Efficient Interest Forwarding for Vehicular Information-Centric Networks

by

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Abstract

Content Distribution in Vehicular Ad-hoc Networks (VANETs) has always been a critical challenge, due to the peculiar characteristics of VANETs, such as high mobility, intermittent connectivity, and dynamic topologies. In fact, traditional Host-Centric Networks have shown to be unable to handle the increasing demand for content distribution in VANETs. Recently, Information-Centric Networks (ICN) have been proposed to VANETs to cope with the existing issues and improve the content delivery. In Vehicular Information-Centric Networks, instead of communicating in a host-to-host pattern and maintaining host-to-host links during the communication, consumers opportunistically send the Interest requests to the neighbor vehicles, which may have the desired Data packets that can satisfy the Interest packets. However, uncontrolled Interest packet transmissions for content search will result in a waste of resources and diminish the performance of applications in VANETs.

In the thesis, we focus on two daunting problems that have limited content distribution in Vehicular Information-Centric Networks when using Vehicle-to-Vehicle (V2V) communication: (i) unreliable content delivery and (ii) broadcast storm. We proposed a suite of protocols, OIFP, LISIC and LOCOS, destined to tackle these and other issues. In the proposed protocols, we have considered different metrics in VANETs that may influence the content distribution, such as distance, velocity, directions and the locations of the producers and consumers. By utilizing a small deferred timer, which is the time holden by the forwarding vehicles before sending the Interest packets out, priority is given to the selected vehicles to forward the Interest packets.

Extensive simulations show that all the proposed protocols outperform the vanilla VNDN protocol regarding transmission delay, content satisfaction rate and the average number of Interest transmissions. Besides, we have also implemented several related works and compared with our protocols. The overall performance of the proposed LOCOS protocol outperforms the related works. Moreover, our protocols do alleviate the broadcast storm problem and improve the content delivery rate.

List of Publications

The following listed are the publications related to this thesis.

- Rodolfo WL Coutinho, Azzedine Boukerche, and Xiangshen Yu. Information-Centric Strategies for Content Delivery in Intelligent Vehicular Networks. In Proceedings of ACM 8th International Symposium on Design and Analysis of Intelligent Vehicular Networks and Applications, DIVANet, 2018. (Accepted)

- Rodolfo WL Coutinho, Azzedine Boukerche, and Xiangshen Yu. A Novel Location-Based Content Distribution Protocol for Named Data Vehicular Networks. In Proceedings of IEEE 23rd Symposium on Computers and Communications, ISCC, 2018. (Accepted)

- Azzedine Boukerche, Rodolfo WL Coutinho, and Xiangshen Yu. LISIC: A Link Stability-based Protocol for Vehicular Information-centric Networks. In Proceedings of IEEE 14th International Conference on Mobile Ad Hoc and Sensor Systems, MASS, pages 233-240. 2017.

- Xiangshen Yu, Rodolfo WL Coutinho, Azzedine Boukerche, and Antonio AF Loureiro. A Distance-based Interest Forwarding Protocol for Vehicular Information-centric Networks. In Proceedings of IEEE 28th International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC, pages 1-5. 2017.

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Nomenclature

VANET	Vehicular Ad-hoc Networks
ICN	Information-Centric Networks
NDN	Named Data Networks
VNDN	Vehicular Named Data Networks
V2V	Vehicle-to-Vehicle
OIFP	Opportunistic Interest forwarding protocol for VNDN
LISIC	Link stability-based protocol for VNDN
TraCI	Traffic Control Interface
CDN	Content Delivery Networks
V2I	Vehicle-to-Infrastructure
V2X	Vehicle-to-Everything
RSU	Road Side Unit
MANET	Mobile Ad-hoc Networking
SDN	Software Defined Network
OBU	On Board Unit
ITS	Intelligent Transport System
CCN	Content Centric Networks
AODV	Ad hoc On-demand Distance Vector routing
AoI	Area of Interests
TCP	Transmission Control Protocol
IP	Internet Protocol

GPSR	Greedy Perimeter Stateless Routing
LAL	Link Adaptation Layer
VCC	Vehicular Cloud Computing
RoI	Region of Interest
V-CDN	Vehicular Content Delivery Network
LCE	Leave Cope Everywhere
P2P	Peer-to-Peer File Sharing
PCD	Popular Content Distribution
SLNC	Symbol Level Network Coding
QoS	Quality of Service
QoE	Quality of Experience
LTE	Long-Term Evolution
DSRC	Dedicated Short Range Communications
LOCOS	Location-based content distribution protocol for VNDN
CS	Content Store
WAVE	Wireless Access in Vehicular Environments
PIT	Pending Interest Table
FIB	Forwarding Information Base
WSN	Wireless Sensor Networks
GPS	Global Positioning
TTL	Time to Live
RTT	Round-Trip Time
WANETs	Wireless Ad Hoc Networks
IoT	Internet of Things
5G	5th Generation Mobile Networks

Chapter 1

Introduction

This chapter introduces the background of the VANETs and ICN. The motivation of our research in VNDN is given as well. Then, we analyze the existing problems in current VNDN. Besides, the contributions of our research work are concluded in this chapter. At the end of this chapter, the outline of this thesis is listed.

1.1 Motivation

Vehicular Ad-hoc Networks (VANETs) are initially envisioned as an enabling technology for distributed applications aimed to improve safety and comfort of drivers and passengers. According to the Global Auto Report [84], International car sales are anticipated to be more than 100 million by 2020. There is an increasing amount of vehicles running on the road, which have caused problems like car accidents and massive traffic jams. Seeking efficient traffic management and improving the drivers and passengers' experience in the vehicles drive technology companies, academic, and car manufacturers to focus on the research on driverless cars and Intelligent Transportation Systems (ITS). Therefore, VANETs have also been seen as a primary information and telecommunication technology for intelligent transportation and smart city applications [10].

On the one hand, the demand for the basic safety and navigation information in VANETs is significantly increasing. On the other side, for the vehicle itself, there is also a lot of information generated, such as data from road condition sensors, brake force sensors and short-range radar sensors, to name a few. Moreover, drivers, as well as passengers would have a higher demand for traffic information, popular content and entertainment applications on the road, such as weather information, breaking news, live video streaming and online games.

Thus, there is a significantly increased demand for vehicular network applications, the need for efficient content delivery is boosting. All of these services cannot perform well without effective organization and proper caching in VANETs. As a result, efficient content delivery in VANETs is demanded.

In this regard, connected cars have emerged as one of the primary ICT resources for the realization of smart transportation systems [10, 94]. Unlike nodes in traditional wireless ad hoc and sensor networks [25, 26], a node has sufficient sensing, computing, and communication capabilities in VANETs. And different wireless communication technologies (IEEE 802.11p, 5G, Wi-Fi, and Bluetooth) can be deployed, which can lower communication costs and improve communication efficiency and quality over poor-quality wireless links.

In smart transportation systems, the current well-studied data dissemination protocols in vehicular networks [1, 114, 118, 130, 131, 151] will be unable to handle the ever-increasing expected demand for infotainment multimedia content distribution. Traditionally, data dissemination algorithms and protocols designed for VANETs rely on the broadcast of produced messages in a given area of interest to notify circumventing vehicles about the occurrence of an event [24]. Therefore, these protocols are not suitable for multimedia content distribution between end-to-end vehicles.

Moreover, content dissemination protocols developed for VANETs are host-centric. Host-centric protocols rely on the discovery and established of end-to-end paths between the requester and the sender. They will be unfeasible for content distribution in smart transportation systems [12, 91, 103], due to the high overhead to frequently establish new end-to-end paths when the vehicular network topology changes.

In addition, the host-centric paradigm has shown the signs that it is becoming unable to handle the ever-increasing demand for multimedia content even in the backbone of traditional Internet. It is worrying in vehicular networks since most conventional protocols for data dissemination and content delivery in these networks are based on the Dedicated Short Range Communications (DSRC)/Wireless Access in Vehicular Environments (WAVE) standard and driven by content producers' and clients' identifiers and locations, instead of the content itself [130].

Recently, Information-Centric Networks (ICN) have gained increasing attention for content distribution in vehicular networks [14, 93, 142]. ICN has the capability of seamlessly handling the intermittent and short-lived connected vehicular network characteristics by providing in-network content cache and content-oriented search and retrieval. Therefore, the frameworks of ICN have been proposed to tackle the bottleneck of host-centric networks.

However, it is not easy to deploy ICN in VANETs. The intermittent connectivity and unstable topology are the realistic problems. Also, the problem like broadcast storm caused by uncontrolled Interest packets is ticklish.

Therefore, our goal is to develop novel ICN-based protocols for VANETs, which considers the characteristics of VANETs scenarios, multiple metrics and utilize V2V communication. Furthermore, based on the study of different simulators, testbed and simulation principles [27, 32, 66, 67], we want to do a large scale discrete event-based simulation in the urban scenario.

1.2 Problem Statement

Unlike the wired networks, the broadcast storm is a critical problem in wireless ad-hoc networks, which is caused by uncontrolled flooding. The data packet may either bounce between two nodes leading to a dead loop or be over broadcasted by neighbor nodes in the broadcast storm, which results in the packet collision due to the excessive broadcasted packets.

The situation is even worse in VANETs when all the vehicles keep moving on the street, which may result in intermittent connectivity and unstable topology. For content delivery in VANETs, packet propagation for content search is challenging and has a significant impact on the network performance and the application. Hence, the traditional Host-Centric Networks are no longer suitable for VANETs since the end-to-end connectivity cannot be maintained.

Recently, Named Data Networks (NDN) is proposed and considered as the next generation networks [3]. We notice that NDN reduces the overhead produced in route discovery and maintenance between endpoint hosts. Each content has a globally unique name. Therefore, Interest request for the same content can be easily aggregated so that the overhead can be reduced. Additionally, NDN is seamlessly compatible with the high mobility environment. Since all the Interest and Data packet requests are based on the name instead of the IP address, the requests are still valid even when the locations of the vehicles have changed leading to the change of IP address or the server. Likewise, integrated security in NDN can also be facilitated. Furthermore, Delay-tolerant Networks (DTN) match ICN. ICN has the feature of in-network caching, which provides enough storage for the vehicles to perform store-and-forward scheme when there are no neighbor vehicles around.

However, the Interest propagation mechanism of a traditional NDN implementation might not perform very well in VANETs scenarios. In fact, the conventional Interest propagation of NDN will lead to broadcast storms in VANETs, which will diminish the performance of critical applications. One of the main challenges in Vehicle-to-Vehicle (V2V) communication is packet collision. Uncontrolled Interest transmissions will increase packet collisions. Unfavorably, collision avoidance techniques, such as Request to Send (RTS) and Clear to Send (CTS) that are frequently used to avoid packet collision in wireless networks, are not designed for V2V communication [70]. In this regard, packet loss occasioned by packet collisions will delay data delivery, since multiple retransmissions will take place [141]. This data delivery delay will be critical for hard deadline safety-related applications.

On the other hand, as a result of the center of the network moving from IP addresses to the name of content chunks, more Interest packets generate in V2V communication. Whereas, uncontrolled Interest transmissions will increase packet collisions, which leads to packet loss and Interest and Data packets delivery delay. As a consequence, efficient Interest packet forwarding for VNDN is very much needed. Nonetheless, we noticed that there is a lack of efficient routing protocols that suit VNDN, which motivates us to go deep in this area.

1.3 Contributions

The main contribution of this thesis is the development of three protocols aimed to mitigate the broadcast storm problem of Interest packet transmissions in Information-Centric Vehicular Networks. A summary of the developed protocols is presented below:

- Firstly, we proposed and implemented the opportunistic Interest propagation protocol (OIFP) [148] to tackle the broadcast storm problem happened during Interest packets propagation in vehicular Information-Centric Networks based on the distance information. Simulation results show that the OIFP decreases the average number of Interest transmissions by around 35%, decreases the average delay of content delivery by approximately 38%, while increasing content delivery rate by 93%, vanilla VNDN in the 400-vehicles scenario.

- Secondly, we proposed and implemented the link stability-based Interest forwarding for content request (LISIC) [30] protocol to mitigate the broadcast storm problem in the vehicular Named Data Networks. The basic idea is to select the most stable links among vehicles during the Interest and Data propagation based on the relative velocity and moving direction. Simulation results show that the OIFP and LISIC protocol decreases the average number of Interest transmissions by around 55%, decreases the average delay of content delivery by about 50%, while increasing content delivery rate by 140% compared with vanilla VNDN in the 400-vehicles scenario.

- Thirdly, we proposed and implemented the Location-Based Content Distribution for Vehicular Information-Centric Networks (LOCOS). This protocol is aimed to reduce Interest transmissions in the VANETs, and consequently mitigate the broadcast storm of content search by leveraging the mobility information of the content server. Since there are two phases of the Interest transmission, LOCOS can be extended to two protocols (LOCOS-OIFP and LOCOS-LISIC) based on different strategies. Moreover, LOCOS-LISIC protocol improves content delivery rate by 3% while reducing Interest transmissions for content searching by 18% and reducing average delay by 8% compared with LISIC in the 400-vehicles scenario.

1.4 Thesis Outline

The remaining of this thesis is structured as follows:

- Chapter 2 presents the background of our research. An introduction of VANETs, CDN, and ICN is given. Two major categories based on different network types, host-centric strategy, and information-centric strategy, are discussed as well.

- Chapter 3 discusses the state-of-the-art of content delivery solutions for vehicular Information-Centric Networks. Besides, we present a comparative study of recent proposed vehicular Information-Centric Networks.

- Chapter 4 proposes our protocols, OIFP, LISIC, LOCOS-OIFP, and LOCOS-LISIC. We introduce the metrics we consider and the principle and pipelines of how our protocols work. Meanwhile, we present the pseudocode of our protocols as well.

- Chapter 5 conducts the simulation-based performance evaluation of the proposed protocols against related work. We also implement several related works in VNDN and compare them with our works. Based the results of different metrics, we demonstrate the efficiency of our proposed protocols.

- Chapter 6 gives a conclusion about this thesis and our future work. We also list some future possibilities in this area.

Chapter 2

Background

In this chapter, we present the background of our research. We give an introduction of VANETs in Section 2.1, in which we describe the architecture of VANETs and the applications in VANETs. Then we present the recent proposed network architecture, ICN in Section 2.2. After that, we introduce CDN and how it works in VANETs. We also classify content delivery strategies in VANETs into two major categories based on different network types: Host-Centric Strategy and Information-Centric Strategy. In each category, a detailed description is discussed. At last, we list a comparative study between the two strategies.

2.1 Vehicular Ad-hoc Networks

Vehicular Ad Hoc Networks (VANETs) are initially a subclass of the Mobile Ad Hoc Networks (MANETs). MANETs are the network that every device follows a self-configure pattern and interconnects with each other via the wireless data link and moving randomly in one domain.

Wireless Ad Hoc Networks (WANETs) and Wireless Sensor Networks (WSNs) are widely used in many areas, such as underwater scenario [76, 77], healthcare [58, 126] and VANETs.

Therefore, a lot of characteristics and problems in VANETs are inherited from WANETs or WSNs. For example, the localization and mobility management discussed in WANETs [2, 19, 49, 51, 59, 62, 156], the load balancing and fault or loop identification discussed in [9, 16, 29, 31, 40, 45, 55, 87, 117], security and trust verification [34, 42–44, 48, 57, 85, 86] and the coverage and data extraction discussed in [37, 38, 65] are still problems in VANETs since all the vehicles are highly mobile. However, efficient routing and data forwarding protocols are challengeable and significant in both wireless ad hoc networks and VANETs [47, 53, 54, 81, 155].

Whereas, VANETs have some unique characteristics that make it differentiated from the WANETs family. A series of features of VANETs are summarized below: First, the topology is changing dramatically based on different traffic density and time, and the connection is not stable because of high mobility. Second, each vehicle is equipped with GPS. The path and the location of the vehicles may be predictable based on the GPS information. Third, unlike other ad-hoc networks, the power supply is not a problem in VANETs. Additionally, the vehicles can provide massive storage, which makes the equipment of various applications and microcomputers possible. However, some safety applications would be delay sensitive.

2.1.1 Architecture of VANETs

The Road Side Unit (RSU) is the communication infrastructure placed at the roadside. On-board Units (OBUs) are the devices embedded into the vehicle to support communication. Both of them enable vehicular communication. Three main connection patterns are addressed in VANETs [50].

The first scenario is vehicles only communicate with each other via the RSU, which is similar to the WiFi hotspot connection. This communication pattern is referred as Vehicle-to-Infrastructure Communication (V2I) as shown in Figure 2.1a. The second scenario is the real ad-hoc situation where vehicles interconnect with each other through OBU directly without any infrastructures involved. This communication pattern is referred as Vehicle-to-Vehicle Communication (V2V) as shown in Figure 2.1b. The third scenario is called hybrid

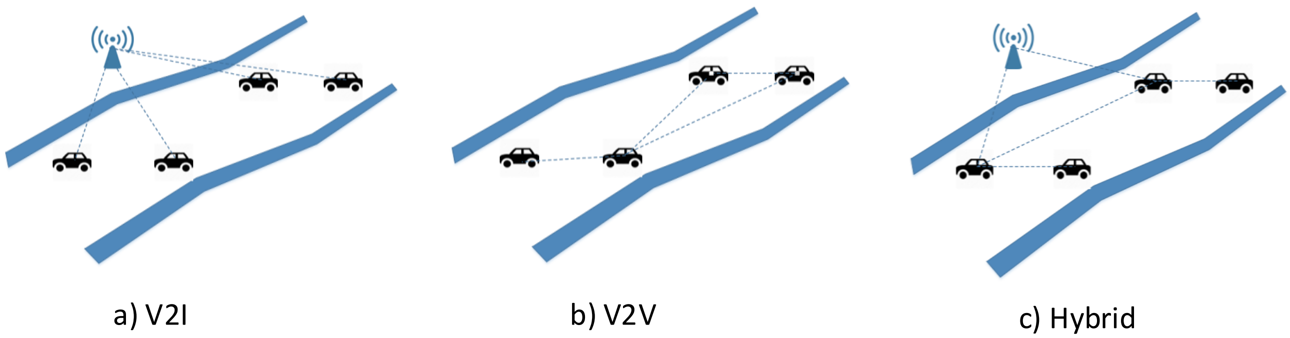

Figure 2.1: Three main connection patterns in VANETs

situation as illustrated in Figure 2.1c, which means both the RSU based communication and ad hoc connection exists at the same time to support the overall network communication.

A wide variety of wireless technologies and standards have been used to implement the three communication patterns. As the appearance of the Internet of Things (IoT) [18] and the need of Intelligent Transport System (ITS) and smart cities, communication is moving from V2I and V2V to V2X (vehicle-to-everything), which is considered as a hybrid communication mode. Vehicle-to-bike, vehicle-to-pedestrian, even vehicle-to-wearable devices like an intelligent watch, intelligent glasses could be possible in the near future.

A series of wireless technology could probably be used in VANETs. However, there is a tradeoff between data rate and mobility. 802.11 technology today is widespread all over the world for its high speed and low cost (unlicensed frequency). Lacking mobility support, however, would be the bottleneck of QoS or QoE in highly moveable scenarios.

2.1.2 VANETs Applications

According to [28, 115, 138], applications in VANETs can be summarized into three categories:

• **Applications related to safety.** These kinds of applications can provide information such as harsh weather reminder, emergency avoidance, car accident avoidance for the sake of the road safety and reducing traffic accidents [59]. Therefore, these messages are time-sensitive [120, 133].

- **Applications related to traffic management.** These sorts of applications can get road information and traffic information. On the one hand, they assist the drivers to drive in an intelligent mode and to have a better decision on route selection. On the other hand, this information can be gathered for traffic prediction [153] and congestion detections [59], and to fulfill the ITS.

- **Applications related to entertainment.** These applications are becoming very popular. By equipping the online devices, internet surfing, video streaming, and online games are becoming possible to improve a better experience in the vehicles [127]. These applications need a significant amount of bandwidth. Some solutions have been proposed to assist the widespread of multimedia packets [41, 52, 144]and provide QoS support [60] in VANETs.

2.2 Information-Centric Networks

The Information-Centric Networks (ICN) paradigm was proposed as an architecture for the Internet of the Future. This paradigm proposes a signifcant change in the way content is addressed and retrieved, as discussed in this section.

As the development of the Internet and the appearance of the variety of applications, people seem to have more interest in what data they want rather than where it is located. The traditional TCP/IP-based network model cannot match the requirement perfectly. Since the IP-based packets can only be transferred to a specific link based on two endpoints, the resource of IP address is valuable and is also considered as the limitation of today's networks.

In the traditional host-centric networking paradigm, desired contents are retrieved through direct requests to the host that has it. Therefore, it is first necessary to discover the host that has the desired content, i.e., its IP addresses and, after that, to issue requests addressed to the discovered host, in order to retrieve the content. Moreover, the host-centric approach is a connection-oriented paradigm, which means that an end-to-end routing path must be discovered and established for the data routing among the two end-

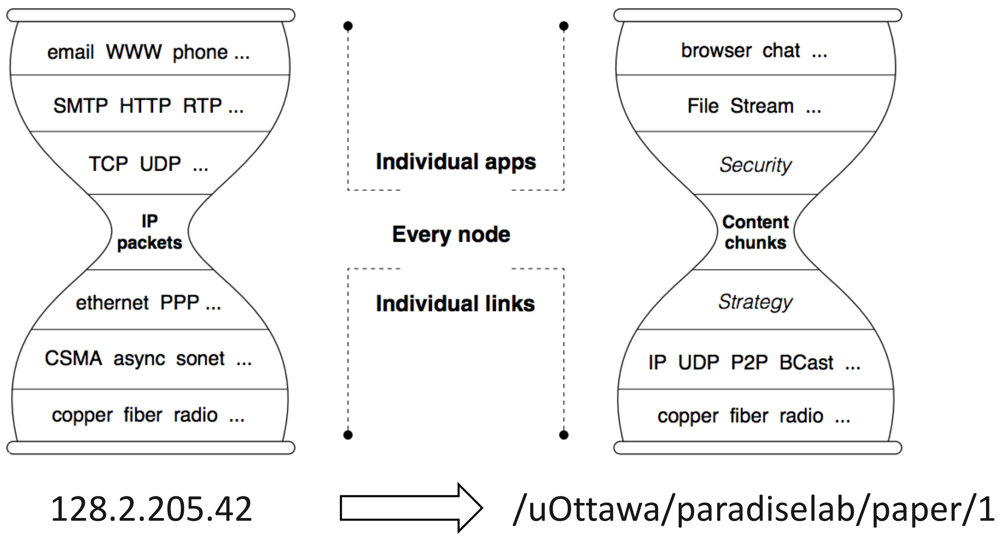

Figure 2.2: Change in hourglass architecture

point entities. This approach has been showed severe limitations to handle the increased amount of traffic exchange.

Conversely, the information-centric networking paradigm proposes a shift in the way content is addressed, requested and retrieved. The importance is given to the content itself, instead of the location where it is. With this principle in consideration, unique names are assigned to each content, which is used for its search and retrieval. As the appearance of ICN, the center of the network moves from IP address to the name of the packets(as shown in Figure 2.2). By doing this, the networks open the door to the new world. The IP address is finite. However, there is no limitation in the ICN namespace. Each different content can be uniquely named and distinguished. What is more, no fixed end-to-end link needs to be maintained. The request can be satisfied by any node during the transmission. Therefore, in network caching is meaningful. Also, the security protocol design and security management in traditional WSN and VANETs are very complex and unsafe [23, 35, 36, 56, 68, 125]. Instead of securing the communication channel, ICN provides built-in security, which means securing the packet itself. The signature and key verification binding names to the Interest and Data packets provide a fundamental of trust model.

