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ÉCOLE DOCTORALE DE
SCIENCES POUR L'INGÉNIEUR DE CLERMONT-FERRAND

Thèse

Présentée par

Bin TIAN

Pour obtenir le grade de

DOCTEUR D'UNIVERSITÉ

Spécialité : INFORMATIQUE

**« Protocole de Dissémination de données et Modèle de
Mobilité pour Réseaux Ad hoc Véhiculaires »**

Soutenue publiquement le 17 Oct. 2016 devant le jury :

Directeur de la thèse :
Prof. Kun Mean HOU

Membres du jury :
Mme. Edwige Pissaloux (rapporteuse)
M. Fabrice Valois (rapporteur)
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M. Alain Quilliot (président du jury)
M. Christophe de Vaultx (invité)



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This thesis is dedicated to my parents for their love and support.

此文献给我最爱的父母

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Abstract

In the last two decades, Vehicular Ad hoc Network (VANETs) were developed significantly by both academic institute and industries association, since VANETs originate from traffic safety and are also an important application of Internet of Things / Web of Things (IoT/WoT) for Intelligent Transportation System (ITS), Intelligent Vehicles and Smart Cities. As an essential component of VANETs, Inter-Vehicle Communication (IVC) protocols face many critical challenges, in particular, because they relate to various specific applications. In this thesis, after elaborating on related knowledge of VANETs and state-of-the-art of IVC protocols, we propose a data dissemination protocol for vehicular networking, named TrAD, to disseminate efficiently warning messages from a source to vehicles in a range of interest (ROI). TrAD considers the status of road traffic and network traffic to adapt locally the strategy and the parameters of transmissions in order to optimize the global performance of IVC application. Moreover, a local vehicular cluster classification algorithm is designed to support TrAD to be performed in both highway and urban scenarios. In addition, an illustrative congestion control mechanism is used to avoid channel congestion using a distributed approach. Three state-of-the-art IVC protocols have been compared with TrAD by means of realistic simulations. The performance of all those protocols is evaluated quantitatively in various scenarios by taking into account different real road maps, traffic routes and vehicular densities. Compared with the reference protocols, TrAD gains an outstanding overall performance in terms of packet delivery ratio, number of transmissions and delay. Furthermore, TrAD also can tolerate a reasonable degree of GPS drift while achieving efficient data dissemination. In order to ensure the quality of simulations, we deeply investigated the mobility model of road traffic simulator, and then performed the bidirectionally coupled simulation in which the network simulator and the road traffic simulator can exchange information in real-time. Upon understanding of the mobility model, we obtained a chance to develop a low-cost tram simulator for the local public transportation provider, the T2C (Transports en Commun de l'agglomération Clermontoise). We attempt to design accurate mobility models from different scenarios for the specific type of tram used by T2C. Real world trials are carried out to explore the key parameters required by theoretical deduction for our mobility model. Moreover, the display GUI relies on a video stream, rather than 3D graphics, which can reduce the cost while guaranteeing the quality of service. This project was supported for two years by T2C.

