sources to elevate ITS services including traffic event detection, vehicle routing, etc.
[149]	Designs a cognitive agent for route optimization for autonomous vehicles in urban cities, that minimizes road clogging and maximizes the count of automatic vehicles
[150]	The proposed central SDN controller serves as the learning agent to achieve an acceptable communication policy to help routing
[151]	Designs a deep learning based routing that takes packet forwarding decisions on the basis of current surrounding conditions

In [149], the authors discuss using the metabolic processes involved in cell survival for the first time in VANETs. A cognitive routing optimization agent is proposed for autonomous vehicles in urban cities. The agent helps enhance traffic flow over the network to minimize road clogging and maximize the number of automatic vehicles that reach their destination. Applications like traffic management and transport efficiency are important in VANETs. However, VANETs are sensitive to malicious nodes. SDN has recently been proven able to manage VANETs in a dynamic way and address this issue. In [150], a trust-based software-defined VANET architecture is proposed in which a central SDN controller serves as the learning agent to achieve an acceptable communication policy using the Q-learning approach. Packet routing is a challenging issue in VANETs due to the network topology and traffic management. In [151], the authors explore deep learning to propose an algorithm and a routing architecture that makes packet forwarding decisions on the basis of the current surroundings' conditions. Table 20 highlights the contributions of the works that consider SDN-based approaches, topology, and traffic management in V2X routing.

F. NETWORK MANAGEMENT AND CONGESTION HANDLING

The reinforcement learning-based adaptive routing protocol (ARPR) is proposed in [152], where it learns using distributed Q-learning and proactively gets fresh network link status information from periodic HELLO packets. Simulation results show that ARPR achieves better performance than existing protocols with respect to end-to-end delay, route path hops, and packet delivery ratio while keeping network overhead in a permissible range. A congestion game-based routing algorithm is proposed in [153] to resolve the issue of network congestion in VANETs and provide Internet access paths. The routing algorithms proposed in that work are more feasible and effective than baseline mechanisms for communicating in VANETs. Furthermore, efficient message delivery is a challenge in VANETs. The work in [154] addresses this by introducing a Q-learning-based protocol for routing that considers microscopic as well as macroscopic issues when making a routing decision.

The authors of [155] present an ML-based approach that can successfully detect local and global invasions in VANETs. The model is claimed to be more resilient to changes in the environment when cluster heads (CHs) and RSUs are considered. To make sure that road conditions are reported properly, the work in [156] introduces data forwarding using location information from roadside sensors and K-shortest course routing. Q-learning is combined with this routing approach to achieve sensor convergence faster than is possible with techniques that find the shortest path using simple Q-learning. Multi-hop routing is combined with Huffman and arithmetic coding to compress data packet payloads. The work in [157] addresses communication proficiency and routing in VANETs by using a support vector machine (SVM)-based ML scheme to study and process data

TABLE 21. Learning-Based V2X Routing Considering Network Management and Congestion

Item	Contributions
[152]	Designs a Q-learning-based proactive network link status extraction mechanism using periodic HELLO packets
[153]	The proposed routing approach resolves the network congestion difficulty in VANETs
[154]	Proposes a Q-learning-based routing protocol for handling microscopic as well as macroscopic issues while taking a routing decision
[155]	Proposes a ML-based approach to detect local and global invasions in VANETs
[156]	Handles data forwarding using location on roadsides with the help of k-shortest course routing
[157]	Designs a SVM-based study of the analysis and process of using probes to collect car data
[158]	Learning automata improves multipath routing with the help of leapfrog method with Particle Swarm Optimization
[159]	Reinforcement learning-based routing mechanism adaptively chooses the optimal path for charging data delivery in large-scale dynamic VANET environments
[160]	Predicts a routing strategy to control traffic congestion in VANETs using Geographic Information System
[161]	The proposed clustering-based mechanism reduces traffic congestion and significantly increases throughput
[162]	The learning-based routing scheme has the ability to select routing strategies dynamically using edge server computational power
[50]	Detects network loads and timely adjusts the routing decision such that the network congestion can be prevented
[53]	Predicts the vehicle movement patterns based on past traces such that the transmission performance can be increased
[163]	Addresses the issue of the inefficient data dissemination in V2X communications, and accordingly designs a cluster-based solution

collected from cars.