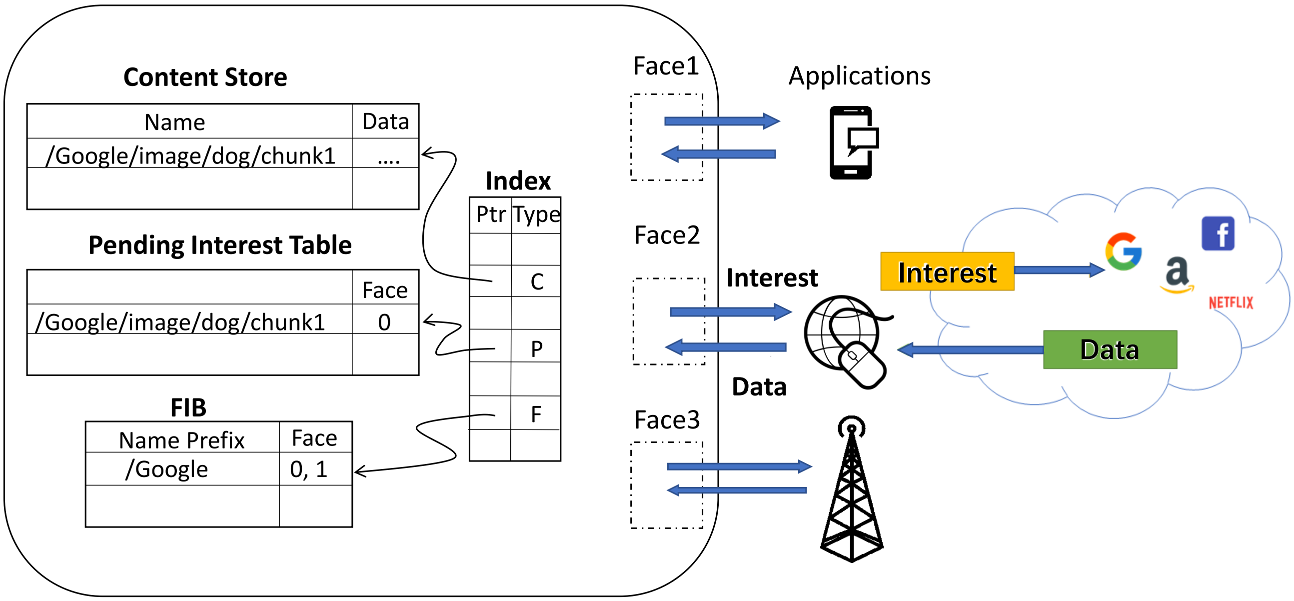

Figure 2.3: Architecture of ICN

A couple of architectures are developed in ICN, among which Content-Centric Networks (CCN) [96] and Named Data Networks (NDN) [152] have been widely discussed in ICN in recent research works. NDN is considered as an enhanced version of the CCN architecture.

There are three common roles in ICN, producer, consumer, and forwarder. Each node in ICN can be any role for them. Moreover, the request message is called Interest, and the replied message with requested content is called Data.

The architecture of an NDN node is shown in Figure 2.3. There are three data structures maintained in an NDN node [152], which are Pending Interest Table (PIT), Content Store (CS) and Forwarding Information Base (FIB). All these data structures are stored in NDN Daemon, which is the core of NDN framework. Meanwhile, NDN Daemon is the bond of the application layer and the physical layer via application face and network face.

PIT records the Interest requests that have not been satisfied. In other words, all the Interest packets waiting for the replied Data packets are stored in the PIT. Also, the incoming face information is recorded. When there are multiple Interest packets requesting for the same content, only one request is sent out instead of sending out all the Interest packet. Since all the content is uniquely named, if same name prefix of the Interest packet found, aggregation is executed in the PIT to reduce the overhead of sending same multiple Interest.

CS is the cache in each vehicle storing plenty of Data chunks based on the cache policy. Since the naming of an Interest or a Data packet is independent of IP address, Interest packets can be satisfied by any vehicle which has the Data packet. It is the content itself rather than where the packet comes from that matters. Therefore, in-network caching is meaningful in NDN. CS can cache the Data packets in the networks for future satisfying Interest request. Besides, FIB contains the interfaces and next hops information. Routing is named-based instead of IP-based. Depending on the number of network interfaces equipped with each vehicle, FIB is an optional choice in vehicular NDN.

There can be more than one interface equipped with an NDN node. Since the content from the different source is named uniformly, content can be obtained from multi-interfaces like WIFI, wired Internet, LTE for mobile devices and et al.

2.3 Content Delivery Networks

The basic idea of Content Delivery Networks (CDN) is to distribute content from the source to several replica servers and cache the content on the edge servers, which are closer to the user end [119, 139]. Faster and more reliable application and service can be offered by redirecting the request to the most appropriate cache so that the network performance can be significantly improved.

2.3.1 Vehicular Content Delivery Networks

Since the feature of high mobility and large scale of the vehicular network, many problems need to be considered, such as the number of replicas, where the replicas should be cached, and the forwarding strategy to retrieve the replicas, to fulfill the demand for efficient bandwidth and so on. Therefore, the design of vehicular content delivery networks (V-CDN) is coming up.

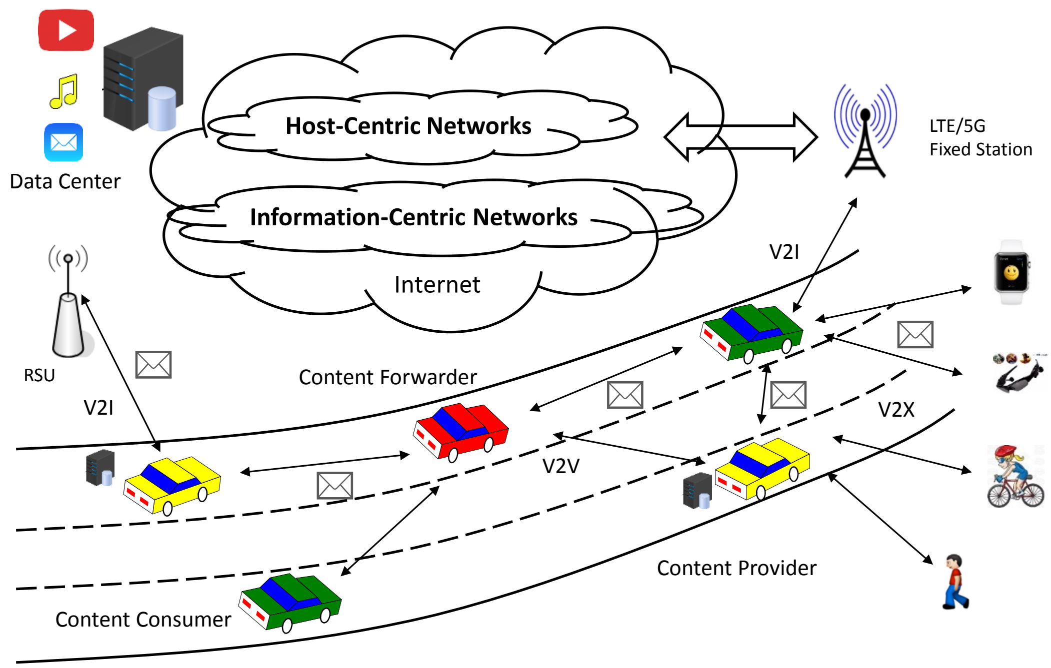

Figure 2.4: Architecture of V-CDN

Based on previous researches [69, 112], the idea of V-CDN is to organize the vehicles as a content delivery network as shown in Figure 2.4. Each vehicle acts as a content provider, content receiver, and also a forwarder. Approaches like traditional TCP/IP, SDN, vehicular cloud, Content-Centric Networks (CCN) and Named Data Networks (NDN) can all be applied in V-CDN as potential solutions to support specific Quality of Service (QoS) or Quality of Experience (QoE) requirements, low transmission delay and high hit ratio.

As recent massive demand for content in VANETs, CDN is considered to apply in VANETs. However, leveraging CDN in VANETs has a lot of difficulties and challenges. Some existing facts make content delivery in VANET hard to realize:

• First, topology in VANETs is dynamic as vehicles have high mobility [130]. Different vehicles have different speeds, and the behavior of vehicles is affected by the traffic light and different traffic conditions. Hence, VANETs cannot be like the traditional fixed wireless network. Connection interrupt and new vehicles joining in the topology are very common in VANETs. It is hard to make the prediction and make the decision to select the appropriate replica vehicles. However, object-trackingy [128] and intelligent traffic light controly [147] can enhance the content delivery.

• Second, the density of vehicles varies in different areas at the different time, such as city and highway, morning and night. The demand for the content and the number of replications of content are in direct proportion to the density of the vehicles in a specific area. The redundant replications can improve the storage cost. As a result, the number of replicas should be cached based on the different density of the traffic based on various times and locations.

• Third, some applications are sensitive to the location information, which leads to some content have local meaningy [39]. Since the rapid location changing, the challenge could be how to keep content in some particular areas.

• Fourth, the RSU and cellular network cannot guarantee stable and continuous connection. For example, the vehicles may be out of connection range in a high way scenario or the connection may be blocked by the buildings in the urban situation. Hence, the connection is not stable. The challenge is to improve the radio coverage and enhance the stability of the connection.

• The last challenge is burst congestion. When a traffic jam happens, there could be hundreds or thousands of vehicles in a particular area. There must be a large demand for some popular content. Large request for the same content at the same time would lead to the burst traffic congestion. Long responding time will result in bad QoE of the users.

To address the challenges, the main idea is to use both V2V and V2I communications to realize the content distribution. Meanwhile, content should not be downloaded all from RSUs or infrastructure stations. On the one hand, it is expensive for the LTE communication cost. On the other hand, it is slow and Round-Trip Time (RTT) could be much longer since thousands of requests for the same popular content and delay may happen. Instead, keep some popular content in the network, which means replicating and storing the content in the vehicles. Therefore, leveraging V2V communication for content distribution in VANETs is significant. However, it is also a problem to select the proper vehicles. Some metrics need to be considered. As a result, content replication is the process of choosing the proper vehicles to keep replicas of content in local vehicles and realize optimal delivery

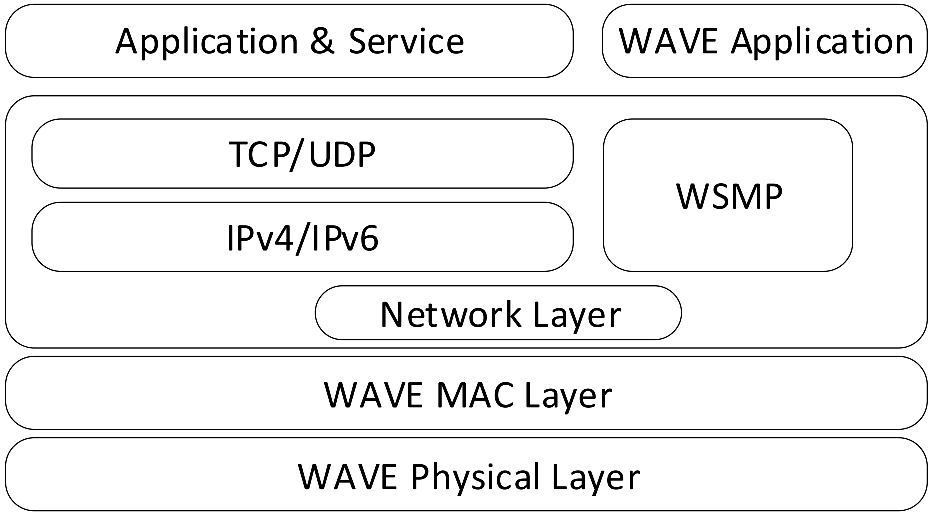

Figure 2.5: Architecture of Vehicular Host-Centric Networks

process.

Based on different types of network (traditional Host-Centric Networks and recently proposed Information-Centric networks), content delivery strategies VANETs are classified into two categories in our thesis, which are Host-Centric Strategies (details in Section 2.3.2) and Information-Centric Strategies (Details are presented in Section 2.3.3).

2.3.2 Host-Centric Strategy

In this strategy, content in VANETs is delivered through solutions based on the traditional TCP/IP and DSRC/WAVE standard. The architectural model is shown in Figure 2.5. Content delivery in Host-Centric Networks are affected by the link condition and content locations. Vehicles and road-side infrastructures are wirelessly interconnected through TCP/IP based networks, where the host is identified by using IP address. Normally, two tasks are needed to be considered, which are replica placement and content delivery. Properly placing the replica can reduce the retrieve time. Efficient content delivery can reduce the transmission delay. Both of them are considered as the foundation of Host-Centric Strategy.

For replica placement, to select the appropriate vehicles as the replicas is the main task.

Some decisions are made based on the overall view of the VANETs which needs the aid of infrastructures and RSUs to provide the large-scale computation. Some decisions are made by the vehicles themselves in an ad-hoc cooperative way. Some decisions are made by the cluster head among the vehicles according to the control of the infrastructure and the information in the local ad-hoc network. Concerning content scale, type, popularity, and location information, some metrics can always exist as the measurement criteria for the replica selection. Also, the demand information, topology information, and vehicle information can decide the selection of replica.

Three main tasks need to be considered for replica placement. First, select the appropriate vehicles as the replica vehicles. The appropriate vehicle may not be a single one. It could be many vehicles in an area. Second, keep the content in replica vehicle as caching. The connection may not be stable. Most of the replica vehicles are in carry-and-forwarding mode. Third, instruct the content requester to use the content in the replica vehicle by utilizing V2V communication instead of downloading the content directly from the fixed stations using V2I communication.

Many factors can be used to measure and improve the efficiency of replica placement, like the travel time, the popularity of content, the content lifetime, content transmission delay, the departure and arrival locations and etc.

Some original ideas are utilizing peer-to-peer (P2P) in VANETs [80, 105], where infrastructures do not facilitate the replica placement. Instead, the vehicles are organized as a group. Replicas are placed in some of the vehicles. By exchanging Gossip messages among vehicles, replica vehicles can be discovered, and replica content can be retrieved in this kind of cooperative P2P VANETs.

Besides some of the replica placement solutions (Infocast [129], Figaro [113], VTube [111]) take advantages of infrastructures, such as RSU, RSB, station, Broker. The names are different, but the original ideas are the same. Facilitated by the infrastructure, large-scale storage, high computational ability and global view of the underlying topology can be provided, which can optimize replica placement.

For content delivery, the routing and forwarding strategies are mainly based on proactivity and reactivity. The proactive method is also called pull-based solution. Meanwhile, the reactive method is called push-based solution. Most of the entertainment content uses pull-based delivery and most of the safety content utilize push-based delivery. Many technologies can facilitate content delivery such as opportunistic communication, P2P network, collaborative network, Game Theory, network coding, etc. Network information (like topology and link condition), content information (popularity and scale), prediction information (based on vehicle track and user behavior) and vehicle information (like source and destination location) all affect content delivery and have been considered in the previous work.

Since the high cost and downloading speed limit, as well as the unstable connection between vehicles and infrastructures, some solutions (BitTorrent [75], SPAWN [80] and CarTorrent [105]) apply peer-to-peer (P2P) in VANETs. By utilizing P2P in VANETs, infrastructures do not facilitate the content delivery and replica placement. Instead, the vehicles are organized as a group and replicas are placed in some of the vehicles.

Some content delivery schemes in Host-Centric Networks, such as CodeTorrent [106], VANETCODE [5] and Codeon [108] are based on network coding [89]. In vehicular CDN, network coding is addressed to improve the performance in a highly mobile scenario. By dividing the content into several small chunks which are linearly coded, content can be decoded with the help of some of the encoded chunks. As a result, the ability of fault-tolerant and single node failure tolerance can be significantly improved. Network coding in VANETs can also ensure a reliable and efficient content delivery.

Some works have been proposed to consider SDN and vehicle cloud as the possible solutions for content delivery in traditional host-based vehicular ad hoc network. The idea is to improve the performance of VANET by decoupling the control and data planes and providing large-scale computing ability. Thus, VANET could be programmable, flexible, scalable and controllable. Same as the architecture of SDN, there are three layers in Software Defined VANET, which are application layer, control plane, and data forwarding plane. Both northbound and southbound API are also applied in Software Defined VANET [71, 101, 107, 157]. By leveraging SDN functionalities in VANETs, resource utilization, routes selection, and network programmability are all improved. Meanwhile, it is much easier for a controller to reserve frequency or select an interface for a content flow for emergency use. Unlike other wireless ad-hoc nodes, vehicles can provide sufficient storage and continuous power supply, which makes Network as a Service (NaaS) and Storage as a Service (SaaS) possible to assist content distribution. Vehicles can also be taken as resource units (RUs). When a request is received, the controller can decide the number of allocated RUs based on the overview of the vehicular network [116]. To improve the computing capability and management of content delivery, the vehicular cloud is deployed in some recent researches [143].

Some works have been proposed to consider prediction and popularity. TPD is prediction based content delivery solution proposed in [97]. Content delivery is based on the topology formed by the predicted vehicles which would encounter. Based on the travel time, the probability of encounter can also be predicted. Roadcast is popularity-aware content delivery solution [154]. Content with the higher popularity, smaller scale, and lower previous retrieve delay has the higher cost. As a result, the most relevant and popular content will be given the top priority for content delivery.

Additionall, some well-known geo-location-based and topology-based protocols in Wireless Sensor Network (WSN), like GPSR [100], DSDV [121], and AODV [73], can also be considered to assist content delivery in VANETs. However, the drawback is that they lack mobility support. Moreover, in some location-based host-centric V-CDN solutions [88, 131, 132], the city is divided into several Area of Interests (AoI) or Region of Interests (RoI). Replicas are needed to keep in these areas as the content source efficiently based on the prediction and popularity. Forwarding decisions are made based on the location of origin and destination.

As a consequence, plenty of traditional host-centric routing protocols have been proposed in V-CDN. Furthermore, traditional data distribution management approaches in WSN [33, 63, 64] can still be applied in V-CDN. But they are still complex which increases the overhead and is hard to maintain in VANETs. Moreover, the tradeoff between content availability and communication cost always exists in traditional vehicular Host-Centric

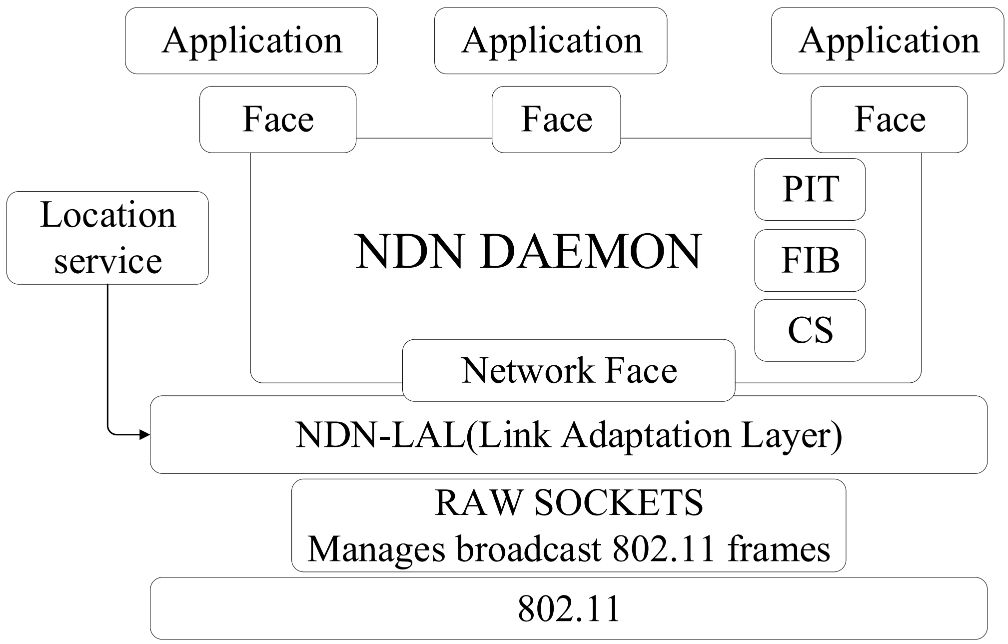

Figure 2.6: Architecture of Vehicular Named Data Networks

Networks.

2.3.3 Information-Centric Strategy

In this strategy, content in VANETs is delivered through solutions based on the Information-Centric Networks. The name of the content instead of IP address is used to fetch the content. In this thesis, we are focusing on Named Data Networks (NDN) [152] in VANETs.

The protocol stack layer of a vehicle using the Named Data Networks implementation of ICN framework is shown in Figure 2.6. Accordingly, applications run on top of the NDN Daemon, where the communication between them is done via application Faces. The NDN Daemon implements three main parts of the NDN architecture: a Pending Interest Table (PIT), a Content Store (CS) and a Forwarding Information Base (FIB). The Link Adaptation Layer is used to broadcast all the Interest and Data packets through one of the available communication interfaces in the vehicle (e.g., the IEEE 802.11p).

The information-centric network paradigm has been showed several benefits for vehicular networks, connected and autonomous cars, and smart transportation systems. However, when combining the NDN and VANETs, some challenges we have to face. Since all the vehicles keep moving on the street, it is impossible to maintain a fixed topology like a wired network. Therefore, flooding is the most common forwarding strategy adopted. However, flooding brings new trouble to VNDN, which is the broadcast storm. Unnecessary Interest packet dissemination leads to the frequent collision in the communication channel, which results in low content delivery ratio.

Many research works have focused on this issue. Some of them establish a neighbor table in each vehicle. Some use deferred timer to give priority to the desired forwarder. Some use geo-location information. More details are given in Chapter 3, where we discuss recent and relevant studies that addressed the challenges of designing ICN protocols for vehicular networks.

2.3.4 Comparison between Host-Centric and Information-Centric Strategy

The comparison has been given in Table 2.1. Each of the strategy has its advantages and disadvantages.

• For Host-Centric Strategy, there are plenty of routing protocols can be used in traditional TCP/IP-based network. Also, the abundant research from network coding to Game Theory and from topology to user behavior analysis have facilitated the real VANETs. However, host-based naming and forwarding solutions are still used, which is not suitable for the highly mobile scenarios like VANETs. This is because the topology is rapidly changing and the location of vehicles are ever-changing. As a result, compared with the other strategy, Host-Centric Strategy is less efficient for caching management and has a longer delay for replica discovering and retrieving.

• For Information-Centric Strategy, content is named by the name itself instead of IP address. The need for an application and a content is the focus. In this case, content can be discovered and fetched anywhere. Even the vehicles keep changing the location and IP address, it would not affect content delivery since it is information-centric instead of host-centric. Since every single Interest or Data has a signature part which is like a password, the security for content distribution in VANETs is ensured. What is more, content does not need to be transferred to the remote servers. Hence, content fetching and retrieving can be scalable and efficient. Some naming schemes have been summarized in this chapter. However, there is no uniform naming scheme, which is considered as one of the drawbacks of Information-Centric Strategy. Also, Information-Centric Strategy lacks the support of sufficient routing protocols. Moreover, the management cost and overhead for maintaining CS, PIT, and FIB cannot be ignored. Furthermore, cache pollution is much easier to happen in Information-Centric Strategy.

Table 2.1: Comparison of host-centric and information-centric strategy.

