A Novel Traffic Aware Data Routing Protocol in Vehicular Networks

by

Heqi Cui

Thesis submitted to the University of Ottawa
in partial fulfillment of the requirements for the
Master of Applied Science degree in
Electrical and Computer Engineering

School of Electrical Engineering and Computer Science
Faculty of Engineering
University of Ottawa

Abstract

Recently, according to people's requirements for safe and congestion-free driving in the public transportation system, the intelligent transportation system (ITS) has been widely concerned. To achieve a safe and time-saving driving experience in ITS, various data sharing methods are proposed to provide traffic information for drivers to perceive their surrounding driving environment. However, the high dynamic characteristic of the vehicular network (VNET) results in a challenging environment for establishing stable communication among vehicles.

To face this challenge, a Cellular network-assisted Reliable Traffic-Aware Routing protocol (CRTAR) is proposed in this thesis to provide support for vehicle's data routing process in a heterogeneous vehicular-cellular network environment. In the method, city-wide traffic information, i.e., traffic density and data transmission density of the road segments, is introduced into vehicle's data routing process to assist the vehicle in selecting the optimal data transmission route to deliver data packets. To further improve the stability of inter-vehicle communication, the link lifetime between vehicles is also considered to select the next forwarder that can establish relatively robust communication. CRTAR takes advantage of the reliability and low-latency features of the communication technology in the cellular network and combines the cellular network with VNET to achieve real-time and reliable Vehicle-to-Infrastructure (V2I) communication. Meanwhile, it realizes the Vehicle-to-Vehicle (V2V) communication by the Dedicated Short Range Communication (DSRC) to mitigate the overload of backbone resources caused by using the cellular network.

To be specific, in the method, vehicles can request city-wide traffic information via the cellular network from a cloud service that is connected to the remote data center located in the traffic management agency without latency. According to the real-time traffic information, the source vehicle can execute the data routing process with a global view of the system to calculate the data transmission route that has sufficient transmission resources to the target vehicle. The source vehicle then transmits data to the target via the vehicles in the calculated transmission route. During the forwarding process, vehicles prefer to forward the data packet to the next vehicle with a longer link lifetime. Furthermore, effective backup and recovery strategies are designed for route maintenance. The effectiveness of CRTAR is further verified by conducting simulation experiments.

Acknowledgements

First of all, I would like to express my sincere gratitude and great appreciation to my supervisor, Prof. Azzedine Boukerche, who provides the chance for me to start my graduate study. His profound academic background and abundant academic experience helped me a lot during the development of my research work. He kindly provided me the opportunity to know my research field and helped me develop the ability to research. This learning ability will become a cherished experience to help me face all future challenges.

Secondly, I would like to give my thanks to Dr. Peng Sun, who supported me a lot with his valuable technical suggestions. He is always patient, and generous with his time to give me feedback, which spawned great advances for the revision of my research paper and thesis.

Thirdly, I would like to thank all the group members of the PARADISE lab. Although the epidemic has prevented us from seeing each other for the time being, the learning experience we work hard together will become my precious memory.

Finally, I wish to thank my parents, who always encourage me and provide me with incredible support during my graduate study.

Table of Contents

List of Tables

List of Figures

Nomenclature

P^3R	Peeking at the Past and Present Routing
ACO	Ant Colony Optimization
AF	Amplify-and-Forward
AODV	Ad-hoc On-Demand Distance Vector
BER	Bit Error Rate
CADD	Connectivity-Aware Data Dissemination
CCS	Cloud Computing Service
CLARR	Cross-Layer Autonomous Route Recovery
CMDS	Cloud-assisted Message Downlink dissemination Scheme
CPP	Connectivity Probe Packet
CR	Cognitive Radio
CRP	Centralized Routing Protocol
CRTAR	Cellular network-assisted Reliable Traffic-Aware data Routing protocol
CS	Control Server
CTGR	Connectivity-aware Transmission quality guaranteed Geographic Routing
DF	Decode-and-Forward
DIBAAGKA	Dynamic Identity Based Authenticated Asymmetric Group Key Agreement
DSDV	Destination Sequenced Distance Vector
DSR	Dynamic Source Routing

DSRC	Dedicated Short Range Communication
DTN	Delay Tolerant Networks
ECD	Expected Connectivity Degree
EGSR	Efficient Geographic Source Routing
En-AODV	Enhanced AODV
ETT	Excepted Transmission Time
FFRDV	Fastest-ferry Routing in DTN-enabled VNET
FPBR-DTN	Fuzzy-assisted Position-based Routing protocol with DTN capability
FSR	Fisheye State Routing
GeoDTN+Nav	Geographic DTN routing with Navigator
GeOpps	Geographical Opportunistic
GPCR	Greedy Perimeter Coordinator Routing
GPSR	Greedy Perimeter Stateless Routing
GS	Group Signature
GSR	Geographic Source Routing
HN	Head Node
IDTAR	Intersection-based Distance and TAR
ITS	Intelligent Transportation System
IVD	Inter-Vehicle Distance
Ivd-CAR	IVD based Connectivity Aware Routing
LCs	Local Controllers
LTE	Long-Term Evolution
MAC	Medium Access Control
MANETs	Mobile Ad hoc Networks

MCC	Mobile Cloud Computing
MEC	Mobile Edge Computing
METD	Minimum Estimated Time Of Delivery
MIMO	Multi-Input Multi-Output
MOCA	Mechanism for cOnnectivity management in Cognitive vehiculAr networks
MOT	Minimum Optimistic Time
MPBRP	Mobility Prediction Based Routing Protocol
NFS	Next Forwarder Selection
NNs	Neural Networks
Non-DTN	Non-Delay Tolerant Network
NPA	Next-hop Prediction Algorithm
NS	Navigation System
OLSR	Optimized Link State Routing
PDR	Packet Delivery Ratio
PRE	Proxy Re-Encryption
PRHMM	Predictive Routing based on the Hidden Markov Model
QoS	Quality-of-Service
R-FM	Real-time Forwarding Method
RLS	Recursive Least Squares
RREP	Route Reply
RREQ	Route Request
RSUs	Road Side Units
RTAR	Reliable Traffic-Aware Routing
RTNSM	Real-time Traffic and Network Status Measurement

SCL-ACO-AODV	Selective Cross-layer based ACO-AODV
SDGR	SDN-based Geographic Routing
SDN	Software-Defined Networking
SDVN	SDN-Based VNET
SI	Segment Information
SNR	Signal Noise Ratio
SVAO	SDN-based Vehicle Ad-hoc On-demand
TAR	Traffic-aware Routing
TASR	Traffic-Aware Segment-based Routing
TO-GO	Topology-assisted Geo-Opportunistic
TORA	Temporally Ordered Routing Algorithm
TQ	Transmission Quality
V2I	Vehicle-to-Infrastructure
V2P	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
V2X	Vehicular-to-Everything
VADD	Vehicle-Assisted Data Delivery
VC	Vehicular Cloud
VCC	Vehicular Cloud Computing
VCN	Vehicular-Cellular Network
VNET	Vehicular Networks
WNN	Wavelet Neural Network
ZHLS	Zone-based Hierarchical Link State
ZHLS-GF	ZHLS with Gateway Flooding
ZRP	Zone Routing Protocol

Chapter 1

Introduction

In this chapter, the background of data transmission in VNET is introduced at first. Then, according to existing researches, the motivation and objective of the proposed protocol are presented. After that, the contributions of the work are summarized, and the outline of the thesis is given.

1.1 Background

Currently, the development of the intelligent transportation system (ITS) has drawn widespread attention from the public [111,236]. Various ITS applications, e.g., driving safety [119,163], traffic congestion avoidance [213, 225], traffic signal control [103, 224], and entertainment service [153]), are developed to benefit the public transportation system and people's life [91]. To realize the functions of these applications, providing real-time traffic information in the corresponding area for users is necessary [33, 199]. Hence, how to achieve effective data transmission to share traffic information for users in the ITS becomes a crucial issue.

As the essential component of the ITS, data transmission in VNET plays a significant role [92, 239]. According to the main components of VNET, i.e., moving vehicles and roadside infrastructures such as roadside units (RSUs), two types of typical communication, the Vehicle-to-Vehicle (V2V) and the Vehicle-to-Infrastructure (V2I), are implemented to in charge of the data transmission in VNET. As illustrated in Figure. 1.1, the V2V communication (the yellow dotted arrow) represents the communicating between vehicles. It allows a vehicle to share surrounding traffic information with other vehicles without relying on any fixed infrastructure. On the other hand, the V2I communication (the blue dotted arrow) provides vehicles the capability to access the backbone resources via roadside infrastructures to obtain needed information [6] such as the weather or the traffic congestion in a certain area from the traffic management center. Relying on the V2V and V2I communication, drivers can gain local traffic information of neighbor vehicles and global traffic information in a large area so as to obtain the awareness of the surrounding traffic condition to realize the effective driving strategy [127].

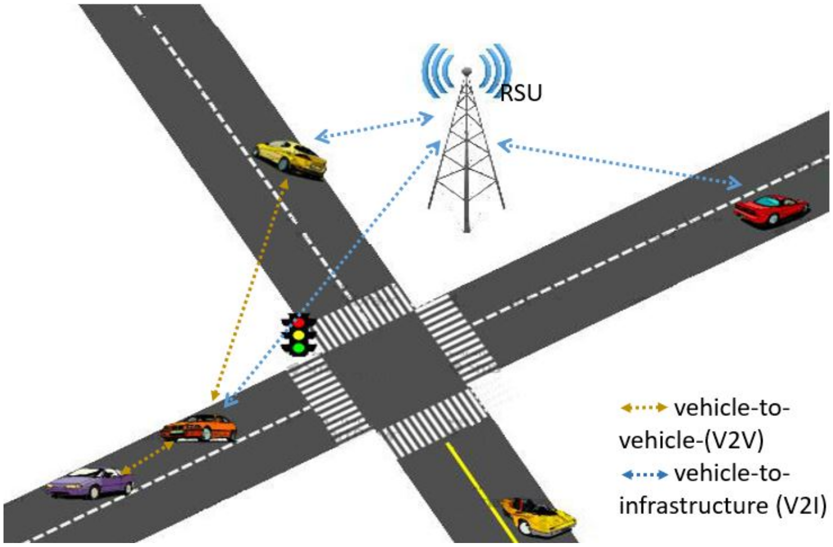


Figure 1.1: An illustration of V2V and V2I communication in the VNET

Moreover, on the basis of the improvement of wireless communication technologies and mobile equipment, more types of communication can be attained. For instance, Vehicle-to-Pedestrian (V2P) is presented to achieve communication between vehicles and pedestrians' mobile devices. The location of pedestrian devices will be announced to the nearby vehicles to avoid the potential collision between vehicles and pedestrians [124]. The integration of various kinds of communications, i.e., the Vehicular-to-Everything (V2X) communication, can support a vehicle in communicating with other vehicles and its surrounding environment [120].

Though a variety of communication technologies have been proposed, the high dynamic characteristic of VNET caused a huge challenge for stable communication among vehicles, especially vehicles that cannot communicate with each other directly [211]. To realize the robust communication and transmit data packet from the source vehicle to the target vehicle, selecting the data transmission route is crucial for the source vehicle. In the thesis, a novel data routing protocol is proposed to assist vehicles in transmitting data packets to the target. Detailed motivations and contributions of our work will be further introduced as follows.

1.2 Motivation and Objective

At the beginning stage of the development of data routing protocol in VNETs, many protocols designed for mobile ad hoc networks (MANETs) were applied in VNETs [9,37] because of the similarity in self-organization [29, 106, 107] and finite bandwidth aspects [105]. For instance, Ad-hoc On-Demand Distance Vector routing (AODV) [171] and Dynamic Source Routing (DSR) [129] can be utilized to establish the data transmission route based on the topology information of VNET. However, the data routing protocols proposed for MANET typically assume that the node in the network moves at a relatively low speed, which conflicts with the highly dynamic feature of the VNET [140]. On account of the high-speed movement of vehicles, network topology changes rapidly in VNET. The vehicle calculating the data transmission route based on network topology will frequently request the latest topology information. To avoid the overhead caused by frequent information updating, data routing methods depending on vehicle's geographic position are developed [78]. For example, by leveraging the geographic information of on-road vehicles, the vehicles in Greedy perimeter stateless routing (GPSR) [132] selects the vehicle closest to the target from its neighbors as its data forwarder.

Nevertheless, many geographic routing protocols select transmission routes only according to vehicle's local information, which means that the selected transmission route may be constrained by local optimal selection. In order to select the optimal transmission route with the global view of the system, the real-time traffic information of the relevant area is considered by vehicle. Traffic-aware routing (TAR) protocols are proposed to provide the global traffic information and the network condition for vehicles in the data routing process [96].

In TAR protocols, vehicles can obtain global traffic information of the network, e.g., traffic density of road segments and link condition between vehicles, from the traffic agency via advanced network communication technologies and vehicles' hardware equipment. Relay on the assistance of global traffic information, vehicles can select the optimal route with a global view of the traffic system.

For example, because on-road vehicles work as both the customer who requests data transmission and the service that forwards the data packet, the number of vehicles on a road segment will affect the data transmission performance on that road. Take Intersection-based Distance and TAR (IDTAR) [10] as an example. In IDTAR, the intersection whose traffic density is higher will be chosen as the next intersection to pass the data packet. Also, in [152], the author considered the traffic density while evaluating the score of road junctions. Traffic density is directly proportional to the junction score, and the data transmission route is established based on the junction score. However, a high traffic density of the segment may also cause channel congestion due to numerous transmission requests from on-road vehicles. To avoid this issue, the authors in [173] proposed a routing method that allows vehicles to select the road with lower traffic density to deliver the data packet. Accordingly, how to find a balance between the dual identities (i.e., as the customer and as the resource) of the on-road vehicle and effectively utilize the traffic density of road segments as a metric of data transmission route selection to enhance the transmission performance can be a crucial issue.

Moreover, in addition to the road traffic density, the connectivity between vehicles, i.e., the capacity to forward a packet between two vehicles, is also significant during the data transmission process. To select a reliable forwarder in charge of delivering the data packet, connectivity between vehicles can be evaluated in various ways. For instance, the authors in [121] estimate the connectivity of vehicles based on the distance between vehicles. In [144], the connectivity between vehicles is evaluated according to the effective connection time calculated based on vehicles location and velocity. On the basis of the connectivity between vehicles, stable forwarders can be selected to assist the data delivery process in VNET.

In most aforementioned methods, vehicles obtain traffic information relay on the data packet exchanging among vehicles. Conventional communication standards such as short-range communication (DSRC) can support vehicles in implementing this communication free of charge. While benefiting from the development of communication technologies, especially the development of cellular networks, vehicles can acquire real-time traffic information effectively with a short delay via the V2I communication implemented by cellular networks. The high stability and low delay characteristics of the cellular network are suitable to be utilized in TAR protocols to assist vehicles in the traffic information collecting process. However, because of the commercial feature of the cellular network, relying on the cellular network to transmit large amounts of data [77, 166] will cause a high cost. Moreover, transmitting data only depending on the cellular network will occupy the backbone network resource. A large number of data transmission requests from vehicles may affect the performance of other co-existing communication services in the cellular network.

To take advantage of cellular networks' reliability properly for real-time traffic information providing in TAR protocols, the combination of using cellular networks and VNET to form a heterogeneous vehicular-cellular network (VCN) for data transmission is worth to be investigated.

1.3 Contribution

The main contributions of this thesis are summarized as follows.

In this thesis, a road traffic density-aware data routing protocol is present to achieve an effective data routing process for vehicles transmitting data packets in the VCN environment.

Firstly, a VCN environment that implemented both the cellular network and DSRC communication technologies to take advantage of cellular networks' reliability in VNET is defined. As mentioned before, according to the commercial characteristics of cellular networks and the backbone resources utilization, the cellular network is only allowed to transmit the small size request message, i.e., vehicle's real-time traffic information. For high-volume data transmission among vehicles, DSRC communication technology is adopted to reduce the workload of the backbone network.

I designed a communication system to realize the V2V and V2I communication in the VCN environment above. To be specific, vehicles in our system have an interface to connect the infrastructure of the cellular network and another interface to communicate with other vehicles via DSRC. A cloud computing service (CCS) is connected to a traffic agency by the wired backbone network with trivial delay. The traffic agency can monitor the traffic condition of the system in real-time. Hence the CCS can provide real-time public traffic information to vehicles in a stable and low-latency way via the roadside infrastructure of the cellular network.

In the proposed protocol, the source vehicle will request real-time traffic information, i.e., real-time information of the traffic density and data transmission density, to obtain the global view of the system via the cellular network. Based on the global view of the system, the source vehicle can figure out a data delivery route that has relatively high transmission resources and low congestion.

Then, an improved greedy manner is employed to transmit the data along with the selected route among vehicles. In this improved manner, the link lifetime between vehicles is considered to avoid the link which may expire in a short time. By estimating the link lifetime, robust forwarders can be selected to take charge of data delivery so that further enhance the stability of the data transmission process.

Furthermore, to maintain the transmission process, the backup solution and the recovery strategies have been presented to deal with unexpected link failures.

Finally, the effectiveness of data delivery is verified by conducting simulation experiments in NS3 and comparing our results with other existing schemes.

1.4 Outlines

The remainder of this thesis is organized as follows: Chapter 2 discusses the existing data routing protocols for VNET, both the conventional routing protocol and the state-of-the-art routing protocol are analyzed. Model assumption of the system and detailed design of our methodology are described in Chapter 3. Chapter 4 shows the simulation results and analysis of our method. Finally, the conclusion of the approach and the future work of the study are presented in Chapter 5.

Chapter 2

Literature Review

In this chapter, a brief description of several essential communication modes in VNET is provided firstly. Based on these communication modes, a few possible V2V and V2I communication scenarios can be introduced. Then, conventional routing methods and state-of-the-art data routing protocols will be discussed and classified. To be more specific, by summarizing the conventional routing methods (i.e., the topology-based routing approach and the position-based routing approach), we introduce the development of the data routing protocols in VNET. Moreover, according to the protocols we discussed, the advantages and disadvantages of the topology-based routing approach and the position-based routing approach are analyzed separately. Furthermore, two kinds of state-of-the-art routing protocols are introduced: the approach enhanced the conventional protocols of VNET, and the method combined with some latest new technologies. Discussion and future work of the data routing process in the VNET is also be concluded according to the vehicular routing methods we mentioned above.

Vehicles' high-speed movement and limited transmission range caused a challenging environment for the end-to-end data transmission process in VNET. Similar to the cooperative communication in MANET that a node can communicate to the target beyond its transmission range via forwarders [22], in VNET, neighboring vehicles and roadside infrastructures, e.g., roadside units (RSUs), can assist the source in delivering data packets [59]. As illustrated in Figure. 2.1, three classic examples of cooperative communication in VNET are discussed [11].

In (a) and (b) scenarios, depending on neighbor vehicles, the source vehicle and RSU can deliver the data packet to the target separately. In (c), RSU works as the source and transmits the data packet via another RSU and the neighbor to the target vehicle.

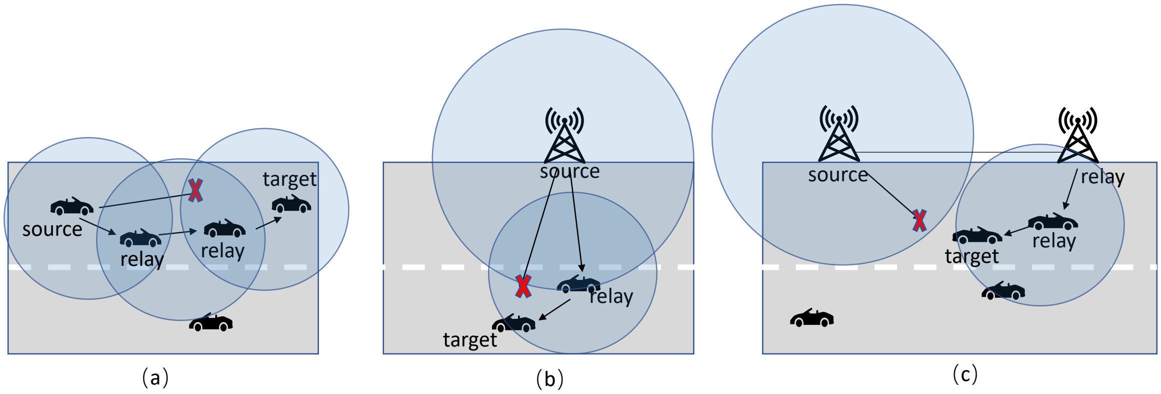


Figure 2.1: An illustration of cooperative communication in the VNET

This communication procedure provides multiple alternative transmission methods for the source establishing the data transmission route.

2.1 Conventional Data Routing Methods

Due to the high mobility feature of the VNET, building a stable connection among vehicles for data transmitting from the source vehicle to the target vehicle is challenging. Various methods are presented for data transmission route calculation and packet forwarder selection. In this section, we will briefly introduce the basic concepts of some conventional routing approaches to show the development of the routing protocol in VNETs.

As shown in Figure. 2.2, two main categories of data routing protocols are involved, namely, the topology-based routing approach and the position-based routing approach. Moreover, on the basis of the proposed protocols, each category can be divided into three parts, the main feature of each part will be discussed in more detail as follows.

2.1.1 Topology-based Routing Protocols

Topology-based routing protocols utilize the topological information of the network to decide the data routing path from the start node to the target node. According to the different methods of acquiring and updating topology information, we classify topology-based protocols into three main types, i.e., proactive routing, reactive routing, and hybrid

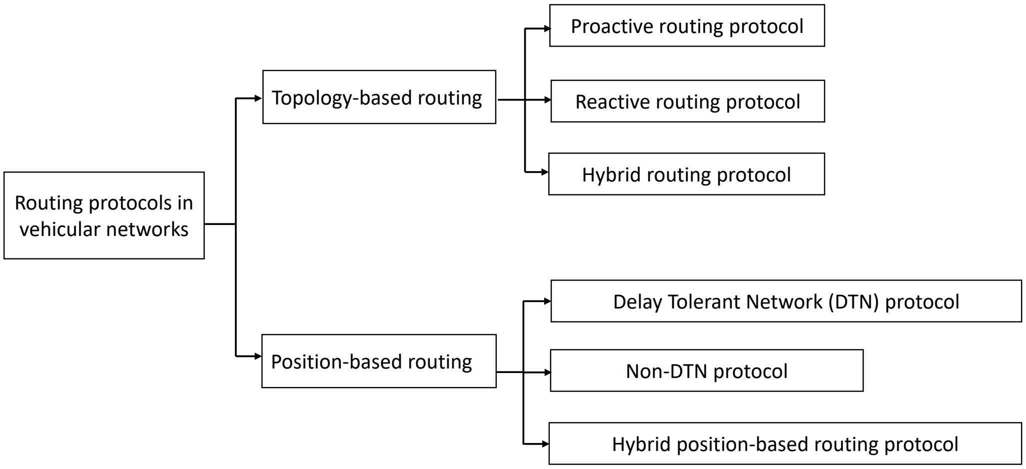


Figure 2.2: Classification of conventional data routing methods in VNETs

routing [100, 137]. In the following, we will discuss and analyze the features of these three types in detail.

Proactive Routing Protocols

The proactive routing protocol is typically implemented in a table-driven manner. A routing table containing the information of all connected neighbors is built for each node. The nodes in the proactive routing protocol find the data transmission route based on accessible routes information saved in the local routing table [137]. This routing table can be maintained by updating network topology periodically and updating when topology changes, e.g., detecting a new node entry into the network, detecting a link failure, etc.

Obviously, because of the transient feature of the network topology in vehicular networking, topology-based algorithms require frequent information exchange to ensure the accuracy of the network topology recorded by the system, which leads to considerable control overhead. To address this problem, the existing topology-based methods often reduce the number of transmitted control messages in two ways. The first approach is to reduce the number of nodes involved in recording network topology changes. The most representative of these approaches is the well-known optimized link state routing (OLSR) protocol [84], in which only the selected nodes are allowed to take charge of forwarding the data and transmitting the link-state information. The second approach is to adjust the frequency of topology information updates. For example, in Destination Sequenced Distance Vector Routing (DSDV) [39, 170] protocol, each entity in DSDV has a routing table that records the reachable destinations and corresponding hop count to achieve these destinations. The information in this routing table can be updated in two modes by broadcasting different kinds of information packets. Information of the entire route will be updated by full dump mode at a relatively low frequency, while insignificant change will be updated by incremental mode at a relatively high frequency. Similarly, the authors in [168] defined the update frequency for nodes according to the different scopes. Nodes located in the farther scope of the sender have lower updating frequency.

Reactive Routing Protocols

Different from the proactive routing protocol that needs to update topology information periodically, the reactive routing protocol updates topology information in an on-demand manner [30, 31]. It triggers the route discovery process when the source node needs to transmit data to the destination and only updates topology information for the routes in use to reduce the bandwidth occupation of route maintenance [137]. Three classic methods are briefly discussed as follows to introduce the characteristics of the reactive routing protocol.

For example, in AODV [171] routing protocol, the route discovery process only be triggered when a packet needs to be transmitted. The start node discovers the data transmission route to the target by the route request packet (RREQ) broadcasting between neighbors. After the target receives the RREQ, a receive reply packet (RREP) will be sent back to the start node. Also, the DSR [129] adopted the on-demanded mode to avoid the periodic update of the routing table. The source node in DSR starts to discover the route by sending a route query message. Different from the AODV that establishes the route based on the routing table of each forwarder, DSR builds the transmission route by source routing, i.e., the whole route is included in the packet header by the source node. Moreover, the start node in Temporally Ordered Routing Algorithm (TORA) [165] also creates the transmission route in an on-demanded manner. It constructs the route to the target according to different weights allocated for nodes in the network. Furthermore, to achieve an effective topology update mode for the route maintenance process, the effect of network topology change is mitigated by limiting the broadcasting range of the control message.

Hybrid Routing Protocols

As discussed above, proactive routing protocols can effectively obtain the data transmission route based on known topology information. Reactive routing protocols can decrease the control overhead of the routing process by using on-demanded update mode [16]. To take the advantages of proactive and reactive routing protocols, hybrid routing approaches are designed [54, 61, 63]. Normally, the network in hybrid routing methods is divided into different parts. Proactive and reactive routing methods will be adopted by nodes separately in the different divided parts.

For example, in Zone Routing Protocol (ZRP) [69, 172], each node defines a zone area based on the hop distance and the topological distribution. Proactive routing is chosen to assist the packets delivery inside the zone, and reactive routing is used to support transmission between zone and zone.

Moreover, in Zone-based Hierarchical Link State (ZHLS) [128], topology between different zones and nodes are considered. Both the zone Id and the node Id are assigned to each node to implement the hierarchical routing method for the route routing process. Proactive mode is employed when the source and the destination are in the same zone. Otherwise, the reactive mode is utilized for requesting the destination zone Id. However, broadcasting zone information to all nodes when zone topology changes will result in plenty of consumption of the network source. To overcome this drawback, the ZHLS with gateway flooding (ZHLS-GF) [118] is proposed. ZHLS-GF reduces the overhead of the network for zone topology updating by only using the flooding scheme for gateway nodes in zones.