In [158], it is noted that learning automata and the leapfrog method improve multipath routing with particle swarm optimization (PSO). The work in [159] proposes an efficient charging details transmission strategy for spatiotemporally coordinated V2V charging services. Spatial systems (areas that are measured as GPS point systems, like malls, market areas, and housing areas), in which traffic density is generally high, are considered in [160]. The system proposed in that work predicts a routing strategy to control traffic congestion using VANETs and a GIS architecture. The routing protocol proposed in [161] is based on clustering and the K-means algorithm. In that work, the proposed algorithm is applied to a vehicular environment on a highway to improve performance compared to baselines. Moreover, traffic congestion is reduced, throughput is significantly increased, the time delay is decreased, and mobility is enhanced. In [162], a routing scheme is proposed that is based on Penicillium reproduction and is able to dynamically select routing strategies using edge server computational power. To this end, the proposed mechanism learns the network traffic pattern in VANETs.

The V2X routing protocol proposed in [50] is intersection-based and takes into consideration the learning mechanism of historical traffic flows, network status monitored in real-time, and Q-learning. The proposed mechanism is efficient at detecting network loads and making timely routing decision

adjustments so that network congestion can ultimately be prevented. In the proposed approach, packets are reliably transmitted with reduced latency and communication overhead. However, the network resources are not optimally utilized, and an increase in hop count is observed due to the addition of RSUs. The hidden Markov model is used in [53] to propose a predictive routing-based protocol, that predicts vehicle movement patterns based on past route traces such that transmission performance can be increased. The proposed model helps in V2I and V2V communications by improving network performance, the delivery ratio, traffic overhead, buffer occupancy, and delay. However, real-world implementation is required to verify the protocol's performance in real VANET scenarios. The work in [163] addresses the issue of inefficient data dissemination in V2X communications, which is caused by a shortage of bandwidth in very dense networks. The clustering system proposed in that work has two levels – in level 1, the CHs are selected using the fuzzy logic algorithm, and in level 2, the CHs are selected by applying a Q-learning mechanism such that the gateway selection iteration count is reduced. However, in a very dense environment, multiple actions and agents are present, which leads to increased iterations being discovered in a gateway. Furthermore, temporal connectivity calculations are very time-intensive. Table 21 highlights the contributions of the works that consider network management and congestion in V2X routing.

V. OVERALL OBSERVATIONS ON EXISTING NON-LEARNING- AND LEARNING-BASED V2X ROUTING PROTOCOLS

In this section, we present our overall observations on the existing works that consider non-learning- and learning-based V2X routing approaches.

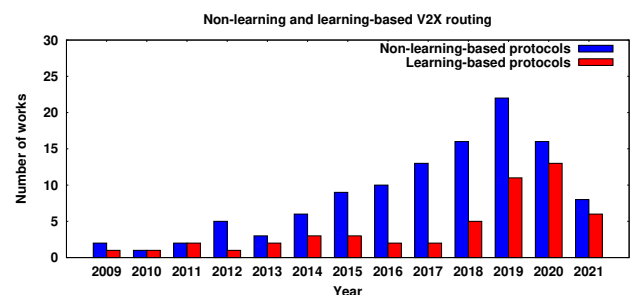


FIGURE 6. Number of works considering non-learning and learning-based V2X routing

Fig. 6 shows the number of works published each year (since 2009) that consider non-learning- and learning-based routing in V2X communications. From Fig. 6, it is noted that the number of works that consider learning-based routing approaches is quite a bit lower than the number that consider non-learning-based routing approaches. Therefore, there is a huge opportunity related to the application of ML in designing intelligent V2X routing mechanisms, where