	Host-Centric Strategy	Information-Centric Strategy
Advantages	• Plenty of routing protocols based on TCP/IP network • Abundant research support • Already deployed in real VANETs	• Content centric naming • Security ensured • Suitable for mobile scenario • Fast content discovery and retrieving • Easy merged with SDN and vehicular cloud • Large scale computing and storage
Disdvantages	• IP based naming is not suitable for VANETs • Longer delay for searching and retrieving replica • Less efficient for management • Routing complexity is higher	• No uniform naming scheme • Few routing protocols for CCN/NDN • Management cost and overhead for routing tables

As a consequence, Information-Centric Networks, especially CCN/NDN, are new concepts for V-CDN, which is considered as the next generation internet. The Information-Centric Strategy is much more suitable for a mobile scenario than Host-Centric Strategy. Also, solutions based on Information-Centric Networks in V-CDN can be easier merged with SDN and vehicle cloud, which hold an overall view of the topology and large computing capability. Hence, routes selection and content resource management can be more efficient especially in terms of a large volume of content.

2.4 Summary

In this chapter, we gave an overview of the research background, such as VANETs, CDN, ICN, and VNDN. Moreover, the reason we choose vehicular ICN to enhance content delivery in VANETs was explained. And at the end of this chapter, a brief discussion about the advantages and disadvantages of the Information-Centric Networks and Host-Centric Networks was given as well.

Chapter 3

Vehicular Information-Centric Networks

In this chapter, we present an extensive survey of the existing research works that have been proposed for ICN in VANETs. A detail classification, summary, and comparison are given based on the feature of the solutions. Moreover, a brief discussion of the related work and a table summarizing some recently proposed protocols used in the vehicular ICN are listed as well. The solutions for content naming schemes, content delivery strategies and content caching policies in Vehicular ICN are also concluded in this chapter. This chapter is organized as follows. Section 3.1 gives an introduction of vehicular ICN and the classification of vehicular ICN in this thesis. Section 3.2 presents the naming schemes that most used in vehicular ICN. We summarize the state-of-the-art forwarding strategies and classify them into six categories in Section 3.3. At last, we also list some content caching policies in Section 3.4. Some of the summary work in this chapter has been published in [78] accepted by ACM DIVANet.

3.1 Introduction

Focusing on information-centric strategy for content delivery in VANETs, three aspects need to be considered, which are content naming schemes, content forwarding strategies,

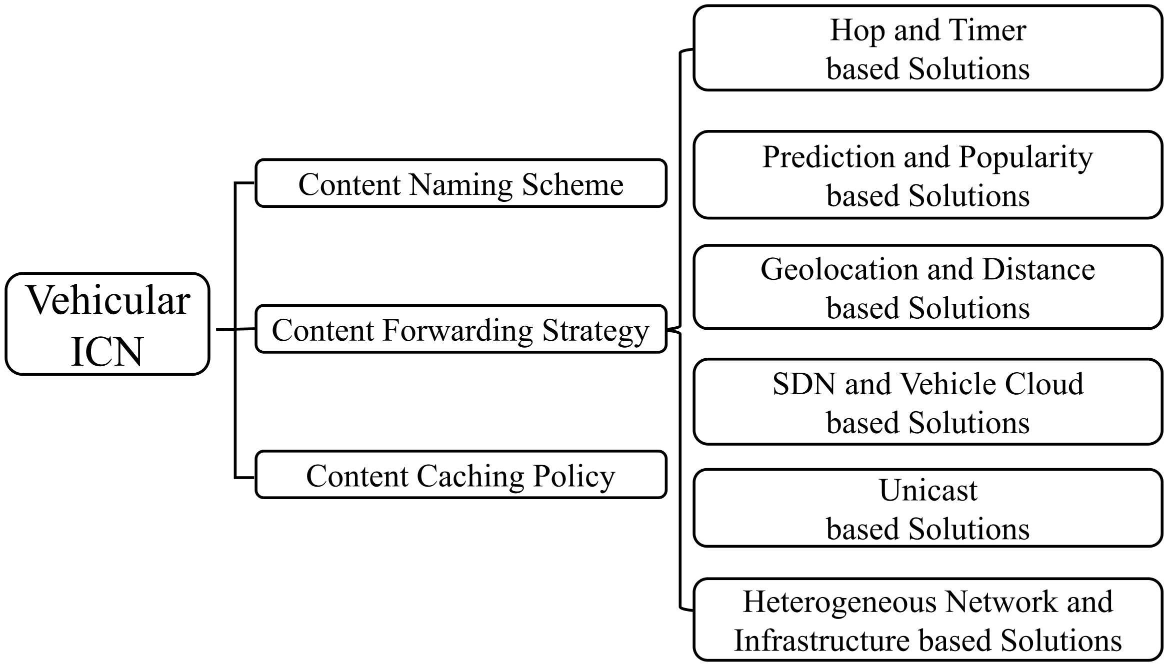

Figure 3.1: Classification of Vehicular ICN

and content caching policies. For content forwarding strategies, the works are classified into six major categories based on different solutions(As shown in Figure 3.1).

Content naming is the core of vehicular ICN. An efficient naming scheme can provide a lot of useful information such as location, timestamp, speed, and the type or the popularity of the content. Therefore, naming can enhance routing and forwarding.

Content forwarding strategies are the area we are focusing on. We summarize the related works and classify them into six categories. Hop and Timer-based Solutions and Geolocation and Distance-based Solutions are the most common solutions used to enhance the forwarding. The information can be carried in either Interest packets or Data packets. Another category is Prediction and Popularity-based Solutions. Prediction-based Solutions use the prediction model to predict the trace of the vehicle. In this way, transmission delay can be reduced by pre-caching the Data packets in the desired area. For Popularity-based Solutions, the transmission priority is given to most popular content to reduce the popular content fetching time. Additionally, instead of using a flooding broadcast scheme, Unicast-based Solutions use the vehicle ID or MAC address to limit the packet transmission of multi-users. Besides, some most recent proposed strategies combine SDN, vehicle cloud or heterogeneous networks. We summarize the solutions as SDN and Vehicle Cloud-based Solutions, and SDN and Heterogeneous Network and Infrastructure-based Solutions. Details are summarized in Section 3.3

Efficient content caching policies can enhance content discovery in vehicular ICN as well. The aim of content caching is to improve the Data packets hit ratio and reduce the delay spending on fetching the Data packet.

3.2 Content Naming Scheme in Vehicular ICN

For content naming, a globally unique name is assigned to content to distinguish each other as identification. Unlike the traditional TCP/IP-based strategy, replica content can hold the same name in various vehicles [22]. It is possible to fetch the content from multi sources instead of getting the content from only one host depending on the end-to-end link in the Host-Centric Networks. On the one hand, efficient naming can reduce the scale of FIB. On the other hand, it can benefit the progress of routing and forwarding, which makes search and retirement faster and less overhead cost. Naming in ICN can be concluded as four main methods: flat, hierarchical, attribute-based and hybrid solutions. However, due to the high scalability of VANETs, flat naming is hard to aggregate so that it is not suitable for this case. As a result, hierarchical naming is widely used in vehicular CCN/NDN [124]. Several similar methods have been proposed in [122, 140, 142, 146, 149].

In [142], content naming includes the following information: application identification, geolocation, timestamp, data type and a nonce value which is used to distinguish different publisher. The global uniform unix epoch is used in the timestamp section. For example, a content is named as `/traffic/Highway 417/north/144,145/1480536000, 1480539600/speed/24569568`. The content is restricted to exits 144 and 145 on highway 417 northbound based on geolocation information. And the lifetime of the content is from @8:00-9.00pm (UTC) on November 30th, 2016.

A three-level hierarchical naming is proposed in [146]. The proposed solution is also a geolocation-based method. Accordingly, three sections contribute to this structure: the location of the destination, the source and the location of next hop from source to destination. The content name of the same city, district, or street can be aggregated, which is considered as scale-based aggregation.

Similarly, another hierarchical naming scheme is proposed in [13]. The pair of (CID, PID) is the identification used to distinguish different content and different chunks. The Nonce is also a large random number assigned by the requester to avoid duplications. Hop count increases one when the packet passes by each hop, which is used to count the hops before the packet reaches the content provider. Provider Info has the information of the provider identification and location, which can enhance the forwarding decision based on the nearest and most responsive scheme. Some more features can be added in Option to enhance content delivery.

Based on the content popularity and shareable level, another hierarchical naming is addressed in [149]. The name consists of the fields: category, service, and additional information. The content can be classified by popular shareable/unshareable content and unpopular content, which are labeled by category. Service is used to distinguish different provider and additional information is used to identify different content.

Another geolocation method is proposed in [122]. The location is labeled as a two-dimension pair (x, y), each of which is consisted of several digital bits. From lowest digit to top digit bit, several digital bit pairs $(x[i], y[i])$ can be generated. By leveraging Cantor pairing function, the two-dimension pair can be changed to one-dimensional sequence c[i], which is used as the component of naming.

A Hybrid Multimedia Naming Design is proposed in [124], which is consisted of three portions: Routable Prefix, Flat Content Identifier, and Primary Attribute Labels. The first portion is used for content distribution. Whereas, the middle part is used to make caching retrieval faster. The last part is to ensure optimal QoE. By combining the hierarchical and flat naming method, this hybrid method holds the scalable and efficient features.

Some naming schemes proposed in vehicular CCN and NDN are summarized in Table 3.1. The comparison is given regarding different features, methods used for naming

Table 3.1: Summary of naming schemes in CCN/NDN

Name	Type	Feature	Architecture
Wang et al. [142]	Hierarchical	Geolocation and timestamp-based	`/Traffic/Geolocation /Timestamp/Data type/Nonce`
Pesavento et al. [122]	Hierarchical	Geolocation-based	`/ndn/ucla/parking/.../c1 /c2/.../cn`
Amadeo et al. [13]	Hierarchical	Counter-based	`/Sub-type/(CID, PID)/Nonce /HCnt/Provider Info/Options`
Yan et al. [146]	Hierarchical	Location-based	`/Destination location/Source location/Next hop location`
Quan et al. [124]	Hybrid	QoE enhancement	`/Hierarchical prefix/Flat content identifier/Attribute labels`
Yu et al. [149]	Hierarchical	Popularity aware	`/Category/Service_name /Additional_info`

and the naming architecture.

3.3 Content Forwarding Strategy in Vehicular ICN

For content forwarding, there are two types of packets in vehicular CCN/NDN: Interest and Data packets. Content forwarding is the process of Interests and Data packets distribution. Content forwarding is also hop-based, which is instructed by PIT and FIB.

Based on the CS, PIT, and FIB, Interest and Data packets forwarding scheme in CCN/NDN is shown in Figure 3.2. When a vehicle receives a packet, the first thing to do is to identify if it is an Interest packet or a Data packet.

- **For an Interest packet:**

1. Check the NONCE value. NONCE value is a globally unique random value, which is used to distinguish different packets. If the NONCE value matches the recorded value, which means this Interest packet is a duplicate one. It should be dropped. Otherwise, it is forwarded to the PIT.

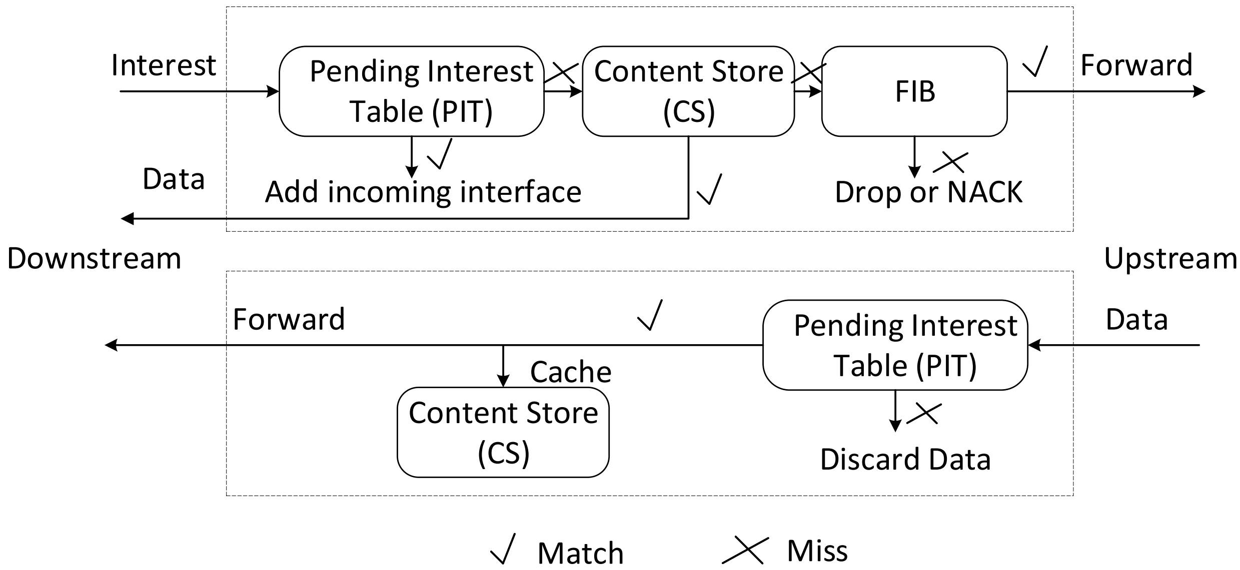

Figure 3.2: Interest and Data packet forwarding in VNDN

2. Look up the PIT to figure out if there is a matching. If so, there are some other Interests requesting for the same content. The new incoming face should be added to the PIT entry and discard the Interest. Otherwise, forward the Interest to content store (CS).

3. Look up CS to see if the packet has already cached in the storage. If the packet is found in CS, then retrieve the replica directly and return it to the requester. If not, forward the Interest packet to FIB.

4. The Interest is forwarded to FIB based on the longest prefix match policy. If the matching is found in FIB, then forward the Interest to the matched face in FIB and then update PIT. Otherwise, drop the Interest packet.

- **For a Data packet:**

1. Check the pending list in the PIT. If there is a matching found, forward the Data packets to the faces in the pending list. Otherwise, drop the Data packets.

2. Before removing the pending Interest, store the replica in CS according to different caching schemes.

3. Remove the pending Interest entry in the PIT.

3.3.1 Hop and Timer based Solutions

Hop and timer are always considered in some works. The forwarding decision is based on hop limitation. The timer could not only be the content lifetime timer but also be the retransmission timer for both Interest and Data packets. Hops and timer are also considered in some naming schemes, which are used as content naming.

In [11], Content-Centric Vehicular Networking (CCVN) is proposed. The content forwarding can be driven either by the consumer or by the provider. In the former mode, the decision is made by the consumer to select the closest content provider based on the hops. In the latter mode, the node can decide to become a provider by itself if it is closer to the consumer than other providers even it is not selected as a provider.

Grassi et al. [90] proposed a Vehicular Named Data Networking (V-NDN) prototype. In their prototype, content search and retrieval is performed according to the basic steps of Named Data Networks [152]. To mitigate the broadcast storm of such steps in wireless scenarios, the authors proposed a timer-based Interest forwarding mechanism at vehicles. Accordingly, upon the reception of an Interest packet, a vehicle calculates a deferred time and use this time to delay its transmission of the received Interest. The deferred time is calculated from the distance from the node to the Interest sender and an additional random component. The idea is to prioritize neighboring nodes that make higher packet advancement in any direction. Hence, when a vehicle hears that an Interest packet was transmitted by a high priority vehicle, it suppresses its transmission if it scheduled the transmission of the same Interest.

Kuai et al. [102] proposed the density-aware delay-tolerant (DADT) protocol. The DADT protocol also entails on deferred timers to prioritize Interest transmissions among neighboring vehicles to mitigate the broadcast storm problem. To calculate the deferred timer in the nodes, the DADT protocol considers not only the distance from the vehicle to the sender but also the distance to the content producer. It relies on periodic beaconing for neighborhood discovery and to know the location of content producers. Therefore, one may argue that it does not entirely decouple consumers from content producers since it maintains the producer information and the path to reach it.

CONET [8] is an NDN-based forwarding solution for VANETs. Theoretically, the data packet would be delivered in the same reverse path with the interest packet. However, the management mechanism is inadequate to ensure that the data is sent back on the same path. CONET is proposed to solve this problem. By adding a hop count value in interest and time to live (TTL) value in the data, every time the interest or data forwarded to the next hop would affect the value by adding 1 or minus 1. The data will be dropped if the value does not match. By doing this, CONET can minimize the forwarding delay and limit the redundancy replica of data.

RUFS [6] is a forwarder selection protocol in vehicular CCN. Each vehicle needs to maintain two lists, Neighbors Satisfied List (NSL) and Recent Satisfied List (RSL). RSL stores the Interest information about the vehicle itself, and NSL stores the Interest information about the neighborhood vehicles. By exchanging the RSL with neighbors periodically, the NSL is updated every time. The forwarding decision is made based the metrics recorded in NSL, such as hop count, satisfaction time and speed. Each metric is assigned different weight. Through the calculation, all the neighbors are ranked, among which the best vehicle would be chosen as the forwarder.

An enhanced version of CCVN (ECCVN) is proposed in [13], deferred timer parameter is added to avoid redundancy broadcast, and the simple routine can strengthen the retransmission mechanism. As a result, there is lower packet loss and collision in ECCVN.

By leveraging CCN, a new network model is proposed in [17], which is suitable for hybrid VANETs. Some new features are added to the data packet, named as Event Packet object. Compared with the traditional Data Packet, Event Packet has an additional portion which is used as Expiry Timer. The cost of each link between the nodes is measured by the travel time between them. The forwarding decision is made based on the expiration time and prioritization. This method is a push-based and suitable for non-safety content delivery.

RTID NDN [141] focus on rapid traffic information forwarding. Pushing timer and retransmission timer are set. Pushing timer is triggered when traffic safety messages need to be pushed. Both NDN-layer and Application-layer are responsible the packet retransmission if no confirmation is received. With the aid of smart random scheduling, the collision can be reduced in the progress of forwarding according to the location information. The further available vehicle from the content provider would be chosen as the next hop. Also, the content forwarding is proactive and push-based by utilizing the broadcasting.

3.3.2 Prediction and Popularity based Solutions

Some works have been proposed to consider prediction and popularity. The prediction includes the location, the traveling route, the density of the vehicles in an area and also the popularity of the content. For popularity itself, content forwarding and caching strategies can be different according to the various levels of popularity.

A Hierarchical Bloom-Filter Routing (HBFR) [149] is a forwarding strategy that is using bloom filter. The name consists of the fields: category, service, and additional information. The content can be classified by popular shareable/unshareable content and unpopular content, which are labeled by category. Service is used to distinguish different provider and additional information is used to identify different content. Based on the packet popularity and the admission of sharing and caching, content is divided into three different kinds. For the popular non-sharable content, this forwarding strategy takes advantages of lower delay and less redundancy by leveraging geographical partition. However, compared with reactive strategy, this proactive strategy has more overhead.

An active caching scheme (P-CCR) is proposed in [123]. The popularity is affected by content references, which means the number of interest requests for the specific content. A threshold is set to limit the number of the interest requests. If the threshold is exceeded, which means the content is popular. Then vehicles would be informed to cache this content. The algorithm is designed to predict the potential popular content, which can be cached in advance. This caching scheme can enhance QoE of users and reduce the RTT.

3.3.3 Geolocation and Distance based Solutions

Some works have been proposed, which consider the geolocation and the distance information. Not only considered in naming scheme in CCN/NDN which is used to label location information of the content, but also geolocation and distance are considered by routing and forwarding for making the decision.

LER [150] is geo-location based forwarding strategy. There are two routing modes. The interests are flooded to the provider on condition that the nodes have no idea about the content provider. However, it will change to geo-location based mode as soon as it gets the information about the location of the destination and also updates the latest information based on the last encounter of every vehicle. According to the simulation, a significant reduction of flooding overhead can be seen.

Differently, the Navigo [92] protocol forwards Interest packets by using geo-location information. By doing so, it uses the Military Grid Reference System (MGRS) that identifies each region of the world by a label. Hence, data names are mapped to geo-areas where they are produced. This protocol is designed for location-dependent applications of VANETs, such as road traffic condition and available parking space. For Interest forwarding, the Navigo introduces the concept of Geographic Faces that are mapped to geo-areas. In summary, Interest forwarding is performed through the shortest path, among the street topology, towards to the area where the content is produced.

Another geo-location based forwarding strategy is proposed in [21]. The naming of an Interest packet in this strategy has the desired data location information. Whenever a vehicle receives an Interest packet, it checks the neighbor table to see if there is a neighbor in the desired area. If the vehicle itself is located at the intersection, it will choose the furthest neighbor as the next hop forwarder. Otherwise, if its neighbor is located at the intersection in the forwarding direction, this neighbor vehicle will be chosen as the next hop.

DASB is proposed in [109], which is a distance assisted Interest forwarding protocol for VNDN. A forwarding table (FT) and a waiting table (WT) are introduced in DASB. FT stores the Interest information to avoid redundant transmission and WT stores the deferral time based on the distance to other nodes. Moreover, a forwarding suppression angle is adopted. That is, only the vehicles who are the given angle of the are able to forward the packets. In this way, a large amount of Interest transmission can be reduced.

3.3.4 SDN and Vehicle Cloud based Solutions

Some works focus on the combination of SDN and ICN and also concentrate on the combination of vehicle cloud and ICN. SDN can bring flexibility and programmability to ICN. Meanwhile, vehicle cloud can offer the enormous ability of computing and resource management. The virtualized network functions and optimal forwarding and caching strategies can enhance dynamical and stable content distribution in ICN.

A Software Defined Content-Centric Networking Approach (SDCCN) is proposed in [74]. The idea is to decouple the control plane and data plane. The centralized controller is located in the control plane, whereas the data plane comprises CCN switches. The routing and forwarding rules are programmable and can be dynamically installed in CCN switches to instruct the content delivery process. Replica allocation policies are kept in Cache Rules Table (CRT) in each CCN router, which is directed by the CCN controller. As a consequence, path selection, cache placement, and forwarding strategies can be much more flexible and efficient.

Cloud computing provides a lot of benefit to wired networks. However, when it comes to vehicle cloud, the highly dynamic traffic makes it hard to implement vehicle cloud [61]. The resource management in vehicle cloud is challengeable and significant [46]. Some motivations have been inspired to combine vehicle cloud and ICN [135]: (i) Merge content types. (ii) Share computing and storage resource. (iii) Support ICN-based applications.

A new concept, vehicular cloud networking (VCN), is proposed in [104], which is the integration of vehicular cloud computing (VCC) and ICN. Unlike the traditional cloud, the primary resources and services that the vehicle cloud can provide are sensing, storage and computing. Three aspects of the designed model are included, which are the system, networking, and service. Since the platform works in a decentralized manner, each vehicle acts as both a service provider and a resource consumer. Meanwhile, since each vehicle can join the cloud and share their resources freely, the reward mechanism is necessary. With regard to content distribution, content can be shared in a P2P way or can be uploaded to the storage.

Similar idea is also proposed in [136]. The decision of content distribution can gain benefits from a higher level view of the topology, especially for the ICN. In other words, the vehicle cloud can enhance resource integration and provide optimal management. Also, information topology is proposed in this paper since ICN brings plenty of semantic meanings. What is more, the attributes of the packets and a learning-based model are used to make optimal forwarding decisions.

Xu et al. [145] proposed the GrIMS (green information-centric multimedia streaming) architecture for energy efficient multimedia streaming in VANETs. In the GrIMS, the computing/control tier is responsible for content searching, resource scheduling and making the delivery decision through the IC-Cloud that a vehicle is participating, while the forwarding/ caching tier manages data forwarding and content caching. In the proposed architecture, Interest packets are not only employed for the content request, but also they are used for the IC-Cloud management, which includes content list exchange between the vehicles and controller of the IC-Cloud, for instance. Content requests (i.e., Interest packets) reaching the IC-Cloud are then forwarded to the proper content provider, which delivers the content through a determined path.