Pros and Cons for Topology-based Protocols

According to the topology-based routing protocols summarized in table 2.1, data transmission routes can be calculated efficiently by awareness of existing network links in these protocols. Nevertheless, on account of the highly dynamic characteristic of the VNET, the network topology changes frequently. Topology information saved locally can be expired in a short time, even without time to execute the update process. Also, the routing table size will increase with network size, and the update procedure will occupy bandwidth in the network [8], which will cause a high overhead in the network. The protocols more applicable for VNETs character should be designed.

Table 2.1: Topology-based routing protocols

Protocol	Classification	Topology Update Manner
DSDV [170]	Proactive	Updating entire route at low frequency and insignificant change at high frequency
OLSR [84]	Proactive	Only selected nodes forward the data and transmit the link-state information
FSR [168]	Proactive	Nodes located in the farther scope of the sender have lower updating frequency
AODV [171]	Reactive	Using RREQ and RREP obtain the topology information
DSR [129]	Reactive	Sending route query message to obtain the topology information
TORA [165]	Reactive	Broadcasting control message in limited range
ZRP [172]	Hybrid	Proactive update utilized in a zone area and reactive update inter-zone
ZHLS [128]	Hybrid	Proactive update for inner-zone information and reactive update for zone information

2.1.2 Position-based Routing Protocols

As mentioned before, the high-speed movement of vehicles in the VNET causes frequent topology changes. Routing protocol based on topology will lead to a considerable overhead due to the frequent updates of the topology information in the routing table. In order to avoid the dependency of recorded network topology information in the data routing process, calculating the transmission route based on nodes' geographic location is considered as an alternative solution. Technically, through the increasingly popular positioning technologies such as GPS, vehicles can be easily located, which provides a solid foundation for the study of position-based routing methods.

By assuming the start vehicle knows the geographic information of both itself and the target, the location information of the target will be contained in the packet header to assist forwarders in the packet delivery procedure [228]. However, due to the high mobility nature of the VNET and the uneven distribution of vehicles, the next forwarder may be unavailable or out of transmission range during the delivery process. To overcome the potential interruption of the data transmission and transmit the packet to the destination, storing the packet until meeting a suitable next forwarder is considered by the current forwarder. Nevertheless, this temporary storage will cause a considerable transmission delay, which may not satisfy the transmission requirement in some scenarios. To apply the data transmission methods adaptively according to different vehicular traffic conditions, both delay-tolerance and none-delay tolerance methods are proposed, e.g., the delay-tolerance protocol for the scenario with sparse traffic and the none-delay tolerance protocol for the scenarios with sufficient forwarders.

Typically, to face the scenarios with different vehicle distribution and the delay requirement, existing position-based routing methods can be mainly divided into three types: Delay Tolerant Networks (DTN) protocols, Non-Delay Tolerant Network (Non-DTN) protocols, and Hybrid Network protocols [78,195]. In this part, we provide a briefly to introduce the position-based routing protocol by summarizing a few protocols for each type. The characteristics of each protocol can be shown in corresponding tables, i.e., the table 2.2 and table 2.3.

DTN Protocols

Traffic density in the scenario can affect the communication condition among vehicles. Disconnected communication between vehicles is likely to occur in an area with low traffic density. According to this discontinuous communication condition, a forwarder in the DTN protocol will store the packet until it expires or be transmitted to other forwarders instead of discarding the data packets immediately when the data delivery route between the start vehicle and the target vehicle is unavailable [204].

For example, the vehicle in vehicle-assisted data delivery (VADD) approach [238] transmits the data in a store-and-forward mode. According to the limitation of road topology, a vehicle's mobility is predictable. In VADD, considering the location of a vehicle on the road, i.e., at the intersection, on a straight road, close to the destination, three transmission mode is presented by the authors. Moreover, the authors proposed a stochastic model for evaluating the delay of data packet transmission. On the basis of the delay, the forwarder will wait until finding a suitable neighbor exists in the transmission range to forward the data packet in different transmission modes.

Moreover, a similar next forwarder selecting method is also used in the DTN-enabled VNET (FFRDV) [226] approach that proposed for sending messages to the specific destinations in DTN. In FFRDV, roads to the destination are segmented into logic blocks. The vehicle in the FFRDV will deliver the data to the forwarder with faster velocity in current block until the data packet reaches the destination. If a faster forwarder is not available, the packet will be carried by the current vehicle.

Furthermore, the store-and-forward method can also be used in Geographical Opportunistic Routing (GeOpps) protocol [142]. In GeOpps, the navigation system (NS) provides a suggested route to the target for the vehicle. The vehicle then evaluates the Minimum Estimated Time Of Delivery (METD) according to the suggested route and its speed. By using opportunistic routing, broadcasting can be used to figure out the appropriate forwarder [87, 89, 93]. The vehicle carrying the packet will broadcast the target to neighbors periodically to find the forwarder that can send data packets to the target with less time. If the forwarder with less transmission time is unavailable, the current vehicle will keep carrying the packet.

Non-DTN Protocols

To face emergency events and achieve the requirements of some real-time applications, delay-sensitive conditions need to be considered [114, 167]. Unlike the DTN protocols, the vehicles in Non-DTN protocols aim to deliver packets to the destination with a short delay [24]. Therefore, the store-and-forward mode that may introduce a considerable forwarding delay is abandoned in designing the Non-DTN protocols. In this section, three classic protocols will be introduced in detail to illustrate the data routing process in the Non-DTN. Also, because the Non-DTN protocol is appropriate for the scenarios with sufficient forwarders [24], the city environment that has relatively high traffic density is suitable to apply Non-DTN protocols. However, due to the weak penetration of the 2.4GHz signal used in VNETs, dense buildings in the urban environment can severely limit the propagation of radio signals, which makes VNETs' data transmission is typically confined to urban road networks. Hence, how to make effective utilization of urban road network characteristics (such as road network topology, vehicle density, etc.) is often the focus when designing NON-DTN protocols.

Firstly, we use GPSR method [132] as an example to illustrate the data routing process in Non-DTN. In GPSR, the start vehicle uses greedy forwarding to find out the neighbor who has a shorter distance to the target vehicle to transmit the packet. Forwarders will continue this selecting mode until the data packet is received by the target. When the current vehicle is unable to find a forwarder closer to the target vehicle, the perimeter forwarding mode that follows the right-hand rule according to the network topology will be adopted.

In Geographic Source Routing (GSR) [149], the source vehicle utilizes the city map and the location of the destination to calculate the transmission route without buildings. Then it adopts the greedy forwarding manner to transmit data from the start vehicle to the target vehicle along the calculated route. Moreover, the authors in [150] proposed the Greedy Perimeter Coordinator Routing (GPCR) method to utilize the road topology without requesting a static city map. Instead of the source routing method that calculated the end-to-end transmission route before forwarding data packets, the packets in GPCR are forwarded without a predefined route. The transmission route of data packets is decided segment by segment based on the assistance of the vehicles at the intersection area, and the greedy manner is adopted to transmit the data on each segment.

Table 2.2: Position-based routing protocols

Protocol	If DTN	Forwarder/Route selection metric	Forwarding manner
VADD [238]	Yes	Vehicles position and expected delivery delay	store-and-forward
FFRDV [226]	Yes	Velocity and city map	store-and-forward
GeOpps [142]	Yes	Suggested route from NS and METD	store-and-forward
GPSR [132]	No	Distance to the target	Greedy forwarding
GSR [149]	No	City map and destination location	Greedy forwarding
GPCR [150]	No	Road topology and node position	Restricted greedy forwarding

Hybrid Position-based Routing Protocols

To overcome the challenging transmitting environment in VNETs, i.e., the rapidly changed network topology and high-speed moving nodes, hybrid protocols are proposed to combine advantages of multiple routing protocols [16]. In this section, we introduce two kinds of hybrid protocols that enhance the routing performance based on different combination approaches: the combination of DTN and Non-DTN protocols that can adjust data routing strategies on the grounds of different traffic conditions and the combination that introduces topology information into position-based routing protocols.

For example, to overcome the transmission interruption caused by unevenly distributed vehicles, hybrid protocols which combined the routing mode of DTN and Non-DTN protocols were presented. The hybrid protocol can dynamically adjust the routing strategies according to different traffic densities. The transmission mode in the Non-DTN protocol is adopted when the traffic density is high, and the transmission mode such as store-and-forward is applied when the appropriate next forwarder is unavailable. Moreover, the authors in [83] proposed a hybrid approach named GeoDTN+Nav to adjust the data routing strategy in the partitioned network. A virtual navigation interface is designed to select the forwarder based on the vehicle's movement information provided by the navigation system. Vehicles adopt multiple transmission modes (i.e., the greedy mode, the perimeter mode as well as the DTN mode) based on the network connectivity and forwarders' delivery quality in the network. Similarly, in FPBR-DTN method [175], the DTN transmission mode will be adopted by vehicles when both the greedy and perimeter forwarding manner fail. In the DTN mode, a vehicle will hold the failed packet until finding the appropriate next forwarder.

In addition to combining different position-based routing approaches, data transmission performance can also be enhanced by merging the local topology information of vehicles into the position-based routing method. The authors in [139] introduced the Topology-assisted Geo-Opportunistic routing (TO-GO) method by considering both the road topology and the vehicles' local topology in the data routing process. The vehicle in the TO-GO method collects local topology information from its neighbors by the enhanced two-hop beacon messages. Based on the acquired local topology information, the furthest neighbor can be obtained. On the other hand, according to the road topology and the destination's position, the vehicle can determine whether the data packet needs to change forwarding direction to reach the destination. Relying on the local topology information and the road topology, a Next-hop Prediction Algorithm (NPA) is presented to assist the current sender in selecting the anchor nodes, i.e., the nodes that data packets need to pass. If the data packet does not need to change forwarding direction, the furthest neighbor will be selected. Otherwise, the vehicle at the intersection will be selected. To improve the packet delivery ratio (PDR), opportunistic forwarding is applied by the current sender to transmit the packet to the anchor node. The node with shorter distance to the anchor node in the candidate set will be selected to forward the packet.

Pros and Cons for Position-based Protocol

In position-based routing protocols, frequently updating the topology changes for entities to maintain the end-to-end transmission route is unnecessary. Instead of using a predefined transmission route, vehicles in the position-based routing protocol choose transmission forwarders based on nodes' local information, which is more adapted to the high mobility condition in the VNET. Additionally, by avoiding the frequent message exchange in the topology routing protocol, network overhead can be decreased in the position-based routing

Table 2.3: Hybrid position-based routing protocols

Protocol	Combination	Forwarder/Route Selection Metric	Forwarding Manner
GeoDTN+Nav [83]	DTN and Non-DTN	Network connectivity and forwarders' delivery quality	Greedy forwarding and store-and-forward
FPBR-DTN [175]	DTN and Non-DTN	Vehicles' speed, direction, and distance	Greedy forwarding and store-and-forward
TO-GO [139]	Topology and position-based	Vehicle's local topology, vehicle's position, and road topology	Opportunistic forwarding

protocol.

On the other hand, without topology information of the network, vehicles make decisions only based on the local position information. Buildings in the city or tunnel on the highway may block the signal of the vehicle which is traveling along the selected transmission route, which can further affect the data transmission performance. Since the routing decision is made based on the local information, deriving the global optimal route is hard for the vehicle in position-based routing methods. Meanwhile, avoiding the local optimum problem needs to be considered for position-based routing protocols. Researchers in position-based routing protocols have a vast space to future improve the data routing process.

2.2 State-of-the-art Routing Protocols in VNETs

In the previous section, we briefly discussed the development of the protocols in VNETs by analyzing a number of classic conventional routing protocols. Considerable research efforts have been made to analyze the data routing protocols that are in accordance with the conventional classification we discussed, e.g., [5, 190, 223], etc. In addition to the methods proposed in conventional classification protocols, the data routing approach in VNET still has a huge space to be studied. Recent developments in on-board computing devices, roadside devices, wireless communication technologies, and artificial intelligence technologies have provided more technical means that can be used and referenced in the design of routing algorithms in VNETs. Data delivery performance can be improved in a variety of aspects during their data routing process.

For example, the discussion of the routing protocols in [223] indicates that the transmission performance can be affected by the traffic density in the scenario. Hence, allowing vehicles to be aware surrounding environment can render assistance to them for their transmission route selection. Vehicles can select appropriate transmission routes for the data delivery under the global view provided by system-wide traffic information and network condition. Traffic-aware routing (TAR) protocols can play a considerable role in the further study of the data routing procedure in the VNET. Moreover, as mentioned in [5,190], overcoming the high dynamic mobility of vehicles can be the common challenge for the data routing in the VNET. As indicated in [4], accurate prediction of vehicle mobility can assist vehicles in achieving reliable communication in this highly dynamic network. Meanwhile, the authors in [179] pointed out that to achieve robust data transmission for ITS applications, stringent Quality-of-Service (QoS) requirements need to be accomplished. However, Due to the features of VNETs (e.g., highly dynamic topology, etc.), satisfying the QoS requirements is challenging. According to [180], the cross-layer approach has high effectiveness for robust communication among vehicles. The cross-layer method can be a valuable approach for the further development of data transmission in VNETs.

In this section, we analyze the state-of-the-art protocols mainly in three categories, which are different from the conventional classification: TAR protocols, prediction-assisted routing protocols, and cross-layer routing protocols. Each category will be introduced with more detail based on the different improvement methods they used as follows.

2.2.1 Traffic-Aware Routing Protocols

The rapidly changing traffic condition in the VNET results in a challenging environment for multi-hop communication among vehicles. Though various routing protocols have been presented to derive data transmission routes, transmission failures caused by traffic status are hard to avoid without a global view of the network. For example, lacking forwarders on a certain road segment is hard to avoid without knowing the system-wide traffic condition. Also, as mentioned before, many position-based routing protocols calculate the transmission route based on the local information, which may only achieve the local optimal selection for data delivery. To select the optimal route on a system-wide scale, allowing vehicles to be aware of the global traffic information and the network condition is a promising solution [96].

In TAR protocols, by knowing system-wide information on traffic conditions, vehicles can find relatively robust data transmission paths. For instance, on-road vehicles can obtain real-time traffic information from the traffic agency via V2I communications or acquire traffic condition information from other vehicles relying on the V2V communications. Through real-time traffic information, vehicles can enhance the conventional routing method by considering traffic information such as traffic density when calculating the transmitting route. Also, vehicles can gain network conditions such as link condition by sending messages to neighbor nodes. With the assistance of link condition information, a robust transmission route can be figured out. Extraordinary improvement in transmitting performance can be achieved by TAR protocols [205]. In this part, we will mainly introduce two types of TAR protocols based on different influencing metrics they considered to support the transmission route calculation procedure in VNETs, i.e., traffic density and link condition. The classification of the protocols we will introduce is illustrated in Figure. 2.3.

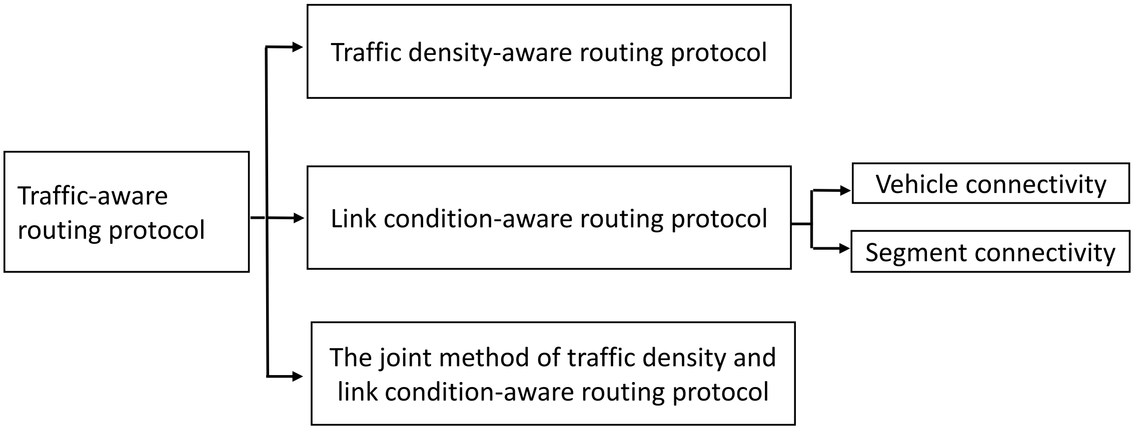


Figure 2.3: Classification of traffic-aware routing protocols

Traffic Density-Aware Routing Methods

Based on our previous discussion, it is clear that the vehicle in the VNETs works as both a user of data communication services and a provider of communication resources. Therefore, we can easily conclude that the number of vehicles on the road may directly affect the performance of the corresponding data transmission on the road. Accordingly, effectively measuring the number of vehicles on the road and using it as a metric in the routing algorithm is an important research direction in current TAR protocols. The traffic density in the VNET is most widely estimated by the vehicle number in a predefined area, e.g., a lane, a certain area in urban, and a predefined cluster. Based on different areas, traffic density can be defined as $vehicles/km$ or $vehicles/km^2$. The estimation of traffic density can be done in two ways: 1) the infrastructure-based mode that uses detection devices such as road sensors and monitors and 2) the infrastructure-free mode that gets information by communicating among vehicles [94]. Since vehicles' movement is constrained by the city road topology, various segment-based routing methods are proposed; and the traffic density plays an important role in such methods. In the following, we will discuss the segment-based routing approach based on its two main selections, i.e., the road segment selection and the forwarder selection. The effect of the traffic density in such methods will also be introduced in more detail.

In the Real-time Forwarding Method (R-FM) [173], vehicles will request for the road traffic density from RSU when passing the intersection area. The roads with lower traffic density will be selected to transmit packets to avoid network saturation and channel congestion. After selecting the transmitting road, the vehicle calculates Next Forwarder Selection (NFS) to find the next forwarder in its neighbors. The NFS is evaluated by the vehicle's direction (Dr), distance (Ds), and excepted transmission time (ETT). The corresponding equation is shown as follows:

$$NFS = \alpha * Dr + \beta \frac{1}{Ds} + \mu \frac{1}{ETT}. \tag{2.1}$$

The candidate who has higher NFS will be chosen as the next hop. The simulation result in [173] shows that vehicles can achieve real-time transmission with low latency by adopting the R-FM method.

On the opposite, to gain more transmission resources, e.g., potential next forwarders, some protocols prefer to select the route with higher traffic density. The authors in [10] propose an approach named Intersection-based Distance and TAR (IDTAR) Protocol to use the traffic density for intersection selection. In IDTAR, data packets will be transmitted following the selected intersections. Traffic density and street topology of the digital map are utilized to select the intersection whose traffic density is higher and closer to the destination. Greedy forwarding is adopted for the transmitting process between two selected intersections. Also, during the transmission process, if the Local-Maximum-Problem occurs, the selected intersection will be recomputed.

Link Condition-Aware Routing Methods

In addition to the traffic density, the link condition of a route to transmit the data is also critical for successful data delivery. In this part, we defined the data transmission capability as the connectivity of objects to represent the link condition of the inter-vehicle communication. Both the connectivity between vehicles and the connectivity of road segments will be discussed in more detail as follows.

Vehicle Connectivity-Aware Routing Methods Obviously, a more robust communication link will have a lower possibility of link failure and thus is more likely to obtain a higher data transmission success rate (or packet delivery rate). Because connectivity plays an important role and is commonly used to measure communication capability between nodes [188], we adopted vehicle connectivity (i.e., the capacity to forward a packet between two vehicles) as the metric to evaluate the connectivity in VNETs.

To estimate the connectivity of vehicles, inter-vehicle distance (IVD) is utilized. In [121], an IVD based connectivity aware routing (Ivd-CAR) approach was proposed for data routing in VNETs. In Ivd-CAR, the sender will send RREQ to the candidate forwarders in a computed forwarding area as illustrated in Figure. 2.4. In this method, the vehicle V_n who received RREQ will calculate the inter-vehicle distance IVD_{nk} between itself and the previous forwarder V_k, and then update the average IVD of the current forwarding route. Also, Cooperative Localization (CL) and Geometry based Localization (GL) are used to deal with instantaneous interruption caused by the location provider such as GPS when calculating the IVD. Both IVD_{nk} and average IVD will be inserted in the RREP message and sent back to the sender. After receiving RREP, the sender calculates the standard deviation according to the IVD_{nk} and the average IVD to select the next forwarder who has a minimal standard deviation.

Moreover, to evaluate the unstable connection among vehicles in the VNET, the connectivity-aware data dissemination (CADD) protocol is presented [144]. CADD introduced two new metrics, namely effective connection time and network throughput, to enhance the performance of data transmission. The effective connection time is calculated on the basis of the location and velocity of vehicles that can be obtained by exchanging hello messages. The throughput is computed by a three-layer Wavelet Neural Network (WNN) model that has autoregressive feedback. During the transmitting procedure, captured data packets will be the input of this model, and the result will be updated periodically every ten minutes. With the information above, neighbors' forwarding capability can be evaluated. The vehicle with the higher forwarding capability will be the next hop. Meanwhile, Dijkstra's algorithm is adopted to assist transmission from the start vehicle to the target vehicle.

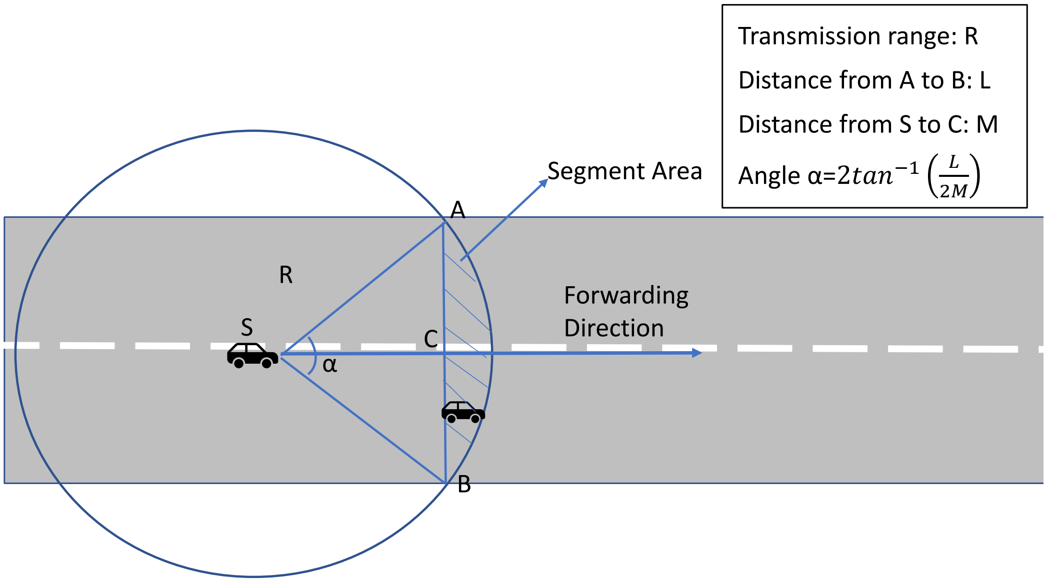


Figure 2.4: The definition of the selected area

Segments Connectivity-Aware Routing Methods Besides considering the vehicle connectivity to support the data routing process, evaluating the segment connectivity (i.e., the capability of the vehicles on the road segment to transmit data) can also assist vehicles in selecting a reliable transmission route.

In [133], the authors designed the Traffic-Aware Segment-based Routing (TASR) approach for VNETs. In TASR, vehicles exchange the location and velocity information with neighbors via hello messages. The vehicle at the endpoint of a segment can declare as the Head Node (HN) of the corresponding road segment. HN collects the Segment Information (SI) that includes parameters of the current segment, e.g., segment ID and traffic density, and shares it with other accessible HNs in the neighborhood. With the traffic information, the Expected Connectivity Degree (ECD) can be computed for the next two segments selection.

$$ECD = 1 - \sum_{i=1}^{n} (-1)^{i-1} \binom{V_{num} - 1}{i} (1 - i\frac{R}{L_s}), \tag{2.2}$$

where $n = min\left\{V_{num} - 1, \left[\frac{L_s}{R}\right]\right\}$. Also, R is defined as the transmission range of vehicle, L_s is the length of the road segment, V_{num} indicates the average number of on-road vehicles, and i is the number of the road segment. Vehicles then evaluate the connectivity of segments based on the ECD. After selecting the segments, RREQ/RREP method is adopted to find the delivery path with the least hop counts. By considering the segment connectivity, a robust data transmission route can be found.

Also, segment connectivity can be evaluated adaptively based on real-time traffic conditions. Take the efficient GSR (EGSR) approach [116] that combines the GSR protocol with the ACO algorithm as an example. In EGSR, the city map is declared by a grid map in which road segments are represented by the edges between junction points. The weight of each road segment is defined in terms of the segment length and segment connectivity. To adaptively estimate the segment connectivity, the ACO algorithm is adopted. The vehicle arriving at the intersection area will work as an ant holder to launch the ant packets, i.e., the small control packets. These ant packets will be broadcasted via the POCA method [155] to the next intersection with a relatively higher number of vehicles in the ant holder's neighborhood. Vehicles will increase the value of the connectivity condition parameter after receiving the ant packet to indicate the pheromone update process in the ACO algorithm. Also, in order to update the segment weight with traffic conditions, pheromone evaporation is designed based on the traveling time of an ant packet through the segment. The travel takes a long time can represent unsatisfactory traffic conditions such as low traffic density or traffic congestion. With this update mode, the source vehicle can calculate the optimal route based on real-time traffic conditions via Dijkstra's algorithm and transmits the packet by greedy forwarding to follow the route.

As mentioned previously, the link condition information of the network has a significant effect on the data routing process. The transmission link with high quality can enhance the stability of the communication between vehicles. The authors in Connectivity aware Transmission quality guaranteed Geographic Routing (CTGR) protocol considered transmission quality during evaluating the connectivity of the road segment for the data routing process [147]. CTGR provides two models to evaluate the weight of the road segment based on different link conditions, i.e., the transmission quality (TQ) model for the connected link and the connectivity model for the disconnected link. When achieving the intersection area, the sender v_s will send a connectivity probe packet (CPP) to the target vehicle v_t who at the neighbor intersection to evaluate the connectivity of the link. v_t then updates the road weight and sends it back to the v_s. If v_s can receive the feedback, the link between the sender and the target is connected. For the connected link that consists of n vehicles, The TQ, i.e., the delivery cost included PDR, is defined as follows:

$$TQ = \frac{T_{cost} + (\sum_{i=2}^{n} t_{k(k-1)})LPDR_n}{LPDR_n}. \tag{2.3}$$

Where, $LPDR_n$ represents the PDR, T_{cost} indicates the expected transmission cost, and $t_{k(k-1)}$ is the transmission time between two forwarders. If v_s cannot receive the feedback from the v_t, and the link is disconnected, the connectivity model will be adopted to calculate the weight of the segment. Based on the assumption in the article, the segment is a two-lane unidirectional road. IVD is employed to judge the link connection probability of the segment that is defined in the following equation:

$$P_{connection} = \sum_{l=0}^{N-1} P_F(l) P_B(l), \tag{2.4}$$

where N is the number of vehicles of lane 1, $P_F(l)$ is the connected probability that if all the broken links on lane 1 are fixed by the vehicle on lane 2. $P_B(l)$ represents the number of link failure under a binomial distribution. For intersection selection, the intersection close to the destination will get priority evaluation. The connected link with minimal TQ is preferred to be chosen. For the next-hop selection, enhanced greedy forwarding is utilized. The vehicle with the max IVD and meets the requirement of link connection time will be the next hop.