Résumé

Pendant les deux dernières décennies, les technologies de réseaux ad-hoc de véhicules (VANETs : Vehicular Ad-Hoc Networks) ont été développées sous l'impulsion du monde de la recherche comme de l'industrie, étant donnés les liens des VANETs avec la sécurité routière, l'internet des objets (IoT/WoT : Internet of Things/Web of Things) pour les systèmes de transport intelligents (ITS : Intelligent Transportation Systems), les villes intelligentes et les villes vertes. Composant essentiel des VANETs, les protocoles de communication inter-véhicules (IVC : Inter-Vehicle Communication) font face à des défis techniques, en particulier à cause de la diversité des applications dans lesquelles ils sont impliqués. Dans cette thèse, après une présentation des VANETs et de l'état de l'art des IVC, nous proposons un protocole de dissémination de données, TrAD, conçu pour diffuser de manière efficiente des messages d'une source vers les véhicules présents dans la zone d'intérêt (ROI : Range of Interest). TrAD se base sur les états du trafic routier et du trafic réseau pour adapter localement la stratégie et les paramètres de transmission des données afin d'optimiser les performances des applications qui l'utilisent. De plus, un algorithme de classification des clusters locaux de véhicules est conçu pour permettre l'usage de TrAD sur autoroute aussi bien qu'en ville. Pour éviter l'encombrement des canaux de communication, un mécanisme illustratif de contrôle de la congestion reposant sur une approche distribuée est utilisé. Trois protocoles IVC de l'état de l'art ont été comparés à TrAD dans des scénarios réalistes de simulation, basés sur différentes villes réelles, différents trajets et densités véhiculaires. Les performances de TrAD surpassent celles des protocoles de référence en termes de taux de délivrance des paquets (PDR : Packet Delivery Ratio), nombre de transmissions et latence. De plus, nous montrons que TrAD est tolérant, dans une certaine mesure, aux erreurs sur les données GPS. Pour s'assurer de la qualité des simulations, nous avons étudié le modèle de déplacement employé dans le simulateur de trafic, puis couplé ce dernier au simulateur de réseau, afin que les deux s'échangent des informations en temps-réel. Grâce à la compréhension acquise lors de l'analyse du modèle de déplacement, nous avons pu développer un simulateur de conduite de tramway pour la T2C (Transports en Commun de l'agglomération Clermontoise). Des tests menés sur le matériel roulant nous ont permis d'élaborer des modèles de déplacement fidèles correspondants aux diverses situations rencontrées par le tramway. L'affichage de la simulation est assuré par un flux vidéo ajusté plutôt que des images de synthèse, ce qui

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permet de limiter le coût de développement tout en garantissant un certain réalisme dans l'affichage. Ce projet est soutenu par la T2C pour une durée de deux ans.

Key Words

Vehicular Ad hoc Networks (VANETs) ; Inter-Vehicle Communication (IVC) Protocols ;
Traffic Adaptive Data Dissemination (TrAD) ; Road Traffic Scenarios ; Bidirectionally
Coupled Simulation ; Tram Simulator ;

Mots Clés

Réseaux Ad hoc Véhiculaires; Protocoles de Communication Inter-Véhicules; Trafic Diffusion Adaptive Données; Scénarios de la Circulation Routière; Simulation Bidirectionnellement Couplé; Tram Simulateur;