3.3.5 Heterogeneous Network and Infrastructure based Solutions

Some of the content forwarding solutions are based on infrastructures, such as RSU, RSB, and base stations and use heterogeneous networks like V2V accompanying with LTE or V2I communication. Facilitated by the infrastructure, large-scale storage, high computational ability and global view of the underlying topology can be provided, which can optimize replica placement. Therefore, these solutions aim to enhance the V2I performance when the content has not been downloaded from the infrastructure or for the first time to download content from RSU and to improve the hit rate of the desired replica and efficiency of content distribution.

Content download by means of LTE cellular networks is another way to reduce Interest propagation in VANETs. In this context, the authors in [82] proposed the prior-response-incentive-mechanism (PRIM) for cooperative downloading and distribution of big-size and popular content in heterogeneous VANETs (i.e., vehicles equipped with the IEEE 802.11p and LTE Advanced cellular interfaces). Using the PRIM, an Interest packet might be immediately responded when the current receiver decides to download the content using the cellular network. This decision is made based on the Share-Value of the content requester, which measures the current coordination of the requesters.

A VNDN forwarding solution is proposed in [20]. The idea is leveraging the cellular network. Since the high mobility and the existing shield (e.g., buildings and trees) in VANET, the Interest packets may lose before reaching the data provider. To improve the stability and Interest delivery ratio, cellular communication is adopted for interest packets delivery. Compared with Data packets, the Interest packets are much smaller. Hence, the Interest packets would not occupy high bandwidth. The simulation result shows this method can realize fast and stable Interest delivery, offload data delivery by using cellular networks and enhance data packets delivery.

CRoWN [12] a CCN based V-CDN solution, where the content discovery and delivery are based on broadcasting packets. Forwarding strategy can benefit both V2V and V2I communication. A retransmission mechanism is triggered when the transmission failure happens. By storing the content in vehicles, CRoWN can significantly reduce the load of V2I, and more RSU resource can be reserved.

3.3.6 Unicast based Solutions

A multihop and multipath routing protocol (MHMP) is proposed in [99]. The vehicles are distinguished by different MAC addresses, which are considered as globally unique identifications. To get the information for possible next-hop vehicles, blind flooding is adopted as the original forwarding strategy. The information of the neighbors will store in the FIB. When receiving the same Interest packet, the MAC address of next-hop vehicle will be put in the Interest. All the neighbors without the same the MAC address will discard the Interest packet. When facing multiple paths selection, the forwarding decision is made based on hop counter and the latency of each hop. The vehicle with the lowest latency and hop counter would be chosen as the forwarder and the MAC address information of this vehicle will be put in the Interest packet as the target vehicle.

DU is also an unicast-based protocol, proposed in [15]. Two faces are introduced in DU, broadcast face and unicast face. When there is matching name found in the FIB, the Interest packet will be forwarded to the broadcast face. When receiving data packets, the unicast face is registered in the FIB. However, if no Data packet is received from the unicast face for a while, the unicast face will be deleted. Depending on the unicast faces used in the unicast forwarding, either single face forwarding or parallel face forwarding is adopted before broadcast.

A summarizing table of some recent research about forwarding strategies in the vehicular ICN mentioned in this section are attached as shown in Table 3.4 and Table 3.3.

3.4 Content Caching Policy in Vehicular ICN

Content caching in CCN/NDN combines the benefits of both CDN and P2P network. On one hand, CCN/NDN caches content closed to the user end. On the other hand, it is easy to realize in-network caching since the content is not named as IP address so it does not belong to any specific location. In other words, content can be cached in any vehicles and RSUs. Caching in CCN/NDN is the replica stored in the CS. When a hit appears in CS, Data would be sent back to the user end. Efficient caching can enhance content discovery and content retrieve. Basically, what to cache and where to place is what caching needs to consider.

An ICN-based Cooperative Caching solution (ICoC) approach is proposed by [124]. Both the partner and courier corporation assist the progress of cache placement. ICoC focuses on the QoE of multimedia and enhances multimedia distribution. Low startup delay and slow loading for playback can be solved by this probabilistic caching scheme.

By using the prefetching mechanism [98], the possible next interest could be predicted.

Table 3.2: Summary of relevant content delivery solutions in information-centric strategy(1)

Name	ICN	Type	Feature	Comments	Simulator
CCVN [11]	CCN	Hops and Timer based Solution	Consumer and provider driven forwarding	Reliable and low-delay content delivery, lower signaling overhead	NS-2
LER [150]	CCN	Geolocation and Distance based Solution	Opportunistic geo-inspired content based forwarding	Reduce the congestion	NS-3
HBFR [149]	CCN	Prediction and Popularity based Solution	Scalable proactive forwarding	Shorter response time, requires more overhead	Qualnet 6.1
RTID NDN [141]	NDN	Hops and Timer based Solution	Proactive and push-based forwarding	Minimize collisions, reduce the Interests travel distance	NS-3
ECCVN [13]	CCN	Hops and Timer based Solution	Path-state information distribute forwarding and soft-sate forwarding	Efficient and reliable broadcast, trade-off between efficiency and effectiveness	NS-2
Navigo [92]	NDN	Geolocation and Distance based Solution	Self-learning location oriented forwarding	Adaptive discovery and selection, shortest path over road topology	ndnSIM
CONET [8]	NDN	Hops and Timer based Solution	Hop count value and TTL, value constrained forwarding	Control the data flooding/ broadcast storm, minimize Interest Satisfaction Delay	NS-2
CRoWN [12]	CCN	Heterogeneous Network and Infrastructure based	Three data structures: B-Int, A-Int, C-Obj; countermeasures based forwarding	Reduce average travel hops, reduce the duty of the RSU	NS-2

Table 3.3: Summary of relevant content delivery solutions in information-centric strategy(2)

Name	ICN Type	Type	Feature	Comments	Simulator
MHMP [99]	NDN	Unicast-based Solutions	Utilizes the MAC addresses	Low latency, increase the QoS and QoE of users	ndnSIM SUMO
Cellular Aided V-NDN [20]	NDN	Heterogeneous Network and Infrastructure based	Cellular network participating interest forwarding	Improve the delivered contents with low density , reduce transmission delays	SHINE
DU [15]	CCN	Unicast-based Solutions	Broadcast and unicast faces, Single or paralle face forwarding	Shorter content retrieval time, fewer Data transmissions	NS-3
P-CCR [123]	CCN	Prediction and Popularity based Solution	Threshold is set for prefetching and popularity	Improve QoE and reduce RTT, lighten network loads and avoid wasting resources	ccnSim
CCN for Hybrid VANETs [17]	CCN	Hops and Timer based Solution	Graph theory based scheme, collaborative caching based on social relation	Event packet based and Expiry Timer (ExpT) based forwarding	NS-3
DADT [102]	NDN	Hops and Timer based Solution	Retransmission based on directional network density	Higher satisfaction ratio, reduce transimission overhead	SUMO ndnSIM
GrIMS [145]	NDN	SDN and Vehicle Cloud based Solution	IC-Cloud management, two logical tiersc	Lower delay, suitable for multimedia transmission	SUMO ndnSIM
RUFS [6]	CCN	Hops and Timer based Solution	Periodically update NSL, multi metrics	Mitigate Interest broadcast strom	SUMO NS-2
Boosting NDN [21]	NDN	Geolocation and Distance based Solution	Periodically update NSL, multi metrics	Mitigate Interest broadcast strom	SUMO NS-2

When the adjacent vehicles cannot provide sufficient replica, search enlargement mode can be triggered to enhance the discovery. As a result, this method can enhance QoE of multimedia content distribution like video streaming.

An active caching scheme (P-CCR) is proposed in [123]. The solution is a popularity based scheme. The popularity is affected by content references, which means the number of interests requests for the specific content. A threshold is set to limit the number of the interest request. If the threshold is exceeded, which means the content is popular. Then vehicles would be informed to cache this content. The algorithm is designed to predict the potential popular content so that the popular content can be cached in advance. This caching scheme can enhance QoE of users and reduce the RTT.

A CCN based cooperative caching is proposed in [110]. Based on the graph theory, minimum vertex cover set (MVCS) is used in replica selection. Also, the social relationship is considered among collaborative vehicles. By doing this, the number of caching nodes can be minimized and faster content retrieves and video streaming can be realized.

An in-network caching scheme (ICS) is proposed in [137]. First, the vehicle sends the interest to file server via RSU. Then RSU downloads the file from the server and broadcast to a portion of vehicles through R2V communication, which is named Group 1. Vehicles in Group 1 cache the file. Other vehicles are named as Group 2. The files delivered from Group 1 to Group 2 through V2V communication. A caching strategy of Leave Copy Everywhere (LCE) is also proposed. The interest is delivered in a relay mode. Same for the files propagation, the file is replied in the same reverse way and stored in each node on the reverse path so that the file is copied everywhere on the path.

DPC [83] is a probabilistic caching, which can enhance the in-network caching. As in an in-networking scheme, replica vehicles may cache every request content, which is called caching pollution. DPC is proposed to enhance the decision of individual node based on the collecting the interests and the relativity of the interest requesters and data providers. As a result, DPS can reduce redundant caching to reduce the unnecessary caching cost and improve the caching efficiency.

Here is a summary of the caching mechanism in vehicular CCN and NDN shown in

Table 3.4: Summary of relevant caching mechanisms in vehicular ICN

Name	Type	Scheme	Simulator	Comments
Cooperative CCN [110]	CCN	Graph theory based scheme	NS-3	Faster retrieving and smooth video
ICoC [124]	NDN	Social cooperation schemes	ndnSIM	Improve QoE of multimedia
DPC [83]	NDN	Probabilistic caching scheme	ndnSIM	Improve hit ratio
CCF [98]	ICN	Prefetching caching scheme	NS-2	Improve video quality, low delay
ICS [137]	ICN	In-network caching based scheme	Omnet++, veins, sumo	High delivery ratio and coverage ratio
P-CCR [123]	CCN	Prefetching and popularity based scheme	ccnSim	Improve QoE and reduce RTT

Table 3.4. The comparison is given in terms of different technology schemes, advantages of each solution and the simulator used in the simulation.

3.5 Summary

In this chapter, we gave an overview of the recently proposed works in vehicular ICN concerning three aspects, which are content naming scheme, content forwarding strategy, and content caching policy, Discussing the state-of-art related work, a detailed classification, summary, and comparison are presented. Moreover, a brief discussion about the advantages and disadvantages of the related work is given.

Chapter 4

The Proposed Protocols

In this chapter, we demonstrate our proposed three protocols in details. Interest forwarding decision could be made based on several factors, such as content type, vehicular speed, trajectory, content popularity, storage capabilities, moving direction, and the position of the content provider. Different protocols may focus on different metrics. Therefore, we propose a set of protocols for vehicular Information-Centric Networks based on selected metrics. The main goals of the proposed protocols are to mitigate the broadcast storm problem of Interest transmissions and improve content delivery reliability and successful ratio. The protocols differ in the metrics they use for selecting next-hop vehicles to continue forwarding Interest packets for content search. This chapter is organized as follows. Section 4.1 proposes the OIPF protocol, which uses the distance for opportunistic Interest transmission. The related work of OIFP has been published in [148]. Section 4.2 proposes the LISIC protocol, which considers the link stability for next-hop selection. The related work of LISIC has been published in [30]. Section 4.3 presents the LOCOS protocol, which utilizes the location information of the content provider. The benefit of in-network caching can be enlarged by considering the potential location of the content provider. The related work of LOCOS has been published in [79]. Also, the description of the architecture, flowcharts and pseudo codes of our protocols are presented in this chapter.

4.1 The OIFP Protocol

In this section, we present our proposed opportunistic Interest forwarding protocol (OIFP). The OIFP is a lightweight protocol and is proposed to mitigate the broadcast storm. This is achieved by the opportunistic Interest transmission at each hop, where ideally, only one neighbor forwards the Interest packet, while the other neighbor vehicles suppress their transmission. To do so, the OIFP relies on a deferred timer-based prioritization. Prioritization is given to the vehicle that is closer to the transmission edge of the current forwarding vehicle.

In contrast to other solutions, the proposed protocol entails on the location information of the current forwarder vehicle and the location of each neighboring vehicle to calculate the Interest transmission priority at each receiver. Deferred timers, calculated by the distance between neighboring vehicles and the current forwarder vehicle, are used to prioritize the neighbors' Interest forwarding. According to this prioritization, the further a vehicle is from the sender, the lower is its Interest transmission deferred timer.

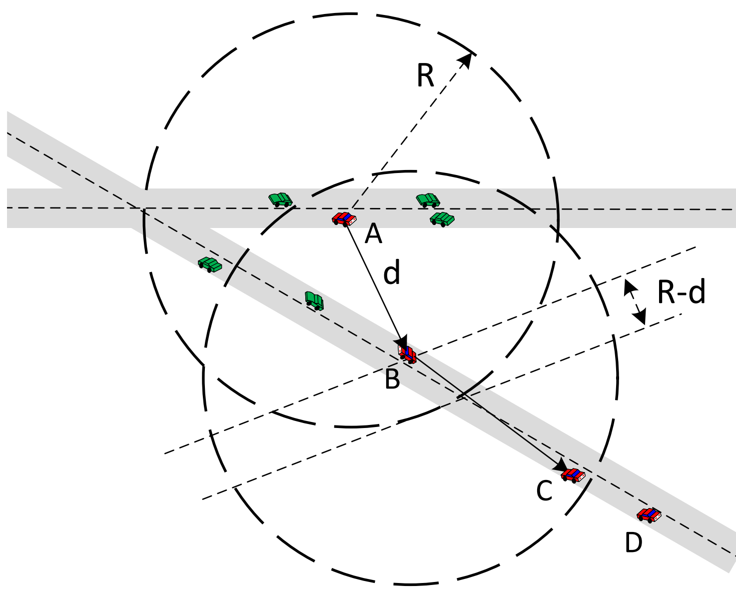

Figure 4.1: The forwarding strategy of OIPF.

Figure 4.1 shows the forwarding strategy of OIFP. Assuming there are many vehicles moving on the street. When vehicle A broadcast an Interest request, all the neighbors that have received the Interest would continue to forward the Interest if they are not the Data producer. There exists a serious problem, which is the broadcast storm. The Interest packets may be trapped in a loop and occupy the communication bandwidth.

Therefore, we propose OIFP leveraging the distance information and deferred timer. The deferred timer is a small timer holden before being rebroadcasted in the forwarder. In our protocol, the deferred timer holden in each vehicle is in direct proportion to the distance between the current location to the edge of the communication range of the last hop. For example, all the neighbors of the vehicle A (shown in Figure 4.1) need to hold on a small deferred timer before rebroadcasting the Interest packet. However, the priority is given to the vehicle B because it is closer to the edge the vehicle A's communication edge. When other vehicles receive the same Interest packet from vehicle B, their events of rebroadcasting the Interest are canceled. In this way, vehicle C continue to rebroadcast the Interest packet.

4.1.1 Interest Packet Processing in OIFP Protocol

4.1.1.1 Procedures

Algorithm 3 presents the Interest packet processing of the OIFP protocol. Whenever a vehicle receives an Interest packet, it verifies whether this incoming Interest was already forwarded or not, i.e., if it is not in the PIT (Line 2). A receiver vehicle will cancel a corresponding Interest transmission if it previously received the incoming Interest packet and scheduled it for later forwarding (Lines 11-15). A vehicle upon receiving a given Interest for the first time will check if it has the requested data. The vehicle then forwards the data packet to the appropriate face (channel or application) if it has it in its cache (Line 9). The appropriate face is determined from the in-face of the Interest packet, i.e., from which face the Interest is coming. An Interest can be received from the channel, when it was produced by another vehicle, or from an application on the vehicle.

Algorithm 1 Received `Interest` Packet

```
1: Received [Name, Selector(s), NONCE, h]
2: if h < TTL then
3:    if Name not in PIT then
4:       if Content not in CS then
5:          PIT.insert (Interest)
6:          d ← distance (receiver, sender)
7:          deferredTimer ← (2/v)(R − d) + β
8:          Schedule [Interest, deferredTime]
9:       else
10:         Send DATA to Face
11:      end if
12:   else
13:      if Interest is scheduled then
14:         Cancel Interest transmission
15:      end if
16:   end if
17: else
18:   Drop Interest;
19:   Cancel Unsatisfy and Straggler Timer;
20: end if
```

4.1.1.2 Interest Transmission Coordination

The main contribution of the proposed protocol is the procedure to cope with an incoming Interest packet when the vehicle is receiving the incoming Interest for the first time and does not have the requested data in its CS. The vehicle then calculates its distance to the sender vehicle (Line 5). The distance is determined by the current location of the vehicle and the location information of the vehicle that forwarded the Interest, which is included in the Interest packet. After that, the vehicle calculates its deferred timer and then schedules the Interest transmission (Lines 6-7).

We proposed a linear function to calculate the deferred time of each vehicle. This calculation is straightforward and works as follows. Let R be the communication range of the vehicles and v be the signal propagation speed which equals to 3.0×10^8 m/s. For a given vehicle i located at distance d_i meters from the current forwarder vehicle, its deferred time will bec slightly higher than the required time to the packet to reach the limit of the communication range and come back, that is $2 \times (R - d_i)/v$. Therefore, the closer the vehicle is to the boundary of the communication range, the lower is its deferred time. In addition, it is important to mention that this proposed linear function advantageously does not suppress transmissions among different directions, which helps in the process of content searching. The variable β is the transmission delay, which is calculated by the length of NDN Interest packet divided by the transmission rate (Line 6).

4.1.2 Data Packet Processing in OIFP Protocol

Algorithm 2 is used to process an incoming data packet. Whenever a vehicle receives a data, it checks in its PIT if there is a pending request for that content (Line 2). The vehicle cancels scheduled Interest transmission (Lines 4-5) if there is a scheduled Interest transmission of that content. Finally, the vehicle sends to the adequate face the incoming data and removes the pending interest entry of its PIT (Lines 6-9). It is important to mention that in our implementation, vehicles will always cache data packet, even if they are unsolicited (Line 11).

Algorithm 2 Received `Data` Packet in OIFP

```
1: Received [Name, MetaInfo, Content];
2: if Name in PIT then
3:    if Corresponding Interest is scheduled then
4:       Cancel Interest transmission
5:    end if
6:    Send Data to Face;
7:    Remove PIT Entry: Interest, Face;
8:    Cancel Unsatisfy Timer;
9:    Cancel Straggler Timer;
10: end if
11: Cache the Data;
```

4.2 The LISIC Protocol

In this section, we propose the link stability-based Interest forwarding for content request (LISIC) protocol to tackle the broadcast storm problem in vehicular networks. The basic idea of our proposed protocol is to select the most stable links among vehicles during the Interest and Data propagation. The stability is measured by using connection time based on the relative velocity and moving direction, $\vec{v_i}$ and $\vec{v_j}$, between a current Interest sender A and receiver B. Therefore, the selected path is the best in terms of stability.

4.2.1 Interest Packet Processing in LISIC Protocol

4.2.1.1 Link Stability Function

Let's consider two vehicles A and B are moving on the street at time point t, as shown in Figure 4.2. They are both each other's neighbor, which means they are in each others communication range. Each of them is moving in their own lane with the current speed $\vec{v_i}$ and $\vec{v_j}$ respectively.

The angles between the latitude and the longitude directions are θ_i and θ_j, respectively. Let (x_i, y_i) and (x_j, y_j) be the current location of the vehicle A and vehicle B. There may exist a time point where A and B will lose connection and go further away from each other. Let A' and B' denote the position of vehicle A and B at that time point t'. As shown in Figure 4.2, there will exist a right triangle whose hypotenuse is the communication range R.

We estimate the link duration s, i.e., link stability, between the vehicles A and B as follows. First, let's define m (Eq. 4.1) and n (Eq. 4.2) as the relative position and p (Eq. 4.3) and q (Eq. 4.4) as the relative speed of A and B, respectively.

$$m = x_i - x_j. \tag{4.1}$$

$$n = y_i - y_j. \tag{4.2}$$

$$p = v_i \times cos\theta_i - v_j \times cos\theta_j. \tag{4.3}$$

$$q = v_i \times sin\theta_i - v_j \times sin\theta_j. \tag{4.4}$$

In Eq. 4.1 and Eq. 4.2, the terms m and n represent the position difference in the

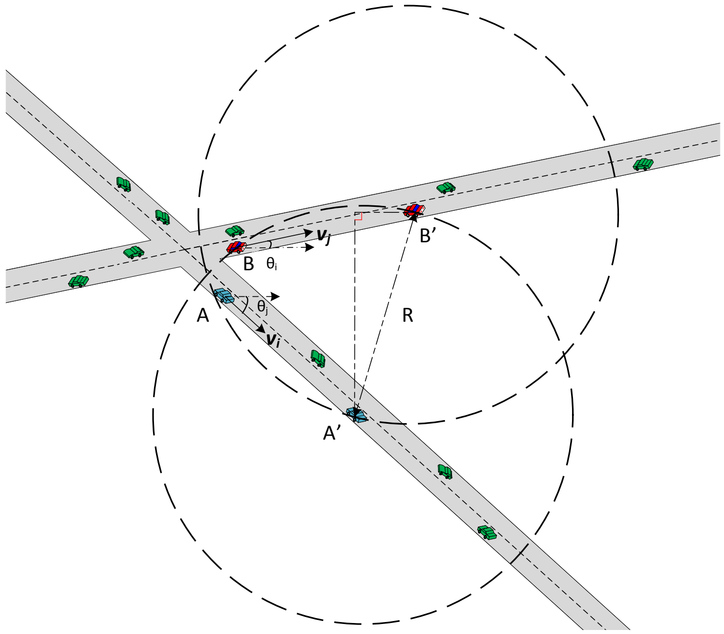

Figure 4.2: The mechanism of LISIC.

horizontal and vertical directions between the vehicle requesting content and the vehicle that received the transmitted Interest packet. Similarly, the terms p and q in Eq. 4.3 and Eq. 4.4, respectively, denote the speed difference in the latitudinal and longitudinal directions.

Finally, the possible connection time s between vehicle A and B can be calculated by using Eqs. 4.1 to 4.4, as:

$$s = \frac{-(mp + nq) + \sqrt{(p^2 + q^2) \cdot R^2 - (np - mq)^2}}{p^2 + q^2}. \tag{4.5}$$

where $m^2 + n^2 < R^2$ and $0 < \theta < 2\pi$. When the speed of a vehicle A ($\vec{v_i}$) is infinitely close to the speed of its neighbor B ($\vec{v_j}$), as well as their latitudinal and longitudinal directions θ_i and θ_j are infinitely close, s is infinitely approaching to ∞. Therefore, the more similar moving pattern (direction and velocity) the vehicles A and B have, the longer is the connection between A and B and the more stable is the link between them.

4.2.1.2 Deferred Timer Function

In this section, a deferred timer function is proposed for the Interest transmission prioritization among neighboring vehicles. Accordingly, whenever a low priority level vehicle hears that a high priority vehicle transmitted an Interest packet, the vehicle suppresses its transmission of the same Interest. Therefore, the number of Interest transmissions decreases, which improves the channel efficiency and, consequently, the application performance.