The Joint Method of Traffic Density and Link Condition-aware Routing Protocols

To further improve the selecting process of data routing problem in VNETs, the joint method considered traffic density and the link condition has been presented. For example, the authors in Reliable Traffic-Aware Routing (RTAR) protocol [97] introduced a dependable method for segment selection during the data routing process. Two algorithms are proposed in the RTAR to select the next forwarder according to the position of vehicles. If current forwarder in the road region, the neighbors whose signal strength of received beacon messages is over the required threshold will be selected as candidate forwarders. The Candidate whose predicted location is closest to the target point will be selected. Otherwise, if the CF at the junction, its next junction will be selected at first by Real-time Traffic and Network Status Measurement (RTNSM) proposed in [95]. control packets are generated to evaluate the road states, i.e., traffic density, link condition, and network load of the road. control packets are updated by vehicles between two junctions, and its result will be announced in the junction area. With evaluation results, the best next road segment can be found. Then the neighbor closest to the selected junction will become the forwarder.

The mainly characteristics of TAR protocols have been summarized in Table 2.4.

Table 2.4: Traffic-aware routing protocols

Protocol	Assistance Information	Information Acquistion	Route Selection	Forwarder Selection
R-FM [173]	Traffic density	Hello message and RSU	Selecting the road with low traffic density	Delivering the packet to the vehicle has height NFS in neighborhood.
IDTAR [10]	Traffic density	City map and traffic estimation mechanism	Selecting the intersection closest to the destination with highest vehicular density	Greedy forwarding manner
Ivd-CAR [121]	Vehicle connectivity	RREQ and RREP	By computing a segment area	Selecting the vehicle with minimal standard deviation of IVD in the computed segment area.
CADD [144]	Vehicle connectivity	Wireless adaptor and hello messages	Dijkstra's algorithm	Selecting the vehicle with best forwarding capability.
TASR [133]	Segment connectivity	Hello message	Selecting the segment based on ECD	Greedy forwarding manner.
EGSR [116]	Segment connectivity	Ant control packet	Dijkstra's algorithm based on evaluated segment weight	Greedy forwarding manner.
CTGR [147]	Segment connectivity	CPP	The intersection with best link connectivity (TQ and connection possibility)	Selecting the vehicle has maximal IVD and meets the requirement of link connection time.

Discussion About TAR Protocols

Traffic density is the normally considered traffic information in the TAR protocol. It can not only be defined by the number of vehicles in a specific unit area but also be estimated from other criteria. For instance, in [110], the traffic density is evaluated by data dissemination delay during the V2X communicating procedure. Though the evaluation of the traffic density in routing procedure can improve the performance of data delivering on the selected optimal route, the optimal path selection only based on traffic density is not reliable enough. Link condition is also important for calculating the optimal data transmission route. Due to the dual identities of the on-road vehicles (i.e., as the transmission resource and the users), the impact of the traffic density is multifaceted. Plenty of simultaneous requests from vehicles in the area with high traffic density may cause channel congestion, while the area with sparse vehicles may cause the lacking of next forwarders. The balance between the count of forwarders and the channel condition is a noteworthy problem.

Another aspect of enhancing TAR protocols is the method to obtain traffic information. Traffic information can be gained from the messages exchanged among vehicles or external information resources such as the traffic control system. The traffic information acquiring method can be benefited from the development of wireless communication technologies in recent years. For example, the high-speed cellular network (e.g., 5G) can provide stable information interaction capability for vehicles to obtain the traffic information [136, 206]. Researches relaying on these technologies can be considered in the future.

2.2.2 Prediction-Assisted Routing Protocol

Due to the highly dynamic characteristic of the VNET, vehicles' position and network topology change frequently. An accurate prediction of the network's future state can prevent the optimal route calculation process from frequently updating the traffic information of network information, thereby reducing the corresponding control overhead. With accurate prediction, transmission failures caused by routing based on expired information can also be decreased. Various prediction-assisted routing protocols have been presented to provide a foresight of the network to assist vehicles in the data routing process. For example, in [201], the vehicle derived the optimal data route with the highest end-to-end path connection probability by exploiting the predicted vehicular traffic volume. In this portion, three types of prediction-assisted methods based on different objects they predicted are mainly introduce: trajectory prediction-assisted routing protocol, link duration prediction-assisted routing protocol, and the channel condition prediction-assisted routing protocol.

Trajectory Prediction-Assisted Routing Protocols

In trajectory prediction-assisted routing protocol, vehicles' future trajectories are predicted to assist the optimal forwarder selection. Based on the vehicle's future trajectories, the transmission of the data packet can be restricted in the right direction towards the target vehicle.

The prediction of the vehicle's position is utilized in Peeking at the Past and Present Routing (P^3R) method [228] to improve the performance of delay-sensitive packet delivery in VNETs. The general transmission process of the method is introduced as follows. In the beginning, the flooding method is adopted to discover the position of the target vehicle. Locations of the start vehicle and the target vehicle are then saved in the data packet header for packet delivery. In the transmission process, if the next hop in the routing table is unavailable, the next-hop selection will be triggered. According to the location and angle from the current forwarder to the destination, three different scenarios are discussed. In the first scenario, if the start vehicle and the target vehicle are on the same road, the neighbor closest to the destination will be the next hop. In scenario two, if a neighbor closer to the target is unavailable, the right-hand approach is adopted. In scenario three, the start and the target are on parallel roads. If an available neighbor is closer to the target and on the straight line from the start to the target, this neighbor will be the next hop. Otherwise, neighbors in the intersection area will be chosen.

Moreover, to further improve the performance of data delivery, vehicles' trajectory is predicted. In the P^3R, the position and moving direction of forwarders are predicted to provide more accurate location information for the next-hop selection process. To obtain the latest information of neighbors for future prediction, each vehicle broadcasts the beacon message to one-hop neighbors to update its location and velocity. The same prediction method in [218] is adopted to predict the trajectory. The authors assumed that vehicles' acceleration is under the normal distribution, and speed direction prediction follows linear regression. The change of moved distance Δx_f in Δt time and the speed direction k_f in n second of the neighbor f can be declared by the formula as follows:

$$\begin{cases} \Delta x_f = v_f \Delta t + \frac{1}{2} a \Delta t^2 \\ k_f = \beta_0 + \beta_1 k_{f1} + \ldots + \beta_n k_{fn} \end{cases} \tag{2.5}$$

In the formula, v_f is the latest velocity and $a \sim N\left(\mu,\ \sigma^2\right)$. Based on the prediction result, the source vehicle can accurately select the optimal forwarder by evaluating neighbors with adjustable weight. To be more specific, the next hop can be selected based on the formula with adjustable weights $\alpha_1, \alpha_2, \alpha_3$:

$$\begin{aligned} & \underset{i}{min}\ \alpha_1 d_i + \alpha_2 \theta_i + \alpha_3 I_i \\ & s.t.\ \alpha_1 + \alpha_2 + \alpha_3 = 1,\ i = 1, 2, ..., N \end{aligned} \tag{2.6}$$

For the neighbor i, d_i is the distance and θ_i is the driven direction angle from i to the destination. I_i equals 0 or 1 to indicate whether i is in the intersection area. With this method, the performance of the packet delivery is improved on both end-to-end delay and PDR aspects.

In Mobility Prediction Based Routing Protocol (MPBRP) [222], the predicted distance and the angle between the neighbor and the destination in a short future are used as the weight to select the next forwarder. The predicted position is calculated based on the vehicle's velocity and acceleration. Relying on the predicted position, changes of distance and the angle can be figured out, and the further intention of vehicles can be known.

Moreover, the vehicle's trajectory can be predicted by the Hidden Markov Model (HMM). The authors in [220] proposed a *p*redictive *r*outing based on the HMM (PRHMM) for data routing problem. PRHMM utilizes vehicles' regular trajectory to predict their future position. In terms of the movement history and current location of the vehicle, several possible destinations will be selected in HMM. The next road segment is regarded as the observable state, and the destination location is considered as a hidden state. After predicting the trip sequences between the present location and the most possible destination, vehicles will select the next hop on the basis of the transmission delay and the transmission probability of neighbors.

Link Duration Prediction-Assisted Routing Protocols

Besides the future trajectory of vehicles, link duration between vehicles also has a significant effect on data transmitting. The link duration can be evaluated in various ways [230]. For instance, it can be represented by the link lifetime [215] that is predicted based on vehicles' location and constant speed. Also, the spatial locality similarity [143] that is calculated in terms of the distance and relative speed of vehicles can define the link duration. The robust links between vehicles with a longer duration can form a stable transmission route for data delivery, which is important in the highly dynamic environment of the VNET. Various approaches are proposed to predict the link duration to decrease the link breakage of the packet delivery process.

In [230], the authors used multiple metrics (i.e., distance, velocity, and link lifetime [215]) to estimate the link duration between vehicles. AdaBoost [109], a meta machine learning approach that forms a strong classifier by a few weak classifiers is adapted to combine the aforementioned metrics. Candidate weak classifiers corresponding to link metrics are selected based on the classifiers' misclassification ratio in defined link duration threshold $lD, l = 1...n$. Then, the strong classifier $f(., lD)$ is constructed with the following function:

$$f(., lD) = sign(\sum_{t=1}^{T} \alpha_{t,l} h_{k_t,\theta^*_{k_t}(lD)}(.)), \tag{2.7}$$

where $\theta^*_{k_t}(lD)$ represents the selected candidate of weak classifiers. Vehicles construct $f(., lD)$ by received broadcasted AdaBeacon messages from the RSU. For each link k, the authors defined that $l^* = arg\ min_{l=1}^{n} f(k, lD) < 0$. Based on the calculated result of l^*, the link duration $L^*(e)$ is predicated as follows:

$$\begin{cases} L^*(e) = (l^* - 1/2)D, \ if \ f(k, lD) < 0 \\ L^*(e) = nD. \qquad Otherwise \end{cases} \tag{2.8}$$

By considering multiple link metrics, the prediction method in [230] achieved a preferable performance to evaluate the link duration between vehicles.

The authors in [14] proposed a method that utilizes neural networks (NNs) to implement the prediction of link duration. The mobility information of neighbors can be gained by exchanging the safety message among vehicles, and the information about the intersection and lanes can be obtained from the scenario map. To predict the vehicles' average speed in a specific time window, factors such as the speed of the current vehicle, the average speed of the neighbors who are in front of the current vehicle, and the distance to the intersection, etc., are considered as the input of the NNs. According to the predicted speed, the relative mobility between vehicles can be figured out. Then, the link residual time between vehicles is calculated based on the different moving scenarios defined by the authors.

Link duration can also be estimated by predicting the link frailer for vehicles. Transmission stability will be increased by avoiding the link breakdown. The authors in [156] proposed an approach to anticipate the link frailer in the data transmission process. Newton's divided difference interpolation is applied for computing the availability of the link in the short future. It calculates the approximate cut off time of a link according to the signal strength of the received packet. Moreover, if a link breakdown is detected, vehicles will use the routing protocol named AQRV to figure out a new path to transmit the packet.

Channel Condition Prediction-Assisted Routing Protocols

The availability of the transmitting channel is essential for the data delivery process in VNETs. Channel prediction can benefit vehicles to find the transmission route with enough resources and high transmission quality, which can further improve the success rate to deliver the data packets in VNETs.

In [198], MOCA was proposed to deal with link disruption in the Cognitive Radio (CR) VNETs. CR allows the vehicle to use the channel which is not occupied by the primary user for data transmitting. Based on this fixable character of the CR, MOCA provides a periodical prediction method to gain available transmission resources through the following stages: Firstly, the spectrum occupation condition is obtained by the channel sensing process. Meanwhile, the information about the channel performance is evaluated by signal noise ratio (SNR), bit error rate (BER), vehicle direction, and vehicle mobility. This performance information is collected by local nodes at the observation stage. Secondly, the predicting approach at time t+1 has been shown in the Eq. (2.9). The prediction of the channel's quality is defined by the normalization value of three parameters obtained from nodes' local information.

$$Qua_c(t+1) = \alpha Mob(t)^{'} + \beta Chp_c(t)^{'} + \gamma Dir(t)^{'}, \tag{2.9}$$

where, $\alpha + \beta + \gamma = 1$. $Mob(t)$ represents the mobility, $Chp_c(t)$ is the channel performance based on Shannon's equation, and $Dir(t)$ is defined as the relative direction of vehicles. According to the prediction of the future average distance between the node and neighbors and the predicted channel capability, $Mob(t)$, $Chp_c(t)$, and $Dir(t)$ can be further predicted. The final decision will be made on the basis of the channel quality result. Also, the weight of these three parameters can be adjusted based on different network conditions. The difference value of the aforementioned parameters between different time is recorded and normalized to adjust the weight for a more accurate result. Based on this method, low-quality channels can be avoided during the transmission process.

Another channel prediction-based scheduling approach was presented in [227] to assist the control server (CS) in data dissemination scheduling. Three steps are designed in the approach: firstly, the position and velocity information of vehicles is collected by the RSU. Secondly, CS makes the prediction of the channel condition with recursive least squares (RLS) algorithm [122] and decides the scheduling strategy to select the relay. By using RLS, channel prediction in a large area can be achieved with comparative low computational complexity. The CS then calculates SNR with predicted information for transmission utility estimation. Finally, the node with maximum transmission utility will be selected as the relay to transmit the current transmission frame.

The characteristics of the aforementioned protocols are summarized in Table 2.5.

Table 2.5: Prediction-assisted routing protocols

Protocol	Predicted Object	Involved Objects	Prediction Method	Achievement
P^3R [228]	Vehicle trajectory	Neighbor's location, direction	Based on vehicles' acceleration; linear regression destination	Improved performance of PDR and end-to-end delay
MPBRP [222]	Vehicle trajectory	Neighbor's further intention	Based on acceleration and velocity	Improved performance of PDR, end-to-end delay, and average hops
PRHMM [220]	Vehicle trajectory	Vehicle's trip sequence	Hidden Markov model	Increased PDR and decreased delivery delay with lover buffer occupation
Zhang et al. [230]	Link duration	Link duration	AdaBoost algorithm	Prediction accuracy is improved and the chosen of link metrics is flexible
Alsharif et al. [14]	Link duration	Link duration	Neural networks	controlled the overhead in prediction model
Naresh et al. [156]	Link duration	Link frailer	Newton's divided difference interpolation	Improved QoS by preventing link frailer occur
MOCA [198]	Channel condition	Channel quality and vehicle's mobility	Based on future average distance between vehicles and predicted channel capability	Adapted to the changing environment
Zeng et al. [227]	Channel condition	Channel condition	RLS algorithm [122]	Decreased the communication overhead and improved system throughput

Discussion About Prediction-Assisted Routing Protocols

Based on the protocols introduced above, vehicles can utilize neighbors' future locations or link quality to select a more stable data transmission route. Awareness of the location or the channel condition in the short future can reduce the data transmission failure caused by the high-speed movement of vehicles. Various technologies have been used for accurate prediction. As one of the most popular novel topics, machine learning is applied for providing accurate prediction results for vehicles [134,138,217]. With the increased number of traffic monitoring devices and the advanced wireless communication technologies, collecting vehicular traffic-related data for the corresponding training process of machine learning technologies is easier nowadays. By taking advantage of the improved computing capacity, more advanced machine learning technologies are available to achieve an accurate prediction. For example, the authors in [187] proposed a deep reinforcement learning-based routing method to provide the accurate traffic density result, which can further assist vehicles in establishing the durable transmission route. In addition to establishing the transmission route, deep learning can also be used to enhance the safety aspect for vehicles [81,169]. With great development potential, the method to train the model for vehicle location and link condition prediction with low overhead and high accuracy is worthy of being considered.

2.2.3 Cross-Layer Routing Protocols

Currently, lots of researches for the data routing process in VNET have been done with the layered structure. To enhance the data transmission process at each layer, various methods have been proposed to improve the service provided by different layers.

For example, at the physical (PHY) layer, the cooperative diversity among multiple channels is utilized to enhance the limited capability of the single-channel transmission. For the sake of the higher delivery ratio, the message of the source vehicle is transmitted through multiple channels and integrated at the destination. Cooperative multi-channel transmission methods such as amplify-and-forward (AF) [157], decode-and-forward (DF) [12], and Multi-Input Multi-Output (MIMO) [11] are presented to increase the data transmission performance. Moreover, for the medium access control (MAC) layer, nodes' characters, such as node buffer, can be employed as the routing metric to find the optimal forwarder of data transmission [233]. Also, service at the MAC layer can assist nodes in accessing the channel without the congestion, which decreases the waiting time for the node to transmit the data [131,233].

However, the layered design is not flexible enough for a highly dynamic wireless network, e.g., the VNET [19]. The blocking between layers can restrict nodes from gathering comprehensive information about the network. To deal with this problem, the cross-layer design is proposed [237]. In cross-layer protocols, vehicles can consider information such as channel quality and buffer vacancy from different layers to make the optimal decision for the data routing process. In [19], the authors illustrated various routing metrics that can be gained from different network layers (see Figure. 2.5). The optimal transmission path will be selected on the basis of the information that comes from three different layers. Similarly, the authors in [112] indicated that multilevel comprehensive information could provide support for establishing the vigorous data transmission route in VNETs.

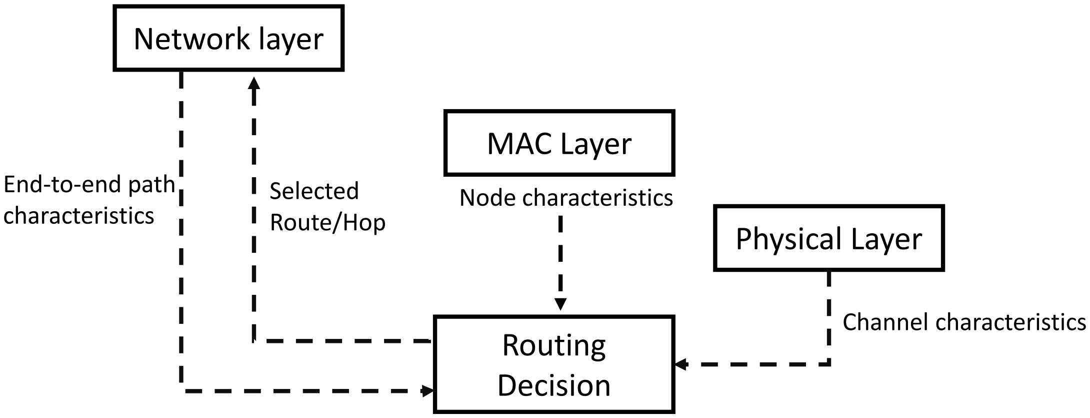


Figure 2.5: Various routing metrics from different networks layers

In [154], an enhanced AODV (En-AODV) protocol was proposed to increase the stability of the data transmission process in the VNET. En-AODV enhanced the AODV routing function by considering the PHY metric, namely the link quality, for the routing process at Network (NET) layer. If the transmission route from the start vehicle to the target vehicle does not exist, the AODV route discovery procedure will be employed to select the forwarder with the enhanced routing function. The link quality in the routing function is evaluated by link lifetime that is estimated according to the PHY information, i.e., received signal power and vehicle mobility information. The definition of the link lifetime has shown as follows:

$$t \leq \left(\frac{\lambda}{4\pi * Vrv}\right)\sqrt{\frac{Pt * Gt * Gr}{Pr}}, \tag{2.10}$$

where Pt is the emission signal power and Pr is a defined threshold for the received signal. Gt represents the gain of the transmitter, and Gr represents the gain of the receiver. Vrv represents relative velocity between nodes. Also, the authors defined the destination region to reduce broadcasting overhead during the transmission. The city map is divided into blocks in terms of postal zones, only the vehicles moving to or nearby the destination can broadcast the RREQ from the source. Moreover, a route maintenance approach is designed to recover the link failures caused by vehicles' high-speed movement. If a link break is detected by periodic hello messages during the estimation lifetime, the involved forwarders will send RREQ messages to discover an alternative route to repair the broken link effectively.

Furthermore, to establish a route with high stability and the minimum hop counts, Cross-Layer Autonomous Route Recovery (CLARR) protocol is proposed [189]. The hop count information from the NET layer and the link lifetime information from the PHY are considered in CLARR. The route stability can be enhanced by considering link lifetime, and the transmission delay can be decreased by taking route hop counts into account. At the route discovery stage, the link lifetime between vehicles is evaluated according to vehicles' relative velocity and transmission delay. The link with lower relative velocity has a longer lifetime. Also, the delay of sending an RREQ packet between two nodes is calculated. A lower delay can represent a lower relative distance which further represents the longer lifetime. Each forward's delay is accumulated during the sending process, and the destination will select the route with the longest lifetime. Also, to overcome the unexpected link breaks, a new RREQ packet will be generated for the new field to estimate the link lifetime.

Moreover, cross-layer design can be combined with the heuristic algorithm, such as ACO and genetic algorithm, to increase the data transmission performance in the VNET. For example, in [113], by exploiting ACO, the authors proposed a Selective Cross-layer based ACO-AODV (SCL-ACO-AODV) approach for satisfying the QoS requirement of the data transmission. If there is no relay that can connect to the destination directly, the source vehicle will send the path exploration messages towards to destination and leave the pheromone on the passed route. This pheromone can be defined by various cross-layer parameters, including packet loss, delay, signal quality strength, link lifetime, the throughput of the global route, etc. The optimal route will be selected based on the value of the pheromone left by ants. After the selection process, the AODV protocol is used to transmit packets with the selected optimal route. The energy and the distance from a

Table 2.6: Cross-layer protocols in VNETs

Protocol	Used Layer	Evaluation Metrics	Achievement
En-AODV [154]	PHY and NET	Link lifetime and destination region	Improved the stability of the transmission route
CLARR [189]	PHY and NET	Link lifetime and hop counts	Found the stability route with low possible hop counts
SCL-ACO-AODV [113]	Application, Transport, PHY, and MAC	The pheromone that can contains packet loss, delay, signal quality strength, etc.	Improved routing performance in PDR, delay, throughput, and overhead aspects
Liu et al. [148]	PHY and MAC	Vehicle density, vehicle velocity, frame length, modulation	Increased system throughput

forwarder to the end node are considered as the selection metrics to choose the stable next forwarder along the route.

Also, the authors in [148] presented a high-dimensional cross-layer method for the optimal route selection in terms of the parameters from the MAC layer and the PHY layer. In the method, a cross-layer system model is defined to formulate parameters from different layers. To satisfy the QoS requirement, the throughput and BER of the system are considered. To be more specific, vehicle density, vehicle velocity, and packet frame length are evaluated to enhance system throughput. Also, the effect of the modulation methods is analyzed for the system BER. The fuzzy measure approach is utilized for the optimal selection process with this system model. Choquet integral is adopted for parameter classification, and the genetic algorithm is employed for the optimal calculation. System performance can be improved by using this optimal selection method. Aforementioned protocols are concluded in Table 2.6.

Discussion About Cross-Layer Protocols

Vehicles can make a holistic routing decision through cross-layer methods that involve parameters from multiple layers during the optimal routing process. Based on different objectives and application scenarios, metrics from different layers can be combined and adopted to assist the routing procedure in various ways. It is worth studying a more efficient combination of multi-layer information to conduct the data forwarding path exploration in the VNET environment.

In addition to the combination of routing metrics, the effect of the architecture design in cross-layer methods is also noticeable. As demonstrated in [19], an improper cross-layer design may cause the disorganization problem, which disturbs the encapsulation of layers. Designing an adjustive architecture and keeping the layer modularity at the same time is a significant challenge for the architecture design procedure.

Moreover, cross-layer methods can be used to solve some specific security problems in VNETs. In [21], the authors proposed a cross-layer scheme for detecting the black hole attack. The signature key and an improved watchdog technique are used for detection on different layers. Furthermore, in [174], a cross-layer protocol was presented to detect the conspire Sybil attack on a large scale. The directional antenna is utilized to verify the vehicles' presence. Furthermore, the authors in [203] proposed a two-period game-based protocol to achieve the balance between the security and QoS requirements by utilizing the cross-layer design concept. With the cross-layer design, more reliable communication can be realized among vehicles, which leaves a huge room for researchers to continue the further study of enhancing the data routing performance.

2.2.4 Data Routing Protocols in Vehicular-Cellular Network

With the deployment of cellular network communication technology, there are more alternative ways to realize V2X communication. The combination of the cellular network and the VNET can be a profitable environment for the further study of data transmission among vehicles. In this part, we first briefly reviewed the development of the communication technologies of the cellular network. Then, we introduced a few approaches to show how to utilize the Vehicular-Cellular Network (VCN) environment to enhance data transmission performance for vehicles.

The Development of the Communication Technologies of Cellular Networks

Plenty of work has been done to promote the development of wireless communication technology, such as providing a parallel [23,38,73,74] and distributed [42,70,71,98] simulation environment for wireless network research [40]. As one of the significant wireless communication technology, the cellular network extended its capability to cover services from voice to multimedia in recent decades [32]. Currently, users in the cellular network can obtain reliable communication by accessing to the based station in each cell [41, 49] with low delay. This improvement of the communication technology in the cellular network provides a stable and effective way for vehicles to acquire data. In this part, we will briefly introduce the development of the communication technologies of the cellular network.

The 1rst generation (1G) introduced the conception of the cells into the wireless network. It achieved great commercial success via supporting the voice service. However, the 1G has limitations in various aspects, e.g., low spectrum utilization, limited service categories, etc. To further improve the service performance, the 2nd generation (2G) is launched. 2G adopts digital mobile communication technology to provide better services in terms of voice service sound quality and communication security. However, with the development of the internet and multimedia service, basic voice service supported by 2G can no longer satisfy the requirement of the public. To serve the communication with multimedia, the 3rd generation (3G) is designed to increase the data transmission speed. Nevertheless, the data transmission speed of the 3G did not achieve the expectations of the public. The transition from 3G to the 4th generation (4G), i.e., Long-Term Evolution (LTE), is proposed to upgrade the transmission speed further [79]. Moreover, based on the LTE, LTE-Advanced is proposed as the 4G standard to afford the high-speed data transmission service among devices.

Furthermore, because of the emergence of the Internet of Things, amount of data generated by the networking of smart devices has exploded. New requirements such as extreme speed, ultra-low delay, and high reliability are presented for the service of the cellular network [196]. Through 4G has a relatively high transmission speed than the previous standards, it is difficult to meet these requirements. The deployment of the 5th generation (5G) network is necessary. In addition to the Internet of Things, technology such as the Internet of Everything has stricter requirements of the services provided by communication technologies. A new stander such as the 6th generation is needed to satisfy the high requirements proposed by users [125]. The development and application of cellular network technologies still have a huge room to be studied.

Data Transmission Methods in VCNs

Emerging of advanced communication technologies in cellular networks provides strong assistance for data transmission and management. For example, the authors in [141] indicate that by adopting 5G, spots data can be well collected from corresponding applications, which further support the study for spots education. Also, the authors in [176] find out an appropriate LTE scheduling algorithm that can manage traffic flow information with low delay. As mentioned before, stable and low-latency characteristics of the cellular network can provide a reliable communication way for vehicles to transmit data in VNET. However, transmitting data only depending on the cellular network may cause a high cost and excessive occupancy of the backbone resources. Therefore, combining the cellular network into the VNET suitable to take advantage of its reliability becomes a considerable study issue. To deal with this issue, various approaches have been proposed to assist the vehicle in transmitting data under VCN heterogeneous environment.