TABLE 22. Learning-Based V2X Routing Protocols

Item	Learning Model	Strengths	Weaknesses
Wu <i>et al.</i> [48]	Reinforcement learning	(1) QTAR has a leading packet delivery ratio in varying traffic conditions, (2) Less packet delivery delay, (3) Insignificant network overhead	(1) Irregular vehicle density, (2) Obstacles like buildings, vehicles, trees, etc.
Tang <i>et al.</i> [6]	Artificial Neural Network	(1) Vehicular service delay is minimized, (2) Model performs better with varying vehicle speeds	(1) Lack of end-to-end vehicle communication maintenance, (2) Irregular vehicle density
Wu <i>et al.</i> [137]	Reinforcement learning	(1) Improves efficiency in multihop communication, (2) Provides adjustable, convenient and achievable solution for VANET routing	(1) Lack of reliability in multihop communication, (2) Irregular vehicle density, (3) Dearth of wireless channels
Wu <i>et al.</i> [47]	Reinforcement learning	(1) Real-life experiments as well as simulations have been used, (2) The protocol is strong against estimation errors, (3) Using reinforcement learning, it finds the best route and not the optimal path derived from theory, (4) Computation overhead of the protocol is very low	(1) Less multihop data transmission efficiency, (2) Uncertain node mobility
Wu <i>et al.</i> [46]	Reinforcement learning	(1) Considers load balancing to find the best route to reach the destination on or before time, (2) Increases the accuracy of the information given to the ITS without Internet or RSU support	Requirement of storing information without the help of RSUs
Yu <i>et al.</i> [139]	Distributed learning	(1) A new example, called "Learning-From-Others", was used where information is learned from others and not by exchanging complete community knowledge base, (2) Reduces overhead	Requirement of storing information without the help of RSUs
Rettore <i>et al.</i> [44]	Supervised learning (kernels)	Navigation systems, road planners and the general public can access a more descriptive and enriched transportation system data	Needs real-time information from vehicles and road network to optimize traffic flows
Vitello <i>et al.</i> [149]	Bio-inspired cognitive agent	(1) Traffic flow refined, (2) Decreases road cloggings, (3) Improved global routing optimization, (4) Vehicle traffic optimization on available roads using cell survival metabolic mechanisms	Requirement of real-time knowledge from vehicles as well as road system to improve traffic flows for autonomous vehicles
Zhao <i>et al.</i> [157]	SVM	(1) Packet loss is reduced, (2) Network delay is decreased	(1) Insufficient ways of data routing, (2) Lack of communication proficiency
Bi <i>et al.</i> [138]	Reinforcement learning	(1) Stability between nodes is improved, (2) Number of hops is decreased, (3) Adoption of multi-step update mechanism for better learning rate, (4) Faster recognition of ideal multi-hop forwarding paths, (5) Improves the efficiency and reliability of the route	Irregular vehicle density
Saritha <i>et al.</i> [158]	Learning automata	(1) Predetermination of line breaks and update of paths at the earliest to avoid packet loss, (2) Improves multiple paths for stable link based transmission	Lack of ideal multipath routing
Kerkacha <i>et al.</i> [140]	A learning process to capture the mobility pattern in Bus-based Routing Technique (BRT)	Overcomes the original BRT on the basis of end-to-end delay	(1) Low delivery ratio, (2) High latency, (3) Uncertain node mobility
Ji <i>et al.</i> [147]	Reinforcement learning	(1) Controlled broadcast, (2) Strategies to avoid obstacles, (3) Enhanced packet delivery ratio, (4) Less delay, (5) Less overhead	(1) Absence of a fixed topology, (2) Variable bandwidth, (3) Blind path problem
Li <i>et al.</i> [154]	Reinforcement learning	(1) The proposed routing protocol is more efficient and effective than position based routing protocols, (2) Real GPS data pertaining to Shanghai taxis was used to examine the proposed mechanism, (3) Both microscopic and macroscopic aspects were considered to make a routing decision, (4) Inherits the benefit of both offline and online methods	Inefficient message delivery
Mabrouk <i>et al.</i> [153]	A learning mechanism based on Boltzmann-Gibbs distribution	(1) Routing methods are more feasible and effective for communication, (2) Comparatively low network congestion, (3) The optimal Internet access paths	Comparatively high implementation complexity
Paramasivan <i>et al.</i> [144]	Ensemble learning	(1) Network connectivity with a minimum energy consumption, (2) Predicts connection lifetime and link state information, (3) Provides the benefit to each node for taking the decision of selecting the best path, (4) Reliability in data transmission	(1) Connectivity problems, (2) Network overhead
Li <i>et al.</i> [159]	Reinforcement learning	(1) Diverse framework is built for the communication with cross exchange patterns, (2) Minimal communication cost, (3) Enhanced packet delivery ratio, (4) Less overhead	Inadequate and brittle delivery of huge charging data
Kumbhar <i>et al.</i> [141]	Reinforcement learning	(1) The proposed protocol has upto 16% packet delivery ratio with an accuracy of 99%, (2) Longer connectivity, (3) Takes only 3 or 4 hops	(1) Insufficient ways of routing data, (2) Methodical message delivery, (3) Irregular vehicle density, (4) Uncertain node mobility, (5) Bounded connectivity