In the proposed LISIC protocol, the priority of a neighboring vehicle will be given as a function of the link duration between the current sender and itself, calculated by Eq. 4.5. This is because Data packets are delivered through the reverse path of the Interest transmission. Since VANETs have highly dynamic topologies due to the vehicular mobility [72], LISIC prioritizes more stable link between vehicles. The deferred timer of an Interest packet received by a vehicle B is given as:

$$T_B = \left(\alpha \times \frac{2R}{c}\right)^2 \times \frac{1}{s} \times (1 + T_r) + \frac{R}{c}. \tag{4.6}$$

where α is the time scale factor, c is the signal transmitting speed, which is the light speed $3 \times 10^8\,\mathrm{m/s}$, s is the predicted connectivity duration (link stability) between the sender and the receiver, given by Eq. 4.5, and T_r is a random value in the interval [0, 0.1], used to avoid Interest or Data packet collision when two scheduled time is the same or close. In Eq. 4.6, the term R/c is to ensure that the further vehicle from the Interest sender can receive the Interest packet before the deferred timer of the nearer vehicle finishes. The goal is to guarantee that the vehicle with the longest connection time with the current sender can be able to forward the Interest before a low priority level vehicle does so.

4.2.1.3 Procedure

The LISIC protocol is implemented under the Named Data Networks paradigm for content request and delivery. Thus, a vehicle creates and transmits an Interest packet whenever it is requesting for a content. In the LISIC protocol, Interest packet is augmented with three additional fields: sender location, sender speed and hop count. The first two fields are used by the receiver to calculate the link duration (please refer to Eq. 4.5). The hop count field is used to limit the propagation of Interest packets, based on the configured time-to-live (TTL) value.

Figure 4.3 depicts the processing path of an incoming packet in a vehicle. The very first step for a vehicle when receiving a packet is to know if it is an Interest or a Data packet (Step 1). For different packet types, the next step goes into different pipelines.

Whenever a vehicle receives an Interest packet, it executes the following steps:

- First of all, the hop count is abstracted and compared with the pre-set hop limitation (TTL). Determine whether this value exceeds the limit (Step 2). That is, if the Interest goes further than that value, the Interest would be dropped (Step 12).

- Secondly, determine if the incoming Interest has been already processed and forwarded, which is the same as in the vanilla NDN. This step is to avoid redundant schedule of the Interest packet that has been satisfied or the same Interest packet that has been received again by checking the dead NONCE list and NONCE value in the Interest packet(Step 3-4). The receiver cancels a scheduled transmission of the corresponding Interest if match found in the dead NONCE list and NONCE value in the Interest packet.

- Then, a lookup operation is performed in the PIT (Step 5). If the vehicle receives the Interest for the first time, which means no pending Interest in the PIT. The vehicle then checks its content store. If a pending Interest is found in the PIT for the same Data chunk, we aggregate the received Interest with the existing PIT entry (Step 6).

- Before rebroadcast the Interest packet, some more procedures need to be done since we do not want all the neighbor vehicles who have received the same Interest packet to rebroadcast the Interest (Step 9-11). To do so, the receiver vehicles calculate the possible link duration between itself to the current sender. From the received Interest packet, the vehicle can obtain the location and speed information of the sender. After that, it calculates the relative position and speed of the sender vehicle

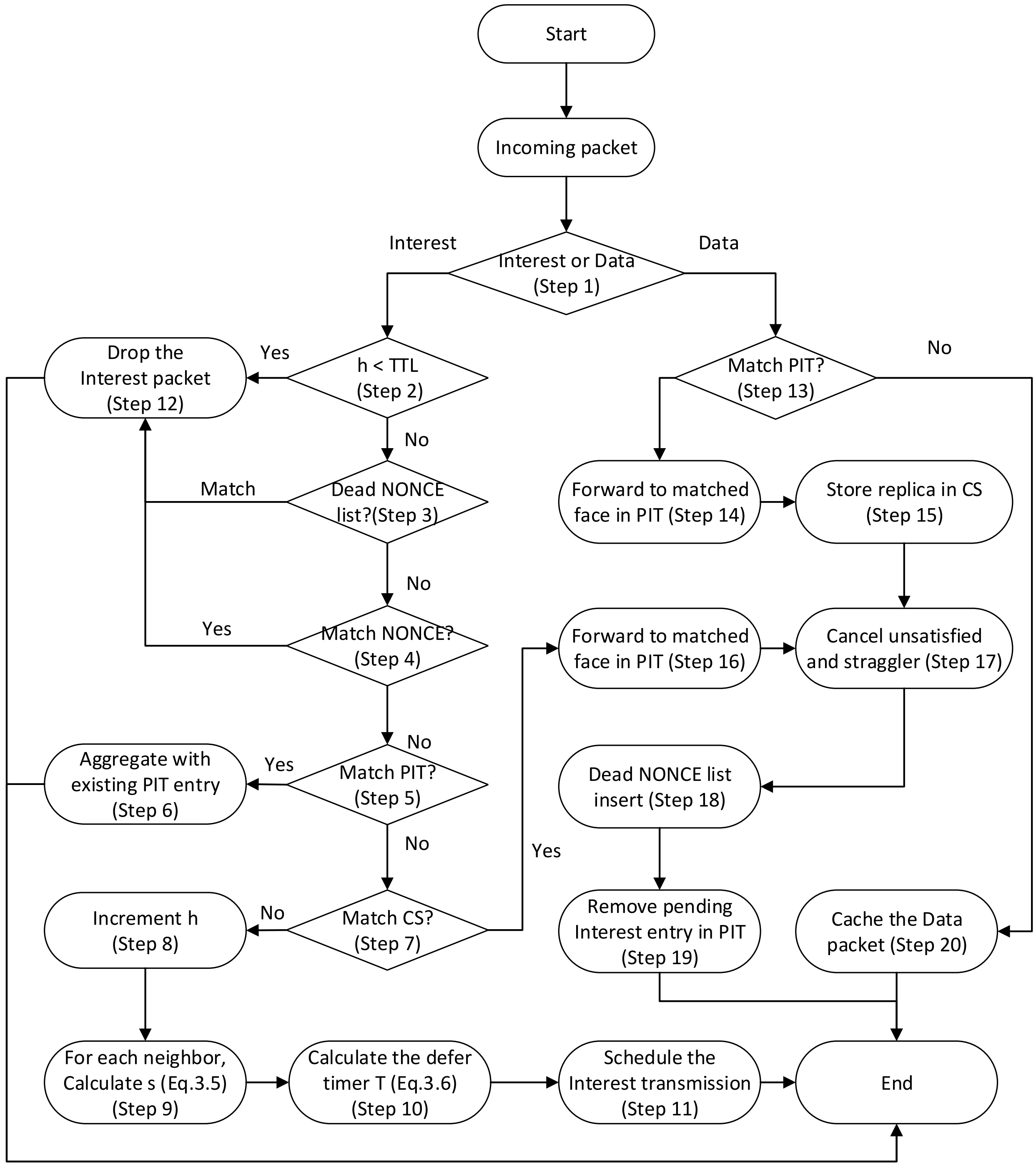

Figure 4.3: Flowchart of the processing path of an incoming packet in LISIC.

by using Eq. 4.1 to Eq. 4.4. From these values, the receiver then estimates its link duration to the sender and the deferred time is calculated in Eq. 4.5 and Eq. 4.6 respectively.

- Finally, the rebroadcast of the Interest to the next hop event is scheduled by the receiver vehicle based the calculation which deciding the priority of the Interest forwarding. On the other hand, if the Interest is satisfied by the Data chunk in the CS (Step 7). The vehicle should delete the corresponding PIT entry and cancel the unsatisfied the timer and straggle timer and record the Interest information in the dead NONCE list, which means the Interest has been satisfied and no more process needed for the Interest (Step 16-19).

4.2.2 Data Packet Processing in LISIC Protocol

Whenever a vehicle receives a Data packet, it executes the following steps:

- First, a lookup operation is performed in the PIT (Step 13). This step is to determine if there is an Interest request by the vehicle or if the vehicle is a forwarder of the desired Data chunk.

- Second of all, if there is a match in the PIT, the Data packet will be sent to the face that recorded in the PIT entry (Step 14). The face would be an app face or a network face depending on if the vehicle is a consumer or forwarder of the received Data packet. If there is no match found in the PIT. The vehicle just keeps the overheard Data chunk in the CS without doing more actions (Step 15).

- After the Data sent to the desired face, the Data will be stored in the CS for future use (Step 20). In this case, when receiving the Interest packet for the same Data chunk next time, he Interest will be satisfied by current vehicle without further propagation.

- In the end, the vehicle deletes the corresponding records of the Interest packets in the PIT. Cancel all the timers related this Interest and record the NONCE value of the Interest in the dead NONCE list (Step 17-19). Up to now, the Interest has been satisfied by the Data packet.

4.3 The LOCOS Protocol

Similar to the aforementioned works we have done, our proposed LOCOS protocol is aimed to reduce Interest transmissions in the VANETs, to improve Interest satisfaction by forwarding it to an area where it may find the data and consequently mitigate the broadcast storm of content search in VNDN. The idea of LOCOS is to leverage the mobility information of a content caching vehicle to reduce the number of Interest packet transmissions. The mobility information about a vehicular content server can be represented by its current location, destination or even better, its trajectory. This information can be obtained from several GPS-aided applications used for route planning. During the content delivery, this information is able to be piggybacked in the Data packet.

Considering each content consists of several chunks, there is a strong correlation between them. That is, there is a high probability that a client will find subsequent chunks in the vehicle that has delivered the previous ones. Therefore, we do not need to opportunistically request the missing Interest chunks over all directions. When the requester receives the first Data chunk, which has the location information of the content source, this information can be used for the other Interest chunks of the same content.

Therefore, two forwarding phases are proposed in LOCOS. For the first Interest chunk transmission, we need an efficient routing protocol to get the location information of the content source. Hence, we adopt OIFP (Section 4.1) or LISIC (Section 4.2) protocol for the first forwarding phase. Assume that the producer of one Interest chunk may have the remaining chunks of the Data, we also offer a producer location-based routing protocol (Section 4.3.1) for the remaining Interest chunks transmissions in the second forwarding phase.

Depending on the different protocol used in the first forwarding phase, LOCOS can be extended into two possible protocols, LOCOS-OIFP and LOCOS-LISIC. Both protocols have different advantages, as discussed in the following:

- For LOCOS-OIFP protocol: The distance information between current vehicle and the potential next hop vehicle is used in OIFP. That is, the furthest vehicle from the last hop has the priority to forward the Interest packet to the next hop vehicle.
- For LOCOS-LISIC protocol: The LISIC protocol uses the link stability among neighboring vehicles to prioritize them during the Interest forwarding process. Thus, vehicles with low priority will suppress their transmission when they hear that the Interest was transmitted by a high priority vehicle.

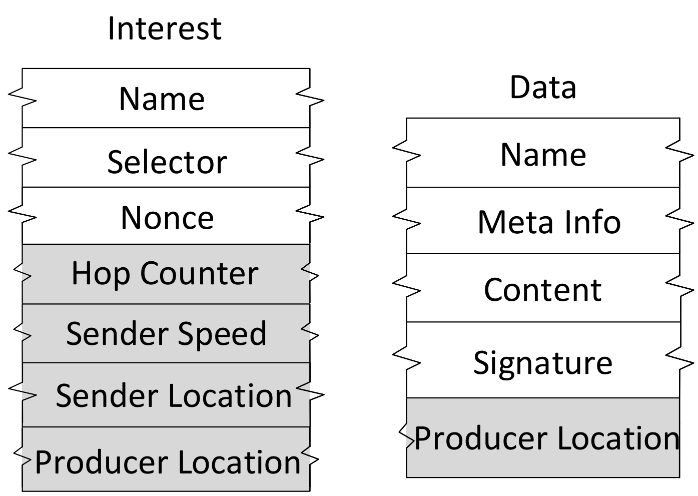

Figure 4.4: Extension in Interest and Data packet.

Moreover, it is important to highlight the differences between the proposed LOCOS protocol and the traditional geographic routing. First, geographic routing needs discovery procedure to determine the location information of the destination (content producer). Conversely, our proposed LOCOS protocol provides this functionality by implementing a controlled Interest flooding for content discovery when a vehicle does not have any information of a content source. Second, geographic routing protocols forward packet until the established location and they additionally rely on the vehicles' identification to directly delivery packets to them. In contrast, any neighboring vehicle that has the content in its cache can stop the content search and start delivering the requested content, independently if the request reached the considered location or if the intended content source was found there.

In order to realize the new function, additional features are extended in Interest and Data packets marked as grey and illustrated in Figure 4.4. The very first Interest request for one chunk of a content adopts the OIFP or LISIC routing protocol, which need the location and the speed information. Therefore, several new sections are added in Interest packets, which are hop counter, last hop speed and location, and producer location. In the replied Data packet, the information of the producer location is stored in the extension section in the new Data packet structure.

4.3.1 Interest Packet Processing in LOCOS Protocol

4.3.1.1 First Forwarding Phase

The first forwarding phase uses OIFP or LISIC protocol to do the Interest forwarding. The task of the first forwarding phase is to get the content source location information and record the information in each vehicle. Then there appear two questions: 1. How to get to the location information? 2. Where to store the information?

Since the replied Data packets are able to carry the location information of the content source, we can extend the Data packet and put the location information in the Data packet. By doing this, every vehicle on the forwarding path can get this information.

Meanwhile, we assume that there is only one IEEE 802.11p interface equipped in each vehicle. Thus, FIB is not needed to decide which interface should be used to forward the incoming packets or chunks. Instead, we use the FIB for the mobility-based forwarding. That is to say, we leverage FIB to store the information of the producer location for each content. Therefore, except the first Interest packet, all the other Interests for the same content have a target destination, which may be used in the second forwarding phase.

Also, we have considered the location information is time sensitive. If this information is stored in the FIB for too long, the content provider may leave the desired area. Therefore, to make the location information meaningful, we use an FIB entry to describe and record the location information.

Table 4.1: Example of the FIB in a vehicle

Content Name Prefix	**Location**	**Timestamp**
`/CBC/Ottawa/chunk1`	(lat_D, lon_D)	Fri Feb 16 13:36:23 EST 2018
`/Spotify/Pop/chunk5`	(lat_P, lon_P)	Fri Feb 16 13:36:45 EST 2018
`/Google/Photo/chunk8`	(lat_Q, lon_Q)	Fri Feb 16 13:37:09 EST 2018
`/CBC/Ottawa/chunk3`	(lat_D, lon_D)	Fri Feb 16 13:38:35 EST 2018

The FIB table in each vehicle has three attributes, which are Interest name prefix for each chunk, producer location, and timestamp, as the example shown in Table 4.1. Upon an Interest reception by a vehicle, the LOCOS protocol compares the content name in the Interest packet with the content name prefix in the FIB. The entry with the longest prefix match is used to obtain the probable location of a content cache vehicle that might have the requested content. The entry is used if it is still valid (freshness lower than a considered threshold),

The Interest is then forwarded towards the location (latitude, longitude) of the known content cache vehicle. If there is no entry in the FIB with the prefix name of the requested content, the LOCOS protocol uses the OIFP or LISIC, based on the considered configuration, for content source discovery.

4.3.1.2 Second Forwarding Phase

As shown in Figure 4.5, assume that the vehicle S has sent out the Interest request, whose name prefix is `/CBC/Ottawa/chunk10`. The other vehicles have the FIB table like Table 4.1. When the neighbors of vehicle S receives the Interest packet. They check the FIB table and find the FIB entry with the same name prefix. Then, the corresponding recorded location value in the FIB entry is abstracted, which is (lat_D, lon_D). That is to say, there is a big chance to get the desired content from the area around (lat_D, lon_D), which is/was the location of vehicle D.

Afterward, each neighbor calculates the distance to the (lat_D, lon_D) and also the distance to the last hop. If the distance to the target destination is even further than the last hop location to the target destination. Then there is no need to do further process. Drop the received Interest packet. Otherwise, we chose to use deferred timer (calculated by Eq. 4.7), which is used to prioritize Interest transmissions among neighboring vehicles. This time, the priority is given the vehicle that is closer the target destination.

Based on the last hop location, current location and the target destination, the deferred timer is calculated in each vehicle independently by using Eq. 4.7), as:

$$\text{deferredTimer} = \frac{Dist(A, D)}{Dist(S, D) \times Dist(S, A)} \times T + T_{random}. \tag{4.7}$$

where $Dist(A, D)$ is the distance between the current forwarding vehicle A and desired destination vehicle D. And $Dist(S, D)$ is the distance between the last-hop vehicle S and desired destination vehicle D. In addition, $Dist(S, A)$ is the distance between the last-hop vehicle S and desired destination vehicle D. T is the maximum transmission time to limit deferred timer. T_{random} is a random timer to avoid two events scheduled at the same time.

This function reflects that the deferred timer is proportional to $Dist(A, D)$ and is inversely proportional to $Dis(S, A)$. That is, the vehiclec closer to the producer has the shorter deferred timer, and the closer the current vehicle is to the last hop vehicle, the longer the deferred time is. The event of the vehicle with the longer deferred timer will be scheduled later. In this case, the vehicle A will be chosen as the only forwarder to pass the Interest packet to the next hop.

Subsequently, the same process is done by the neighbors of vehicle A and vehicle B. Both vehicle A and vehicle B are chosen as the next hop vehicle during the transmission of Interest $/CBC/Ottawa/chunk10$. And finally, the Interest is satisfied by vehicle D. During the transmission, assume that the desired Data is not found in CS. Of course, if the desired Data is found in CS, then the Interest can be satisfied immediately. The Interest and Data Packet Processing will be explained in the following section.

As a consequence, the LOCOS protocol differs from recent related work in the follow-

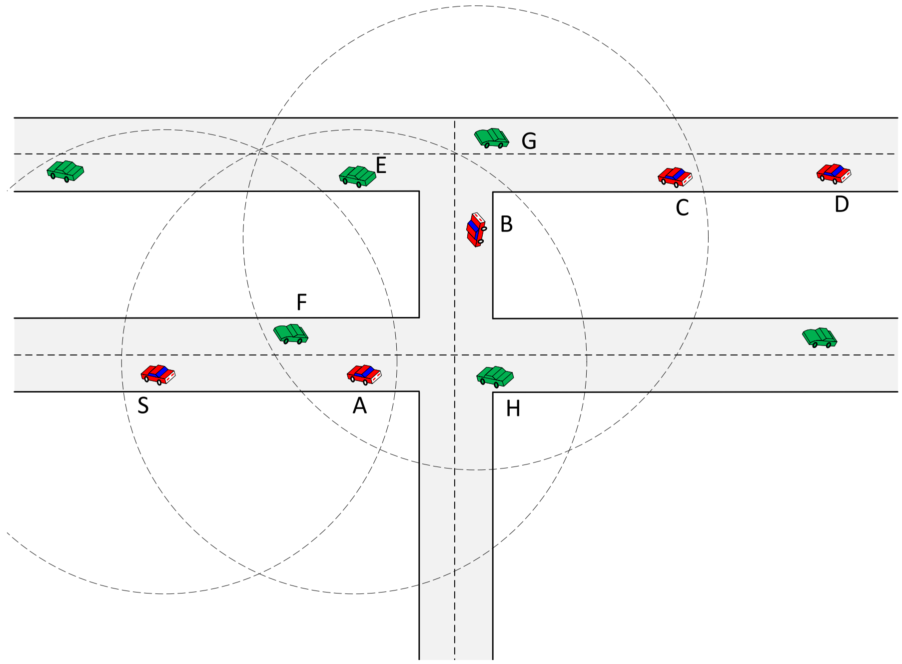

Figure 4.5: The second forwarding phase of LOCOS.

ing aspects. First, it only maintains the content source location instead of the next-hop information. Thus, it is less affected by the topological changes in the routing path. Second, it can retrieve the content even when the source is not in the exact known location, that is, the content search will be performed the proximity, while the traditional approach cannot retrieve the content when a next-hop is no longer in the communication range of the previous hop.

4.3.1.3 Procedure

Algorithm 3 shows the procedures performed upon an Interest packet arrival. First, an incoming Interest packet will be processed in the vehicle only if the packet did not reach the maximum hop count (Lines 2-3). After that, the vehicle will perform a controlled Interest flooding when it did not forward the Interest yet, does not have the requested content and its cache and does not know the location of a probable content source (Lines 4-8). We can use the OIFP [148] or LISIC protocol [30] for the controlled flooding of Interest packets.

If there is a match in the FIB for the content name of the requested chunk, the Interest packet will be forwarded towards the content source vehicle. As mentioned at the beginning of this chapter, a content is composed of several chunks. Therefore, the name `/Google/Photo/chunk8` in the Interest packet, for instance, refers to the 8th chunk of the content `/Google/Photo`. In this example, if the vehicle knows the location information of a content source that delivered any chunk of the content `/Google/Photo`, it uses that location to forward requests from subsequent chunks of that content.

Of course, the content source vehicle may not be any more at the location that the intermediate vehicles have in their FIB. However, since it was there and delivered content for previous requests, there is a high chance that another vehicle in the area has the requested content in its cache. Thanks to the in-network cache property of the NDN paradigm and the broadcast nature of wireless links, which allows neighboring vehicles to opportunistically cache in their content store.

The directed Interest forwarding is performed as follows. First, the vehicle A calculates its distance to the content source vehicle D, the distance from the previous hop that transmitted the Interest from S to D, and the distance from S to itself (A) (Lines 11-12). If the vehicle is able to advance the packet towards the content source vehicle, it calculates its deferred timer and schedule the Interest transmission (Lines 13-17). Otherwise, it discards the packet (Line 18). A vehicle will suppress a scheduled Interest transmission if it receives the same packet from a high priority vehicle, that is, a vehicle closer to the known content source.

In addition, it is important to mention the procedure `ContentStoreMiss` and the procedure `ContentStoreHit`, invoked at Lines 6 and 22, respectively. The first procedure is responsible for creating an entry in the PIT when a content request arrives at the first time in a vehicle. The second procedure is responsible for replaying the content request when the vehicle has the content in its cache. The location of the vehicle is piggybacked in the Data packet. This information is used by intermediate vehicles to update their FIB.

Algorithm 3 Received `Interest` Packet in LOCOS

```
Received [Name, Selector(s), NONCE, h];
h ← HopCount(Interest)
if ++ h < TTL then
    if Name not in PIT then
        if Content not in CS then
            ContentStoreMiss();
            if Name prefix not in FIB then
                OIFP or LISIC-based forwarding;
            else
                Select the longest prefix matched and the latest FIB entry;
                Get desired producer location from FIB;
                Calculate Dist(A,D), Dist(S,D), Dist(S,A);
                if Dist(A,D) < Dist(S,D) then
                    Calculate the deferredTimer (Eq. 4.7);
                    deferredTimer = min(T, deferTimer);
                    Schedule (Interest, deferredTimer);
                else
                    Drop Interest;
                end if
            end if
        else
            ContentStoreHit();
            Set source location in the DATA;
            Send DATA;
        end if
    end if
end if
Insert or update PIT entry record;
```

4.3.2 Data Packet Processing in LOCOS Protocol

Algorithm 4 depicts the procedures performed upon a Data packet reception. Overall, a vehicle will continue forwarding an incoming Data packet, toward its requester that might be itself as well (Lines 4-8), update its FIB with the location information of the content source vehicle, that is, the location contained in the header of the Data packet (Lines 9-11), and cache the Data for future requests (Line 11). Moreover, Data packets are opportunistically cached at vehicles, upon their receptions (Line 13).

Algorithm 4 Received `Data` Packet in LOCOS

```
Received [Name,ProducerLocation,Chunk];
if Name in PIT then
    Remove PIT Entry;
    if request from local face then
        Send Data up to Application;
    else
        Send Data down to Neighbor;
    end if
    Obtain producer location from Data
    Update FIB entry for the content;
    Cache the Data;
else
    Cache the unsolicited Data;
end if
```

4.4 Summary

In the chapter, we explained the design of our proposed protocols in detail. We considered different metrics that may influence the forwarding decision. In our proposed protocols, the priority to forward the Interest packet is given to the desired vehicle rather than all the neighbor vehicles rebroadcast the Interest without priority. The desired forwarder is with the consideration of the distance to the last hop, speed, moving direction, and relative location to the possible content provider in different proposed protocols.