Transmission gateway selection can be an essential problem in the VCN heterogeneous environment. For example, in [193], the authors presented a service-aware algorithm for on-road vehicles selecting their transmission interface, namely, the DSRC interface or LTE interface to transmit the data packet. According to the QoS of required service, vehicles can transmit data flexibly by using DSRC or LTE methods. Meanwhile, in [1], vehicles that follow the 802.11p standard can access the LTE network with the assistance of the vehicle with heterogeneous interfaces. Moreover, selecting the transmission method based on the identity of the vehicle, e.g., if as the cluster header, is worthy of being considered. The authors in the cluster-based approach [145] defined that the vehicle in the method achieves intra-cluster communication by DSRC and realizes the inter-cluster communication via LTE. This method enhances the data transmission performance by increasing the PDR and decreasing the average latency.

Besides the LTE-VNET environment, a variety of data transmission approaches are proposed based on the 5G-VNET environment. Take an adaptive cluster-based transmission approach in [104] as an example. In the approach, the base station gathers the vehicles that have similar signal strength and angle of arrival into a group. IVD is used for further filtering in the group. The vehicle whose speed is similar to the average speed will be selected as the CH to take charge of the communication between cluster and base station. V2I trunk link transmission is adapted based on channel quality, and transmission power is also adapted to satisfy the required signal to interference plus noise ratio (SINR) of the channel. Furthermore, the authors in [200] point out that with the support of 5G, the position of the cluster header can be precisely located with negligible delay. Also, by accessing the base station of the 5G network, vehicles can transmit the data in a large area.

According to the protocols we discussed above, taking advantage of the stable and low-latency feature of the cellular network in VNET can assist vehicles in their data transmission process. The utilization of the VCNs environment to enhance data transmission performance is worth to be considered. How to use two kinds of resources in VCNs to figure out the optimal transmission route can be a crucial issue in further study.

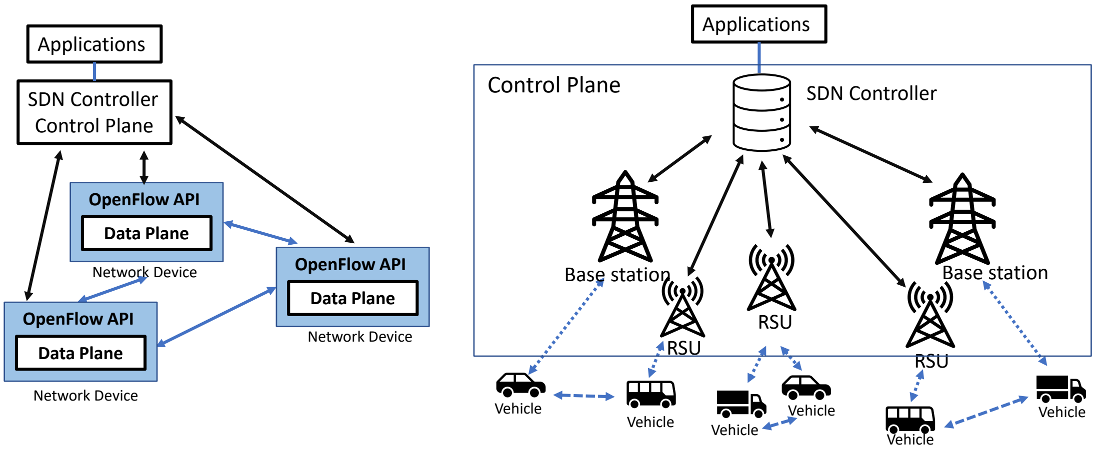
2.3 Improved Data Transmission Protocols with New Technologies

In order to look forward to the future development of data transmission in VNETs, the assistance of the latest technologies can be considered. Combining emerging technologies with conventional data transmission methods can enhance transmission performance in various aspects. In this part, we discussed the usage of two latest technologies, i.e., Software-Defined Networking (SDN) and cloud computing, to enhance the data transmission performance in VNETs. The separated design of the control plane and the data plane allows SDN to gather information from various source [221], which can assist the information gathering process for the traffic-aware data routing protocol. On the other side, cloud computing technology can provide sufficient computing resources for data calculation and data storage during the transmission process [68]. Also, it can be considered to enhance the security of the data transmission process [192]. More details of the aforementioned methods will be introduced in the rest part of this section.

2.3.1 Data Routing Protocols in SDN-Based VNET

With the increasing demand from the public, a variety of applications and technologies have been released for VNETs. However, the increasing number of applications has directly led to a significant increase in the amount of the transmitted data in the vehicle network, making its cost management challenging. Due to the tightly coupled control feature, employing new hardware or technologies in the conventional VNET will cause enormous management cost [80].

To meet this challenge, SDN, as a novel decoupling architecture that has been gradually used in traditional data communication networks in recent years to allow users to participate in network control procedures through software programming, is regarded as a potential solution [85]. Briefly, SDN divided the network into two portions: the control plane and the data plane. Interface such as OpenFlow has been used in charge of the interaction between two planes. Meanwhile, SDN sets a controller for network infrastructure to achieve logically centralized control. Users can control the network by access to the controller. In this way, the management cost for lots of independent decentralized network devices can be avoided, which simplifies the network model and increases the flexibility of the network. Based on this character, SDN is appropriate to satisfy the requirement of increasing numbers of applications in VNETs.



SDN architecture

SDVN architecture

Figure 2.6: Integrating SDN into the VNET

Apparently, SDN can be used to enhance the flexibility of the VNET [221]. The separated data planes and the centralized control center mode of the SDN allow devices that adopt different communication protocols to merge into the network through a standard access interface [221]. Aggregated information can enable effective network management in the VNET [25]. Various researches have been done for integrating SDN into the VNET. The general architecture of the SDN-Based VNET (SDVN) is shown in Figure. 2.6. In the SDVN architecture, the SDN controller can be set in the cloud server is used to merge the information and provide a global view of the network [159]. The controllers of the roadside infrastructure, such as RSU and base station, are employed as local controllers to enable effective communication between the SDN controller and vehicles. As the mobile network devices in the SDN network, the vehicles in SDVN provide information for the SDN controller by accessing the roadside infrastructure. Depending on the sufficient computing capability of the roadside infrastructure and cloud, applying the SDN in the VNET can enhance transmission performance in a variety of aspects. In the following, we will discuss a few SVDN protocols with more detail to introduce the features of them. Corresponding information is summarized in Table 2.7.

In [126], an SDN-based geographic routing (SDGR) protocol is proposed for achieving global optimization during the data routing procedure. SDN central controller provides a global view to assist the optimal route selection. Two main algorithms are proposed to enhance route selection and packet forwarding. In the network, vehicles update their mobility state (i.e., the location and speed) to the server via RSUs periodically. In the route selection phase, both the digital map and the global information from the server are considered. Metrics, namely the segment traffic density D_s and the segment length L_s are used as the weight for segments:

$$Weight_s = \alpha f(L_s) + \frac{\beta}{g(D_s)}, \tag{2.11}$$

where α and β are constant parameters. Dijkstra's algorithm is adopted to calculate the optimal transmission path. Also, if the calculation result is not unique, the density deviation of the route will be evaluated. The path has the lowest density deviation will be selected as the optimal one.

$$Deviation_r = \sqrt{\frac{1}{N_s}\sum(D_{Ri} - D_{avg})^2}, \tag{2.12}$$

where D_{Ri} is the density of the ith segment on the calculated route and $D_{avg} = \frac{1}{N_s}\sum D_{Ri}$. After the selection, the route will be added to the packet header for further forwarding selection. Based on the mobility information in the hello packets, two modes are used for packet forwarding, i.e., the junction mode and the forthright mode. The junction mode will be adopted when vehicles arrive at the intersection area. In the junction mode, the occupancy of the vehicle buffer is considered, which means that the node whose buffer has lower occupancy will be selected. On the other side, the forthright mode will be adopted when vehicles are outside the intersection area. In the forthright mode, the neighbor node that is closest to the target and has the same direction as the sender will be selected as the forwarder.

The authors in [240] proposed an SDN-based routing protocol to decrease the delay and overhead of the data transmission. In the article, an internet-connected remote central controller is set as the routing server to provide global network information for vehicles. Vehicles exchange messages with the routing server via the base station. WiMax is adopted for V2I communications, and WiFi is used to achieve V2V communications. A centralized routing protocol (CRP) is proposed for the vehicles' routing procedure. In CRP, vehicles update position and speed to the server periodically. When the vehicle cannot find a route in the routing table to transmit the data to the destination, it will query the transmission route from the server. The server then calculates the optimal route via the shortest path algorithm. The minimum optimistic time (MOT) that is evaluated according to the vehicle's direction and location is used as the weight of the shortest path algorithm. Selecting the transmission route based on MOT can decrease the transmission delay. The overhead of the network is low because the information exchange among vehicles can be avoided.

Similarly, in [2], the authors proposed a two-level SDN-based approach to implement the data routing process of vehicles with low overhead. Meanwhile, in this work, the cellular network technology is considered for the control packet transmission between the SDN controller and vehicles to reduce the corresponding data forwarding latency. And WiFi takes responsibility for the V2I communications. In this approach, vehicles update their information (e.g., speed, location, and direction) to the edge controllers of the SDN via gateway nodes which can be the on-road infrastructure or the vehicle at the intersection. On the basis of the information collected from vehicles, the SDN controller can provide the shortest route consisting of the segments whose traffic density is from 25% to 80% and be figured out according to vehicles' relative velocity and route's hop count.

In addition to the utilization of the central controller, distributed local controllers (LCs) can be used to support vehicles in solving the data routing problem. In SDN-based Vehicle Ad-hoc On-demand Routing Protocol (SVAO) [102], the roadside units located at each intersection act as the LCs. LC takes charge of collecting the information from the hello messages exchanged among vehicles and calculating the optimal route. A two-level structure is designed in SVAO for packet delivery, i.e., the global level and the local level. On the global level, LCs use a hierarchical query scheme to find the destination's location, two levels of detail information are collected: the detailed level and the wide level. The LC for detailed level keeps collecting all detailed information about the vehicle in its range. The LC for wide level is in charge of collecting the ID of each LC and corresponding vehicle. Destination will be firstly searched based on ID, and then its further information can be obtained from the LCs who collected the detailed information. After the search phase, an improved AODV method with a limited RREQ broadcast range is used to select the optimal route based on the number of involved LC (i.e., LC hop counts). If the LC hop counts are the same, link stability is considered for the optimal selection. On the local level, LC will predict the topology change of the segment according to the information collected from vehicles. Based on the prediction result, the Bellman-Ford algorithm [82] is used to find out the forwarders between two LCs.

As previously mentioned, the roadside infrastructure is in charge of collecting vehicles' traffic information for the controller. Areas not covered by roadside infrastructure, i.e., the communication coverage holes, will affect the information collection procedure in the SDVN. To deal with this problem, the authors in [160] presented an intersection-based routing protocol called SFIR to overcome the communication coverage holes.

In SFIR, the RSU or other designated internet-enabled computing devices (e.g., the fog node mentioned in [28]) located at the junction will be treated as the fog node. The fog node located at each junction serves as the sub-controller to collect the information from vehicles and grade the connected segment on the basis of its traffic density and the Euclid

Table 2.7: Data transmission protocols in SDVNs

Protocol	Communication Technology	Main Purpose	Routing Method
SDGR [126]	IEEE 802.11p	Overcome local maximum and sparse connection problem	Selecting forwarders based on vehicle's mobility information and buffer
Zhu et al. [240]	WiFi and WiMax	Decrease the delay and overhead	calculating the route according to the MOT.
SD-IoV [2]	Cellular network and WiFi	Reduced overhead	calculating the shortest route according to vehicles' relative velocity and route's hop count and the segments' traffic density
SVAO [102]	-	Achieve stable communication	Using the global level mode to select the transmission route and the local level mode to select forwarders on the route
SFIR [160]	IEEE 802.11p	Deal with communication coverage holes	Calculating the optimal route via Dijkstra's algorithm; Selecting forwarders based on vehicle's buffer and distance

distance to the destination. After the grading, the score of each connected segment will be sent to the SDN center controller. According to the score from sub-controllers and the digital map, the SDN controller can calculate the weight of each segment. The controller then utilizes Dijkstra's algorithm to compute the optimal route to the destination based on the weight of segments. Also, on-road vehicles can share traffic information with their neighbors by exchanging the hello message. The vehicle whose buffer capability is under the threshold and closer to the destination intersection will be selected as the forwarder to deliver the packets.

Discussion About SDVN Protocols

Because of the separated design of the control plane and the data plane, SDVN has the ability to support the network devices from different providers. It can gather and share information from various sources through a central control plane, thereby further realizing the information management of the whole network. Accordingly, by taking advantage of this feature of SDVN, some recently proposed approaches considered the heterogeneous network environment. For instance, in [164], the authors proposed an SDN-based path planning method that involves both unmanned aerial vehicles and VNETs.

Additionally, the logical centralization character of the SDVN can enhance the performance of data transmission by providing a global view to support vehicles in route selection. With the information that comes from multiple sources, the local maximum selection can be avoided. To take full advantage of the information gathered at the central controller, SVDN protocols can be combined with the traffic-aware protocol. Both the traffic information (e.g., the traffic density and mobility information) and the link condition of vehicles can be considered as metrics to find out the optimal route during the routing process.

2.3.2 Data Routing Protocols in Cloud Computing-Assisted Vehicular Networks

Due to the dramatic increase of traffic-related applications, data required to be processed are exponentially increasing in the VNET. According to this condition, cloud computing, a powerful data computing technology, is considered to support the vehicle in data processing.

Vehicular Cloud Computing (VCC) is enabled based on the development of cloud computing and VNETs. The evolution towards VCC has been discussed in [68] and shown in Figure. 2.7. Cloud computing has been developed as a powerful computing resource to support the processing of rapidly increasing data. End-users can connect to a data center via the internet for data management or computation, which extends the limited storage and computing ability of local devices. Based on cloud computing technology and the increasing number of mobile devices, Mobile Cloud Computing (MCC) is proposed to support mobile devices using cloud resources to store and compute data. Also, the Mobile Edge Computing (MEC) method is presented for distributing accessing the network service at the edge of the network. Meanwhile, because of the similarity between the mobile devices in MCC and the on-road vehicles in VNETs, VCC emerged from the MCC [68]. VCC provides vehicles an effective way to process and transmit data by allowing vehicles to access the cloud via the internet in VNETs. In this section, we will discuss the data transmission approaches which utilized cloud computing to improve the performance in data routing, data dissemination, and secure transmission, respectively. The main characteristic of aforementioned protocols are summarized the in Table 2.8.

To use the cloud resources to enhance the data transmission performance in VNETs, the RVCloud protocol is proposed in [26]. In the RVCloud protocol, when the vehicle

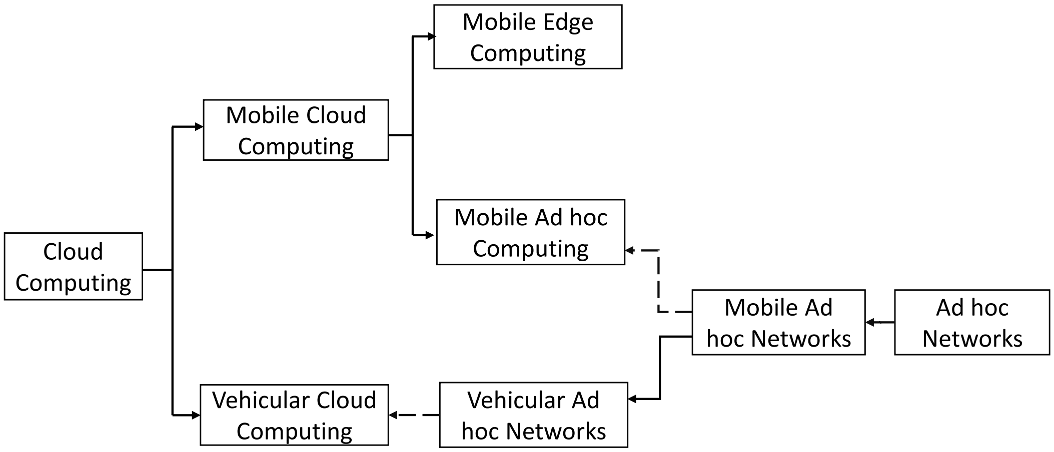


Figure 2.7: Evolution towards to VCC

passes an intersection, it will update a beacon message to the cloud via the nearby RSU. This beacon message contains both the vehicle's traffic information (e.g., location, speed, destination) and the IDs of the RSUs located at the endpoints of the vehicle's current segment. Based on gathered vehicle information, the cloud can obtain a global view of the network. For data transmission between the start vehicle and the target vehicle, the start first sends the message towards the vehicle that is closer to the RSU_a in its moving direction. By receiving this message, the RSU_a will request the target's location and the optimal target RSU_b from the cloud to deliver the message. To figure out the optimal target RSU_b, the cloud firstly finds out the position of the target vehicle and the road it is traveling on. Then the RSUs (i.e., RSU_{b1} and RSU_{b2}) at the endpoints of the road can be found. The assumption routes from the RSU_a to the target via RSU_{b1} and RSU_{b2} are calculated separately. The corresponding expected transmission delay of the routes is evaluated based on transmission delay, propagation delay, queuing and processing delay, as well as the possible carrying delay. In terms of the delay, the optimal RSU_b can be chosen from the RSU_{b1} and RSU_{b2}. The message will be delivered to the RSU_b by internet equipment and be further transmitted to the target vehicle.

In addition to solving the data routing problem, VCC can also support the data dissemination process in VNETs. Information related to safety needs to be forwarded immediately to on-road vehicles. In [146], the authors presented the Cloud-assisted Message Downlink dissemination Scheme (CMDS) that can achieve rapid message dissemination in the VANET–Cellular heterogeneous network with assistance from the cloud. In CMDS, the authors assumed that the bus from the public transportation system could act as the mobile gateway for vehicles. It can access the heterogeneous network via the base station. Buses register themselves to the cloud and update traffic information (e.g., location, access delay, and bandwidth) to the cloud and their neighbor vehicles periodically. Two steps are contained in the CMDS: the gateways selection and the data dissemination. The segments intersecting with the accident segment are considered as the target area. After finding the target area, the cloud selects gateways for each segment in the target area based on the vehicle's condition, i.e., traffic distribution and transmission range of vehicles. Then selected gateways will receive the message from the cloud and broadcast it for vehicles.

Moreover, the security of data transmission in VNETs can be improved by using cloud computing technologies. A novel security MEC architecture is proposed in [235]. Blockchain and edge computing are adopted for secure transmission in VNETs. The blockchain is a considerable method to ensure security in networks because it can save data as a traceable chain via cryptography and hash functions. It also can keep data consistent with a consensus protocol. However, the local computation ability of vehicles cannot satisfy the required computation of blockchain technology. To solve this problem, edge computing is utilized. A three-layer architecture is designed in the article: the perception layer that contains vehicles and RSU for wallet and network routing, the edge computing layer for intensive computation, and the service layer that consists of the cloud server and blockchain for data storage.

Besides the centralized cloud services, a group of interconnected vehicles can also form a cloudlet to perform some computing tasks. The authors in [130] presented a protocol to ensure the security of sharable cloud communication. In this protocol, sharable clouds are in charge of the computing of transmission routes and intricate tasks for vehicles. To ensure the security for messages shared by clouds, Group Signature (GS) and Non-transitive Proxy Re-encryption (PRE) are used. Bilinear pairing is employed to achieve the GS scheme for group members. Non-transitive PRE allows the authorized object to decrypt the re-encrypted messages. The communication procedure can be concluded in the following phases: At the initialization phase, the cloud generates the keys and GS. Vehicles send requests to the cloud for registering as group members and obtaining a unique anonymous credential from the cloud. Before sending a message, the vehicle in the group will send an encrypted routing request to the traffic server for the optimal transmission route. The traffic server then verifies whether the requested vehicle is valid by its GS. If the vehicle is from a valid group, the traffic server calculates the route and encrypts the reply message for the requested vehicle. The message will be signed, encrypted by the sender, and re-encrypted by the cloud. The receiver can decrypt the message with the technologies mentioned above.

Table 2.8: Data transmission protocols in cloud computing-aassisted VNETs

Protocol	Access Method	Main Purpose	Used Method
RVCloud [26]	RSU	Decrease forwarding delay and link break	selecting the optimal destination RSU by cloud
CMDS [146]	mobile gateways	Achieve rapid data dissemination	Cloud selecting gateways by cloud
Zhang et al. [235]	RSU	Achieve security data transmission	Blockchain
Kanchan et al. [130]	Vehicles in same group	Security communication for sharable clouds	GS and PRE
Zhang et al. [231]	Adjacent vehicles form VC	Integrate vehicle resource and share information safely	Pseudonyms and DIBAAGKA

Furthermore, the [231] introduces a scheme designed as a secure and privacy-preserving way for Vehicular cloud (VC) establishment and communication. In this scheme, adjacent vehicles can form a VC to share resources anonymously and securely. The vehicles' pseudonyms are used as the public key and further generate the private key via a trusted institution. With the public and private key, dynamic identity based authenticated asymmetric group key agreement (DIBAAGKA) [232] are adopted for vehicles in a VC for sharing the data securely. Moreover, three data sharing modes are designed based on the distance from the user to VC: the internal usage mode is used by the user in VC, the close-in usage mode is for users around VC, and the remote usage mode responsible for remote users.

Discussion about cloud computing-assisted protocols

Cloud computing provides sufficient computing resources to support the data transmission process in VNETs. Various architectures have been designed to apply cloud computing in the VNET [13, 27, 191]. Cooperation among each part of the architecture is important. How to design an architecture that takes full use of the capability of infrastructure and vehicles is a considerable topic.

Besides the MCC and MEC, technologies such as fog computing can also implement distributed computation in the VNET. Fog computing has the capability to collect and process a mass of data in real-time. The protocol such as [194] introduced a cooperative method that utilized fog computing to process the big data of the internet. The author in [161] proposed a switchable approach to enhance the data transmission performance between vehicles in which fog nodes are in charge of local computing of the network. Also, the approach in [158] implemented traffic management in shot delay with the assistance of fog computing.

Meanwhile, various researches have been done to enhance fog computing performance in the VNET environment. For example, the authors in [234] presented a resource scheduler scheme to decrease the energy consumption of the fog center in an adaptive way. Also, in [123] the authors proposed an offloading scheme to decrease the energy consumption and delay for nodes in the vehicular fog computing environment. More improvement aspects can be considered in the future.

2.4 Summary

In the VNET, effective data transmission among vehicles faces a variety of challenges, e.g., instability topology, unevenly distributed forwarders, and limited bandwidth. To face this challenging condition, various routing protocols have been proposed. In this chapter, we briefly introduced the development of the data routing protocols in VNET by summarizing conventional data routing protocols and state-of-the-art approaches.

According to the protocols we introduced, traffic information such as traffic density and link condition of the system can affect the data delivery performance among vehicles. Because of the dual identities of the vehicle, a road segment with high traffic density may cause channel congestion while providing sufficient transmission resources. Finding the balance to use the traffic density in the data routing process is essential to enhance data delivery performance. Meanwhile, for more robust inter-vehicle communication, link condition between vehicles can be considered when selecting the next forwarder for a vehicle. Moreover, setting the backup solution to recover the transmission route is also significant in instability VNET.

On the other hand, with the development of communication technologies in VNETs, V2X communication can be implemented effectively, which provides opportunities to enhance data transmission performance among vehicles. Communication standard such as DSRC provides expense-free communication among vehicles, while communication via cellular networks (e.g., LTE and 5G) can achieve higher stability. However, due to the commercial nature of the cellular network, relying on it entirely to implement V2X communication will significantly increase the corresponding application cost. Meanwhile, due to the increasing amount of transmission data in VNET, the cellular network-based transmission will occupy the backbone resources to a large extent, which may further affect other cellular network applications. Researches about using different communication technologies concurrently in VNET are valuable to be done. Currently, heterogeneous vehicular networking such as LTE-VNET is presented for vehicles to realize V2X communication. For example, in [17], a multitier LTE-VNET architecture is proposed to combine the DSRC and the LTE. Also, a distributed clustering algorithm is adopted in [207] for the forwarder selection in LTE-VNET. Furthermore, the utilization of 5G technology in VNETs has obtained lots of attention recently. To merge the cellular networks with the conventional VNET, the authors in [214] presented an energy sensing-based spectrum sharing approach to support 5G users in accessing unlicensed channels.

Accordingly, we designed a novel traffic-aware data routing protocol that considered road traffic density and the link condition between vehicles in the VCN environment to enhance the performance of data transmission. Detailed work will be introduced as follows.

Chapter 3

CRTAR: A Novel Traffic Aware Data Routing Protocol

In this chapter, we propose a Cellular network-assisted Reliable TAR protocol (CRTAR) that takes advantage of the reliable feature of the cellular network to enhance the data routing performance for vehicles in the CVN environment. To implement the CVN environment, In CRTAR, we assume that a CCS supported by the remote data center of the traffic agency can provide city-wide real-time traffic information to vehicles. We utilize the cellular network to implement the V2I communication for exchanging the small size request message such as real-time traffic information and adopt DSRC to realize the V2V communication for transmitting the data packet (e.g., data from multimedia service [50, 183]) to reduce the dependency on backbone resources. Vehicles can request real-time traffic information, namely, the traffic density and data transmission density of the system, via the cellular system to obtain a global view for the data routing process with low latency. According to the real-time traffic information, a data transmitting route with relatively high transmission resources and low congestion can be calculated by the sender. Moreover, to further improve the reliability of the data delivery process, an improved greedy manner that considers the link condition among vehicles is employed to assist data transmitting along the calculated transmitting route. Furthermore, robust backup and recovery strategies are presented to reduce the effect of unexpected transmission failures. With the assistance of traffic information and recovery solutions, a stable and effective transmitting procedure can be achieved.

3.1 System Model and Assumptions

In this section, we introduce the communication structure by discussing the main components of our proposed system. To realize the aforementioned process in our proposed protocol, the cooperation of three participants components, i.e., cloud service provider, CVN system, and on-road vehicles, is essential. The function and corresponding assumptions are discussed in detail as follows.

Cloud Computing Service Provider

On the basis of the traffic monitor infrastructures (e.g., RSUs and Induction Loops), city-wide real-time traffic information can be collected by the traffic management agency. Meanwhile, according to the computing and storage capability of the cloud service, a large number of data can be managed well through the cloud service. Hence, we assume a CCS supported by the data center of the traffic management agency to realize the real-time traffic condition monitoring of the system and provide information to vehicles. The communication between the CCS and vehicles can be implemented via the communication architecture discussed in [68].

Network Model

Due to the highly-speed movement of vehicles, wireless communication technology such as DSRC may not provide a reliable connection to CCS in VNET [3]. On the contrary, cellular communication-based methods such as LTE can reliably connect with the devices in a large range area with low latency [115] to support the data delivery process. Nevertheless, the commercial feature of the cellular network may cause a high cost if users rely on it alone to transmit a large amount of data. However, due to the commercial characteristics of cellular networks, if users rely solely on cellular networks to transmit large amounts of data, high costs may be incurred. Moreover, the usage of the cellular network will occupy the backbone resources. Transmitting a mass of data via the cellular network will cause a high workload for the backbone network, which may further affect the performance of other applications that rely on the backbone network. Bsed on the reason above, the CVN environment is worthy of being considered.