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Abbreviations

3GPP: Third Generation Partnership Project

3GPP2: Third Generation Partnership Project 2

AC: Access Category

ACK: Acknowledgment

AIFS: Arbitration Interframe Space

AODV: Ad-hoc On-Demand distance Vector

BGP: Border Gateway Protocol

BSM: Basic Safety Message

BSS: Basic Service Set

CA: Certificate Authority

CAM: Cooperative Awareness Message

CCA: Clear Channel Assessment

CCH: Control Channel

CDMA: Code-Division Multiple Access

CoCar: Cooperative Cars

CoCarX: Cooperative Cars Extended

CSMA/CA: Carrier Sense Multiple Access with Collision Avoidance

CTS: Clear to Send

CW: Contention Window

DCC: Decentralized Congestion Control

DCF: Distributed Coordination Function

DENM: Decentralized Environment Notification Message

DHT: Distributed Hash Table

DSDV: Destination Sequenced Distance Vector

DSR: Dynamic Source Routing

DSRC: Dedicated Short Range Communication

DTN: Delay Tolerant Network

DV-CAST: Distributed Vehicular BroadCAST

DYMO: Dynamic MANET on demand

DynB: Dynamic Beaconing

ECC: Electronic Communications Committee

EDCA: Enhanced Distributed Channel Access
ETSI: European Telecommunications Standards Institute
FCC: Federal Communication Commission (USA)
FDMA: Frequency Division Multiple Access
FOT: Federal Operational Test
GPRS: General Packet Radio Service
GPS: Global Positioning System
GPSR: Greedy Perimeter Stateless Routing
GSM: Global System for Mobility communications
GUI: Graphical User Interface
IBSS: Independent Basic Service Set
ICWS: Intersection Collision Warning System
IEEE: Institute of Electrical and Electronic Engineers
IETF: Internet Engineering Task Force
IFS: Interframe Space
IoT/WoT: Internet of Things / Web of Things
IP: Internet Protocol
ITS: Intelligent Transportation System
ITS-G5: Intelligent Transportation System access layer for the 5-GHz band (ETSI)
IVC: Inter-Vehicle Communication
LAN: Local Area Network
LLC: Logical Link Control
LOS: Light of Sight
LTE: Long Term Evolution
MAC: Medium Access Control
MANET: Mobile Ad-hoc Network
MIMO: Multiple Input Multiple Output
MNO: Mobile Network Operator
MTU: Maximum Transmission Unit
OBU: On Board Unit
OCB: Outside the Context of a BSS
OFDM: Orthogonal Frequency Division Multiplexing
OLSR: Optimized Link State Routing

XVIII Abbreviations

P2P: Peer to Peer

PDR: Packet Delivery Ratio

PeerTIS: Peer-to-peer Traffic Information System

PHY: Physical layer

QoS: Quality of Service

QPSK: Quadrature Phase-Shift Keying

RF: Radio Frequency

RFC: Request for Comments

RIP: Routing Information Protocol

ROI: Range of Interest

RREQ: Route Request

RREP: Route Reply

RSS: Received Signal Strength

RSU: Road Side Unit

RTS: Ready to Send

SAE: Society of Automotive Engineers

SCH: Service Channel

SIFS: Short Interframe Space

SOTIS: Self-Organizing Traffic Information System

SUMO: Simulation of Urban Mobility

TrAD: Traffic Adaptive Data dissemination protocol

TCP: Transmission Control Protocol

TDC: Transmit Data rate Control

TDMA: Time Division Multiple Access

TIC: Traffic Information Center

TIS: Traffic Information System

TO-GO: Topology-assisted Geo-opportunistic routing

TPC: Transmit Power Control

TraCI: Traffic Control Interface (SUMO)

TRC: Transmit Rate Control

TTL: Time to Live

TXOP: Transmission Opportunity

UDP: User Datagram Protocol

UMB: Urban Multiple Broadcast protocol
UMTS: Universal Mobile Telecommunications System
US DOT: US Department of Transportation
UV-CAST: Urban Vehicular BroadCAST
V2V: Vehicle to Vehicle
V2I: Vehicle to Infrastructure
V2X: Vehicle to X (pedestrian, bicycle)
VANET: Vehicular Ad-hoc Network
Veins: Vehicles in network simulation framework
VTL: Virtual Traffic Light
WAVE: Wireless Access in Vehicular Environment
WiMAX: Worldwide interoperability for Microwave access
WLAN: Wireless LAN
WME: WAVE Management Entity
WSA: WAVE Service Advertisement
WSM: WAVE Short Message
WSMP: WAVE Short Message Protocol
WSN: Wireless Sensor Network
XML: Extensible Markup Language

Chapter 1 Introduction

The worldwide economic cost of road crashes and injuries is estimated to be US\$ 518 billion per year and the annual congestion cost in France is estimated to be €5.9 billion [1], [2]. The technology of Vehicular Ad hoc Networks (VANETs) is one of the solutions to improve transport activities such as traffic safety, traffic efficiency and even infotainment on wheels, where a great number of event-driven messages need to be disseminated in a timely way in a region of interest (ROI). In comparison with traditional wireless networks, VANETs have to consider the highly dynamic network topology and lossy links due to the mobility of vehicles and the obstacle on the road (buildings or plants). Nowadays, intelligent vehicle becomes a hot topic in automotive industry and scientific community. Many real-world trials are performed by companies or universities, such as Google Car and Tesla Motors. The communication between intelligent vehicles is exactly performed by VANETs. However, there are still some challenges in Inter-Vehicle Communication (IVC) to be solved, such as scalability, reliability, QoS, security and privacy.