TABLE 23. Learning-Based V2X Routing Protocols (continue...)

Item	Learning Model	Strengths	Weaknesses
Zhang <i>et al.</i> [150]	Deep Q-learning	(1) Supports highly-efficient transportation and traffic safety, (2) The SDN provides the optimal communication link policy, (3) Avoids the impact of malicious vehicles	(1) The requirement of high traffic management in the centralized unit, (2) Retraining of the model in different network environments
Abdellah <i>et al.</i> [148]	Artificial neural network	Investigates the performance of VANETs in terms of throughput and packet loss rate	Lack of details on real-life implementation and retraining of the ANN model
Abdellah <i>et al.</i> [164]	Artificial neural network	Studies the estimation of VANET performance in terms of throughput and energy consumption	Lack of details on training and retraining of the model
Zeng <i>et al.</i> [155]	ANN	(1) Automatically detects intruders locally and globally in VANETs, (2) More robust to environment changes	(1) Constraints on model training and learning are not highlighted, (2) Lack of discussion of the impact of high mobility on the training
Kulkarni <i>et al.</i> [142]	Reinforcement learning	(1) Impact of vehicle mobility on the performance of the proposed model is highlighted, (2) Analyzes the suitability of a routing algorithm which is based on reinforcement learning, (3) Performance analysis under varying load and traffic scenarios	(1) The performance is compared only with the AODV routing mechanism, (2) Lack of discussion on the impact of irregular and high vehicle mobility
Jinqiao <i>et al.</i> [152]	Reinforcement learning	(1) Constantly learns and receives the fresh link status of the network proactively, (2) Dynamic adaptability to the changes of the network is improved, (3) Reactive routing strategy is applied to boost the learning convergence	(1) Energy consumption for the adaptability to the network is not highlighted, (2) Lack of discussion on the training and learning overhead
Kandali <i>et al.</i> [161]	K-means algorithm	(1) A vehicular environment on a highway is considered, (2) Traffic congestion is reduced, (3) Throughput is significantly increased, (4) Time delay is decreased	(1) Learning and network overheads are not highlighted, (2) Lack of discussion on the impact of irregular mobility pattern
Zhao <i>et al.</i> [162]	Penicillium reproduction-based online learning	(1) Dynamically selects a routing strategy considering a traffic scenario by learning the network traffic pattern, (2) Handling of real-time traffic data, (3) Software-defined intelligent data exchange	(1) Learning and network overheads are not highlighted, (2) Lack of discussion on the impact of high-speed vehicles, (3) Communication overhead and delay
Jiang <i>et al.</i> [143]	Q-learning	(1) An adaptive UAV-assisted VANET routing is proposed, which is based on geographic routing considering Q-learning mechanism, (2) The global route is calculated by using the DFS and fuzzy-logic	(1) Communication overhead and congestion between the aerial and ground, (2) Impact of irregular vehicle movement is not highlighted
Luo <i>et al.</i> [50]	Q-learning	(1) An intersection-based V2X routing is proposed considering the learning mechanisms of historical traffic flows, (2) Detects network loads and timely adjusts the routing decision, (3) The network congestion is prevented	(1) The network resources are not optimally utilized, (2) The increase of the hop count due to the addition of RSUs, (3) Impact of irregular vehicle movement is not highlighted
Khan <i>et al.</i> [163]	Q-learning	(1) Addresses the issue of the inefficient data dissemination in V2X communications, (2) The gateway selection iteration count can be reduced, (3) The cluster heads are selected by applying a Q-learning mechanism	(1) In a dense environment, multiple actions and agents will be present, leading to increased iterations in a gateway, (2) Temporal connectivity calculations lead to huge time complexity.