The communication in the CVN environment we assumed can be illustrated by Figure 3.1. As mentioned before, we implement the V2I and V2V based on the cellular network and VNET separately in CVN. The base station of the cellular network can cover a large area and provide reliable communication with negligible latency, as shown by the blue circle and dotted arrow. And the black dotted arrow represents the V2V communication in vehicles' transmission range (the orange circle). Vehicles can request traffic information and target vehicle information from the CCS via the cellular network and then deliver the data packet by forwarders by V2V communication.

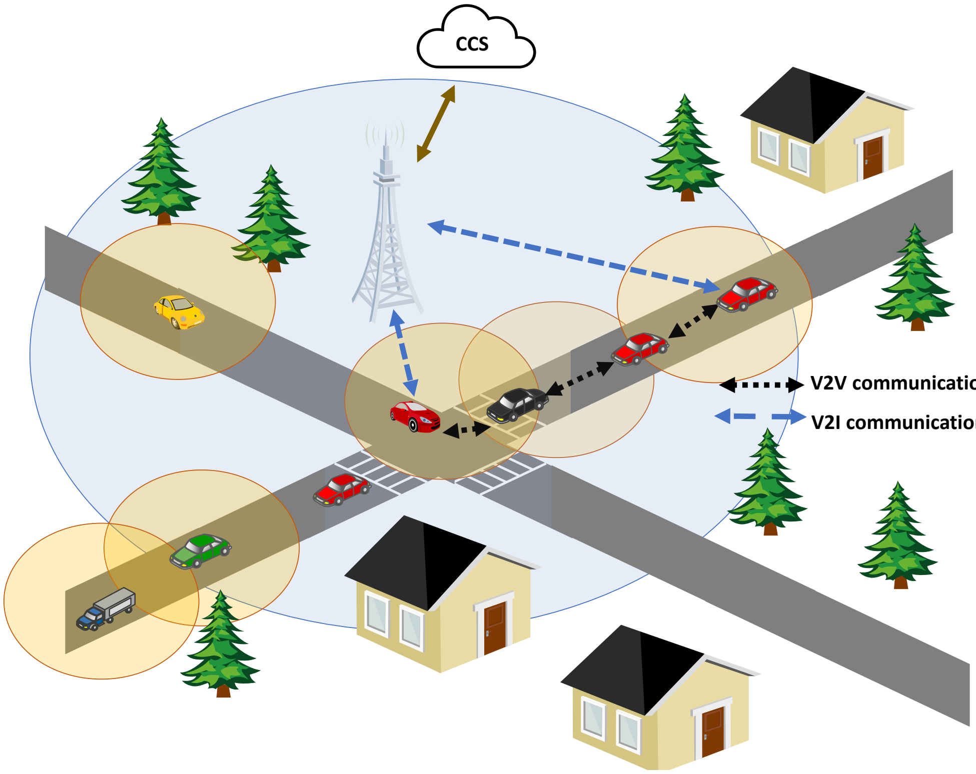


Figure 3.1: Communication in VCNs

On-road Vehicle

Based on the development of onboard hardware devices, on the opposite of the traditional sensor node that has limited capability [72, 151], the vehicle can obtain adequate capacity for computing and storing the data via its engine and onboard chipsets such as CPU and GPU. Meanwhile, unlike conventional wireless networks that utilize localization systems to collect geographical information [47, 57, 58, 60, 99, 162], we assume that all the on-road vehicles are equipped with a navigation system that can provide the city map and onboard sensors that can support self-positioning [7, 67]. Different from the conventional battery-powered mobile devices such as unmanned aerial vehicles and underwater sensors [35, 46, 55, 75, 86, 88, 90], on-road vehicles have sufficient energy for themselves and their onboard digital devices. Hence, in the proposed method, we exclude the energy constraint issue [34, 36,48,62,186,209,210,212] in conventional wireless networks. Moreover, we assume that on-road vehicles are equipped with multiple communication interfaces to access both cellular networks and VNETs.

3.2 Methodology

The methodology of the proposed CRTAR protocol is discussed as follows. The general procedure of CRTAR is firstly overviewed, and the detailed design of each part in the proposed method is introduced separately.

3.2.1 General Procedure of CRTAR Approach

In this section, we introduce the general procedure of our proposed method. According to Figure. 3.2, the general procedure is consists of two main parts. The flow on the right part illustrates the process of the optimal data forwarding route calculation and data forwarding, and the left part surrounded by a dotted line displays the recovery strategies we present for maintaining the data forwarding procedure. The main steps of the general procedure in CRTAR are explained in the following:

1. The calculation for the data forwarding route starts with the request message sent by the source vehicle. The source vehicle will request the optimal data forwarding route and the target's geographical information from the CCS.

2. After receiving the request message from the source vehicle, the CCS takes charge of calculating the optimal data forwarding route via our proposed method in a searching area.

3. The source vehicle then receives the optimal transmitting route and the geographical information of the target vehicle from CCS via the cellular network.

4. The source vehicle transmits data packets to the target vehicle along the received optimal route in an improved greedy forwarding manner.

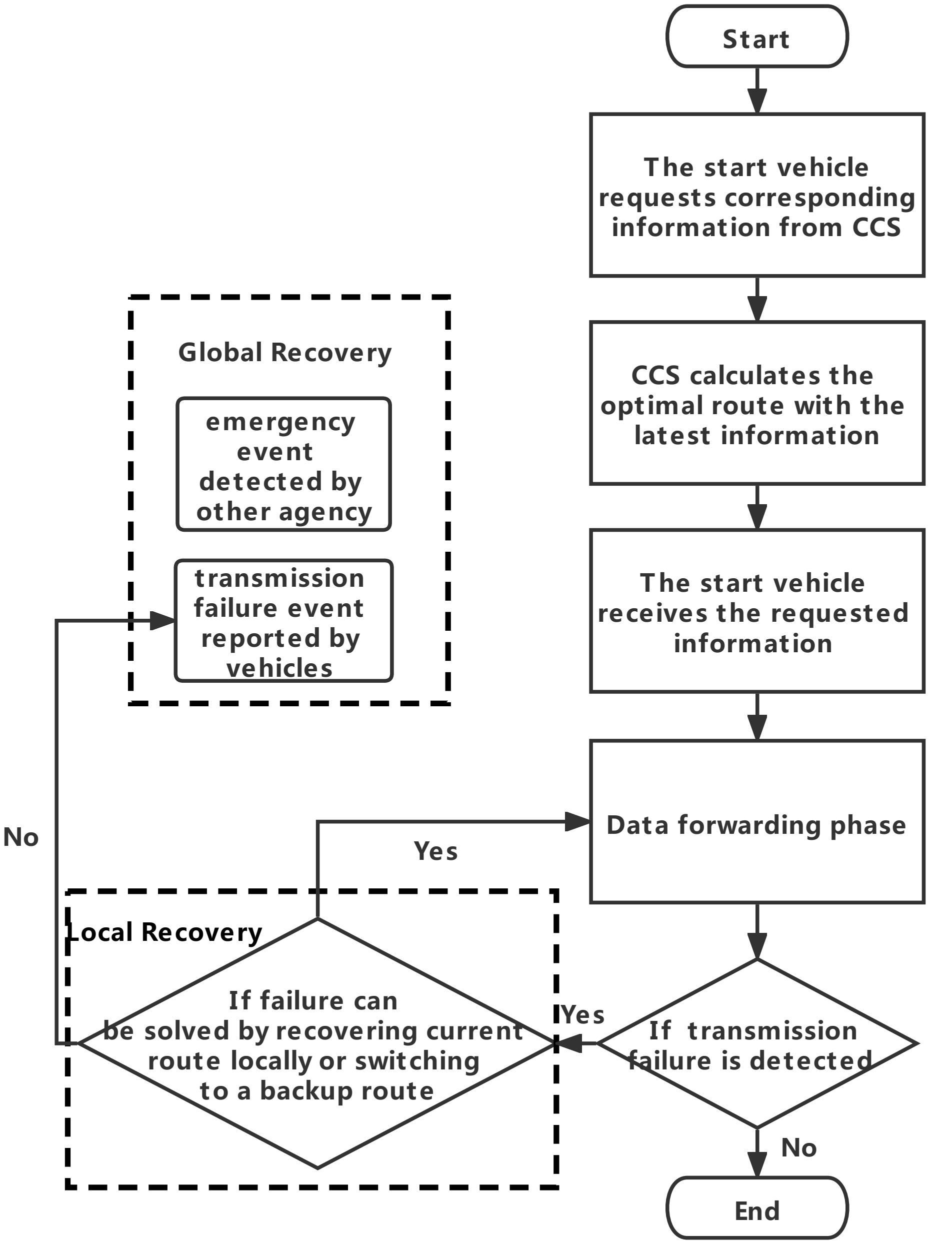


Figure 3.2: Overall transmission process

5. Moreover, to deal with potential communication failures and recover the transmission route timely, we designed two maintenance schemes for local recovery and global recovery. Briefly, the local recovery scheme is designed to solve transmission failures locally without sending a new request for CCS. The global recovery scheme is designed to overcome transmission failures by obtaining the recalculated transmission route from CCS.

In the rest parts of this section, the optimal data forwarding route derivation and the route maintenance schemes will be discussed in detail, respectively.

3.2.2 Route Calculation and Data Forwarding

In this part, we first introduce the communication procedure between the vehicle and the cellular network base station to expatiate how the source vehicle obtains the request information for CCS. Then, we discussed two main steps for forwarding data packets with the optimal route: the optimal forwarding route selection phase and the data forwarding phase. The optimal forwarding route selection phase can be achieved with two steps: information collection and the optimal data forwarding route derivation. Firstly, we will introduce the information collection procedure as follows.

Information Collection Procedure

We illustrate the information collection procedure in the system by Figure. 3.3. In the figure, the source vehicle can obtain the required information from CCS through the following steps:

1. The source vehicle sends a request message to CCS via the cellular network to acquire the optimal transmission route to the target vehicle and the geographic information of the target vehicle. Meanwhile, the source vehicle uploads its geographic information to CCS.
2. According to the target vehicle ID contained in the request message sent by the source vehicle, CCS sends a request message to the target vehicle through the cellular network to obtain the geographic information of the target vehicle.
3. After receiving the geographic information request message, the target vehicle uploads its geographical information to the CCS. Based on the geographical information

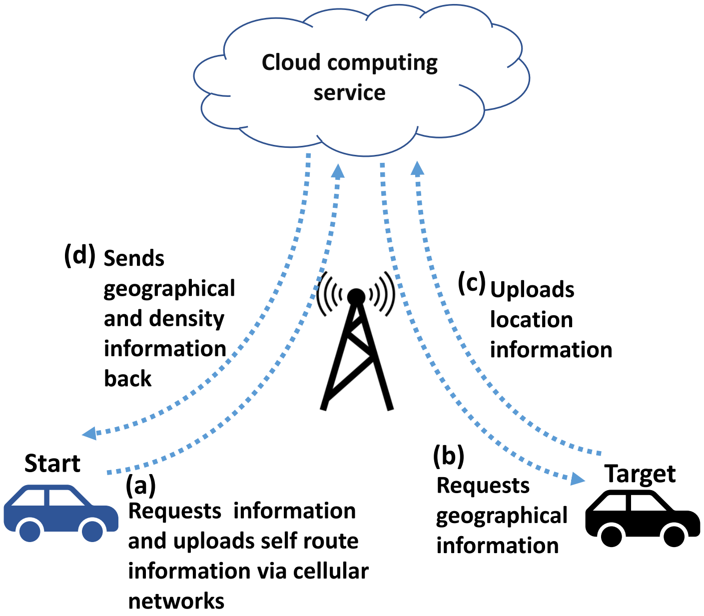


Figure 3.3: Information collection procedure

of the target vehicle and the source vehicle, CCS will collect the traffic condition information in a corresponding searching area and use it to calculate the optimal data forwarding route.

Figure. 3.4 illustrated the definition of the searching area in our method. According to the uploaded geographic information, i.e., the vehicle's location and driving direction, CCS can figure out which endpoint of the current road segment the vehicle will arrive at. This endpoint of the road is then considered to be the farthest point of the vehicle. This endpoint of the road is then considered to be the farthest point of the vehicle. The smallest rectangle area that can cover the farthest endpoints of the source vehicle and the target vehicle is regarded as the searching area, as the R1 and R2 area showed in Figure. 3.4.

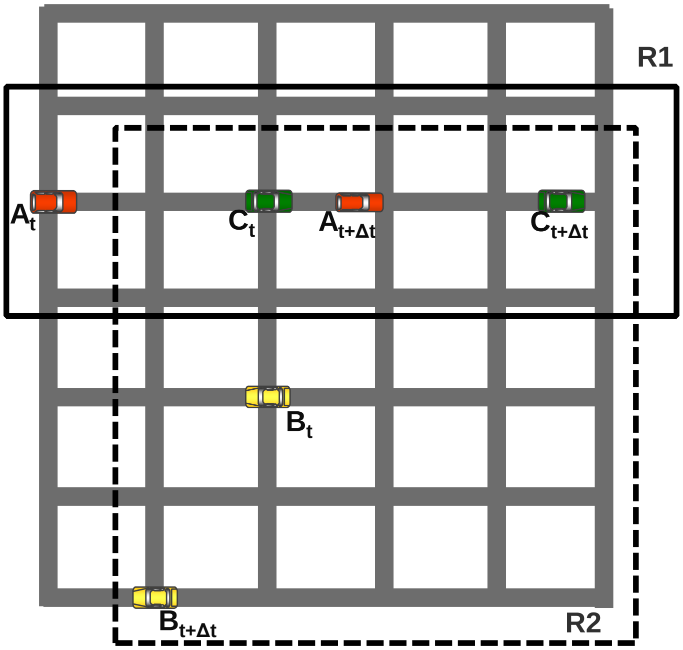


Figure 3.4: Definition of the searching region

4. After calculating the optimal data forwarding route, CCS sends the calculation result and target vehicle's information back to the source vehicle via the cellular network.

The Optimal Forwarding Route Selection Procedure

In this section, we will discuss the detailed optimal route selection procedure executed by the CCS. To figure out the optimal transmission route, two main factors are considered in this article, i.e., the road traffic density and the data transmission density.

The traffic density of the road segment indicates the number of available forwarders on

The traffic density of the road segment indicates the number of available forwarders on the road segment. In [202], the number of vehicles on the segment is used to evaluate the route connectivity for data delivery (i.e., the capability of a route to transmit the data packet successfully). Meanwhile, according to [201], the segment with higher traffic density can provide vehicles with more possible transmission resources to achieve relabel transmission. Choosing the segment with higher density has become one of the considerations during the optimal route selection process [10].

However, when the number of vehicles increases, data transmitting request increases simultaneously, which can cause the packets collision and decrease the packet delivery ratio [135]. Meanwhile, the vehicle on the higher traffic density segments can be overloaded and cause more transmission delay due to being selected to deliver data frequently [133]. To avoid potential channel congestion, protocols such as [173] prefer to choose the routing segment with low traffic density. Based on the analysis above, finding the balance between available transmission resources and on-road vehicle's workload is an essential issue that can affect the transmission performance of the vehicles. In our proposed method, we considered traffic density and data transmission density of the road segment by evaluating the weight of a road segment based on the aforementioned parameters. Based on the weight and the optimal route selection algorithm, a robust data forwarding route can be figured out.

To be specific, in the proposed method, the unique ID such as ID_i is assigned to the corresponding road segment i. Because we adopt an improved shortest path algorithm to calculate the optimal transmission route, the road with lower weight will be preferentially selected, we defined the weight of each road segment as shown in Eq. (3.1):

$$Weight = \alpha \frac{distance}{N_{vehicles}} + \beta \frac{N_{Selected}}{N_{vehicles}}, \tag{3.1}$$

where $N_{vehicles}$ represents the total number of vehicles on the segment. $N_{Selected}$ represents the number of times that a segment is selected as a component of the optimal path at the moment. α and β are algorithm parameters and $\alpha + \beta = 1$.

The parameter $\frac{N_{vehicles}}{distance}$ estimates the number of vehicles per meter of a segment, which can be considered as the traffic density of the road segment. By using the value of available transmission resources (i.e., the total number of vehicles) dividing the selected frequency of a road segment, i.e., the parameter $\frac{N_{vehicles}}{N_{Selected}}$, data transmission density of a road segment can be indicated. When the transmission resources on the road are fixed, the road being selected to transmit data more times will have a higher workload. Because the CCS is responsible for calculating the optimal route of vehicles, it can obtain information about the optimal route of all vehicles, which allows CCS to count how many times a certain road segment is selected to take charge of data delivery currently. With the defined weight above, the segments with relatively high traffic density and relatively low data transmission density can be represented.

To figure out a route consisting of relatively high weight as the optimal transmission route, an algorithm inspired by Dijkstra's algorithm is being adopted based on the weight we defined above to calculate the optimal route consisting of road segments.

The algorithm 3.1 is shown as follows. In the algorithm, all the routes with the optimal weight will be calculated without changing the time complexity of the algorithm. On the basis of Dijkstra's algorithm, the route with the lowest weight will be selected. If more than one route is figured out, one of them will be the optimal route, and the other routes will be the backup route. The utilization of the backup route will be further discussed in the route maintenance section.

With the proposed algorithm and defined weight, the route consist of the segments with relatively high traffic density and relatively low data transmission density can be found. As mentioned before, relatively high traffic density can support vehicles with higher transmission resources and then reveal higher connectivity capability to deliver the data packets. For example, if a 100 meters segment only has one vehicle on it, the transmission capability of the segment is limited. On the other hand, the lower data transmission rate can decrease the channel congestion probability during the packet delivery process. Moreover, by considering data transmission density, the transmission resource on each segment can be utilized more evenly. For instance, if a segment whose traffic density is equal to 0.5 but has been selected sixty times, though the traffic density is high, the actual transmission ability of this segment may be lower than the segment whose traffic density is 0.25 but has been selected once time.

Improved Greedy Manner

After the optimal data forwarding route selection, the calculated optimal route will be sent back to the source vehicle in a list form, i.e., the List of Forwarding Road (LFR). Based on the received LFR from CCS, the source vehicle will transmit the data packet that contains source id, destination id, LFR, and data along the optimal route. Hence, the derived optimal route can assist the source vehicle in establishing a reliable transmission link to the target vehicle in the appropriate forwarding direction via the constraint of the road segment. In addition to following the optimal data forwarding route, choosing appropriate forwarders is also important during the data transmission process.

According to [216], link lifetime between vehicles plays a significant role in achieving stable multi-hop data transmission. To increase the stability of the transmission link, we considered the link lifetime during the forwarder selection process. In CRTAR, we improved the greedy manner by a simple link lifetime evaluation method to establish the effective and stable transmission link between the source and the target for the packet delivery along with the selected optimal segments. Various methods are presented to evaluate the link lifetime between vehicles based on vehicles' location, speed, and direction [15, 144, 178]. According to the vehicle's moving direction, two main kinds of cases are considered in our

Algorithm 3.1 The Proposed Algorithm Inspired by Dijkstra's Algorithm

```
Input: Map and its corresponding weight in searching area.
Output: Result of the segments of the optimal route.
  distance[i]=The weight from the start node to i node
  $N_{min}$=The node with minimum distance
  visit[i] = If the node i is visited
  tab[i][j]=The weight from node i to node j
  Map[i][i+1] =A segment from node i to node i+1

  Initialize the Map[i][i+1] with defined weight
  visit[start] = true

  for each $i \in [0, n)$ do
       $min = INF$
      for each $j \in [1, n)$ do
          if $j$ is not visited && $distance[j] < min$ then
              $mindistance = distance[j]$
              $N_{min} = j$
          end if
       $visit[N_{min}] = true$
      end for
      for each $k \in [0, n)$ do
          if $k$ is not visited then
                if $distance[k] = distance[N_{min}] + tab[N_{min}][k]$ then
              Add $N_{min}$ to Prepoints[k]
                else
                    if $distance[k] > distance[N_{min}] + tab[N_{min}][k]$ then
              $distance[k] = distance[N_{min}] + tab[N_{min}][k]$
              $Prepoints[k].clear()$
              Add $N_{min}$ to Prepoints[k]
                    end if
                end if
          end if
      end for
  end for
```

method, i.e., the sender and target have the same direction, and the sender and target have the opposite direction. We consider the moving direction of vehicles but ignore the angle between two vehicles' velocities because the road width is limited. The equation for link lifetime calculation is shown as follows:

Let D represent the distance between vehicles, and R represents the transmission range of the vehicle. Four main cases can be introduced based on the driving direction and speed of the start vehicle and the target vehicle. Detailed discussion is shown as follows.

When the sender V_s and the receiver V_r have the same direction:

If the speed of V_s is slower than the V_r:

$$T_{sr} = \frac{R - D}{|S_s - S_r|} \tag{3.2}$$

else if V_s is faster than V_r:

$$T_{sr} = \frac{R + D}{|S_s - S_r|} \tag{3.3}$$

When V_s and V_r have the opposite direction:

If V_s and V_r are approaching each other:

$$T_{ij} = \frac{R + D}{|S_s + S_r|} \tag{3.4}$$

Else if V_s and V_r are leaving each other:

$$T_{ij} = \frac{R - D}{|S_s + S_r|} \tag{3.5}$$

In the article, we designed a forwarder selection mode to apply the link lifetime estimation to assist reliable forwarder selection. The performance of both modes will be evaluated and analyzed in the simulation experiments section. Design details are discussed as follows.

Neighbor list-assisted forwarder selection To find a reliable forwarder in the sender's one-hop neighbor range, we proposed a neighbor list-assisted forwarder selecting mode. In this mode, a vehicle can obtain its neighbors' location and speed information by exchanging

Hello packets with one-hop neighbors in the predefined interval. The content of the Hello packets is introduced as follows.

The ID is the identity of the current vehicle and is defined in the first field. The second field represents the vehicle's velocity when the data packet is generated. The third and fourth fields stand for the X, Y coordinate of the vehicle's location, respectively. With the assistance of the location, the distance between vehicles can be figured out. Based on received hello packets, a neighbor list that estimated the number of neighbors and stored neighbors' corresponding conditions could be created locally by each vehicle. If the neighbors' number is over 1, the link lifetime of each neighbor will be evaluated by the current sender, and the neighbor with the longest link lifetime will be chosen as the next forwarder. Otherwise, if the neighbors' number equals 1, the sender will forward packets without evaluating the link lifetime. Meanwhile, to prevent the repeated transmission of the same packet. The packet with the same ID will be discarded automatically.

3.2.3 Route Maintenance

In addition to the selecting process of the data forwarding route, the maintenance of the route is also significant. Unexpected link failures can be caused by various reasons in lower layers of the protocol stack during the communication process among vehicles. For instance, packet congestion may happen at the transport layer due to the limited buffer of the forwarders, the bit error occurs at the MAC layer during the transmission process, and channel congestion happens at the physical layer. To mitigate the effect of unexpected link failure and recover the transmission route effectively, we designed recovery strategies in the local and global range of the network. The general procedure of route recovery for on-road vehicles is shown in Figure. 3.5.

Local Recovery

The local recovery strategy allows the vehicle to recover unexpected transmission failure effectively without recalculating the whole transmission route, which also avoids the unnecessary information request process between the source vehicle and CCS. In this section, we introduce three local recovery strategies are designed for the start vehicle to deal with unexpected transmission failure without sending a request to CCS, i.e., switching the next forwarder, adopting the backup solution, and calculating the local recovery route.

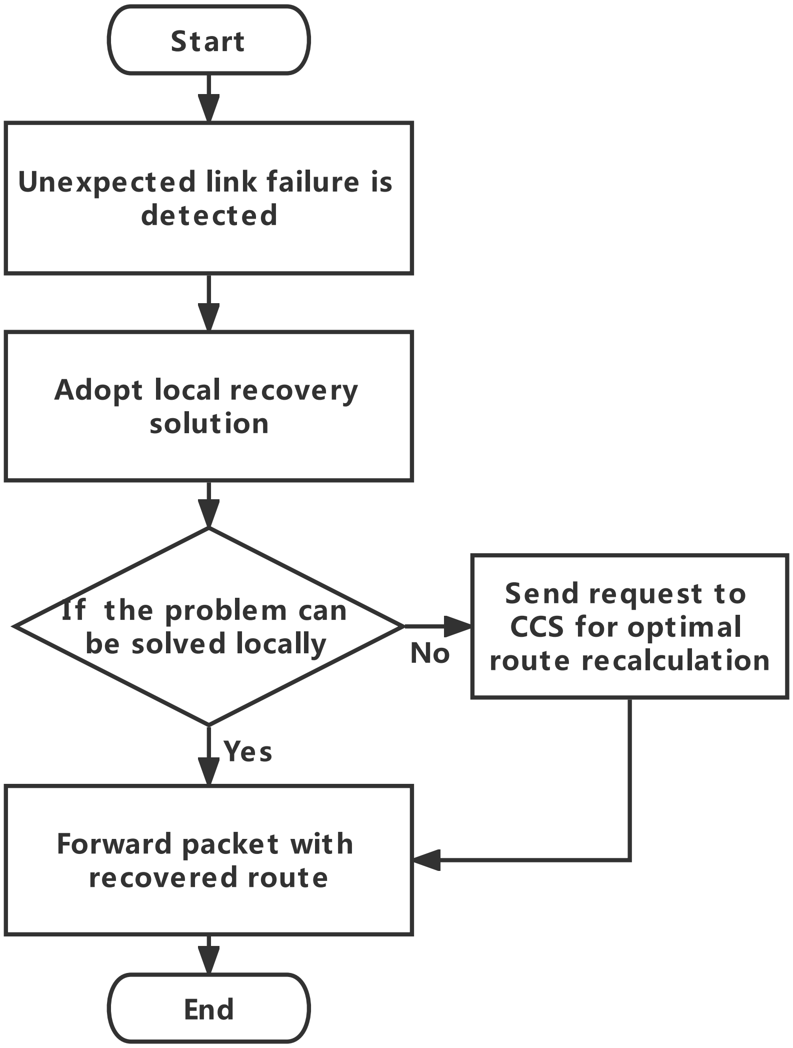


Figure 3.5: Recovery strategies for on-road vehicles

By Switching Next Forwarder For the vehicle that adopted neighbor list-assisted mode to select the forwarder, the neighbor list can assist the sender in switching the next forwarder to recover the route with unexpected link failures. If more than one neighbor exists in the neighbor list, the current sender can switch the next forwarder to the neighbor who has the second-longest link lifetime to fix the link break. If the new forwarder is unavailable, i.e., the neighbor list is empty or only has the ID of the failed forwarder, the backup solution will be adopted.

By Adopting the Backup Solution If the link failure can not be solved by choosing different forwarders, using different segments to transmit the packet can be considered. As we mentioned in the optimal route calculation section, if there is more than one optimal route, the route with the same weight will be saved locally as the alternate route. If the start vehicle detected the backup route exists locally when the link failure occurs, it would switch to the backup route for re-transmission. Also, because the backup routes are saved locally, route recalculating time can be avoided, and the link break can be fixed effectively. If the packet is failed to be delivered by all local routes, locally recalculation will be adopted.

By Calculating the Local Recovery Route To handle the potential transmission failure that cannot be solved by switching forwarder and using backup routes, the source vehicle will recalculate a suboptimal route to avoid the failed segment with local geographic information. We assume that on-road vehicles can obtain the topology of roads from the city map they saved locally. Meanwhile, benefitting from the piggyback technique adopted when delivering the data packet, the failed segment can be detected by the source vehicle. According to the failed segment location, the source vehicle utilizes the Dijkstra algorithm to calculate the shortest data forwarding route to avoid the problem road. The problem road segment and the road segments connected to endpoints of the problem road section will be set as the prohibited path during the calculation. The start vehicle then can obtain a connective alternative route consisting without the failed road segment to fix the unexpected transmitting link break.