First, the density of VANET varies frequently according to events or day time, which requires IVC protocol to well handle the scalability. This requirement is more critical in traffic safety considering the human life. There is another special scenario of VANET because of the huge number of vehicles and the obstacles on the road. For instance, sometimes, a vehicle goes inside of a residence community where there are a few vehicles as so to suffer frequent disconnection. But when it just goes outside of the residence and joins the main road of city, the wireless environment of the vehicle will become tense immediately. For these cases with various scalabilities, IVC protocol should maintain the QoS of application while controlling the congestion of wireless channel. For data dissemination, like warning messages, IVC protocol first should mitigate the broadcast storm problem, and then find a way out to transmit efficiently messages to vehicles in a range of interest, but also handle the transient disconnected network.

Second, the Quality of Service (QoS) is mainly guaranteed by the reliability of IVC. But, the fact is that, the short range communication techniques, e.g., IEEE 802.11p, cannot assure the reliability because of the high mobility of vehicles and the limited communication range. On the other hand, the long range communication techniques, e.g., cellular network (3G/4G), NB-IoT, can provide more reliable connectivity. But they are in need of enough

basic infrastructures in advance, which would be high cost. Although we can utilize our smartphones in the initial phase of VANETs implementation, there are also some applications, e.g., traffic information system, that need specific communication device with dedicated IVC technique. Moreover, it still does not know that the impact of the overhead from IVC on the current existing cellular network. It is possible to build new infrastructures in the future, especially for the 5G network. Intuitively, the integration of these short and long communication techniques is an optimized solution, i.e., multi-support media access technique. In fact, the European Telecommunication Standard Institute (ETSI) already given the concept for the solution, they design an *access layer* in the framework of their ETSI ITS protocol stack. The access layer includes communication modules for IEEE 802.11p (ITS-G5) and cellular network. However, *how to design the protocol to organize these communication techniques* is a key challenge. The protocol needs to consider respective mechanisms from upper layer to underlying layer of the Open System Interconnection (OSI) model.

At the same time, security and privacy of IVC are the crucial issues of VANETs, which decide whether IVC applications can be performed or not. With the increasing of the intelligence of automobile, security issue becomes more and more important. IVC protocol also needs to identify the fake data packet in order to avoid the fraud and malicious attacks. Currently, official standards conduct security service at the layer above the application one. For instance, the Wireless Access in Vehicular Environment (WAVE) protocol stack resorts to IEEE 1609.2 to protect the related data messages. Privacy is a sensitive party not only in VANETs but also in other networks, e.g., Internet and cellular network. If the personal information cannot be protected properly, nobody will agree to share their data for others.

Based on the above-mentioned understanding, this thesis will contribute itself to develop IVC protocols for VANETs, especially focusing on data dissemination protocols for ad hoc formation of VANETs. To evaluate the performance of IVC protocols, a dedicated road traffic scenario is required to be modeled, implemented and coupled to the vehicular network simulator. To ensure the solid simulation results, the mobility model of vehicles is also well investigated. Based on this knowledge preparation, an evolved project about tram simulator was performed thanks to the support of local public transportation company, i.e., T2C.

For this thesis, I would like to write in a style that is lively and not overly formal. For instance, some plain words will be used to make clear my understanding and to discuss the

relationship between some techniques or theories. Sometimes, some question sentences are used to highlight the key issue in the research field. Moreover, there is an overview at the beginning of every chapter, i.e., introduction section, which can give readers a quick look about that chapter.