Chapter 5

Simulation and Evaluation

In this chapter, we conduct simulations to compare the performance of the proposed protocols. In the first part of this chapter, the simulation environment, parameters and scenario are presented. In the second part of this chapter, we discuss the obtained results of our simulation based on different metrics. We compare our proposed protocols in the previous chapter against recent and relevant related work in the area. This chapter is organized as follows. Section 5.1 gives the information of our simulation setup, which includes the simulator and experimental scenario and parameters we used. Section 5.1 presents the simulation results of all the proposed protocols and three related works, DU [15], CODIE [7] and MHMP [99].

5.1 Simulation Setup

The simulation and modeling in VANETs are quite similar to simulation and modeling in WANETs. We choose OMNeT++, a discrete event simulator. It is IDE friendly and is compatible with Veins, which provides the perfect vehicular environment. The simulator and platform we used to implement our protocols are introduced as follows:

OpenStreetMap[1] [95] is used to generate the real world map. And we adopt the OM-

[1]https://www.openstreetmap.org/

NeT++ 5.0 Discrete Event Simulator[2] to implement the studied protocols, the Vehicle in Network Simulation (Veins 4.5) [134] to simulate vehicular networking, and the Simulation of Urban MObility (SUMO 0.25.0)[3] to simulate vehicular mobility.

SUMO is an open source road traffic simulation platform, which is used for generating the trace files. The trace file consists of the vehicles and roads. Besides, the movement and behaviors of the vehicles are described in SUMO.

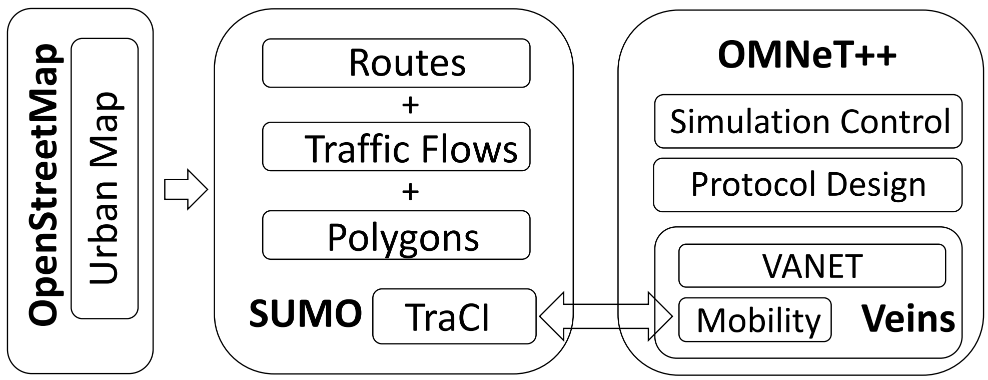

Figure 5.1: The setup of the simulation.

OMNeT++ is an open source network simulator widely considered in the literature, which is used for network simulation. It supports Eclipse-based IDE. Besides, it provides plenty of network models and protocols. It implements a plenty of network models and protocols, such as the traditional GPSR and AOVD in traditional ad-hoc networks.

Veins provide simulation models for vehicular networking. It provides the implementation of the IEEE 802.11p, DSRC/WAVE, and Wave Short Message (WSM) in VANETs. With Veins, OMNeT++ and SUMO are able to work in parallel for each simulation. Figure. 5.1 gives an overview of how things work together among the mentioned frameworks. With Veins, OMNeT++ is able to communicate with SUMO through Traffic Control Interface (TraCI). In this way, the behavior of the vehicles on the street in SUMO is reflected as the movement of the node in OMNeT++ and vice versa.

[2]https://omnetpp.org/
[3]http://sumo-sim.org/

5.1.1 Simulation Framework

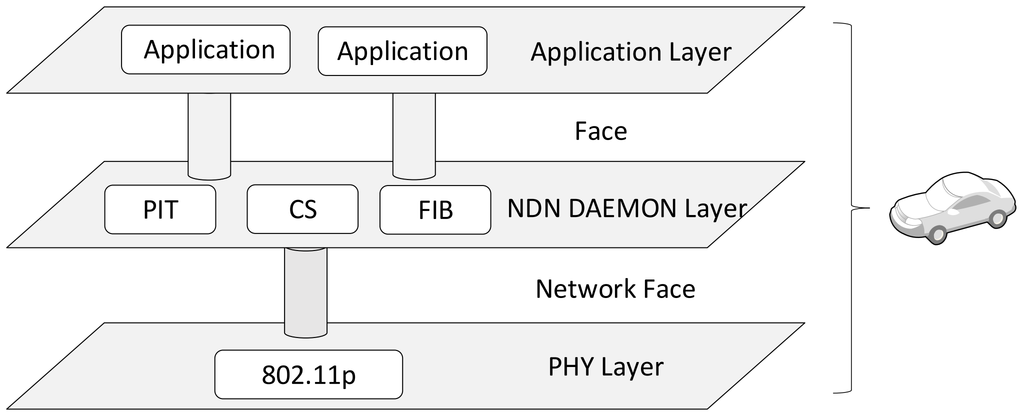

Figure 5.2: The designed VNDN framework in OMNeT++.

According to [4], we implement the VNDN framework in OMNeT++ 5.0. As shown in Figure 5.2, there are three layers, application layer, NDN DAEMON layer and physical layer. Each layer can communicate with the subsequent layer via faces (app face and network face). For instance, the NDN DAEMON layer will receive incoming Interest and Data packets from the physical layer through the network face.

The implementation of the Named Data Networks specification, functions and forwarding pipelines based on the guidelines provided in the NFD Developers Guide [4]. Three data structures, PIT, CS, and FIB, are designed on the NDN DAEMON layer. Besides, a file sharing application is developed on the application layer, where a content composed of 10 chunks will be requested by the client vehicles.

5.1.2 Experimental Scenario and Parameter

The simulation scenario is based on the real world area, which is generated by using OpenStreetMap. The considered area is the downtown area of Ottawa, Canada (please, refer to Figure 5.3).

We consider 200, 300 and 400 vehicles moving in the considered downtown area, following mobility trajectories generated by the SUMO. And we vary the percentage of the

Figure 5.3: Considered area: downtown area of Ottawa, Canada

content producers (which is set to 6%, 9%, 12%, 15%, and 18%) as well to see the influence on the forwarding performance. Moreover, for each replication, we randomly select 30% of the vehicles as content consumers (clients). The remainder simulation parameters are shown in Table 5.1.

In our simulations, each run lasts for 150s. We simulate 25 times for each setting. The results show the average value and the 95% confidence interval.

5.2 Simulation Results

We compare our proposed protocols (OIFP, LISIC, LOCOS-OIFP, and LOCOS-LISIC) with vanilla NDN with ten hops limitation. We also implement three related works, DU [15], CODIE [7] and MHMP [99] and compare our best performance protocol LOCOS-LISIC with them. The same parameters and the same scenario are set in each protocol.

The following performance evaluation metrics are considered:

- *Content delivery rate (%):* represents the percentage of clients that received all

Table 5.1: Simulation parameters

Parameter	**Value**
Simulation time	150 s
Number of runs	25
Transmission power	2.2 mW
Frequency band	5.9 GHz
Bit rate	18 Mbps
Transmission range	300 m
Data message size	10 kb
Number of chunks	10
α	10^6
T	0.1 s
Interest lifetime	1.5 s
Total vehicles	200, 300, 400
Percentage of consumers	30%
Percentage of producers	6% , 9%, 12%, 15%, 18%

chunks of the considered content.

- *Average number of Interest transmissions:* represents the average number of Interest packet transmissions per delivered chunk.

- *Average transmission delay (s):* represents the average delay for delivered content, that is, from the time that the first chunk of the content is transmitted, to the time that the client received the last chunk of the content.

5.2.1 Content Delivery Rate

Figure 5.4 portrays the performance of content delivery rate among our proposed protocols.

Take the 400-vehicles scenario for example, LOCOS-LISIC improves content delivery ratio by 140% on average compared with vanilla NDN. Since we utilize the potential producer's location information, all the Interest packet transmissions using the producer location-based forwarding scheme have a desired destination area. Therefore, the unnec-

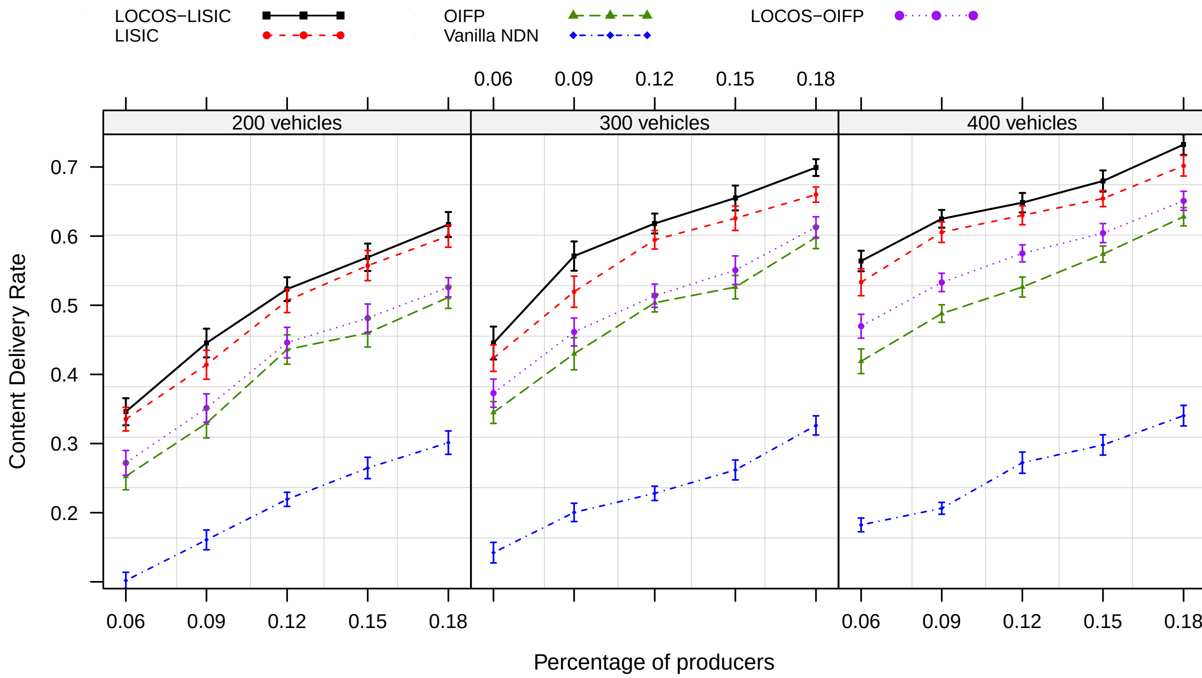

Figure 5.4: Content delivery rate of the proposed protocols

essary Interest transmissions, which may not receive a replied Data packet, would not continue to be scheduled. That is the reason that LOCOS-LISIC works better than LISIC.

However, LISIC works better than LOCOS-OIFP, even though the later one improves content delivery ratio by 115%. For LISIC, there is a 130% improvement in content delivery ratio compared with vanilla NDN. This is due to the efficient Interest forwarding prioritization proposed in the LISIC that reduces the channel overload by reducing the number of Interest transmissions and the use of more stable links for Data delivery through the reverse path.

For OIFP, there is a 93% improvement in content delivery ratio compared with vanilla NDN. This is This is because the distance-based controlled Interest forwarding mechanism of the OIFP protocol improves the content search task as the broadcast storm of Interest packets in the VNDN increases Interest packet collision and consequently, limits its propagation.

Figure 5.5 shows the performance of content delivery rate among our proposed LOCOS-

LISIC protocol and related works. In contrast, the LOCOS-LISIC and DU protocols present better performance. With the growth of total vehicles, the increase in content delivery rate becomes more obvious between LOCOS-LISIC and DU [15]. Take the 400-vehicles scenario for example, the LOCOS-LISIC and DU protocols presented better performance. They improved the content delivery rate in 100% and 170% when compared to the MHMP and CODIE protocols, respectively. This gain is mainly explained by the directional content discovery after the retrieval of the first chunk and the dynamic unicast Interest transmission in DU protocol.

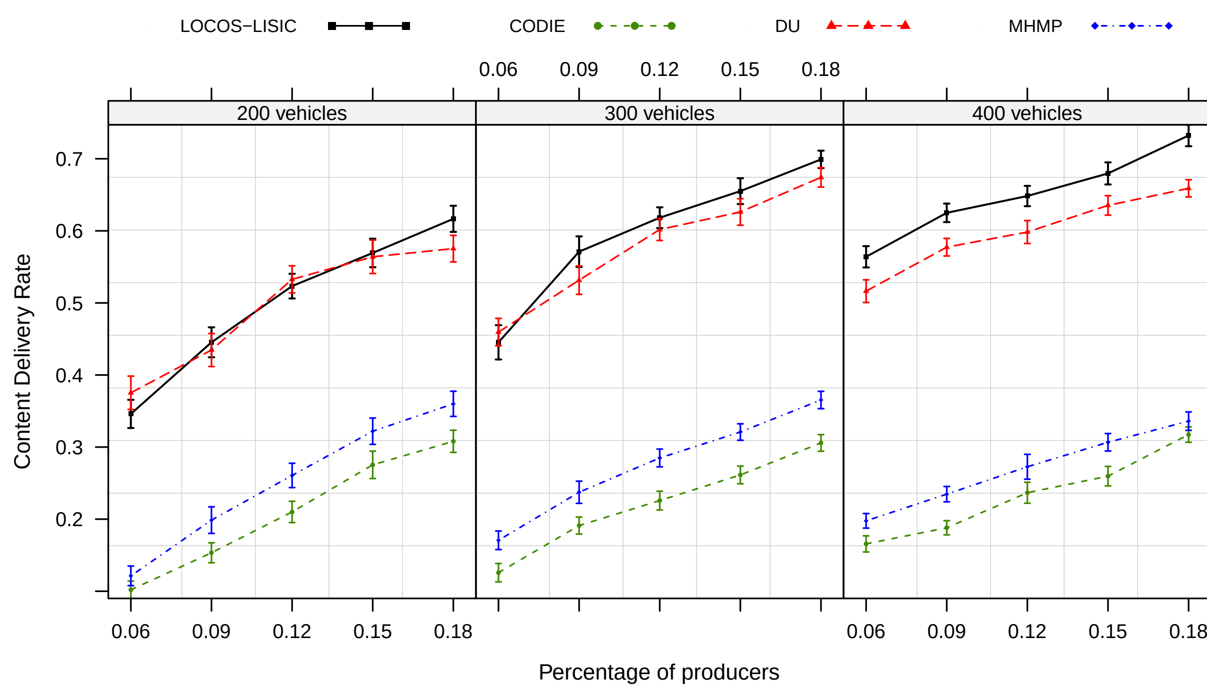

Figure 5.5: Comparison results with related works: Content delivery rate.

Although the LOCOS-LISIC and DU protocols have similar performance, the LOCOS-LISIC protocol should be preferred as it seamlessly handles spatiotemporal dependent content in vehicular networking applications. In fact, its location-based content discovery procedure would boost geographic-based vehicular applications. In contrast, the flooding component of the DU protocol for first chunk discovery would lead to the Interest packet transmissions among unnecessary areas for content search.

MHMP protocol [99] strictly executes unicast by leveraging MAC address of each vehicle. If the receiver is not the desired vehicle, packet transmission will be canceled then. Completely ignore the position change of the vehicle and the possible connection loss between vehicles. For CODIE protocol [7], Interest transmission can be considered as a controlled flooding scheme. The broadcast storm problem still exists in Interest proportion, which leads to lowest content delivery rate among the four protocols.

5.2.2 Average Number of Interest Transmissions

Figure 5.6 depicts the average Interest dissemination for each vehicle during the simulation. Overall, the average Interest transmissions are decreased as the proportion of the producer increases. Also, the average Interest transmissions are decreased as the total number of vehicles increases.

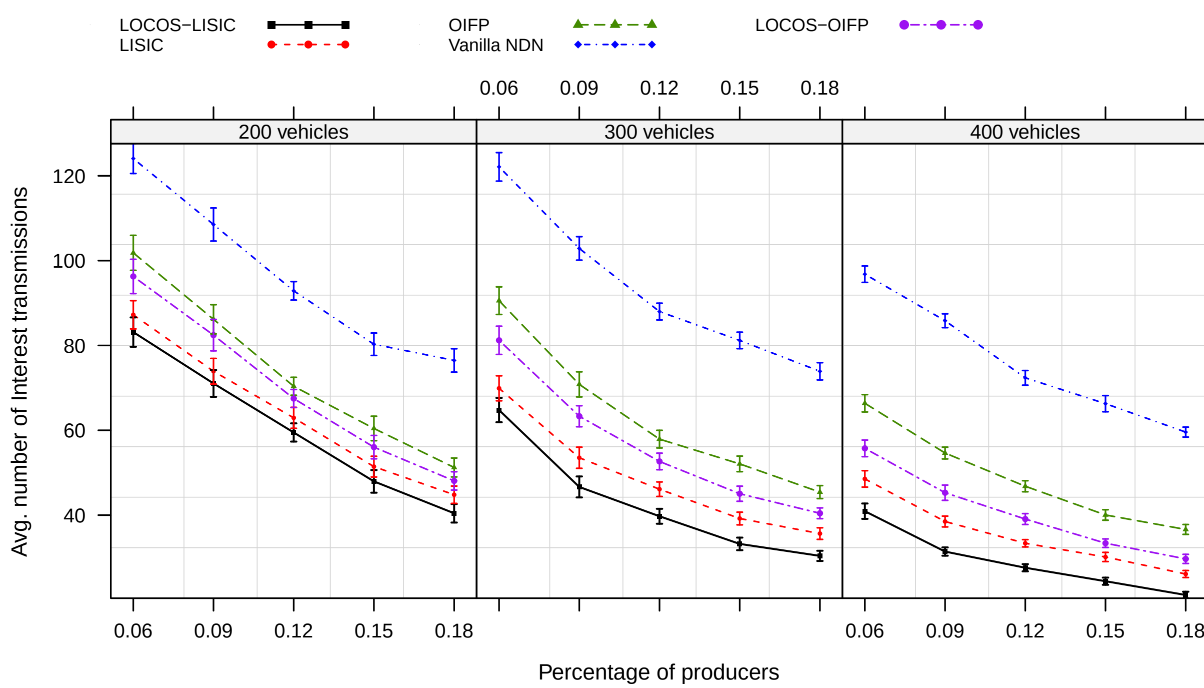

Figure 5.6: Average number of Interest transmissions for the proposed protocols.

Take the 400-vehicles scenario for example, OIFP and LISIC decreases the average number of Interest transmissions by around 35% and 55% compared with vanilla VNDN.

The opportunistic Interest forwarding mechanism of the proposed OIFP protocol decreases the number of Interest transmissions. The decrement seen in LISIC is because of redundant Interest transmission avoidance achieved by the suppression of scheduled transmission whenever a low priority vehicle detects that a high priority vehicle already forwarded the Interest packet.

Additionally, nearly 17% of the Interest transmissions on average are mitigated by LOCOS-OIFP compared with OIFP and about 18% of the Interest transmissions on average are reduced by LOCOS-LISIC compared with LISIC. Among all, LOCOS-LISIC has the best performance. This decrement is because of redundant Interest transmission avoidance achieved by the suppression of scheduled transmission whenever a low priority vehicle detects that a high priority vehicle has already forwarded the Interest packet. On the other hand, when an Interest cannot be satisfied, the consumer would keep retransmission that Interest. When an Interest has no desired producer location, it may be transmitted further from the expected producer, which increases the unnecessary Interest transmissions when not using LOCOS protocol.

Figure 5.7 portrays the performance of the average number of transmissions to retrieve the content among our proposed LOCOS-LISIC protocol and related works. For the considered scenario, the plot shows that the DU protocol outperforms the LOCOS-LISIC protocol, as well as the MHMP and CODIE protocol.

Take the 300-vehicles scenario for example, DU reduces about 25% of the average number of Interest transmissions, when compared to the LOCOS-LISIC protocol. This decrease happened due to the direct content request to a known vehicle having a content. However, such improved performance of the DU protocol over the LOCOS-LISIC protocol might not hold in a more realistic scenario with an increased content library with different content popularities. This is because it directly sends Interest packets to the known node that supposedly has the content. However, in such more realistic scenario, content replacement rate in the cache of vehicles will be frequent, which might lead to the substitution of a past located content at a given node. Hence, subsequent Interest transmissions to that specific node will not be satisfied, and the flooding should take place for the discovery of a new

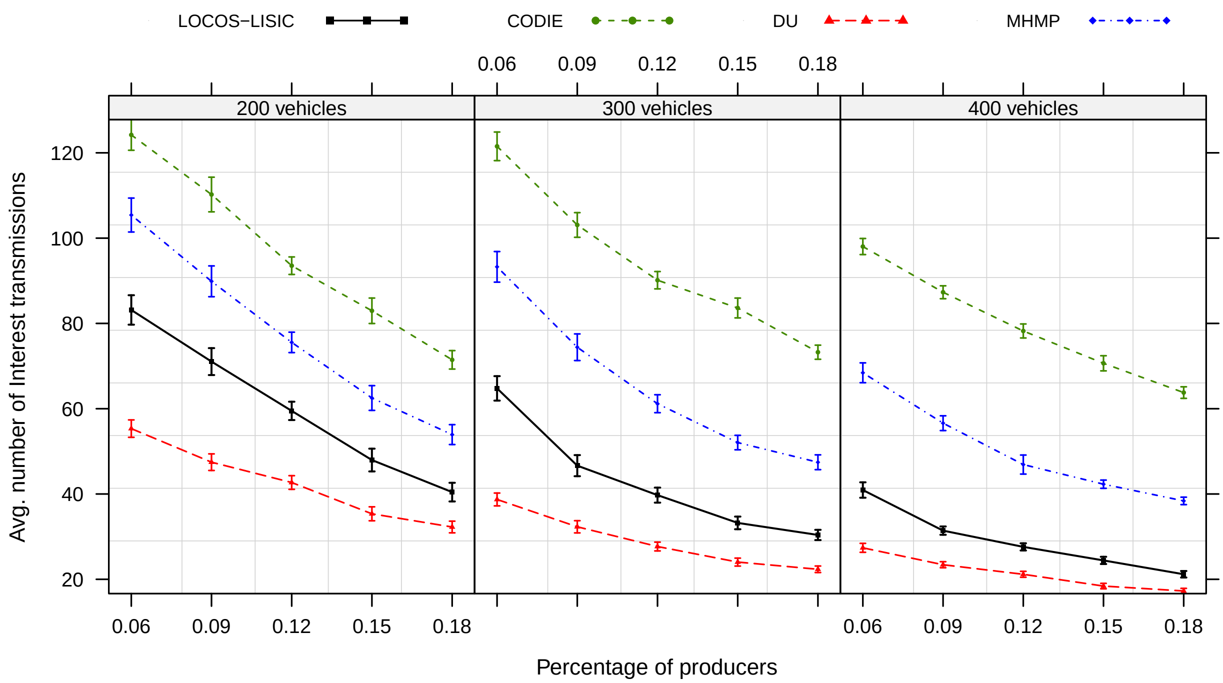

Figure 5.7: Comparison results with related work: Avg. number of Interest transmissions.

vehicle having the content. There is also a drawback of a higher delay in DU protocol, which will be discussed in the following section in detail.