If the source vehicle cannot successfully deliver the packet to the target vehicle with local recovery solutions, the start vehicle will send a request message to the CCS via the cellular network for optimal route recalculation with the latest global information. Meanwhile, when an emergency event such as a traffic accident is detected by vehicles, the vehicle will send a notification message to the CCS as the event report, which allows CCS to collect the failed roads information and broadcast it to other vehicles as the avoidance reminder.

Global Recovery

In addition to the local recovery strategy, the global recovery scheme is designed to recover unexpected transmission failures by recalculating the whole optimal route for vehicles. Global recovery will be triggered when CCS receives the emergency event report. The first kind of emergency event report is the traffic accident report from vehicles, and the second is the report from weather agency, e.g., short-term thunderstorm, tornado, and mudslide. Both the traffic accident and short-term natural disasters can cause the obstructed pathway and a dramatic traffic density changing within a certain geographic area, which further affects the connection of data transmission route for on-road vehicles. The response of CCS to global recovery is shown in Figure. 3.6.

Calculating the optimal road segments for vehicles based on real-time traffic condition information is necessary. The road segment reported by vehicles or other agencies will be marked at CCS in a specific period. In this period, the marked road will not be taken into account as a constituent part of the optimal segment routes for other vehicles.

To implement the global recovery and assist the vehicles in avoiding problem segment timely, we use the CCS to broadcast the updated traffic information, i.e., road density change message (RDCM) containing the ID of the road whose traffic density is changed, to vehicles in the corresponding cells after received emergency event report. In [18], the authors discussed the utilization of the LTE system in VNET. The authors indicated that using the cellular network to broadcast messages such as decentralized environmental notification messages (DENMs) for vehicles to avoid damage caused by emergency events that happen on the road can achieve a favorable performance. Taking the advantages of centralized architecture, the server of the cellular network, such as the LTE system, can filter repetitive report messages (i.e., messages about the same event on the same road segment) from vehicles [108]. Also, the wide range coverage of the cellular network revealed the relay vehicle selection problem in sparse vehicle areas. Based on the reason above, broadcasting via the cellular network is a reliable solution to dissemination DENMs [18]. The broadcasting process is shown in Figure. 3.7.

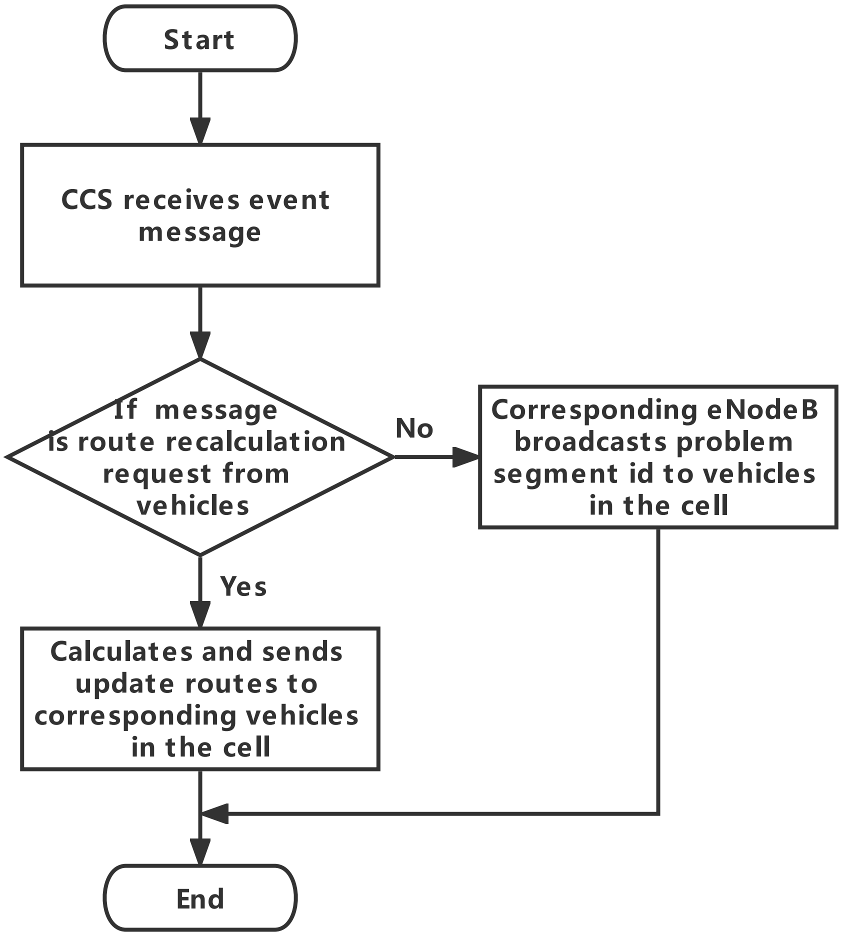


Figure 3.6: CCS response in global recovery strategy

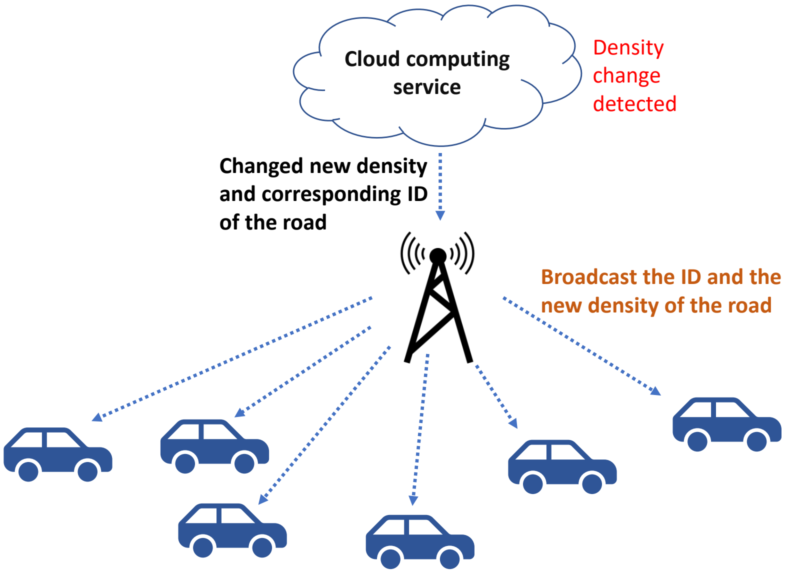


Figure 3.7: Broadcasting process of global recovery

Moreover, to prevent the duplicate message, event reports received by eNodeB from vehicles will be checked by the involved road ID at a certain time, i.e., 5 min. For the same road ID, only the first event report will be processed and responded to at 5-minutes intervals. With the check process, unnecessary broadcasting can be avoided for vehicles on the same road segment.

Chapter 4

Experimental Evaluation

4.1 Performance Evaluation

In this chapter, we evaluate the performance of the proposed CRTAR approach by conducting experiments via the NS-3 and SUMO simulator. Specifically, the NS-3 simulator is utilized to simulate the network environment and the data transmission protocol. The SUMO is in charge of generating the movement of the on-road vehicle and the traffic condition in the city. Moreover, we compare the performance of the CRTAR with existing proposed routing protocols, i.e., GPSR [132], Path Aware GPSR (PA-GPSR) [197], and Maxduration-Minangle GPSR (MM-GPSR) [219], in PDR and end-to-end delay aspects to indicate the efficiency and reliability of our approach. Different scenarios, i.e., the scenario with different traffic density, vehicle's speed, and map size, are adopted. Detailed setup of the experiments and parameters for each scenario are introduced in the following.

In our simulation, SUMO generated a grid-shaped map to simulate the road condition in the urban area. Each edge in the map represents a bidirectional road segment as shown in Figure. 4.1. Moreover, to introduce the traffic condition generated by sumo into the NS-3 simulator, the Traffic Control Interface (TraCI) is adopted to provide vehicles' mobility information for the internet.

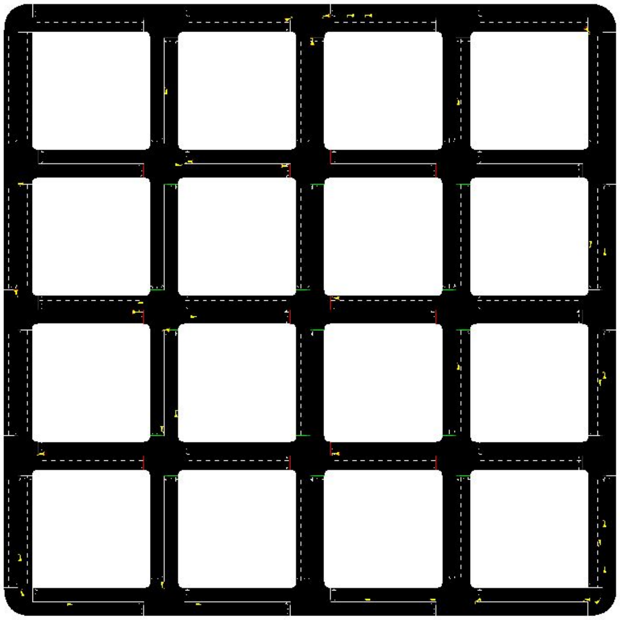


Figure 4.1: Bidirectional road grid-shaped map generated by SUMO

In terms of the setup of the internet aspect, we take the LTE communication as an example to represent the communication of the cellular network to simulate the heterogeneous communication environment of the VCN. Because the cellular network is used to transmit small size traffic information in the proposed protocol, we assume that the size of this traffic information is up to 500 Bytes.

4.1.1 Compare with GPSR

We first compare the performance of our protocol with a classic position-based routing protocol, the GPSR, in two aspects: PDR and the end-to-end delay. A nine-grid SUMO map is adopted to simulate two scenarios that considered effect factors, namely the traffic density and the vehicle's mobility.

Simulation for Scenarios With Different Traffic Density

In this section, we mainly focus on the effect of traffic density on our proposed method. We set different numbers of vehicles in scenarios to simulate different traffic density conditions.

We adopted similar communication range, number of nodes in [197] and [219]. The size of simulation area can be various based on different conditions [185, 197, 219]. In this part, we defined it as shown in Table 4.1. Meanwhile, to ensure simulation time is sufficient, we extend our simulation time to 500 seconds, which is longer than the 200 seconds mentioned in [197, 219].

Table 4.1: Simulation parameters in nine-grid SUMO map

Parameter	**Value**
Simulation Area	600m×600m
Number of Roads	24
Max Communication Range	250m
Simulation Duration	500s
Number of Vehicles	20−100

Figure. 4.2 shows the PDR with different vehicle numbers. The result shows that CRTAR has a higher PDR than GPSR. The success ratio of packets delivery is increased by considering the traffic density and recovery solutions for vehicles. When the number of vehicles is 80, the standard deviation of PDR in CRTAR and GPSR are 0.21 and 0.16. With road traffic density information, vehicles can decrease the possibility of lacking the next vehicle. With recovery solutions, vehicles can fix transmission failures effectively. Based on the advantages mentioned above, higher PDR can be achieved in our protocol.

Moreover, the comparison result of the average end-to-end delay is shown in Figure. 4.3. CRTAR can achieve a relatively lower delay than GPSR during the packet transmission. When the number of vehicles is 80, the standard deviation of the result in CRTAR and GPSR methods at end-to-end delay aspect are 42.26 and 80.67. With the assistance of global real-time traffic information, the start vehicle can deliver data packets by following a more effective transmission path and avoid the road segment prone to losing the packet. Also, robust backup and recovery strategies can mitigate the effect of unexpected link failure and decrease the recovering time for the forwarding route.

Simulation for Scenarios With Different Vehicle's Mobility

In this portion, the number of vehicles is fixed to be 60, and we apply different speeds to vehicles to study the effect of the vehicle's mobility for our proposed data routing protocol.

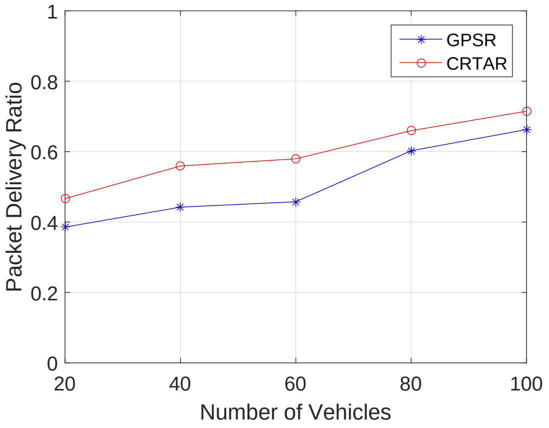


Figure 4.2: The comparisons of the delivery ratio

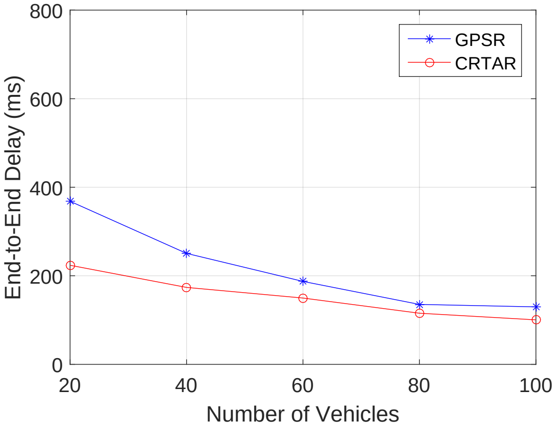


Figure 4.3: The comparisons of the end-to-end delay

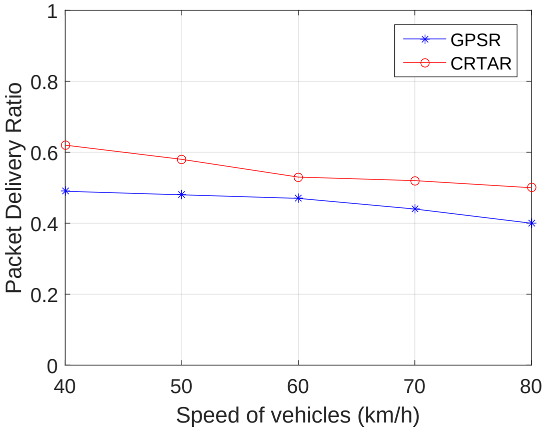


Figure 4.4: The comparisons of the packet delivery ratio

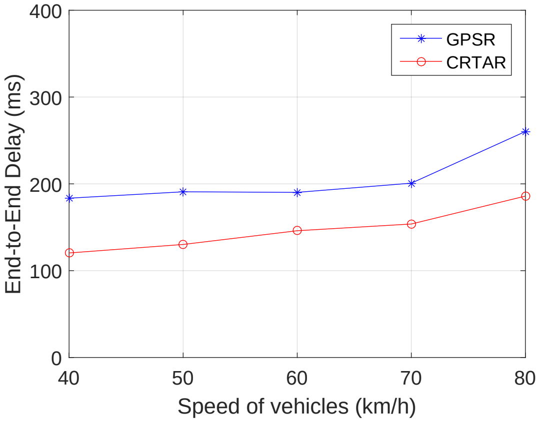


Figure 4.5: The comparisons of the end-to-end delay

As shown in Figure. 4.4, the PDR decreases as the speed of the vehicle increases. While CRTAR still keeps a higher PDR than the GPSR. When vehicle's speed achieves 60km/h, the value of PDR in CRTAR and GPSR is close, and the standard deviation of the result in CRTAR and GPSR methods are 0.15 and 0.13, respectively. Also, in terms of the average end-to-end delay aspect. The broken lines in Figure. 4.5 show that our proposed protocol has higher stability than the GPSR method and can keep lower delay during the vehicle's speed increase. Based on the broken line, the end-to-end delay and PDR of our method illustrate a relatively stable tendency, especially when the vehicle's speed achieves $70-80km/h$, which shows that our proposed protocol has higher stability with the effective information exchange mode and recovery solutions in high dynamic condition.

4.1.2 Compare with PA-GPSR and MM-GPSR

In this section, we will compare the performance of our protocol with PA-GPSR and MM-GPSR routing protocol. Vehicles in our simulation are moving randomly from the start edge to the end edge following the Manhattan mobility model [20]. We further assume that, when a vehicle moves at an intersection, the corresponding turning probability is 0.25 for left and right, respectively. Destinations to deliver the data packets are selected stochastically by the start vehicle. And the number to be chosen as the start vehicle is also randomly from 5 to the total number of vehicles.

In the following, we compare the performance of our protocol with PA-GPSR and MM-GPSR in two aspects: the packet drop ratio (PDR) and the end-to-end delay in scenarios with various traffic densities. We adopted same communication range in [197] and [219]. Also, considering the speed set in these two papers, the 15m/s, we set the max speed of vehicles as a similar value, namely, 50km/h. Moreover, to cover the number of nodes in these two papers, i.e., from 30 to 110, we extend the range of our test value to 20 to 150. Meanwhile, to ensure the simulation time is sufficient, compared to the 200 seconds in [197, 219], we set our simulation time as 500 seconds. Detailed parameters of the scenarios are shown in Table 4.2. Furthermore, we utilized another grid map that has different roads number and lengths to allow the data transmission performance to be evaluated in scenarios with distinct complexity. Corresponding parameters are shown in Table 4.3.

Table 4.2: Simulation parameters in five-line grid map

Parameter	**Value**
Simulation Area	500m×500m
Roads Number	40
Max Communication Range	250m
Simulation Duration	500s
Number of Vehicles	20−100
Vehicles' Max Speed	50km/h

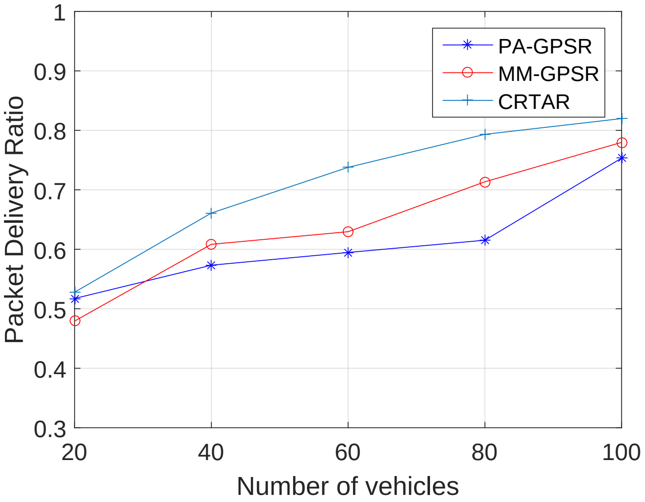


Figure 4.6: The comparisons of delivery ratio in five-line grid map

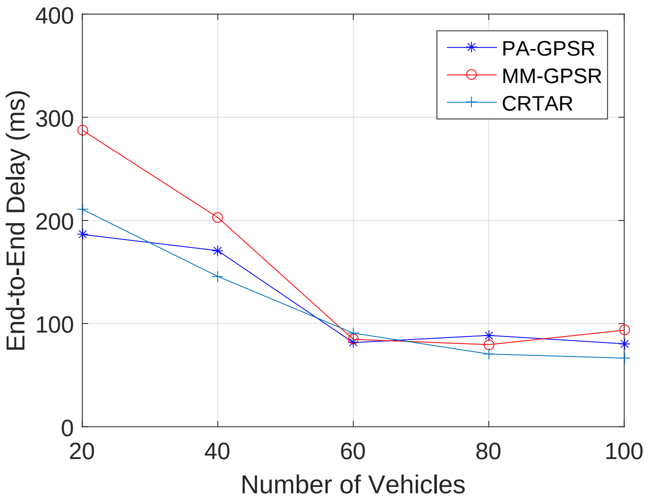


Figure 4.7: The comparisons of end-to-end delay in five-line grid map

Table 4.3: Simulation parameters in seven-line grid map

Parameter	**Value**
Simulation Area	900m×900m
Roads Number	84
Max Communication Range	250m
Simulation Duration	500s
Number of Vehicles	30−150
Vehicles' Max Speed	50km/h

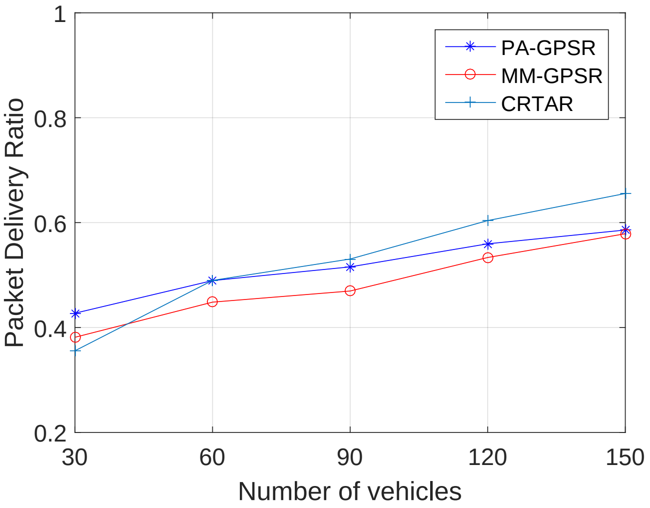


Figure 4.8: The comparisons of delivery ratio in seven-line grid map

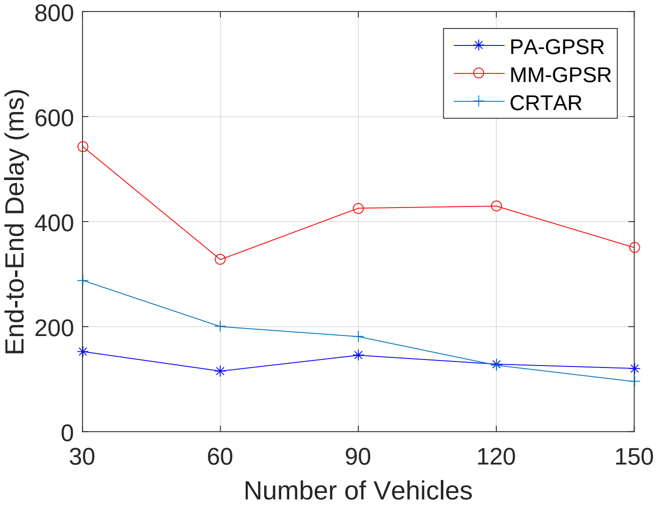


Figure 4.9: The comparisons of end-to-end Delay in seven-line grid map

In Fig. 4.6, with sufficient vehicles, CRTAR can achieve higher PDR than MM-GPSR and PA-GPSR. The success ratio of packets delivery is increased by considering the traffic information and recovery solutions for vehicles. Traffic information assists vehicles in decreasing the possibility of lacking the next vehicle, and recovery solutions allow vehicles to fix transmission failures effectively. While in Fig. 4.8, by applying a more complex scenario, i.e., the map with 84 road segments, the total number of vehicles cannot provide sufficient transmission resources for each road segment all the time. When the number of the vehicle is 30, PA-GPSR and MM-GPSR have better PDR than CRTAR. However, when the number of vehicles increased to 60, the PDR of CRTAR became similar to PA-GPSR. With the number of vehicles increasing, the transmission resource of each segment increased gradually, which further supports CRTAR achieving better performance than PA-GPSR and MM-GPSR.

The comparison result of the average end-to-end delay is shown in Fig. 4.7 and Fig. 4.9. When the transmission resource is not sufficient for each road segment, the end-to-end delay is relatively high in all methods. While with the increase of the number of vehicles, possible forwarders on each segment are increasing, which can benefit both the packet delivery and executing recovery solution in each method. As shown in Fig. 4.7, when the number achieves 60, the delay of all methods is suddenly decreased. CRTAR can achieve a relatively lower delay than PA-GPSR during the packet transmission in the case of 40 road segments and can achieve a lower delay than MM-GPSR in both 40 road segments and 84 road segments scenarios. Also, in the more intricate scenario, with the total number of vehicles increasing, CRTAR gradually shows a comparable trend to PA-GPSR. Meanwhile, compared to the MM-GPSR, the trend is flatter in our proposed protocol, especially in the scenario with 84 road segments. In Fig. 4.9, though the delay of MM-GPSR decreases sharply when the vehicle number is 60, it then shows an increasing tendency when the number of vehicles achieves 90. Hence the vehicle in the CRTAR method can achieve more stable transmission performance than the MM-GPSR by considering backup solutions. Moreover, the calculated Round Trip Time (RTT) of LTE may affect the latency to a small extent. However, based on the development of cellular network communication technologies, e.g., the appearance of 5G, lower V2I communication time can be achieved in the future.

Chapter 5

Conclusion and Future Work

5.1 Conclusion

Efficient and reliable information sharing between vehicles and other participants in the traffic system plays a crucial role in improving road safety. Achieving reliable V2X communication under the highly dynamic environment of VNETs becomes the focus of current research. To improve the reliability of V2V communication in the system, this thesis introduced a cellular network with low latency and high-reliability features to perform the task of real-time traffic information acquisition and help vehicles use the distribution information of traffic flow in the system to calculate the data route with the highest connectivity probability.

Technically, our approach takes full advantage of the respective strengths of the cellular network and DSRC-based VNETs. Specifically, the vehicle can obtain the optimal data forwarding route that is formulated based on system-wide traffic flow information, i.e., the traffic density and data transmission density of the road segment. It then delivers data packets following the derived data transmission routes via neighbor forwarders with relatively high link lifetimes. With the assistance of system-wide traffic flow information, a robust data forwarding route can be calculated. Meanwhile, utilizing the derived data transmission routes to transmit high-volume data via V2V communications allows vehicles to make use of the communication resources in VNETs, thus reducing the workload of the backbone network.

Furthermore, recovery solutions are designed to deal with unexpected transmission failures during the data transmission procedure. Local recovery strategies can assist the source vehicle in recovering the transmission link without sending a request to CCS for recalculating the forwarding route. Meanwhile, the global recovery strategy provides robust recovery capability for all transmission routes in the system. With the assistance of effective recovery solutions, the stability of the data transmission procedure can be further enhanced.

5.2 Future Work

This part discusses a few directions that can be applied to our approach to further enhance the data routing process in VNETs for a better data transmission performance.

5.2.1 Applying Prediction Approaches for Data Routing Process

Due to the highly dynamic characteristic of the VNET, vehicles' position and network topology change frequently. An accurate prediction of the vehicle's future state can assist the start vehicle in calculating the optimal data transmission route with a longer validity period, thereby reducing the overload caused by recalculation and frequent requests [115, 220, 228]. In our method, an accurate predicted location of the vehicle can enhance the optimal transmission route selection by providing a more accurate start point and endpoint of the route. Also, the predicted location can improve the evaluation of the link lifetime in our method to assist the vehicle in selecting a reliable next forwarder.

Moreover, with accurate prediction, transmission failures caused by routing based on expired information can also be decreased [156]. Applying prediction for the traffic flow information in our method can further improve the accuracy of the calculation for the optimal transmission route. For instance, with the currently emerging technology, machine learning, traffic congestion can be predicted by a machine learning-assisted traffic flow prediction method [101]. Our TAR method can be benefited from more accurate traffic information.