In the next chapter, i.e., Chapter 2, the contents about IVC protocols in VANETs are presented. That includes basic knowledge, key wireless access technologies, practical applications and crucial research challenges and so on. These contents are not simply put together, but are composed through my serious thinking, understanding and summarizing. For the wireless communication standards as a instance, e.g., IEEE 802.11, ETSI ITS and WAVE, that section can provide most essential contents of the standards that are extracted from the quite lengthy original standards, while being with my own understanding. The open research issues presented in the chapter are also the problems actually met during my research. I attempt to show a global view of the routing protocol research field for VANETs. For Chapter 3, various classical or useful routing classifications are described from primary routing in MANET to up-to-date routing in VANET. The MANET routing is necessary to be mentioned because it is the foundation of VANET routing and several pioneer routing protocols of VANET are inspired from this kind of routing. After that, the useful and potential VANET routing protocols for different communication paradigms are introduced. Meanwhile, some official standards for IVC are also presented. Furthermore, those crucial techniques highlighted are the ones that can actually help IVC according to my works and experience. The Chapter 2 and Chapter 3 present and analyze the basic knowledge, key issues and the key solutions about IVC protocols for VANETs while being with my understanding. Therefore, these parts of my thesis can be a memo book for me, but also can be a quick guide about state-of-the-art of IVC protocols research field for readers.

The main contributions of my thesis are elaborated from Chapter 4 to Chapter 6, especially in Chapter 5. In Chapter 4, the main mobility model of the road traffic simulator used by us is explained. Based on this understanding, various road traffic scenarios are designed and illustrated, e.g., abstract one and realistic one. Then, the realistic traffic scenarios are coupled with network simulator to perform bidirectionally coupled vehicular network simulations. This type of simulation can contribute to carry out an experiment of vehicular networking more close to the real world. Based on the realistic simulation, in Chapter 5, we explore and propose a data dissemination protocol, i.e., TrAD, for ad hoc formation of VANET. This protocol can perform fast information dissemination in a range

of interest (ROI) in terms of the status of road traffic and network traffic in both urban and highway scenarios. The TrAD protocol contributes itself to develop the advanced algorithm or mechanism for the key techniques to solve the open research issues that are mentioned in Chapter 2 and Chapter 3. By the cooperation between LIMOS and T2C Company, as a main participator, I take part in the project to develop a low-cost tram simulator based on the mobility model of specific type of tram that is used in Clermont-Ferrand, France. In Chapter 6, after presenting the state-of-the-art of current tram simulators, we get inspiration to continue to reduce the cost of current tram simulator. In this thesis, the mobility model of vehicle is the main research object. Therefore, after the introduction of framework design of our tram simulator, the modeling process and the implementation of the mobility model are explained in detail.

Finally, we conclude the thesis and present the perspective for the future work. This thesis not only is the summary of my whole Ph.D. student life, but also the new starting point of my research career.

Chapter 2 Inter-Vehicle Communication (IVC) in Vehicular Ad hoc Networks (VANETs)

2.1 Introduction

Inter-Vehicle Communication (IVC) performs the information exchange among vehicles or between vehicles and available infrastructure by using wireless medium. Those vehicles and infrastructure are connected by wireless communication medium, which form Vehicular Ad hoc Networks (VANETs). One thing needs to make clear, there is another type of vehicular network that is for Intra-Vehicle Communication. It is responsible for the information exchange between sensors or nodes inside of vehicles. However, that is beyond the scope of this thesis. Therefore, notice that, this thesis mainly focuses on the Inter-Vehicle Communication in VANETs, especially on the IVC protocols.

VANETs aim at improving transport activities that include traffic safety, transport efficiency and infotainment on wheels. This chapter is going to give a basic introduction to IVC and VANETs, which provides a necessary knowledge and a theoretical foundation for the following chapters. For more details, first, we will present formations of VANETs and describe the different formations that are with or without infrastructure. Then, various practical and useful wireless medium access technologies and official standards for VANETs are described and commented. Based on this, we will present several main applications to prove the application and the functionality of IVC in VANETs. Finally, we uncover that open issues or limitations in VANETs, understanding which can be beneficial to the design of IVC protocols.