5.2.3 Average Transmission Delay

Figure 5.8 shows the delay for getting the whole content, which is the time between sending the first Interest request and receiving the last Data chunk.

As expected, increasing the proportion of the producer can increase the chance of content being found, which can reduce the content delivery delay. On the other hand, the reduction of Interest transmissions also reduces the probability of unexpected collision happened in the channel.

The delay for data delivery reduced by 38% in the OIFP protocol because Interest transmissions are performed by vehicles that most advance the packets, that is, those vehicles further away from the current forwarder vehicle.

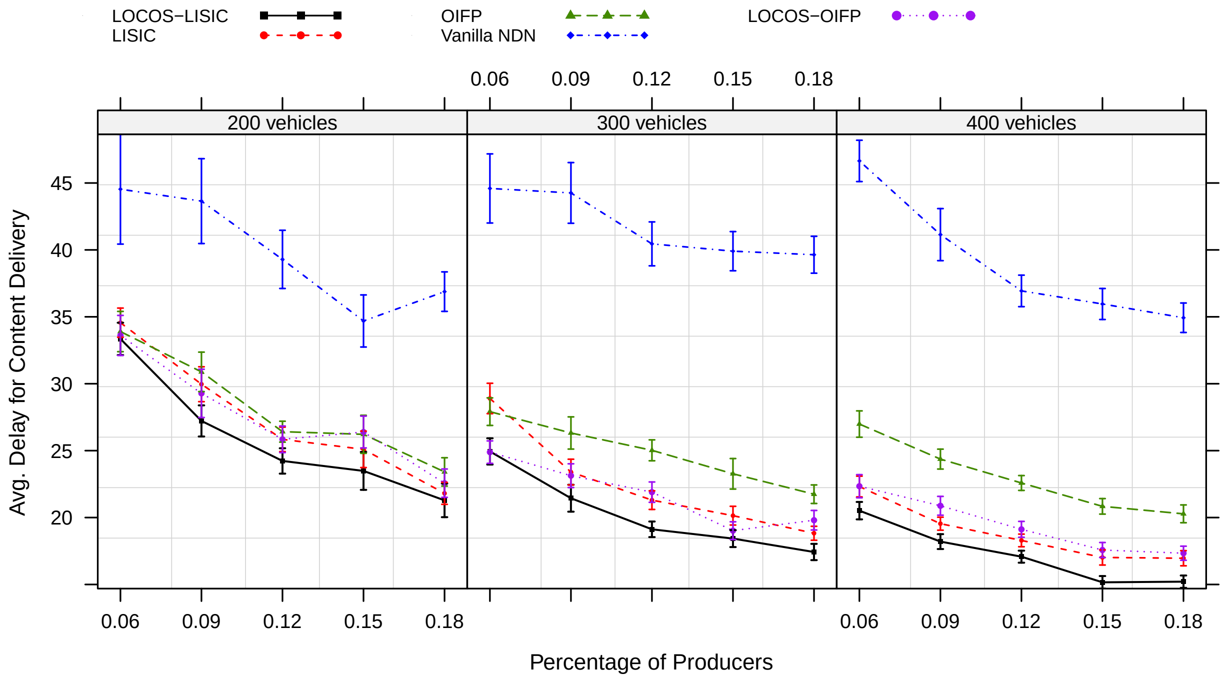

Figure 5.8: Average delay for content delivery of the proposed protocols.

Moreover, the LOCOS-OIFP and LISIC protocol have the similar result this time, which outperforms the vanilla NDN in terms of delay. They achieve 50% reduction in delay. This is due to less contention to access the broadcast channel. The LISIC protocol relies on fewer Interest transmissions, uses the more stable links for Data delivery and leverages the carry-and-forward approach when there is a loss of connectivity, which entail on the reduced delay.

LOCOS-LISIC outperforms the other proposed protocols. This is because of the use of more stable links for Data delivery, which entails on reduced delay than the carry-and-forward approach used when there is a loss of connectivity. Moreover, FIB stores the latest valid expected producer location and the vehicle that closest to the destination area have the priority to forward the Interest. All the facts above benefit to LOCOS-LISIC, which reduces the content delivery delay by around 8% compared with LISIC. And the reduction in average delay for content delivery can reach 55% when compared with the vanilla VNDN approach in terms of 400-vehicles scenario.

Figure 5.9 presents the performance of the average delay for content retrieval among our proposed LOCOS-LISIC protocol and related works. From the simulation results, we can notice that LOCOS-LISIC protocol and MHMP protocol have the better performance this time compared with the DU and CODIE protocol.

However, even MHMP protocol has the similar performance in the average delay, the lower content delivery rate of MHMP protocol cannot be ignored. Let us look at the result of content delivery rate and the average delay for content delivery together. LOCOS-LISIC protocol has a higher content delivery rate, which means more content is delivered. More time is spent on looking for possible forwarders and packets transmission. Nevertheless, LOCOS-LISIC protocol has lower delay compared with MHMP protocol.

The better performance of LOCOS-LISIC protocol is due to the fact that the moving behavior of the vehicle is considered in our protocol and the directional Interest transmission to the area where possibly a content source is located as well. Therefore, Interest packets are forwarded to the vehicles with lower chances to lose connection and to the areas with higher hit ratio to the desired content.

Besides, we also notice that Figure 5.9 presents a significant delay in all protocols. In this scenario, a major aspect that explains the high delay is the absence of end-to-end connectivity for most of the time, due to the low density of vehicles in the considered area.

Since our scenario is abstracted from the real world map instead of scenarios with several simple streets, the area we use is larger and more complicated. We also adopt V2V communication only, and we do not put large numbers of vehicles in the area. Therefore, there exist some clusters, which means some groups of connected vehicles. If the vehicle that has the content is in a different connected component, the client will not receive the content. This leads vehicles to carry and forward Data packets before delivering them, which is the primary contributor to the delay.

The observed high delay may make the studied protocols impractical for safety-related applications. However, this delay can still be tolerated by several other applications, such as vehicular software updates.

All in all, the point is to study the Interest forwarding performance of different protocols

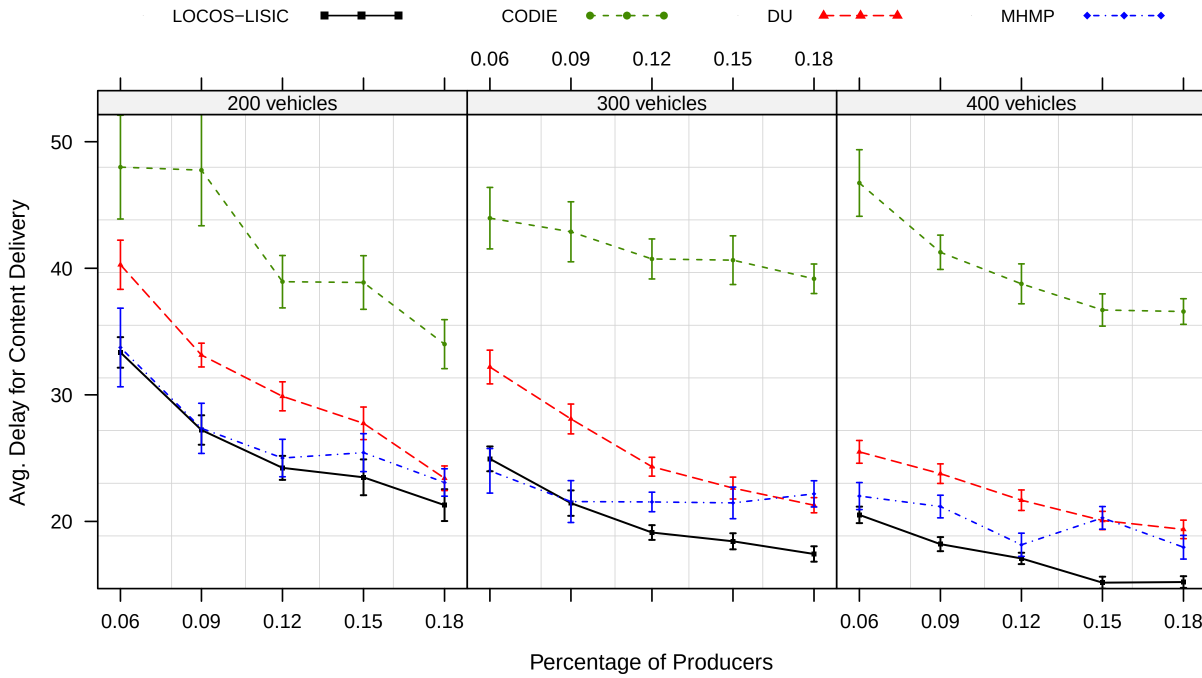

Figure 5.9: Comparison results with related work: Average delay for content delivery.

in the same scenario and same situation. Therefore, the simulation result of average delay can reflect the performance of each protocol.

5.3 Summary

In this chapter, we presented the simulation environment and the simulation results to compare the performance of the proposed protocols with vanilla NDN and three related works. We listed the results based on different metrics, content delivery rate, average number of Interest transmission and average delay.

Simulation results showed that the OIFP and LISIC protocol decreased the average number of Interest transmissions by around 35% and 55%, decreased the average delay of content delivery by around 38% and 50%, while increased content delivery rate by 93% and 130% compared with vanilla VNDN in the 400-vehicles scenario. Moreover, LOCOS-LISIC protocol improved content delivery rate by 3% while reduced Interest transmissions for content searching by 18% and reduced average delay by 8% compared with LISIC in the 400-vehicles scenario.

Among all our proposed protocols, LOCOS-LISIC had the best performance in all the three metrics. When compared with related works, even DU protocol outperformed the other protocols in terms of the average number of Interest transmissions, LOCOS-LISIC had better performance for the overall view of the three metrics.

Chapter 6

Conclusion and Future Work

This chapter presents the concluding remarks of the research work conducted in this thesis. Moreover, it highlights some possible future directions from the developed work. This chapter is organized as follows. Section 6.1 gives the summary of the thesis and Section 6.2 lists some possible future directions.

6.1 Summary of this Thesis

In this thesis, we proposed a suite of protocols, OIFP, LISIC, and LOCOS, for content delivery in vehicular Information-Centric Networks. The proposed protocols are mainly aimed to tackle the broadcast storm problem that critically diminishes the performance of wireless-based systems. In our considered scenarios of vehicular ICN, the broadcast storm problem will appear as the uncontrolled transmission of Interest packets for content discovery and request. This problem will increase the network overhead and reduce the vehicular network applications' performance, in terms of delay, due to the need of packet retransmissions because of the high packet collision rate.

The OIFP protocol implemented deferred timers to prioritize Interest forwarding among neighboring nodes. The deferred time calculation at each receiver node is locally and independently calculated based only on the distance from the node to the current forwarder node.

In the LISIC protocol, a deferred timer function was devised in order to prioritize Interest forwarding among neighboring vehicles. The devised function prioritizes the neighbor that has a more stable link, i.e., high connectivity duration, for the current transmitter of the Interest packet. This is done motivated by the fact that Data are routed through the reverse path of Interest transmissions.

The LOCOS protocol used the location information of opportunistically discovered content source vehicles to forward Interest packet towards the desired area. The idea behind the proposed protocol is to direct Interest transmissions of the content search to the area that the content source would probably be in.

Simulations of the proposed protocols with different parameters were implemented and compared with the vanilla NDN and three related works, CODIE, DU and MHMP protocols. By changing the number of producers and the total number of participating vehicles, we got different simulation results based on different metrics, such as content delivery rate, the average number of Interest transmission and the average delay of content delivery.

As a consequence, the simulation-based performance evaluation showed that the proposed protocols outperformed the related work in terms of improving the content delivery ratio, reducing unnecessary Interest transmission and decreasing the content distribution delay. Overall, LOCOS-LISIC had the better performance among all the proposed protocols, and the three mentioned related works.

6.2 Future Work

Overall, future research work of this thesis includes the investigation of the vehicles' trajectory to boost the data delivery rate in vehicular Information-Centric Networks. Moreover, redundant Data packet transmissions are another problem that is worth to tackle. Another future research direction consists in the study of new metrics and cache policies, considering the peculiar characteristics of the vehicular environment. In the following we summarize a list of short-time future works of this thesis:

- **Efficient replica placement and content forwarding in vehicular ICN**

There is always a need for more efficient replica placement and content forwarding for the fulfillment of a variety of application. Though some metrics like location information, content information, and topology information have been considered, it is still a big challenge to deploy ICN in large-scale VANETs. The requirement of robustness and efficiency to deploy ICN in real VANETs is much higher than the simulation environment.

- **Prediction of vehicle traces, topology and traffic density for vehicular ICN**

  Statistical functions and algorithms for prediction are also the heated directions. Many replica selection solutions are based on the trace or location information. Precise prediction can enhance the replica placement decision. Most of the forwarding decisions are based on the topology. However, since the mobile feature of vehicles, the topology is rapidly changing. Precise prediction can enhance the routing and forwarding decision. Traffic congestion always happens in an urban scenario. Large numbers of vehicles are trapped in some specific areas, where large content resource and large bandwidth are needed. Based on the traffic density prediction, the number of replicas and network resource can be assigned to these specific areas in advanced. As a consequence, considering the prediction of vehicle traces and traffic density in vehicular ICN is also very important to the efficient content delivery.

- **Resource management vehicular ICN**

  A centralized namespace management system can be designed for the uniform naming scheme, efficient management, and security control. Since each node has a CS for caching, if it is not better controlled, cache pollution may happen. Research can focus on what content that should be cached and how long the content should be cached in case cache pollution happens.

- **ICN in Software Defined VANETs**

  Since the programmability, scalability, and centralized control feature in SDN, SDN has already become the trend in the wired network. So it would be the same for VANETs. Software Defined vehicular Network has a lot of advantages to enhance content delivery in VANETs. The controller has the global view of the VANETs, it can easily choose and reserve a dedicated channel for emergency use and also choose the best path for content distribution in the global view. The efficient control mechanisms in SDN controller and routing protocols design for efficient replica forwarding are needed. How to use SDN to control the Interest and Data packet forwarding in vehicular ICN can be a very promising topic as well.

- **Vehicular Cloud Computing enhances ICN in VANET**

  Internet of Thing (IoT) is also a trend. A huge amount of content information will be generated (e.g., information from pedestrians, from bikes, from traffic lights, from the wearable devices and etc.).The amount of data exponentially grows, which needs mobility and computing support. vehicular ICN can provide mobility support. Also, each vehicle is like a small moving data center in VANETs. By gathering all the distributed vehicles together and collecting the resource in each vehicle as a vehicular cloud, the computing ability can be improved significantly. Content and replicas can be distributed through vehicular ICN to spare vehicles to reduce the potential congestion and processing delay. Serves based on cloud computing can be provided and content caching policy in vehicular ICN can be organized.

References

[1] 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.

[2] 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, 2012.

[3] Gergely Acs, Mauro Conti, Paolo Gasti, Cesar Ghali, and Gene Tsudik. Cache privacy in named-data networking. In *Proceedings of IEEE 33rd International Conference on Distributed Computing Systems*, ICDCS '13, pages 41–51, 2013.

[4] Alexander Afanasyev, Junxiao Shi, Beichuan Zhang, Lixia Zhang, Ilya Moiseenko, Yingdi Yu, and Wentao Shang. Nfd developers guide. [Online]. Available: http://named-data.net/wp-content/uploads/2016/10/ndn-0021-7-nfd-developer-guide.pdf, 2016. Accessed on: March, 2018.

[5] Shabbir Ahmed and Salil S Kanhere. Vanetcode: network coding to enhance cooperative downloading in vehicular ad-hoc networks. In *Proceedings of ACM International Wireless Communications and Mobile Computing Conference*, IWCMC '06, pages 527–532, 2006.

[6] Syed Hassan Ahmed, Safdar Hussain Bouk, and Dongkyun Kim. Rufs: Robust forwarder selection in vehicular content-centric networks. *IEEE Communications Letters*, 19(9):1616–1619, 2015.

[7] Syed Hassan Ahmed, Safdar Hussain Bouk, Muhammad Azfar Yaqub, Dongkyun Kim, Houbing Song, and Jaime Lloret. Codie: Controlled data and interest evaluation in vehicular named data networks. *IEEE Transactions on Vehicular Technology*, 65(6):3954–3963, 2016.

[8] Syed Hassan Ahmed, SH Bouk, MA Yaqub, Dongkyun Kim, and Mario Gerla. Conet: Controlled data packets propagation in vehicular named data networks. In *Proceedings of IEEE Consumer Communications and Networking Conference*, CCNC '16, pages 620–625, 2016.

[9] Elie El Ajaltouni, Azzedine Boukerche, and Ming Zhang. An efficient dynamic load balancing scheme for distributed simulations on a grid infrastructure. In *Proceedings of IEEE/ACM 12th International Symposium on Distributed Simulation and Real-Time Applications*, DS-RT '08, pages 61–68, 2008.

[10] Onur Altintas, Falko Dressler, Florian Hagenauer, Makiko Matsumoto, Miguel Sepulcre, and Christoph Sommery. Making cars a main ict resource in smart cities. In *Proceedings of IEEE Conference on Computer Communications Workshops*, INFOCOM WKSHP '15, pages 582–587, 2015.

[11] Marica Amadeo, Claudia Campolo, and Antonella Molinaro. Content-centric vehicular networking: An evaluation study. In *Proceedings of IEEE 3rd International Conference on Network of the Future*, NOF '12, pages 1–5, 2012.

[12] Marica Amadeo, Claudia Campolo, and Antonella Molinaro. Crown: Content-centric networking in vehicular ad hoc networks. *IEEE Communications Letters*, 16(9):1380–1383, 2012.

[13] Marica Amadeo, Claudia Campolo, and Antonella Molinaro. Enhancing content-centric networking for vehicular environments. *Computer Networks*, 57(16):3222–3234, 2013.

[14] Marica Amadeo, Claudia Campolo, and Antonella Molinaro. Information-centric

networking for connected vehicles: a survey and future perspectives. *IEEE Communications Magazine*, 54(2):98–104, 2016.

[15] Carlos Anastasiades, Jürg Weber, and Torsten Braun. Dynamic unicast: Information-centric multi-hop routing for mobile ad-hoc networks. *Computer Networks*, 107(2):208–219, 2016.

[16] Thanasis Antoniou, Ioannis Chatzigiannakis, George Mylonas, Sotiris Nikoletseas, and Azzedine Boukerche. A new energy efficient and fault-tolerant protocol for data propagation in smart dust networks using varying transmission range. In *Proceedings of IEEE 37th annual symposium on Simulation*, page 43. IEEE Computer Society, 2004.

[17] Gérald Arnould, Djamel Khadraoui, and Zineb Habbas. A self-organizing content centric network model for hybrid vehicular ad-hoc networks. In *Proceedings of ACM 1st International Symposium on Design and Analysis of Intelligent Vehicular Networks and Applications*, DIVANet '11, pages 15–22, 2011.

[18] Luigi Atzori, Antonio Iera, and Giacomo Morabito. The internet of things: A survey. *Computer networks*, 54(15):2787–2805, 2010.

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

[20] Alessandro Bazzi, Barbara M Masini, Alberto Zanella, Cristina De Castro, Carla Raffaelli, and Oreste Andrisano. Cellular aided vehicular named data networking. In *Proceedings of IEEE 3rd International Conference onConnected Vehicles and Expo*, ICCVE '14, pages 747–752, 2014.

[21] Chaoyi Bian, Tong Zhao, Xiaoming Li, and Wei Yan. Boosting named data networking for data dissemination in urban vanet scenarios. *Vehicular Communications*, 2(4):195–207, 2015.

[22] Safdar Hussain Bouk, Syed Hassan Ahmed, and Dongkyun Kim. Hierarchical and hash based naming with compact trie name management scheme for vehicular content centric networks. *Computer Communications*, 71:73–83, 2015.

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

[24] Azzedine Boukerche. *Handbook of algorithms for wireless networking and mobile computing*. Chapman and Hall/CRC, 2005.

[25] Azzedine Boukerche. *Algorithms and protocols for wireless and mobile ad hoc networks*, volume 77. John Wiley & Sons, 2008.

[26] Azzedine Boukerche. *Algorithms and protocols for wireless sensor networks*, volume 62. John Wiley and Sons, 2008.

[27] Azzedine Boukerche and Luciano Bononi. Simulation and modeling of wireless, mobile, and ad hoc networks. *Mobile ad hoc networking*, pages 373–409, 2004.

[28] Azzedine Boukerche, Daniel Câmara, Antonio AF Loureiro, and Carlos MS Figueiredo. Algorithms for mobile ad hoc networks. *Algorithms and Protocols for Wireless and Mobile Ad Hoc Networks*, pages 1–20, 2009.

[29] 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.

[30] Azzedine Boukerche, Rodolfo WL Coutinho, and Xiangshen Yu. Lisic: A link stability-based protocol for vehicular information-centric networks. In *Proceedings of IEEE 14th International Conference on Mobile Ad Hoc and Sensor Systems*, MASS '17, pages 233–240, 2017.

[31] Azzedine Boukerche and Sajal K Das. Dynamic load balancing strategies for conservative parallel simulations. In *Proceedings of IEEE 11th Workshop on Parallel and Distributed Simulation*, PADS '97, pages 20–28, 1997.

[32] Azzedine Boukerche, Sajal K Das, Alessandro Fabbri, and Oktay Yildiz. Exploiting model independence for parallel pcs network simulation. In *Proceedings of IEEE 13th Workshop on Parallel and Distributed Simulation*, FCRC '99, pages 166–173, 1999.

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

[34] Azzedine Boukerche, Khalil El-Khatib, Li Xu, and Larry Korba. A novel solution for achieving anonymity in wireless ad hoc networks. In *Proceedings of ACM 1st International Workshop on Performance evaluation of Wireless Ad hoc, Sensor, and Ubiquitous Networks*, MSWiM '04, pages 30–38. ACM, 2004.

[35] Azzedine Boukerche, Khalil El-Khatib, Li Xu, and Larry Korba. Sdar: a secure distributed anonymous routing protocol for wireless and mobile ad hoc networks. In *Proceedings of IEEE 29th International Conference on Local Computer Networks*, LCN '04, pages 618–624, 2004.

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

[37] 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.

[38] Azzedine Boukerche and Xin Fei. A voronoi approach for coverage protocols in wireless sensor networks. In *Proceedings of IEEE 50th International Conference on Global Telecommunications Conference*, GLOBECOM '07, pages 5190–5194, 2007.

[39] 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.

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

[41] 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.

[42] Azzedine Boukerche, Kathia Regina Lemos Jucá, João Bosco Sobral, and Mirela Sechi Moretti Annoni Notare. An artificial immune based intrusion detection model for computer and telecommunication systems. *Parallel Computing*, 30(5-6):629–646, 2004.

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

[44] Azzedine Boukerche, Renato B Machado, Kathia RL Jucá, João Bosco M Sobral, and Mirela SMA Notare. An agent based and biological inspired real-time intrusion detection and security model for computer network operations. *Computer Communications*, 30(13):2649–2660, 2007.

[45] 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.

[46] Azzedine Boukerche and Rodolfo I Meneguette. Vehicular cloud network: A new challenge for resource management based systems. In *Proceedings of IEEE 13th International Conference on Wireless Communications and Mobile Computing*, IWCMC '17, pages 159–164, 2017.

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

[48] 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.