5.2.2 Considering Security Problems During System Design

To ensure a safety and privacy communication, security plays an important role in both wired [53] and wireless network [56, 64, 117]. Though a variety of protocols have been presented for secure data transmission in wireless networks [43–45, 51, 66, 182], the method designed for the data transmission process in vehicular networks still has large room to explore. In our method, we use the CCS to assist vehicles in calculating the optimal forwarding route. Safe communication between the CCS and vehicles plays an essential role for the vehicle to gather the forwarding route information. To build a secure communication method for vehicles accessing the CCS, cloud computing can be adopted. For example, a cloud-assisted certification structure was proposed in [177] for vehicle authentication. Moreover, in [184], an access control system was designed on the basis of the Ciphertext Policy Attribute-Based Encryption (CP-ABE) to ensure messages are transmitted safely among the vehicles and the cloud.

Furthermore, the trustworthiness of neighbors is significant [52, 65, 76, 181] for data transmission in wireless networks. The sender needs to consider the trustworthiness of the next forwarder in the transmission process. In our method, we estimate the link lifetime based on the messages collected from neighbors. If an untrustworthy vehicle with a fake high ability is selected to forward the packet, the delivery process may fail. To figure out trustworthy forwarders, various methods have been proposed. For example, authors in [229] achieve trust management in the network by utilizing deep reinforcement learning for the SDN controller to evaluate the neighbors' behavior during the packet transmitting process. Also, in [208], a similarity-based routing algorithm has been presented to estimate the trust value of forwarders. To select a stable and reliable next forwarders in our method, trustworthiness is worth to be calculated.

References

[1] Driss Abada, Abdellah Massaq, Abdellah Boulouz, et al. An adaptive vehicular relay and gateway selection scheme for connecting vanets to internet via 4g lte cellular network. In *International Conference of Computer Science and Renewable Energies*, pages 1–8, 2019.

[2] Muhammad Tahir Abbas, Afaq Muhammad, and Wang-Cheol Song. Sd-iov: Sdn enabled routing for internet of vehicles in road-aware approach. *Journal of Ambient Intelligence and Humanized Computing*, 11(3):1265–1280, 2020.

[3] Khadige Abboud, Hassan Aboubakr Omar, and Weihua Zhuang. Interworking of dsrc and cellular network technologies for v2x communications: A survey. *IEEE transactions on vehicular technology*, 65(12):9457–9470, 2016.

[4] Islam Tharwat Abdel-Halim and Hossam Mahmoud Ahmed Fahmy. Prediction-based protocols for vehicular ad hoc networks: Survey and taxonomy. *Computer Networks*, 130:34–50, 2018.

[5] Anishka Abraham and Rani Koshy. A survey on vanets routing protocols in urban scenarios. In *Second International Conference on Networks and Advances in Computational Technologies*, pages 217–229, 2021.

[6] Kaouther Abrougui, Azzedine Boukerche, and Richard Werner Nelem Pazzi. Design and evaluation of context-aware and location-based service discovery protocols for vehicular networks. *IEEE Transactions on Intelligent Transportation Systems*, 12(3):717–735, 2011.

[7] Osama Abumansoor and Azzedine Boukerche. A secure cooperative approach for nonline-of-sight location verification in vanet. *IEEE Transactions on Vehicular Technology*, 61(1):275–285, 2011.

[8] SA Ade and PA Tijare. Performance comparison of aodv, dsdv, olsr and dsr routing protocols in mobile ad hoc networks. *International Journal of Information Technology and Knowledge Management*, 2(2):545–548, 2010.

[9] Sabbagh Amani Ahmad and Maxim Shcherbakov. A survey on routing protocols in vehicular ad hoc networks. In *9th International Conference on Information, Intelligence, Systems and Applications*, pages 1–8, 2018.

[10] Abdelmuttlib Ibrahim Abdalla Ahmed, Abdullah Gani, Siti Hafizah Ab Hamid, et al. Intersection-based distance and traffic-aware routing (idtar) protocol for smart vehicular communication. In *13th International Wireless Communications and Mobile Computing Conference*, pages 489–493, 2017.

[11] Ejaz Ahmed and Hamid Gharavi. Cooperative vehicular networking: A survey. *IEEE Transactions on Intelligent Transportation Systems*, 19(3):996–1014, 2018.

[12] Fatima Ezzahra Airod, Houda Chafnaji, and Ahmed Tamtaoui. Green full-duplex relay selection algorithm for decode and forward relaying. In *International Conference on Electrical and Information Technologies*, pages 343–348, 2016.

[13] Ahmed Aliyu, Abdul Hanan Abdullah, Omprakash Kaiwartya, et al. Cloud computing in vanets: architecture, taxonomy, and challenges. *IETE Technical Review*, 35(5):523–547, 2018.

[14] Nizar Alsharif, Khalid Aldubaikhy, and Xuemin Sherman Shen. Link duration estimation using neural networks based mobility prediction in vehicular networks. In *IEEE Canadian Conference on Electrical and Computer Engineering*, pages 1–4, 2016.

[15] Nizar Alsharif and Xuemin Shen. i car-ii: Infrastructure-based connectivity aware routing in vehicular networks. *IEEE Transactions on Vehicular Technology*, 66(5):4231–4244, 2016.

[16] Marwa Altayeb and Imad Mahgoub. A survey of vehicular ad hoc networks routing protocols. *International Journal of Innovation and Applied Studies*, 3(3):829–846, 2013.

[17] S Ansari, Tuleen Boutaleb, Sinan Sinanovic, et al. Mhav: multitier heterogeneous adaptive vehicular network with lte and dsrc. *ICT Express*, 3(4):199–203, 2017.

[18] Giuseppe Araniti, Claudia Campolo, Massimo Condoluci, et al. Lte for vehicular networking: a survey. *IEEE communications magazine*, 51(5):148–157, 2013.

[19] Azlan Awang, Khaleel Husain, Nidal Kamel, et al. Routing in vehicular ad-hoc networks: A survey on single-and cross-layer design techniques, and perspectives. *IEEE Access*, 5:9497–9517, 2017.

[20] F. Bai, Narayanan Sadagopan, and A. Helmy. Important: a framework to systematically analyze the impact of mobility on performance of routing protocols for adhoc networks. In *Twenty-second Annual Joint Conference of the IEEE Computer and Communications Societies*, volume 2, pages 825–835, 2003.

[21] Raghad Baiad, Omar Alhussein, Hadi Otrok, and Sami Muhaidat. Novel cross layer detection schemes to detect blackhole attack against qos-olsr protocol in vanet. *Vehicular Communications*, 5:9–17, 2016.

[22] Athanasios Bamis, Azzedine Boukerche, Ioannis Chatzigiannakis, et al. A mobility aware protocol synthesis for efficient routing in ad hoc mobile networks. *Computer Networks*, 52(1):130–154, 2008.

[23] Rodolfo Bezerra Batista, Azzedine Boukerche, and Alba Cristina Magalhaes Alves de Melo. A parallel strategy for biological sequence alignment in restricted memory space. *Journal of Parallel and Distributed Computing*, 68(4):548–561, 2008.

[24] Amina Bengag and Mohamed El Boukhari. Classification and comparison of routing protocols in vanets. In *International Conference on Intelligent Systems and Computer Vision*, pages 1–8, 2018.

[25] Jitendra Bhatia, Yash Modi, Sudeep Tanwar, et al. Software defined vehicular networks: A comprehensive review. *International Journal of Communication Systems*, 32(12):e4005, 2019.

[26] Sourav Kumar Bhoi and Pabitra Mohan Khilar. Rvcloud: a routing protocol for vehicular ad hoc network in city environment using cloud computing. *Wireless Networks*, 22(4):1329–1341, 2016.

[27] Salim Bitam, Abdelhamid Mellouk, and Sherali Zeadally. Vanet-cloud: a generic cloud computing model for vehicular ad hoc networks. *IEEE Wireless Communications*, 22(1):96–102, 2015.

[28] Flavio Bonomi, Rodolfo Milito, Jiang Zhu, et al. Fog computing and its role in the internet of things. In *Proceedings of the first edition of the MCC workshop on Mobile cloud computing*, pages 13–16, 2012.

[29] Azzedine Boukerche. Performance comparison and analysis of ad hoc routing algorithms. In *Conference Proceedings of the 2001 IEEE International Performance, Computing, and Communications Conference*, pages 171–178, 2001.

[30] Azzedine Boukerche. A simulation based study of on-demand routing protocols for ad hoc wireless networks. In *Proceedings. 34th Annual Simulation Symposium*, pages 85–92, 2001.

[31] Azzedine Boukerche. Performance evaluation of routing protocols for ad hoc wireless networks. *Mobile networks and applications*, 9(4):333–342, 2004.

[32] Azzedine Boukerche. *Handbook of algorithms for wireless networking and mobile computing*. CRC Press, 2005.

[33] Azzedine Boukerche. *Algorithms and protocols for wireless and mobile ad hoc networks*. John Wiley & Sons, 2008.

[34] Azzedine Boukerche, Ioannis Chatzigiannakis, and Sotiris Nikoletseas. A new energy efficient and fault-tolerant protocol for data propagation in smart dust networks using varying transmission range. *Computer communications*, 29(4):477–489, 2006.

[35] Azzedine Boukerche, Xiuzhen Cheng, and Joseph Linus. Energy-aware data-centric routing in microsensor networks. In *Proceedings of the 6th ACM international workshop on Modeling analysis and simulation of wireless and mobile systems*, pages 42–49, 2003.

[36] Azzedine Boukerche, Xuzhen Cheng, and Joseph Linus. A performance evaluation of a novel energy-aware data-centric routing algorithm in wireless sensor networks. *Wireless Networks*, 11(5):619–635, 2005.

[37] Azzedine Boukerche and Amir Darehshoorzadeh. Opportunistic routing in wireless networks: Models, algorithms, and classifications. *ACM Computing Surveys (CSUR)*, 47(2):1–36, 2014.

[38] Azzedine Boukerche and Sajal K Das. Dynamic load balancing strategies for conservative parallel simulations. In *Proceedings 11th Workshop on Parallel and Distributed Simulation*, pages 20–28, 1997.

[39] Azzedine Boukerche, Sajal K Das, and Alessandro Fabbri. Analysis of a randomized congestion control scheme with dsdv routing in ad hoc wireless networks. *Journal of Parallel and Distributed Computing*, 61(7):967–995, 2001.

[40] Azzedine Boukerche, Sajal K Das, and Alessandro Fabbri. Swimnet: a scalable parallel simulation testbed for wireless and mobile networks. *Wireless Networks*, 7(5):467–486, 2001.

[41] Azzedine Boukerche, Sajal K Das, Alessandro Fabbri, and Oktay Yildiz. Exploiting model independence for parallel pcs network simulation. In *Proceedings Thirteenth Workshop on Parallel and Distributed Simulation. PADS 99.(Cat. No. PR00155)*, pages 166–173, 1999.

[42] Azzedine Boukerche and Caron Dzermajko. Performance evaluation of data distribution management strategies. *Concurrency and Computation: Practice and Experience*, 16(15):1545–1573, 2004.

[43] Azzedine Boukerche, Khalil El-Khatib, Li Xu, et al. A novel solution for achieving anonymity in wireless ad hoc networks. In *Proceedings of the 1st ACM international workshop on Performance evaluation of wireless ad hoc, sensor, and ubiquitous networks*, pages 30–38, 2004.

[44] Azzedine Boukerche, Khalil El-Khatib, Li Xu, et al. Sdar: a secure distributed anonymous routing protocol for wireless and mobile ad hoc networks. In *29th Annual IEEE International Conference on Local Computer Networks*, pages 618–624, 2004.

[45] Azzedine Boukerche, Khalil El-Khatib, Li Xu, et al. An efficient secure distributed anonymous routing protocol for mobile and wireless ad hoc networks. *computer communications*, 28(10):1193–1203, 2005.

[46] Azzedine Boukerche and Xin Fei. A coverage-preserving scheme for wireless sensor network with irregular sensing range. *Ad hoc networks*, 5(8):1303–1316, 2007.

[47] Azzedine Boukerche and Xin Fei. A voronoi approach for coverage protocols in wireless sensor networks. In *IEEE GLOBECOM 2007-IEEE Global Telecommunications Conference*, pages 5190–5194, 2007.

[48] Azzedine Boukerche, Xin Fei, and Regina B Araujo. An optimal coverage-preserving scheme for wireless sensor networks based on local information exchange. *Computer Communications*, 30(14-15):2708–2720, 2007.

[49] Azzedine Boukerche, Sungbum Hong, and Tom Jacob. A distributed algorithm for dynamic channel allocation. *Mobile Networks and Applications*, 7(2):115–126, 2002.

[50] Azzedine Boukerche, Sungbum Hong, and Tom Jacob. An efficient synchronization scheme of multimedia streams in wireless and mobile systems. *IEEE transactions on Parallel and Distributed Systems*, 13(9):911–923, 2002.

[51] Azzedine Boukerche, Kathia Regina Lemos Jucá, Joao Bosco Sobral, et al. An artificial immune based intrusion detection model for computer and telecommunication systems. *Parallel Computing*, 30(5-6):629–646, 2004.

[52] Azzedine Boukerche and Xu Li. An agent-based trust and reputation management scheme for wireless sensor networks. In *GLOBECOM'05. IEEE Global Telecommunications Conference, 2005.*, volume 3, pages 5–pp, 2005.

[53] Azzedine Boukerche, Renato B Machado, Kathia RL Jucá, et al. An agent based and biological inspired real-time intrusion detection and security model for computer network operations. *Computer Communications*, 30(13):2649–2660, 2007.

[54] Azzedine Boukerche, Anahit Martirosyan, and Richard Pazzi. An inter-cluster communication based energy aware and fault tolerant protocol for wireless sensor networks. *Mobile Networks and Applications*, 13(6):614–626, 2008.

[55] Azzedine Boukerche and Sotiris Nikoletseas. Protocols for data propagation in wireless sensor networks. In *Wireless communications systems and networks*, pages 23–51. Springer, 2004.

[56] Azzedine Boukerche and Mirela Sechi M Annoni Notare. Behavior-based intrusion detection in mobile phone systems. *Journal of Parallel and Distributed Computing*, 62(9):1476–1490, 2002.

[57] Azzedine Boukerche, Horacio ABF Oliveira, Eduardo F Nakamura, et al. Localization systems for wireless sensor networks. *IEEE wireless Communications*, 14(6):6–12, 2007.

[58] Azzedine Boukerche, Horacio ABF Oliveira, Eduardo F Nakamura, et al. Secure localization algorithms for wireless sensor networks. *IEEE Communications Magazine*, 46(4):96–101, 2008.

[59] Azzedine Boukerche, Horacio ABF Oliveira, Eduardo F Nakamura, et al. Vehicular ad hoc networks: A new challenge for localization-based systems. *Computer communications*, 31(12):2838–2849, 2008.

[60] Azzedine Boukerche, Horacio ABF Oliveira, Eduardo Freire Nakamura, et al. Dv-loc: a scalable localization protocol using voronoi diagrams for wireless sensor networks. *IEEE Wireless Communications*, 16(2):50–55, 2009.

[61] Azzedine Boukerche, Richard Werner Nelem Pazzi, and Regina B Araujo. Hpeq a hierarchical periodic, event-driven and query-based wireless sensor network protocol. In *The IEEE Conference on Local Computer Networks 30th Anniversary (LCN'05) l*, pages 560–567, 2005.

[62] Azzedine Boukerche, Richard Werner Nelem Pazzi, and Regina Borges Araujo. A fast and reliable protocol for wireless sensor networks in critical conditions monitoring applications. In *Proceedings of the 7th ACM international symposium on Modeling, analysis and simulation of wireless and mobile systems*, pages 157–164, 2004.

[63] Azzedine Boukerche, Richard Werner Nelem Pazzi, and Regina Borges Araujo. Fault-tolerant wireless sensor network routing protocols for the supervision of context-aware physical environments. *Journal of Parallel and Distributed Computing*, 66(4):586–599, 2006.

[64] Azzedine Boukerche and Yonglin Ren. A security management scheme using a novel computational reputation model for wireless and mobile ad hoc networks. In *Proceedings of the 5th ACM symposium on Performance evaluation of wireless ad hoc, sensor, and ubiquitous networks*, pages 88–95, 2008.

[65] Azzedine Boukerche and Yonglin Ren. A trust-based security system for ubiquitous and pervasive computing environments. *Computer communications*, 31(18):4343–4351, 2008.

[66] Azzedine Boukerche and Yonglin Ren. A secure mobile healthcare system using trust-based multicast scheme. *IEEE Journal on Selected Areas in Communications*, 27(4):387–399, 2009.

[67] Azzedine Boukerche, Cristiano Rezende, and Richard W Pazzi. Improving neighbor localization in vehicular ad hoc networks to avoid overhead from periodic messages. In *GLOBECOM 2009-2009 IEEE Global Telecommunications Conference*, pages 1–6, 2009.

[68] Azzedine Boukerche and E Robson. Vehicular cloud computing: Architectures, applications, and mobility. *Computer networks*, 135:171–189, 2018.

[69] Azzedine Boukerche and Steve Rogers. Performance of gzrp ad hoc routing protocol. *Journal of Interconnection Networks*, 2(01):31–48, 2001.

[70] Azzedine Boukerche and Amber Roy. Dynamic grid-based approach to data distribution management. *Journal of Parallel and Distributed Computing*, 62(3):366–392, 2002.

[71] Azzedine Boukerche, Amber Roy, and Neville Thomas. Dynamic grid-based multicast group assignment in data distribution management. In *Proceedings Fourth IEEE International Workshop on Distributed Simulation and Real-Time Applications (DS-RT 2000)*, pages 47–54, 2000.

[72] Azzedine Boukerche and Samer Samarah. A novel algorithm for mining association rules in wireless ad hoc sensor networks. *IEEE Transactions on Parallel and Distributed Systems*, 19(7):865–877, 2008.

[73] Azzedine Boukerche and Carl Tropper. A static partitioning and mapping algorithm for conservative parallel simulations. *ACM SIGSIM Simulation Digest*, 24(1):164–172, 1994.

[74] Azzedine Boukerche and Carl Tropper. A distributed graph algorithm for the detection of local cycles and knots. *IEEE Transactions on Parallel and Distributed Systems*, 9(8):748–757, 1998.

[75] Azzedine Boukerche, Begumhan Turgut, Nevin Aydin, et al. Routing protocols in ad hoc networks: A survey. *Computer networks*, 55(13):3032–3080, 2011.

[76] Azzedine Boukerche, Li Xu, and Khalil El-Khatib. Trust-based security for wireless ad hoc and sensor networks. *Computer Communications*, 30(11-12):2413–2427, 2007.

[77] Azzedine Boukerche, Lining Zheng, and Omar Alfandi. Outlier detection: Methods, models, and classification. *ACM Computing Surveys (CSUR)*, 53(3):1–37, 2020.

[78] Souaad Boussoufa-Lahlah, Fouzi Semchedine, and Louiza Bouallouche-Medjkoune. Geographic routing protocols for vehicular ad hoc networks (vanets): A survey. *Vehicular Communications*, 11:20–31, 2018.

[79] Jin Cao, Maode Ma, Hui Li, et al. A survey on security aspects for lte and lte-a networks. *IEEE communications surveys & tutorials*, 16(1):283–302, 2013.

[80] Manisha Chahal, Sandeep Harit, Krishn K Mishra, et al. A survey on software-defined networking in vehicular ad hoc networks: Challenges, applications and use cases. *Sustainable cities and society*, 35:830–840, 2017.

[81] Chen Chen, Hongyu Xiang, Tie Qiu, et al. A rear-end collision prediction scheme based on deep learning in the internet of vehicles. *Journal of Parallel and Distributed Computing*, 117:192–204, 2018.

[82] Chunhsiang Cheng, Ralph Riley, Srikanta PR Kumar, et al. A loop-free extended bellman-ford routing protocol without bouncing effect. *ACM SIGCOMM Computer Communication Review*, 19(4):224–236, 1989.

[83] Pei-Chun Cheng, Kevin C Lee, Mario Gerla, et al. Geodtn+ nav: Geographic dtn routing with navigator prediction for urban vehicular environments. *Mobile Networks and Applications*, 15(1):61–82, 2010.

[84] Thomas Clausen, Philippe Jacquet, Cédric Adjih, et al. Optimized link state routing protocol (olsr). 2003.

[85] Sergio Correia, Azzedine Boukerche, and Rodolfo I Meneguette. An architecture for hierarchical software-defined vehicular networks. *IEEE Communications Magazine*, 55(7):80–86, 2017.

[86] Rodolfo WL Coutinho, Azzedine Boukerche, Luiz FM Vieira, et al. Gedar: Geographic and opportunistic routing protocol with depth adjustment for mobile underwater sensor networks. In *IEEE International Conference on communications*, pages 251–256, 2014.

[87] Rodolfo WL Coutinho, Azzedine Boukerche, Luiz FM Vieira, et al. Geographic and opportunistic routing for underwater sensor networks. *IEEE Transactions on Computers*, 65(2):548–561, 2015.

[88] Rodolfo WL Coutinho, Azzedine Boukerche, Luiz FM Vieira, et al. A novel void node recovery paradigm for long-term underwater sensor networks. *Ad Hoc Networks*, 34:144–156, 2015.

[89] Rodolfo WL Coutinho, Azzedine Boukerche, Luiz FM Vieira, et al. Design guidelines for opportunistic routing in underwater networks. *IEEE Communications Magazine*, 54(2):40–48, 2016.

[90] Rodolfo WL Coutinho, Azzedine Boukerche, Luiz FM Vieira, et al. Underwater wireless sensor networks: A new challenge for topology control–based systems. *ACM Computing Surveys (CSUR)*, 51(1):1–36, 2018.

[91] Felipe Cunha, Leandro Villas, Azzedine Boukerche, et al. Data communication in vanets: Protocols, applications and challenges. *Ad Hoc Networks*, 44:90–103, 2016.

[92] Felipe Domingos Da Cunha, Azzedine Boukerche, Leandro Villas, et al. *Data communication in VANETs: a survey, challenges and applications*. PhD thesis, INRIA Saclay; INRIA, 2014.

[93] Amir Darehshoorzadeh and Azzedine Boukerche. Underwater sensor networks: A new challenge for opportunistic routing protocols. *IEEE Communications Magazine*, 53(11):98–107, 2015.

[94] Tasneem Darwish and K Abu Bakar. Traffic density estimation in vehicular ad hoc networks: A review. *Ad Hoc Networks*, 24:337–351, 2015.

[95] Tasneem Darwish and Kamalrulnizam Abu Bakar. Lightweight intersection-based traffic aware routing in urban vehicular networks. *Computer Communications*, 87:60–75, 2016.

[96] Tasneem Darwish and Kamalrulnizam Abu Bakar. Traffic aware routing in vehicular ad hoc networks: characteristics and challenges. *Telecommunication systems*, 61(3):489–513, 2016.

[97] Tasneem SJ Darwish, Kamalrulnizam Abu Bakar, and Khalid Haseeb. Reliable intersection-based traffic aware routing protocol for urban areas vehicular ad hoc networks. *IEEE Intelligent Transportation Systems Magazine*, 10(1):60–73, 2018.

[98] Robson E De Grande and Azzedine Boukerche. Dynamic balancing of communication and computation load for hla-based simulations on large-scale distributed systems. *Journal of Parallel and Distributed Computing*, 71(1):40–52, 2011.

[99] Horacio Antonio Braga Fernandes De Oliveira, Azzedine Boukerche, Eduardo Freire Nakamura, et al. An efficient directed localization recursion protocol for wireless sensor networks. *IEEE Transactions on Computers*, 58(5):677–691, 2008.

[100] Anil D Devangavi and Rajendra Gupta. Routing protocols in vanet—a survey. In *International Conference on Smart Technologies for Smart Nation*, pages 163–167, 2017.

[101] Suguna Devi and T Neetha. Machine learning based traffic congestion prediction in a iot based smart city. *International Research Journal of Engineering and Technology*, 4:3442–3445, 2017.

[102] Baihong Dong, Weigang Wu, Zhiwei Yang, et al. Software defined networking based on-demand routing protocol in vehicle ad hoc networks. In *12th International Conference on Mobile Ad-Hoc and Sensor Networks*, pages 207–213, 2016.

[103] Changqing Dong, Kaixin Yang, Jinwei Guo, , et al. Analysis and control of intelligent traffic signal system based on adaptive fuzzy neural network. In *5th International Conference on Transportation Information and Safety*, pages 1352–1357, 2019.

[104] Xiaoyu Duan, Yanan Liu, and Xianbin Wang. Sdn enabled 5g-vanet: Adaptive vehicle clustering and beamformed transmission for aggregated traffic. *IEEE Communications Magazine*, 55(7):120–127, 2017.

[105] Mourad Elhadef, Azzedine Boukerche, and Hisham Elkadiki. Diagnosing mobile ad-hoc networks: two distributed comparison-based self-diagnosis protocols. In *Proceedings of the 4th ACM international workshop on Mobility management and wireless access*, pages 18–27, 2006.

[106] Mourad Elhadef, Azzedine Boukerche, and Hisham Elkadiki. Performance analysis of a distributed comparison-based self-diagnosis protocol for wireless ad-hoc networks. In *Proceedings of the 9th ACM international symposium on Modeling analysis and simulation of wireless and mobile systems*, pages 165–172, 2006.

[107] Mourad Elhadef, Azzedine Boukerche, and Hisham Elkadiki. A distributed fault identification protocol for wireless and mobile ad hoc networks. *Journal of parallel and distributed computing*, 68(3):321–335, 2008.

[108] ETSI. Framework for public mobile networks in cooperative its (c-its). Technical report, European Telecommunications Standards Institute, 2012.

[109] Yoav Freund and Robert E Schapire. A decision-theoretic generalization of on-line learning and an application to boosting. *Journal of Computer and System Sciences*, 55(1):119–139, 1997.

[110] Sosina Gashaw and Jérôme Härri. V2x data dissemination delay for vehicular traffic density estimations. In *IEEE 16th International Symposium on A World of Wireless, Mobile and Multimedia Networks*, pages 1–6, 2015.

[111] Vinay Gautam. Analysis and application of vehicular ad hoc network as intelligent transportation system. In *Mobile Radio Communications and 5G Networks*, pages 1–17. Springer, 2021.

[112] Mahadev A Gawas and Sweta Govekar. State-of-art and open issues of cross-layer design and qos routing in internet of vehicles. *Wireless Personal Communications*, 116(3):2261–2297, 2021.

[113] Mahadev A Gawas and Sweta S Govekar. A novel selective cross layer based routing scheme using aco method for vehicular networks. *Journal of Network and Computer Applications*, 143:34–46, 2019.

[114] Baraq Ghaleb, Ahmed Y Al-Dubai, Elias Ekonomou, et al. A survey of limitations and enhancements of the ipv6 routing protocol for low-power and lossy networks: A focus on core operations. *IEEE Communications Surveys & Tutorials*, 21(2):1607–1635, 2018.

[115] Marco Giordani, Andrea Zanella, and Michele Zorzi. Lte and millimeter waves for v2i communications: An end-to-end performance comparison. In *IEEE 89th Vehicular Technology Conference*, pages 1–7, 2019.

[116] Forough Goudarzi, Hamid Asgari, and Hamed S Al-Raweshidy. Traffic-aware vanet routing for city environments—a protocol based on ant colony optimization. *IEEE Systems Journal*, 13(1):571–581, 2018.

[117] Hadi Habibzadeh, Tolga Soyata, Burak Kantarci, Azzedine Boukerche, and Cem Kaptan. Sensing, communication and security planes: A new challenge for a smart city system design. *Computer Networks*, 144:163–200, 2018.