2.2 Formations of VANETs

Generally, VANETs are classified into two formations, *infrastructure-based and ad hoc*, according to whether existing available infrastructure or not, as shown in Figure 2-1 and Figure 2-2. The infrastructure elements mainly include the base station of cellular network (3G/4G), roadside units (RSUs) using WAVE standard or using WiFi or, a few of them, using ZigBee and Bluetooth.

2.2.1 Infrastructure-based Formation

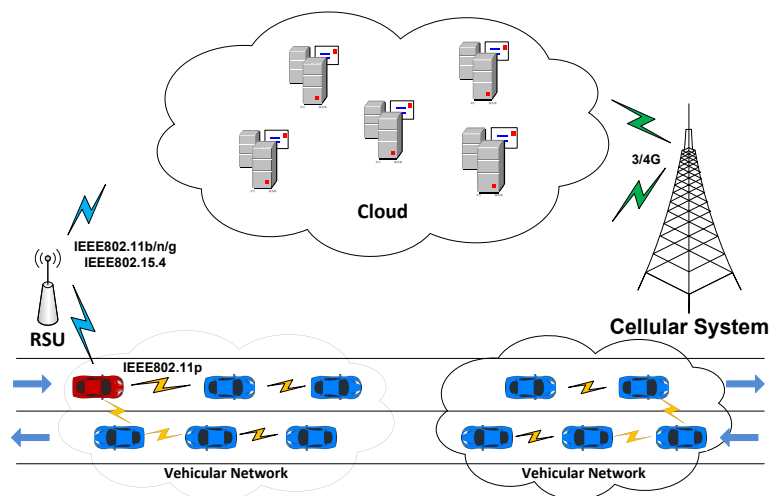


Figure 2-1. Infrastructure-based Formation

For using infrastructure, normally, the provider of a service has a long distance with vehicles client. For instance, the distance is beyond the Dedicated Short Range Communication (DSRC) or the line-of-sight (LOS) signal is blocked by buildings or trees. The most popular application of infrastructure-based formation is navigation service by using smartphones or specific GPS devices, e.g., Google Map [3], TomTom [4] and Waze [5]. These applications use cellular network (3G/4G) to connect smartphones or GPS devices on wheels to the background server, by which the information of navigation can be collected to the server to calculate the traffic condition in the real-time. Google Map provides three color lines, i.e., green one, orange one and red one, to represent different levels of traffic conditions, i.e., no traffic delays, medium amount of traffic and traffic delays. The darker the red, the slower the speed of traffic on the road [6]. TomTom provides API for developers to access its real-time traffic information database. Waze organizes a vehicular community, in which every user can post the surrounding traffic information to the community, such as traffic jam, accident, road maintenance, and even the location of the police patrol. However, the number of users using each application is not enough. Consequently, the information collected from users cannot reflect the real traffic situation. The reasons can be seen as follows: First, the multiple choices of navigation applications split the user resource. Moreover, the servers of various applications do not share the data with each other. In addition, some off-line navigation smartphone applications are more and more popular, such as maps.me [7], which can save a great amount of mobile data flow for users.

Many projects are performed for evaluating the applicability of using the roadside WiFi or the public WiFi [8]. Given the existence of a great number of Access Points (AP), this internet access technology is very practical and has big potential. There are also some other access approaches, e.g., WAVE and ZigBee, but they are rarely used currently; yet they are the key technologies for the future. If the law confirms that every new car must equip the DSRC device, vehicles can communicate with RSUs by using WAVE stack. There is an interesting idea proposed by Sommer et al. [9]. They discussed the utility of parked cars beside streets to reply the data. These parked cars, like the RSUs, can complement the drawback of short range communications. Moreover, the car parked in a street corner can also help forward the data to pass around buildings. In the future, the smart city will use ZigBee to connect tons of sensors or nodes, in which there must be a great number of road traffic related devices. Therefore, if vehicles can access these devices, a considerable number of services can be developed.