[49] Azzedine Boukerche, Horacio ABF Oliveira, Eduardo F Nakamura, and Antonio AF Loureiro. Secure localization algorithms for wireless sensor networks. *IEEE Communications Magazine*, 46(4), 2008.

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

[51] Azzedine Boukerche, Horacio ABF Oliveira, Eduardo Freire Nakamura, and Antonio AF Loureiro. Dv-loc: a scalable localization protocol using voronoi diagrams for wireless sensor networks. *IEEE Wireless Communications*, 16(2), 2009.

[52] Azzedine Boukerche and Richard Werner Nelem Pazzi. A peer-to-peer approach for remote rendering and image streaming in walkthrough applications. In *Proceedings of IEEE International Conference on Communications*, ICC '07, pages 1692–1697, 2007.

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

[54] 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 ACM 7th International Symposium on Modeling, Analysis and Simulation of Wireless and Mobile Systems*, MSWiM '04, pages 157–164, 2004.

[55] 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.

[56] 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 ACM 5th Symposium on Performance Evaluation of Wireless Ad hoc, Sensor, and Ubiquitous Networks*, pages 88–95, 2008.

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

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

[59] Azzedine Boukerche, Cristiano Rezende, and Richard W Pazzi. Improving neighbor localization in vehicular ad hoc networks to avoid overhead from periodic messages. In *Proceedings of IEEE Global Telecommunications Conference*, GLOBECOM '09, pages 1–6, 2009.

[60] Azzedine Boukerche, Cristiano Rezende, and Richard W Pazzi. A link-reliability-based approach to providing qos support for vanets. In *Proceedings of IEEE International Conference on Communications*, ICC '09, pages 1–5, 2009.

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

[62] Azzedine Boukerche and Steve Rogers. Gps query optimization in mobile and wireless networks. In *Proceedings of IEEE 6th Symposium on Computers and Communications*, ISCC '06, pages 198–203. IEEE, 2001.

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

[64] Azzedine Boukerche, Amber Roy, and Neville Thomas. Dynamic grid-based multicast group assignment in data distribution management. In *Proceedings of IEEE/ACM*

International Symposium on Distributed Simulation and Real Time Applications, DS-RT '00, page 47, 2000.

[65] 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.

[66] Azzedine Boukerche and Carl Tropper. A static partitioning and mapping algorithm for conservative parallel simulations. In *Proceedings of ACM SIGSIM Simulation Digest*, volume 24, pages 164–172, 1994.

[67] 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.

[68] Azzedine Boukerche and Damla Turgut. Secure time synchronization protocols for wireless sensor networks. *IEEE Wireless Communications*, 14(5), 2007.

[69] Rajkumar Buyya, Mukaddim Pathan, and Athena Vakali. *Content delivery networks*, volume 9. Springer Science and Business Media, 2008.

[70] Claudia Campolo, Antonella Molinaro, Claudio Casetti, and Carla-Fabiana Chiasserini. An 802.11-based MAC protocol for reliable multicast in multihop networks. In *Proceedings of IEEE 69th Vehicular Technology Conference*, VTC-Spring '09, pages 1–5, 2009.

[71] Yi Cao, Jinhua Guo, and Yue Wu. Sdn enabled content distribution in vehicular networks. In *Proceedings of IEEE 4th Innovative Computing Technology*, INTECH '14, pages 164–169, 2014.

[72] Clayson Celes, Fabrício A Silva, Azzedine Boukerche, Rossana Maria de Castro Andrade, and Antonio AF Loureiro. Improving vanet simulation with calibrated vehicular mobility traces. *IEEE Transactions on Mobile Computing*, 16(12):3376–3389, 2017.

[73] E. Perkins Charles and M. Belding Elizabeth. Ad-hoc on demand distance vector routing. In *Proceedings of IEEE 2rd Workshop on Mobile Computing Systems and Applications*, ICC '99, pages 90–100, 1999.

[74] Sergio Charpinel, Celso Alberto Saibel Santos, Alex Borges Vieira, Rodolfo Villaca, and Magnos Martinello. Sdccn: A novel software defined content-centric networking approach. In *Proceedings of IEEE 31st International Conference on Advanced Information Networking and Applications*, AINA '16, pages 87–94, 2016.

[75] Bram Cohen. Incentives build robustness in bittorrent. In *Proceedings of Workshop on Economics of Peer-to-Peer Systems*, IPTPS '03, pages 68–72. ACM, 2003.

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

[77] Rodolfo WL Coutinho, Azzedine Boukerche, Luiz FM Vieira, and Antonio AF Loureiro. Geographic and opportunistic routing for underwater sensor networks. *IEEE Transactions on Computers*, 65(2):548–561, 2016.

[78] Rodolfo WL Coutinho, Azzedine Boukerche, and Xiangshen Yu. Information-centric strategies for content delivery in intelligent vehicular networks. In *ACM 8th International Symposium on Design and Analysis of Intelligent Vehicular Networks and Applications*, DIVANet '18, 2018.

[79] Rodolfo WL Coutinho, Azzedine Boukerche, and Xiangshen Yu. A novel location-based content distribution protocol for named data vehicular networks. In *Proceedings of IEEE 23rd Symposium on Computers and Communication*, ISCC '18, 2018.

[80] Shirshanka Das, Alok Nandan, and Giovanni Pau. Spawn: a swarming protocol for vehicular ad-hoc wireless networks. In *Proceedings of ACM 1st International Workshop on Vehicular ad hoc networks*, VANET '04, pages 93–94, 2004.

[81] Horacio Antonio Braga Fernandes De Oliveira, Azzedine Boukerche, Eduardo Freire Nakamura, and Antonio Alfredo Ferreira Loureiro. An efficient directed localization

recursion protocol for wireless sensor networks. *IEEE Transactions on Computers*, 58(5):677–691, 2009.

[82] Gang Deng, Fengchao Li, and Liwei Wang. Cooperative downloading in vanets-lte heterogeneous network based on named data. In *Proceedings of IEEE Conference on Computer Communications Workshops*, INFOCOM WKSHPS '16, pages 233–238, 2016.

[83] Gang Deng, Liwei Wang, Fengchao Li, and Rere Li. Distributed probabilistic caching strategy in vanets through named data networking. In *Proceedings of IEEE Conference on Computer Communications*, INFOCOM WKSHPS '16, pages 314–319, 2016.

[84] Scotiabank Economics. Global auto report. [Online]. Available: http://www.gbm.scotiabank.com/English/bns_econ/bns_auto.pdf, 2016. Accessed on: Octorber, 2016.

[85] Mourad Elhadef, Azzedine Boukerche, and Hisham Elkadiki. Diagnosing mobile ad-hoc networks: two distributed comparison-based self-diagnosis protocols. In *Proceedings of ACM 4th International Workshop on Mobility Management and Wireless Access*, pages 18–27, 2006.

[86] 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 ACM 9th International Symposium on Modeling Analysis and Simulation of Wireless and Mobile Systems*, MSWiM '06, pages 165–172, 2006.

[87] 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.

[88] Marco Fiore, Claudio Casetti, Carla-Fabiana Chiasserini, and Diego Borsetti. Persistent localized broadcasting in vanets. *IEEE Journal on Selected Areas in Communications*, 31(9):480–490, 2013.

[89] Christos Gkantsidis and Pablo Rodriguez Rodriguez. Network coding for large scale content distribution. In *Proceedings IEEE 24th Annual Joint Conference of the IEEE Computer and Communications Societies*, volume 4, pages 2235–2245, 2005.

[90] G. Grassi, D. Pesavento, G. Pau, R. Vuyyuru, R. Wakikawa, and L. Zhang. Vanet via named data networking. In *Proceedings of IEEE Conference on Computer Communications Workshops*, INFOCOM WKSHPS '14, pages 410–415, 2014.

[91] Giulio Grassi, Davide Pesavento, Giovanni Pau, Rama Vuyyuru, Ryuji Wakikawa, and Lixia Zhang. Vanet via named data networking. In *Proceedings of IEEE Conference on Computer Communications Workshops*, INFOCOM WKSHPS '14, pages 410–415, 2014.

[92] Giulio Grassi, Davide Pesavento, Giovanni Pau, Lixia Zhang, and Serge Fdida. Navigo: Interest forwarding by geolocations in vehicular named data networking. In *Proceedings of IEEE 16th International Symposium on a World of Wireless, Mobile and Multimedia Networks*, WoWMoM '16, pages 1–10, 2015.

[93] Giulio Grassi, Davide Pesavento, Lucas Wang, Giovanni Pau, Rama Vuyyuru, Ryuji Wakikawa, and Lixia Zhang. Vehicular inter-networking via named data. *ACM SIGMOBILE Mobile Computing and Communications Review*, 17(3):23–24, 2013.

[94] Florian Hagenauer, Christoph Sommer, Ryokichi Onishi, Matthias Wilhelm, Falko Dressler, and Onur Altintas. Interconnecting smart cities by vehicles: How feasible is it? In *Proceedings of IEEE Conference on Computer Communications Workshops*, INFOCOM WKSHPS '16, pages 788–793, 2016.

[95] Mordechai Haklay and Patrick Weber. Openstreetmap: User-generated street maps. *IEEE Pervasive Computing*, 7(4):12–18, 2008.

[96] Van Jacobson, Diana K Smetters, James D Thornton, Michael F Plass, Nicholas H Briggs, and Rebecca L Braynard. Networking named content. In *Proceedings of ACM Conference on Emerging Networking EXperiments and Technologies*, CoNEXT '09, pages 1–12, 2009.

[97] Jaehoon Paul Jeong, Jinyong Kim, Taehwan Hwang, Fulong Xu, Shuo Guo, Yu Jason Gu, Qing Cao, Ming Liu, and Tian He. Tpd: Travel prediction-based data forwarding for light-traffic vehicular networks. *Computer Networks*, 93:166–182, 2015.

[98] Shijie Jia, Changqiao Xu, Jianfeng Guan, Hongke Zhang, and Gabriel-Miro Muntean. A novel cooperative content fetching-based strategy to increase the quality of video delivery to mobile users in wireless networks. *IEEE Transactions on Broadcasting*, 60(2):370–384, 2014.

[99] Eirini Kalogeiton, Thomas Kolonko, and Torsten Braun. A multihop and multipath routing protocol using ndn for vanets. In *Proceedings of IEEE 17th Mediterranean Ad Hoc Networking Workshop*, Med-Hoc-Net '17, pages 1–8, 2017.

[100] Brad Karp and Hsiang-Tsung Kung. Gpsr: Greedy perimeter stateless routing for wireless networks. In *Proceedings of ACM 6th Annual International Conference on Mobile computing and networking*, MobiCom '00, pages 243–254.

[101] Ian Ku, You Lu, Mario Gerla, Rafael L Gomes, Francesco Ongaro, and Eduardo Cerqueira. Towards software-defined vanet: Architecture and services. In *Proceedings of IEEE 13th Ad Hoc Networking Workshop*, MED-HOC-NET '14, pages 103–110, 2014.

[102] Meng Kuai, Xiaoyan Hong, and Qiangyuan Yu. Density-aware delay-tolerant interest forwarding in vehicular named data networking. In *Proceedings of IEEE 84th Vehicular Technology Conference*, VTC-Fall '16, pages 1–5, 2016.

[103] Jim Kurose. Information-centric networking: The evolution from circuits to packets to content. *Computer Networks*, 66:112–120, 2014.

[104] Euisin Lee, Eun-Kyu Lee, Mario Gerla, and Soon Y Oh. Vehicular cloud networking: architecture and design principles. *IEEE Communications Magazine*, 52(2):148–155, 2014.

[105] K Lee and I Yap. Cartorrent: A bit-torrent system for vehicular ad-hoc networks. *Technical report*, pages 1–6, 2006.

[106] Uichin Lee, Joon-Sang Park, Joseph Yeh, Giovanni Pau, and Mario Gerla. Code torrent: content distribution using network coding in vanet. In *Proceedings of ACM 1st International Workshop on Decentralized Resource Sharing in Mobile Computing and Networking*, MobiShare '06, pages 1–5, 2006.

[107] He Li, Mianxiong Dong, and Kaoru Ota. Control plane optimization in software defined vehicular ad-hoc networks. 65(10):7895–7904, 2013.

[108] Ming Li, Zhenyu Yang, and Wenjing Lou. Codeon: Cooperative popular content distribution for vehicular networks using symbol level network coding. *IEEE Journal on Selected Areas in Communications*, 29(1):223–235, 2011.

[109] Yuhong Li, Xiang Su, Anders Lindgren, Xinyue Shi, Xiang Cai, Jukka Riekki, and Xirong Que. Distance assisted information dissemination with broadcast suppression for icn-based vanet. In *Proceedings of International Conference on Internet of Vehicles*, IOV '16, pages 179–193. Springer, 2016.

[110] Lan Chao Liu, Dongliang Xie, Siyu Wang, and Zhen Zhang. Ccn-based cooperative caching in vanet. In *Proceedings of IEEE 4th International Conference on Connected Vehicles and Expo*, ICCVE '15, pages 198–203, 2015.

[111] Tom H Luan, Lin X Cai, Jiming Chen, Xuemin Shen, and Fan Bai. Vtube: Towards the media rich city life with autonomous vehicular content distribution. In *Proceedings of IEEE 8th Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks*, SECON '11, pages 359–367, 2011.

[112] Tom H Luan, Sherman Shen, and Fan Bai. *Enabling Content Distribution in Vehicular Ad Hoc Networks*. Springer, 2014.

[113] Francesco Malandrino, Claudio Casetti, and Carla-Fabiana Chiasserini. Content discovery and caching in mobile networks with infrastructure. *IEEE Transactions on Computers*, 61(10):1507–1520, 2012.

[114] Giuseppe Martuscelli, Azzedine Boukerche, Luca Foschini, and Paolo Bellavista. V2v protocols for traffic congestion discovery along routes of interest in vanets: a quan-

titative study. *Wireless Communications and Mobile Computing*, 16(17):2907–2923, 2016.

[115] Mohamed Nidhal Mejri, Jalel Ben-Othman, and Mohamed Hamdi. Survey on vanet security challenges and possible cryptographic solutions. *Vehicular Communications*, 1(2):53–66, 2014.

[116] Hanlin Meng, Kan Zheng, Periklis Chatzimisios, Hui Zhao, and Lin Ma. A utility-based resource allocation scheme in cloud-assisted vehicular network architecture. In *Proceedings of IEEE International Conference on Communication Workshop*, ICCW '15, pages 1833–1838, 2015.

[117] Horacio ABF Oliveira, Eduardo F Nakamura, Antonio AF Loureiro, and Azzedine Boukerche. Error analysis of localization systems for sensor networks. In *Proceedings of ACM 13th International Workshop on Geographic Information Systems*, pages 71–78, 2005.

[118] Renê Oliveira, Carlos Montez, Azzedine Boukerche, and Michelle S Wangham. Reliable data dissemination protocol for vanet traffic safety applications. *Ad Hoc Networks*, 63:30–44, 2017.

[119] George Pallis and Athena Vakali. Insight and perspectives for content delivery networks. *Communications of the ACM*, 49(1):101–106, 2006.

[120] 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.

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

[122] Davide Pesavento, Giulio Grassi, Claudio E Palazzi, and Giovanni Pau. A naming scheme to represent geographic areas in ndn. In *Proceedings of IEEE Wireless Days Conference*, WD '13, pages 1–3, 2013.

[123] Wei Quan, Yana Liu, Xiaoxiao Jiang, and Jianfeng Guan. Intelligent popularity-aware content caching and retrieving in highway vehicular networks. *EURASIP Journal on Wireless Communications and Networking*, 2016(1):200, 2016.

[124] Wei Quan, Changqiao Xu, Jianfeng Guan, Hongke Zhang, and Luigi Alfredo Grieco. Social cooperation for information-centric multimedia streaming in highway vanets. In *Proceedings of IEEE 15th International Symposium on World of Wireless, Mobile and Multimedia Networks*, WoWMoM '14, pages 1–6, 2014.

[125] Yonglin Ren and Azzedine Boukerche. Modeling and managing the trust for wireless and mobile ad hoc networks. In *Proceedings of IEEE International Conference on Communications*, ICC '08, pages 2129–2133, 2008.

[126] Yonglin Ren, Richard Werner, Nelem Pazzi, and Azzedine Boukerche. Monitoring patients via a secure and mobile healthcare system. *IEEE Wireless Communications*, 17(1), 2010.

[127] Cristiano G Rezende, Azzedine Boukerche, Heitor S Ramos, and Antonio AF Loureiro. A reactive and scalable unicast solution for video streaming over vanets. *IEEE Trans. Computers*, 64(3):614–626, 2015.

[128] 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, 2011.

[129] Mohsen Sardari, Faramarz Hendessi, and Faramarz Fekri. Infocast: A new paradigm for collaborative content distribution from roadside units to vehicular networks. In *Proceedings of IEEE 6th Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks*, SECON '09, pages 1–9, 2009.

[130] Fabrício A Silva, Azzedine Boukerche, Thais RM Silva, Linnyer B Ruiz, Eduardo Cerqueira, and Antonio AF Loureiro. Vehicular networks: A new challenge for content-delivery-based applications. *ACM Computing Surveys (CSUR)*, 49(1):11, 2016.

[131] Fabrício A Silva, Azzedine Boukerche, Thais RM Braga Silva, Fabrício Benevenuto, Linnyer B Ruiz, and Antonio AF Loureiro. Odcrep: Origin–destination-based content replication for vehicular networks. *IEEE Transactions on Vehicular Technology*, 64(12):5563–5574, 2015.

[132] Fabrício A Silva, Azzedine Boukerche, Thais RM Braga Silva, Linnyer B Ruiz, and Antonio AF Loureiro. Geo-localized content availability in vanets. *Ad Hoc Networks*, 36:425–434, 2016.

[133] Hossein Soleimani and Azzedine Boukerche. Sla: Speed and location aware lte scheduler for vehicular safety applications. In *Proceedings of ACM 13th International Symposium on Mobility Management and Wireless Access*, MobiWac '15, pages 13–19, 2015.

[134] Christoph Sommer, Reinhard German, and Falko Dressler. Bidirectionally coupled network and road traffic simulation for improved ivc analysis. *IEEE Transactions on Mobile Computing*, 10(1):3–15, 2011.

[135] Peyman TalebiFard, Victor CM Leung, Marica Amadeo, Claudia Campolo, and Antonella Molinaro. Information-centric networking for vanets. In *Vehicular ad hoc Networks*, pages 503–524. Springer, 2015.

[136] Peyman TalebiFard, Hasen Nicanfar, Xiping Hu, and Victor Leung. Semantic based networking of information in vehicular clouds based on dimensionality reduction. In *Proceedings of ACM 3rd International Symposium Design and Analysis of Intelligent Vehicular Networks and Applications*, DIVANet '13, pages 69–76, 2013.

[137] Haiyan Tian, Yusuke Otsuka, Masami Mohri, Yoshiaki Shiraishi, and Masakatu Morii. Leveraging in-network caching in vehicular network for content distribution. *International Journal of Distributed Sensor Networks*, 12(6):1–9, 2016.

[138] Hamed Vahdat-Nejad, Azam Ramazani, Tahereh Mohammadi, and Wathiq Mansoor. A survey on context-aware vehicular network applications. *Vehicular Communications*, 3:43–57, 2016.

[139] Athena Vakali and George Pallis. Content delivery networks: Status and trends. *IEEE Internet Computing*, 7(6):68–74, 2003.

[140] Jiangzhe Wang, Ryuji Wakikawa, and Lixia Zhang. Dmnd: Collecting data from mobiles using named data. In *Proceedings of IEEE Vehicular Networking Conference*, VNC '10, pages 49–56, 2010.

[141] Lucas Wang, Alexander Afanasyev, Romain Kuntz, Rama Vuyyuru, Ryuji Wakikawa, and Lixia Zhang. Rapid traffic information dissemination using named data. In *Proceedings of ACM 1st workshop on Emerging Name-Oriented Mobile Networking Design - Architecture, Algorithms, and Applications*, NoM '12, pages 7–12, 2012.

[142] Lucas Wang, Ryuji Wakikawa, Romain Kuntz, Rama Vuyyuru, and Lixia Zhang. Data naming in vehicle-to-vehicle communications. In *Proceedings of IEEE Conference on Computer Communications Workshops*, INFOCOM WKSHPS '12, pages 328–333, 2012.

[143] Md Whaiduzzaman, Mehdi Sookhak, Abdullah Gani, and Rajkumar Buyya. A survey on vehicular cloud computing. *Journal of Network and Computer Applications*, 40:325–344, 2014.

[144] Hengheng Xie, Azzedine Boukerche, and Antonio AF Loureiro. A multipath video streaming solution for vehicular networks with link disjoint and node-disjoint. *IEEE Transactions on Parallel and Distributed Systems*, 26(12):3223–3235, 2015.

[145] Changqiao Xu, Wei Quan, Hongke Zhang, and Luigi Alfredo Grieco. Grims: green information-centric multimedia streaming framework in vehicular ad hoc networks. *IEEE Transactions on Circuits and Systems for Video Technology*, 28(2):483–498, 2016.

[146] Zhiwei Yan, Sherali Zeadally, and Yong-Jin Park. A novel vehicular information network architecture based on named data networking (ndn). *IEEE Internet of Things Journal*, 1(6):525–532, 2014.

[147] Maram Bani Younes and Azzedine Boukerche. Intelligent traffic light controlling algorithms using vehicular networks. *IEEE transactions on Vehicular Technology*, 65(8):5887–5899, 2016.

[148] Xiangshen Yu, Rodolfo WL Coutinho, Azzedine Boukerche, and Antonio AF Loureiro. A distance-based interest forwarding protocol for vehicular information-centric networks. In *Proceedings of IEEE 29th International Symposium on Personal, Indoor and Mobile Radio Communications*, PIMRC '17, pages 1–5, 2017.

[149] Yu-Ting Yu, Mario Gerla, and MY Sanadidi. Scalable vanet content routing using hierarchical bloom filters. *Wireless Communications and Mobile Computing*, 15(6):1001–1014, 2015.

[150] Yu-Ting Yu, Yuanjie Li, Xingyu Ma, Wentao Shang, MY Sanadidi, and Mario Gerla. Scalable opportunistic vanet content routing with encounter information. In *Proceedings of IEEE 21st International Conference on Network Protocols*, ICNP '13, pages 1–6, 2013.

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

[152] Lixia Zhang, Alexander Afanasyev, Jeffrey Burke, Van Jacobson, Patrick Crowley, Christos Papadopoulos, Lan Wang, Beichuan Zhang, et al. Named data networking. *ACM SIGCOMM Computer Communication Review*, 44(3):66–73, 2014.

[153] Tao Zhang, E Robson, and Azzedine Boukerche. Design and analysis of stochastic traffic flow models for vehicular clouds. *Ad Hoc Networks*, 52:39–49, 2016.

[154] Yang Zhang, Jing Zhao, and Guohong Cao. Roadcast: a popularity aware content sharing scheme in vanets. *ACM SIGMOBILE Mobile Computing and Communications Review*, 13(4):1–14, 2010.

[155] Zhenxia Zhang, Azzedine Boukerche, and Richard Pazzi. A novel multi-hop clustering scheme for vehicular ad-hoc networks. In *Proceedings of ACM 9th International*

Symposium on Mobility Management and Wireless Access, MSWiM '11, pages 19–26, 2011.

[156] 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.

[157] Ming Zhu, Jiannong Cao, Deming Pang, Zongjian He, and Ming Xu. Sdn-based routing for efficient message propagation in vanet. In *Proceedings of 10th International Conference on Wireless Algorithms, Systems, and Applications*, WASA '15, pages 788–797. Springer, 2015.