efficient dynamic routing can be achieved by incorporating a learning agent in VANET systems. Furthermore, Table 24 highlights the various primary directions that are considered in existing works when designing routing mechanisms in V2X communications. From Table 24, it is noted that several directions, such as geographic and position-based routing, intersection-based distribution, fault detection, probability-based approaches, 3D scenarios, and network connectivity, need to be explored when designing an efficient and intelligent V2X routing mechanism.

Findings: Non-learning-based V2X routing protocols.

Several existing works consider non-learning-based V2X routing approaches. Works specifically focus on different directions, such as high node mobility, geographic and position-based routing, SDN-based approaches, clustering, named data network-based approaches, intersection-based distribution routing, QoS, high vehicular speed, security and privacy, probabilistic routing, and congestion. Existing routing mechanisms improve V2X routing performance on the basis of the aforementioned directions. However, since the proposed approaches are primarily threshold- or heuristic-based, these routing schemes' adaptability in different network scenarios, where vehicular network conditions, such as congestion and vehicular movement patterns, can change frequently remains to be determined, and efficient dynamic network management is required in routing.

Findings: Learning-based V2X routing protocols.

When it comes to learning-based routing protocols, several existing works consider different ML mechanisms to automate the routing process in V2X communications. Learning-based routing approaches handle irregular vehicle density, uncertain node mobility, energy efficiency, security and privacy, topology, congestion, etc. The use of ML algorithms makes the proposed routing mechanisms intelligent and able to dynamically perform routing according to current network conditions and vehicle requirements. Consequently, existing learning-based routing mechanisms can significantly improve overall network performance, for example, by decreasing the transmission delay or increasing the throughput. However, existing learning-based routing approaches need to thoroughly analyze learning overhead and convergence, which are key issues in ML algorithms. In addition, a huge volume of real-life data is required to train supervised learning-based routing schemes. Moreover, the adaptability of ML-based routing models in real-life implementations needs to be explored.

VI. CHALLENGES AND FUTURE RESEARCH DIRECTIONS

In this section, we discuss the challenges of and future research directions for designing V2X routing protocols. We first present the challenges, and then highlight possible research directions that could lead to a new era of smart V2X routing mechanisms.

A. CHALLENGES

Based on the discussion of existing V2X routing techniques and their limitations, it can be noted that there are certain areas that need to be further developed to build user trust [151], [156], [165] in VANETs. Several factors that lead to challenges when designing effective V2X routing protocols are:

- *Obstacles*: Man-made obstacles (like buildings and other constructions) and natural obstacles (like trees) reduce signal strength, packet reception rate, route discovery, etc.
- *Lack of centralization*: It is very challenging to design an effective central node that can practically cover a wide range of communications and monitor outgoing and incoming messages.
- *Limited resource availability*: Resources such as power and bandwidth are limited.
- *Irregular topology*: Due to high mobility and changes in topology, there are frequent communication outages in the network, which significantly affect the routing mechanism.
- *Connectivity issues*: Due to the small network range of VANETs, communication between the nodes is weak. Consequently, routing requires that the distance between two vehicles be short.
- *Lack of authentication*: Since messages are broadcast by vehicular nodes, authentication is required to ensure that malicious nodes cannot become part of the network and tamper with crucial routing-related information. This information could be used by malicious nodes to forward the messages to themselves instead of transmitting them to the actual destinations.
- *Packet delivery*: A packet must be delivered in the shortest period of time possible with a minimum packet loss rate such that trust can be ensured in times of crisis.
- *Control overhead*: VANET architectures need to handle high mobility, which leads to frequent topological changes in the network. As a result, the control overhead and the frequency of communication link failures are increased. Therefore, such overhead and losses must be minimized during V2X routing protocol design.
- *Error analysis*: It is indeed challenging but essential to perform error analysis on a huge real-life dataset to predict the actual performance of a routing mechanism. The minimization of errors in routing helps improve the selection of the correct path for packet forwarding.
- *Routing model*: Channel noise, physical layer attributes, and the signal propagation model must be included in the design of a packet routing technique. In addition, malevolent nodes should be classified by their attack type [156], [166] such that routing decisions can be made in advance to avoid attacks that can affect the security of the information transmitted through a routing path.
- *Traffic control*: Long- or short-term traffic prediction is vital in ITSs to consider complex and multi-road intersections. This prediction can reduce the packet loss rate by using a virtual network and efficiently selecting the routing path. Different vehicles have different sizes and speed limits. Therefore, the type of vehicle must be considered when analyzing traffic.
- *Information disclosure principle*: In [167], PKI-based or identity (ID)-based cryptography is used; however, this work does not consider the least information disclosure principle wherein a driver gets to know about its neighbors while keeping their real identity and address under cover.
- *Vulnerability to worm infections*: In VANETs, vehicles can transport, sense, and process information. An attacker can affect these normal vehicle functionalities in VANETs [168]. Therefore, vehicles are more vulnerable to worm infections than conventional hosts.
- *Management of SDN-enabled VANETs*: A VANET that is accompanied by SDN controllers has more control over vehicles with the use of software-based management. However, SDN architectures require a high number of interactions among nodes and efficient control mechanisms. Therefore, the routing mechanism needs to be effectively controlled and managed to perform routing efficiently in SDN-based VANETs.

TABLE 24. A Classification of Different Directions Considered by Existing V2X Routing Protocols

Directions	Non-learning-based routing	Learning-based routing
High and uncertain node mobility	✓	✓
Geographic routing	✓	×
Position-based routing	✓	×
SDN-based approaches	✓	✓
Cluster-based approaches	✓	✓
Named data network based approach	✓	×
Intersection-based distribution routing	✓	×
Improving QoS and power efficiency	✓	✓
High vehicular speed	✓	✓
Hybrid protocol	✓	×
Security and privacy	✓	✓
Fault detection	✓	×
Probabilistic routing	✓	×
UAV in VANETs	✓	✓
Congestion and shadowing effects	✓	✓
Network overhead	✓	✓
Network connectivity	✓	×
3D VANET scenarios	✓	×
Irregular vehicle density	×	✓
Topology and traffic management	✓	✓
Dynamic network management	×	✓

- **Video streaming quality:** VANETs are characterized by variable node mobility, which makes continuous video streaming not yet possible. Stable network protocols must be developed to enhance the quality of video files while routing them in the network.
- **OceanNet VANET architecture:** VANET used in marine environments has been explored; however, systems in such scenarios face several challenges when it comes to maintaining QoS considering sparsely connected nodes.

B. FUTURE RESEARCH DIRECTIONS

In V2X communications, the routing mechanism can be greatly improved. In the last decade, several advancements related to the development of routing protocols in VANETs have been made, which also revealed the associated challenges. For instance, on urban roads, the concept of 'automated vehicles' demands a smart routing approach. Pre-known natural calamities under water can be prevented by VANETs [165], and in this case, we also need effective V2X routing techniques. Possible future research directions for V2X routing are listed below.

- **Driver safety:** There are several areas that require ML-based intervention to ensure the safety of vehicles and drivers of automated or semi-automated vehicles. These areas include driver drowsiness, weather prognosis, accident prediction and prevention, driving habits, obstacle detection, lane detection, and road condition prediction.
- **Routing mechanism scalability:** The scalability and calculative complexity of routing mechanisms must be significantly improved to cope with different networking scenarios in VANETs.
- **Feedback mechanism:** High priority and emergency messages must be routed with a feedback mechanism

to ensure successful transmission of messages.