[118] Takashi Hamma, Takashi Katoh, Bhed Bahadur Bista, et al. An efficient zhls routing protocol for mobile ad hoc networks. In *17th International Workshop on Database and Expert Systems Applications*, pages 66–70, 2006.

[119] Toshiyuki Haramaki, Akihito Yatsuda, and Hiroaki Nishino. A robot assistant in an edge-computing-based safe driving support system. In *International Conference on Network-Based Information Systems*, pages 144–155, 2018.

[120] Monowar Hasan, Sibin Mohan, Takayuki Shimizu, et al. Securing vehicle-to-everything (v2x) communication platforms. *IEEE Transactions on Intelligent Vehicles*, 5(4):693–713, 2020.

[121] Ahmed Nazar Hassan, Omprakash Kaiwartya, Abdul Hanan Abdullah, et al. Inter vehicle distance based connectivity aware routing in vehicular adhoc networks. *Wireless Personal Communications*, 98(1):33–54, 2018.

[122] Monson H Hayes. *Statistical digital signal processing and modeling.* John Wiley & Sons, 2009.

[123] Muzakkir Hussain, Mohammad Saad Alam, MM Sufyan Beg, et al. Towards minimizing delay and energy consumption in vehicular fog computing (vfc). *Journal of Intelligent & Fuzzy Systems*, 38(5):6549–6560, 2020.

[124] Ahmed Hussein, Fernando García, José María Armingol, et al. P2v and v2p communication for pedestrian warning on the basis of autonomous vehicles. In *IEEE 19th International Conference on Intelligent Transportation Systems*, pages 2034–2039, 2016.

[125] Baofeng Ji, Yanan Wang, Kang Song, et al. A survey of computational intelligence for 6g: Key technologies, applications and trends. *IEEE Transactions on Industrial Informatics*, 17(10):7145–7154, 2021.

[126] Xiang Ji, HuiQun Yu, GuiSheng Fan, et al. Sdgr: An sdn-based geographic routing protocol for vanet. In *IEEE International Conference on Internet of Things*, pages 276–281, 2016.

[127] Dongyao Jia and Dong Ngoduy. Enhanced cooperative car-following traffic model with the combination of v2v and v2i communication. *Transportation Research Part B: Methodological*, 90:172–191, 2016.

[128] Mario Joa-Ng and I-Tai Lu. A peer-to-peer zone-based two-level link state routing for mobile ad hoc networks. *IEEE Journal on Selected Areas in Communications*, 17(8):1415–1425, 1999.

[129] David B Johnson, David A Maltz, Josh Broch, et al. Dsr: The dynamic source routing protocol for multi-hop wireless ad hoc networks. *Ad Hoc Networking*, 5(1):139–172, 2001.

[130] Sneha Kanchan, Garima Singh, and Narendra S Chaudhari. Re-encrypting secure and efficient routing in vanet groups using sharable clouds. In *4th International Conference on Recent Advances in Information Technology*, pages 1–6, 2018.

[131] Muhammet Ali Karabulut, AFM Shahen Shah, and Haci Ilhan. Cr-mac: Cooperative relaying mac protocol for vanets. In *Scientific Meeting on Electrical-Electronics & Biomedical Engineering and Computer Science*, pages 1–4, 2019.

[132] Brad Karp and Hsiang-Tsung Kung. Gpsr: Greedy perimeter stateless routing for wireless networks. In *Proceedings of the 6th annual International Conference on Mobile Computing and Networking*, pages 243–254, 2000.

[133] Saifullah Khan, Muhammad Alam, Martin Fränzle, et al. A traffic aware segment-based routing protocol for vanets in urban scenarios. *Computers & Electrical Engineering*, 68:447–462, 2018.

[134] Sahil Khatri, Hrishikesh Vachhani, Shalin Shah, et al. Machine learning models and techniques for vanet based traffic management: Implementation issues and challenges. *Peer-to-Peer Networking and Applications*, 14(3):1778–1805, 2021.

[135] Golnar Khomami, Prakash Veeraraghavan, and F Fontan. Node density estimation in vanets using received signal power. *Radio Engineering*, 24(2):489–498, 2015.

[136] Apostolos Kousaridas, Mikael Fallgren, Edwin Fischer, et al. 5g vehicle-to-everything services in cross-border environments: Standardization and challenges. *IEEE Communications Standards Magazine*, 5(1):22–30, 2021.

[137] Mithun Kumar, Ajay Kumar Nigam, and T Sivakumar. A survey on topology and position based routing protocols in vehicular ad hoc network (vanet). *International Journal on Future Revolution in Computer Science & Communication Engineering*, 4(2):432–440, 2018.

[138] Mohammed Laroui, Akrem Sellami, Boubakr Nour, et al. Driving path stability in vanets. In *IEEE Global Communications Conference*, pages 1–6, 2018.

[139] Kevin C Lee, Uichin Lee, and Mario Gerla. To-go: Topology-assist geo-opportunistic routing in urban vehicular grids. In *Sixth International Conference on Wireless On-Demand Network Systems and Services*, pages 11–18, 2009.

[140] Kevin C Lee, Uichin Lee, and Mario Gerla. Survey of routing protocols in vehicular ad hoc networks. In *Advances in Vehicular Ad-hoc Networks: Developments and Challenges*, pages 149–170. IGI global, 2010.

[141] Tang Lei, Zhu Cai, and Luo Hua. 5g-oriented iot coverage enhancement and physical education resource management. *Microprocessors and Microsystems*, 80:103346, 2021.

[142] Ilias Leontiadis and Cecilia Mascolo. Geopps: Geographical opportunistic routing for vehicular networks. In *IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks*, pages 1–6, 2007.

[143] Yujin Li, Ming Zhao, and Wenye Wang. Internode mobility correlation for group detection and analysis in vanets. *IEEE transactions on vehicular technology*, 62(9):4590–4601, 2013.

[144] Zhiyuan Li, Yue Song, and Junlei Bi. Cadd: connectivity-aware data dissemination using node forwarding capability estimation in partially connected vanets. *Wireless Networks*, 25(1):379–398, 2019.

[145] Bruno A Lima, Carlos HOO Quevedo, Humberto P Marques, et al. Improving the communication of heterogeneous vehicular networks through clusterization. In *IEEE Symposium on Computers and Communications*, pages 590–595, 2018.

[146] Bingyi Liu, Dongyao Jia, Jianping Wang, et al. Cloud-assisted safety message dissemination in vanet–cellular heterogeneous wireless network. *IEEE Systems Journal*, 11(1):128–139, 2015.

[147] Lei Liu, Chen Chen, Zhiyuan Ren, et al. A connectivity aware transmission quality guaranteed geographic routing in urban internet of vehicles. In *IEEE International Conference on Communications*, pages 1–6, 2018.

[148] Xing Liu, Kun Hua, Zheyi Chen, et al. An efficient cross-layer approach for throughput-maximal and delay-minimal green vehicular networks. In *International Conference on Computing, Networking and Communications*, pages 652–658, 2018.

[149] Christian Lochert, Hannes Hartenstein, Jing Tian, et al. A routing strategy for vehicular ad hoc networks in city environments. In *IEEE IV2003 Intelligent Vehicles Symposium. Proceedings (Cat. No. 03TH8683)*, pages 156–161, 2003.

[150] Christian Lochert, Martin Mauve, Holger Füßler, et al. Geographic routing in city scenarios. *ACM SIGMOBILE Mobile Computing and Communications Review*, 9(1):69–72, 2005.

[151] Anahit Martirosyan, Azzedine Boukerche, and Richard Pazzi. A taxonomy of cluster-based routing protocols for wireless sensor networks. In *2008 International Symposium on Parallel Architectures, Algorithms, and Networks (i-span 2008)*, pages 247–253, 2008.

[152] Belghachi Mohammed and Debab Naouel. An efficient greedy traffic aware routing scheme for internet of vehicles. *Computers, Materials & Continua*, 60(3):959–972, 2019.

[153] Abdallah Moubayed, Abdallah Shami, Parisa Heidari, , et al. Edge-enabled v2x service placement for intelligent transportation systems. *IEEE Transactions on Mobile Computing*, 20(4):1380–1392, 2020.

[154] Boubakeur Moussaoui, Soufiene Djahel, Mohamed Smati, et al. A cross layer approach for efficient multimedia data dissemination in vanets. *Vehicular Communications*, 9:127–134, 2017.

[155] Kulit Na Nakorn and Kultida Rojviboonchai. Poca: position-aware reliable broadcasting in vanet. In *2nd Asia-Pacific Conference of Information Processing*, pages 17–18, 2010.

[156] M Naresh, Aayushi Raje, and Karanam Varsha. Link prediction algorithm for efficient routing in vanets. In *3rd International Conference on Computing Methodologies and Communication*, pages 1156–1161, 2019.

[157] Ba Cao Nguyen, Tran Manh Hoang, et al. Performance analysis of vehicle-to-vehicle communication with full-duplex amplify-and-forward relay over double-rayleigh fading channels. *Vehicular Communications*, 19:100166, 2019.

[158] Zhaolong Ning, Jun Huang, and Xiaojie Wang. Vehicular fog computing: Enabling real-time traffic management for smart cities. *IEEE Wireless Communications*, 26(1):87–93, 2019.

[159] Lionel Nkenyereye, Lewis Nkenyereye, SM Islam, et al. Software-defined network-based vehicular networks: A position paper on their modeling and implementation. *Sensors*, 19(17):3788, 2019.

[160] Naserali Noorani and Seyed Amin Hosseini Seno. Routing in vanets based on intersection using sdn and fog computing. In *8th International Conference on Computer and Knowledge Engineering*, pages 339–344, 2018.

[161] Naserali Noorani and Seyed Amin Hosseini Seno. Sdn-and fog computing-based switchable routing using path stability estimation for vehicular ad hoc networks. *Peer-to-Peer Networking and Applications*, pages 1–17, 2020.

[162] Horacio ABF Oliveira, Azzedine Boukerche, Eduardo F Nakamura, et al. Localization in time and space for wireless sensor networks: An efficient and lightweight algorithm. *Performance Evaluation*, 66(3-5):209–222, 2009.

[163] Renê Oliveira, Carlos Montez, Azzedine Boukerche, et al. Reliable data dissemination protocol for vanet traffic safety applications. *Ad Hoc Networks*, 63:30–44, 2017.

[164] Omar Sami Oubbati, Mohammed Atiquzzaman, Pascal Lorenz, et al. Search: An sdn-enabled approach for vehicle path-planning. *IEEE Transactions on Vehicular Technology*, 69(12):14523–14536, 2020.

[165] Vincent Douglas Park and M Scott Corson. A highly adaptive distributed routing algorithm for mobile wireless networks. In *Proceedings of International Conference on Computer Communications'97*, volume 3, pages 1405–1413, 1997.

[166] Richard W Pazzi and Azzedine Boukerche. Propane: A progressive panorama streaming protocol to support interactive 3d virtual environment exploration on graphics-constrained devices. *ACM Transactions on Multimedia Computing, Communications, and Applications (TOMM)*, 11(1):1–22, 2014.

[167] Richard WN Pazzi and Azzedine Boukerche. Mobile data collector strategy for delay-sensitive applications over wireless sensor networks. *Computer Communications*, 31(5):1028–1039, 2008.

[168] Guangyu Pei, Mario Gerla, and Tsu-Wei Chen. Fisheye state routing: A routing scheme for ad hoc wireless networks. In *IEEE International Conference on Communications*, volume 1, pages 70–74, 2000.

[169] Zhe Peng, Shang Gao, Zecheng Li, et al. Vehicle safety improvement through deep learning and mobile sensing. *IEEE network*, 32(4):28–33, 2018.

[170] Charles E Perkins and Pravin Bhagwat. Highly dynamic destination-sequenced distance-vector routing (dsdv) for mobile computers. *ACM SIGCOMM Computer Communication Review*, 24(4):234–244, 1994.

[171] Charles E Perkins and Elizabeth M Royer. Ad-hoc on-demand distance vector routing. In *Second IEEE Workshop on Mobile Computing Systems and Applications*, pages 90–100, 1999.

[172] Kashif Naseer Qureshi and Hanan Abdullah. Topology based routing protocols for vanet and their comparison with manet. *Journal of Theoretical and Applied Information Technology*, 58(3):707–715, 2013.

[173] Kashif Naseer Qureshi, Fasial Bashir, and Abdul Hanan Abdullah. Real time traffic density aware road based forwarding method for vehicular ad hoc networks. In *10th IFIP Wireless and Mobile Networking Conference*, pages 1–6, 2017.

[174] Khaled Rabieh, Mohamed MEA Mahmoud, Terry N Guo, et al. Cross-layer scheme for detecting large-scale colluding sybil attack in vanets. In *IEEE International Conference on Communications*, pages 7298–7303, 2015.

[175] Saeideh Rahimi and Mohammad Ali Jabraeil Jamali. A hybrid geographic-dtn routing protocol based on fuzzy logic in vehicular ad hoc networks. *Peer-to-Peer Networking and Applications*, 12(1):88–101, 2019.

[176] Khadija Raissi and Bechir Ben Gouissem. Lte scheduler algorithms for vanet traffic in smart city. *International Journal of Computer Networks & Communications*, 12(1), 2020.

[177] Ubaidullah Rajput, Fizza Abbas, Jian Wang, , et al. Cacppa: A cloud-assisted conditional privacy preserving authentication protocol for vanet. In *16th IEEE/ACM International Symposium on Cluster, Cloud and Grid Computing*, pages 434–442, 2016.

[178] Sunder Aditya Rao, Manohara Pai, Mounir Boussedjra, et al. Gpsr-l: Greedy perimeter stateless routing with lifetime for vanets. In *8th International Conference on ITS Telecommunications*, pages 299–304, 2008.

[179] Sami Abduljabbar Rashid, Mustafa Maad Hamdi, Sameer Alani, et al. An overview on quality of service and data dissemination in vanets. In *International Congress on Human-Computer Interaction, Optimization and Robotic Applications*, pages 1–5, 2020.

[180] KH Rashmi and Rekha Patil. Survey on cross layer approach for robust communication in vanet. *Wireless Personal Communications*, pages 1–22, 2021.

[181] Yonglin Ren and Azzedine Boukerche. Modeling and managing the trust for wireless and mobile ad hoc networks. In *2008 IEEE International Conference on Communications*, pages 2129–2133, 2008.

[182] Yonglin Ren, Richard Werner, Nelem Pazzi, et al. Monitoring patients via a secure and mobile healthcare system. *IEEE Wireless Communications*, 17(1):59–65, 2010.

[183] Cristiano Rezende, Azzedine Boukerche, Heitor S Ramos, et al. A reactive and scalable unicast solution for video streaming over vanets. *IEEE Transactions on Computers*, 64(3):614–626, 2014.

[184] Qamas Gul Khan Safi, Senlin Luo, Chao Wei, et al. Cloud-based security and privacy-aware information dissemination over ubiquitous vanets. *Computer standards & interfaces*, 56:107–115, 2018.

[185] Ola Salman, Raghid Morcel, Obada Al Zoubi, Imad Elhajj, Ayman Kayssi, and Ali Chehab. Analysis of topology based routing protocols for vanets in different environments. In *2016 IEEE International Multidisciplinary Conference on Engineering Technology (IMCET)*, pages 27–31, 2016.

[186] Samer Samarah, Muhannad Al-Hajri, and Azzedine Boukerche. A predictive energy-efficient technique to support object-tracking sensor networks. *IEEE Transactions on Vehicular Technology*, 60(2):656–663, 2010.

[187] M Saravanan and P Ganeshkumar. Routing using reinforcement learning in vehicular ad hoc networks. *Computational Intelligence*, 36(2):682–697, 2020.

[188] Stefan Schmid, Roger Wattenhofer, and Azzedine Boukerche. Modeling sensor networks. *Algorithms and Protocols for Wireless Sensor Networks*, 62:77, 2008.

[189] Shaik Shafi, BN Bhandari, and D Venkata Ratnam. A cross layer design for efficient multimedia message dissemination with an adaptive relay nodes selection in vanets. In *Conference on Signal Processing And Communication Engineering Systems (SPACES)*, pages 81–84, 2018.

[190] Shivani Sharma and Pooja Sharma. Comprehensive study of various routing protocols in vanet. In *International Conference on Intelligent Computing and Control Systems*, pages 1272–1275, 2019.

[191] Sparsh Sharma and Ajay Kaul. Vanets cloud: Architecture, applications, challenges, and issues. *Archives of Computational Methods in Engineering*, 28:2081–2102, 2021.

[192] S Sharon, T Suriya Praba, R Anushiadevi, et al. Privacy-preserving authentication scheme using reduced-advanced encryption standard for vehicular ad hoc network. In *International Conference on Applications and Techniques in Information Security*, pages 254–265, 2019.

[193] Xiaoman Shen, Jun Li, Lei Chen, et al. Heterogeneous lte/dsrc approach to support real-time vehicular communications. In *10th International Conference on Advanced Infocomm Technology*, pages 122–127, 2018.

[194] Mohammad Shojafar, Nicola Cordeschi, and Enzo Baccarelli. Energy-efficient adaptive resource management for real-time vehicular cloud services. *IEEE Transactions on Cloud computing*, 7(1):196–209, 2016.

[195] Mahmoud Ali Al Shugran. Applicability of overlay non-delay tolerant position-based protocols in highways and urban environments for vanet. *International Journal of Wireless & Mobile Networks*, 13, 2021.

[196] Murtaza Ahmed Siddiqi, Heejung Yu, and Jingon Joung. 5g ultra-reliable low-latency communication implementation challenges and operational issues with iot devices. *Electronics*, 8(9):981, 2019.

[197] Andrey Silva, Niaz Reza, and Aurenice Oliveira. Improvement and performance evaluation of gpsr-based routing techniques for vehicular ad hoc networks. *IEEE Access*, 7:21722–21733, 2019.

[198] Claudio Silva, Michele Nogueira, Donghyun Kim, et al. Cognitive radio based connectivity management for resilient end-to-end communications in vanets. *Computer Communications*, 79:1–8, 2016.

[199] Fabricio A Silva, Azzedine Boukerche, Thais RM Braga Silva, et al. Vehicular networks: A new challenge for content-delivery-based applications. *ACM Computing Surveys (CSUR)*, 49(1):1–29, 2016.

[200] Rohit Singh, Deepak Saluja, and Suman Kumar. 5g enabled vanet: Enhancing the capabilities of vehicular communication network. In *IEEE International Conference on Communications Workshops*, pages 1–5, 2021.

[201] Peng Sun, Noura AlJeri, and Azzedine Boukerche. Dacon: A novel traffic prediction and data-highway-assisted content delivery protocol for intelligent vehicular networks. *IEEE Transactions on Sustainable Computing*, 5(4):501–513, 2020.

[202] Peng Sun and Azzedine Boukerche. Tvdr: A novel traffic volume aware data routing protocol for vehicular networks. In *IEEE Wireless Communications and Networking Conference*, pages 1–6, 2019.

[203] Zemin Sun, Yanheng Liu, Jian Wang, et al. Cross-layer tradeoff of qos and security in vehicular ad hoc networks: A game theoretical approach. *Computer Networks*, 192:108031, 2021.

[204] Sergio M Tornell, Carlos T Calafate, Juan-Carlos Cano, et al. Dtn protocols for vehicular networks: An application oriented overview. *IEEE Communications Surveys & Tutorials*, 17(2):868–887, 2014.

[205] Carolina Tripp-Barba, Luis Urquiza-Aguiar, Mónica Igartua, et al. A multimetric, map-aware routing protocol for vanets in urban areas. *Sensors*, 14(2):2199–2224, 2014.

[206] Gurkan Tuna and Korhan Cengiz. Telematics and mobile internet: current situation and 5g networks. In *Principles and Applications of Narrowband Internet of Things*, pages 373–396. IGI Global, 2021.

[207] Ion Turcanu, Christoph Sommer, Andrea Baiocchi, et al. Pick the right guy: Cqi-based lte forwarder selection in vanets. In *IEEE Vehicular Networking Conference*, pages 1–8, 2016.

[208] R Venitta Raj and Kannan Balasubramanian. Trust aware similarity-based source routing to ensure effective communication using game-theoretic approach in vanets. *Journal of Ambient Intelligence and Humanized Computing*, 12(6):6781–6791, 2021.

[209] Leandro A Villas, Azzedine Boukerche, Horacio ABF De Oliveira, et al. A spatial correlation aware algorithm to perform efficient data collection in wireless sensor networks. *Ad Hoc Networks*, 12:69–85, 2014.

[210] Leandro A Villas, Azzedine Boukerche, Daniel L Guidoni, et al. An energy-aware spatio-temporal correlation mechanism to perform efficient data collection in wireless sensor networks. *Computer Communications*, 36(9):1054–1066, 2013.

[211] Leandro Aparecido Villas, Azzedine Boukerche, Guilherme Maia, et al. Drive: An efficient and robust data dissemination protocol for highway and urban vehicular ad hoc networks. *Computer Networks*, 75:381–394, 2014.

[212] Leandro Aparecido Villas, Azzedine Boukerche, Heitor Soares Ramos, et al. Drina: A lightweight and reliable routing approach for in-network aggregation in wireless sensor networks. *IEEE Transactions on Computers*, 62(4):676–689, 2012.

[213] Nannan Wang, Xi Wang, Paparao Palacharla, et al. Cooperative autonomous driving for traffic congestion avoidance through vehicle-to-vehicle communications. In *IEEE Vehicular Networking Conference*, pages 327–330, 2017.

[214] Pengfei Wang, Boya Di, Hongliang Zhang, et al. Cellular v2x communications in unlicensed spectrum: Harmonious coexistence with vanet in 5g systems. *IEEE Transactions on Wireless Communications*, 17(8):5212–5224, 2018.

[215] Sheng-Shih Wang and Yi-Shiun Lin. Passcar: A passive clustering aided routing protocol for vehicular ad hoc networks. *Computer Communications*, 36(2):170–179, 2013.

[216] Xiufeng Wang, Chunmeng Wang, Gang Cui, et al. Practical link duration prediction model in vehicular ad hoc networks. *International Journal of Distributed Sensor Networks*, 11(3):216934, 2015.

[217] Zhu Xiao, Pingting Li, Vincent Havyarimana, et al. Goi: A novel design for vehicle positioning and trajectory prediction under urban environments. *IEEE Sensors Journal*, 18(13):5586–5594, 2018.

[218] Li Yang, Wang Zhe, Zhang Chuwen, et al. Trajectory prediction algorithm in vanet routing. *Journal of Computer Research and Development*, 54(11):2421, 2017.

[219] Xiaoping Yang, Mengjie Li, Zhihong Qian, and Te Di. Improvement of gpsr protocol in vehicular ad hoc network. *IEEE Access*, 6:39515–39524, 2018.

[220] Lin Yao, Jie Wang, Xin Wang, et al. V2x routing in a vanet based on the hidden markov model. *IEEE Transactions on Intelligent Transportation Systems*, 19(3):889–899, 2017.

[221] Ibrar Yaqoob, Iftikhar Ahmad, Ejaz Ahmed, et al. Overcoming the key challenges to establishing vehicular communication: Is sdn the answer? *IEEE Communications Magazine*, 55(7):128–134, 2017.

[222] Mao Ye, Lin Guan, and Mohammed Quddus. Mpbrp-mobility prediction based routing protocol in vanets. In *International Conference on Advanced Communication Technologies and Networking*, pages 1–7, 2019.

[223] Sumendra Yogarayan, Siti Fatimah Abdul Razak, Afizan Azman, et al. A review of routing protocols for vehicular ad-hoc networks (vanets). In *8th International Conference on Information and Communication Technology*, pages 1–7, 2020.

[224] Maram Bani Younes and Azzedine Boukerche. Intelligent traffic light controlling algorithms using vehicular networks. *IEEE transactions on vehicular technology*, 65(8):5887–5899, 2015.

[225] Maram Bani Younes and Azzedine Boukerche. A performance evaluation of an efficient traffic congestion detection protocol (ecode) for intelligent transportation systems. *Ad Hoc Networks*, 24:317–336, 2015.

[226] Danlei Yu and Young-Bae Ko. Ffrdv: Fastest-ferry routing in dtn-enabled vehicular ad hoc networks. In *11th International Conference on Advanced Communication Technology*, volume 2, pages 1410–1414, 2009.

[227] Fanhui Zeng, Rongqing Zhang, Xiang Cheng, et al. Channel prediction based scheduling for data dissemination in vanets. *IEEE Communications Letters*, 21(6):1409–1412, 2017.

[228] Chuwen Zhang, Huichen Dai, Yong Feng, et al. P3r: Realizing robust routing for vanet using trajectory prediction and crossroad recognition. In *IEEE 25th International Conference on Parallel and Distributed Systems*, pages 695–702, 2019.

[229] Dajun Zhang, F Richard Yu, and Ruizhe Yang. A machine learning approach for software-defined vehicular ad hoc networks with trust management. In *IEEE Global Communications Conference*, pages 1–6, 2018.

[230] Jun Zhang, Mengying Ren, Houda Labiod, and Lyes Khoukhi. Link duration prediction in vanets via adaboost. In *IEEE Global Communications Conference*, pages 1–6, 2017.

[231] Lei Zhang, Xinyu Meng, Kim-Kwang Raymond Choo, et al. Privacy-preserving cloud establishment and data dissemination scheme for vehicular cloud. *IEEE Transactions on Dependable and Secure Computing*, 17(3):634–647, 2018.

[232] Lei Zhang, Qianhong Wu, Josep Domingo-Ferrer, et al. Round-efficient and sender-unrestricted dynamic group key agreement protocol for secure group communications. *IEEE Transactions on Information Forensics and Security*, 10(11):2352–2364, 2015.

[233] Tianjiao Zhang and Qi Zhu. A tdma based cooperative communication mac protocol for vehicular ad hoc networks. In *IEEE 83rd Vehicular Technology Conference*, pages 1–6, 2016.

[234] Wenyu Zhang, Zhenjiang Zhang, and Han-Chieh Chao. Cooperative fog computing for dealing with big data in the internet of vehicles: Architecture and hierarchical resource management. *IEEE Communications Magazine*, 55(12):60–67, 2017.

[235] XiaoDong Zhang, Ru Li, and Bo Cui. A security architecture of vanet based on blockchain and mobile edge computing. In *1st IEEE International Conference on Hot Information-Centric Networking*, pages 258–259, 2018.

[236] Zhenxia Zhang, Azzedine Boukerche, and Richard Pazzi. A novel multi-hop clustering scheme for vehicular ad-hoc networks. In *Proceedings of the 9th ACM international symposium on Mobility management and wireless access*, pages 19–26, 2011.

[237] Zhenxia Zhang, Richard W Pazzi, and Azzedine Boukerche. A mobility management scheme for wireless mesh networks based on a hybrid routing protocol. *Computer Networks*, 54(4):558–572, 2010.

[238] Jing Zhao and Guohong Cao. Vadd: Vehicle-assisted data delivery in vehicular ad hoc networks. *IEEE Transactions on Vehicular Technology*, 57(3):1910–1922, 2008.

[239] Meiyuan Zhao, Jesse Walker, and Chieh-Chih Wang. Challenges and opportunities for securing intelligent transportation system. *IEEE Journal on Emerging and Selected Topics in Circuits and Systems*, 3(1):96–105, 2013.

[240] Ming Zhu, Jiannong Cao, Deming Pang, et al. Sdn-based routing for efficient message propagation in vanet. In *International Conference on Wireless Algorithms, Systems, and Applications*, pages 788–797, 2015.