- **Traffic maintenance:** When designing V2X routing protocols, traffic signals and GPS data must be provided in the virtual wireless network to help predict traffic flow and congestion, and increase the efficiency of the routing approach.
- **Trust-based techniques:** Robust security systems can be incorporated in the design of V2X routing mechanisms to ensure authenticated message delivery and increase end users' confidence in the system.
- **Vehicular cloud computing (VCC):** VCC has been proven to be competent enough to provide optimum solutions to protect networks against various threats and increase the efficiency of traffic control and management systems. Therefore, VCC-based routing can enrich V2X routing mechanisms.
- **Time restriction of VANET nodes:** Broadcasting messages in VANETs requires an efficient and reliable system in which emergency message alerts reach their destination at the right time and not ahead of or behind schedule. Thus, the time delay of message transmission can be minimized by using optimized routing mechanisms.
- **VANET for crossroads:** Existing routing protocols provide information about the shortest or least crowded path in VANETs; however, in the case of crossroads, vehicles are more prone to accidents. Therefore, a protocol should be developed to quickly and accurately warn drivers of the potential crashes that may happen due to vehicles that are not within their eyesight or people that are crossing the road.
- **Parking management:** Drivers generally learn about parking spot vacancies upon arriving at a parking area, which is somewhat of a hassle. By using a methodical

and intelligent V2X routing protocol, drivers could be alerted in advance and choose another route based on parking availability.

- **Automated toll collection:** VANETs can be used to automate toll collection, which is a major reason behind heavy traffic on bridges and highways. Such an automated approach could be incorporated in V2X routing mechanisms as a part of the routing process, which would help accelerate the routing decisions at a breakpoint. However, crucial information like people's address and contact information should not be made available to any unauthorized parties.
- **Improvement of VANET architecture:** In designing V2X routing protocols, SDN can be combined with the internet of things (IoT). SDN helps centralize and automate network management control. The IoT provides enhanced data collection and assists in managing widely distributed network connections.
- **Blockchain in VANETs:** VANETs can be integrated with blockchain, which is a very recent research topic. To ensure security during routing, blockchains can be used to impose a security mechanism in a credit-based approach in which vehicles collectively adhere to a routing decision to communicate among themselves and validate new blocks in blockchains.
- **5G and 6G in VANETs:** 5G and 6G can be used in VANETs to improve network functionality and performance by providing more speed and intelligence. Therefore, a V2X routing mechanism that incorporates features of 5G and 6G needs to be designed to exploit the strengths and advantages of these technologies.
- **OceanNet VANET architecture:** V2X networks can benefit from ML to predict link quality and provide location-based services.
- **Consideration of urban scenarios:** Many cloud-based architectures in VANETs have not been tested in complex real-life urban scenarios. Therefore, the routing protocols proposed in existing works need to be implemented in real life to analyze their effectiveness in practical VANET scenarios.

VII. CONCLUSION

VANETs are a crucial component of ITSs that have the potential to handle traffic management, accident prevention, and emergency services. In this context, routing in V2X communications plays a key role in the reliable and timely delivery of messages. Automated cars, real-time news reports, weather forecasts, file sharing over the Internet, and other entertainment services can be promoted via VANETs. However, due to the high mobility of vehicular nodes, unsteady network connectivity, frequent changes in network topology, and unbounded network size, routing becomes a challenging issue in V2X. Consequently, several researchers have focused on increasing the coordination efficiency of vehicular nodes by designing appropriate routing protocols. Existing routing mechanisms use non-learning- or learning-

based approaches. This survey presents a thorough study of the existing routing protocols by categorizing them as one of the two aforesaid approaches and summarizing their strengths and weaknesses. This paper highlights not only the impacts of these routing schemes on the overall performance of VANETs, but also the limitations of existing research works and future research directions for designing and developing intelligent V2X routing mechanisms. As a result, next-generation VANET technologies will be enriched with more efficient coordination among vehicular nodes.

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