2.2.2 Ad hoc Formation

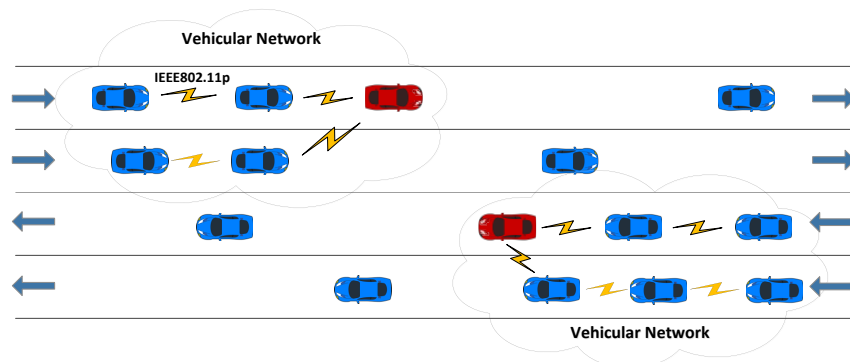


Figure 2-2. Ad hoc Formation

The ad hoc formation of VANETs, as shown in Figure 2-2, mainly is used for safety applications and the platooning. By using IEEE 802.11p, vehicles could cooperate together and be aware of each other in the one-hop neighborhood, so the emergency event can be informed to very vehicle involved in advance, such as intersection assistance systems, abnormal driving warning and Electronic Emergency Break (EEB). The biggest advantage of this formation is the real-time service. Frequent data exchange, e.g., 10 Hz, can be supported by the capacity of IEEE 802.11p. The default data rate is 6 Mbit/s for broadcasting which provides a reasonable balance between the signal robustness and the service requirement. However, the channel would be overloaded due to the dense network and the high transmit frequency. Therefore, the Decentralized Congestion Control (DCC)

standard has been proposed by European Telecommunications Standards Institute (ETSI) [10] [11]. There are also other congestion control protocols proposed by researchers, e.g., PULSAR [12], LIMERIC [13] and DynB [14]. These efficient and well-known protocols adjust the transmit rate of beaconing to maintain a reasonable Channel Busy Ratio (CBR). Another application is worth mentioning, i.e., the platooning or the road train. This service can organize a group of vehicles by using ad hoc formation of VANET to travel smoothly and efficiently on the highway, by which the transport is optimized and the fuel consumption is reduced.

2.3 Wireless Medium Access Technologies and Standards

A suitable wireless medium access technology can significantly improve the performance of applications. Various access technologies and related standards will be discussed in this section. For VANETs, there are two main types of access technologies, i.e., long range communication technologies and short range communication technologies. The former mainly refers to cellular networks and the latter mainly includes WiFi and IEEE 802.11p. Here, we do not want to describe every specific technique in detail, but we will discuss which access technology is, or is not, suitable to what application, and give some conclusions according to the previous research projects. Therefore, we can get a general understanding to each access technology. After that, two ITS protocol stacks, i.e., WAVE and ETSI ITS, are introduced, which are used in the USA and Europe, respectively. At last, a new potential access technology, i.e., NB-IoT, will be presented for the future low cost, low energy consumption long range communication.

2.3.1 Cellular Network

There are three major standardization bodies govern the specification of cellular networks, which include 3GPP (Third Generation Partnership Project), 3GPP2 (Third Generation Partnership Project 2) and IEEE (Institute of Electrical and Electronics Engineer). The standards proposed by 3GPP are GSM, UMTS and LTE. The 3GPP2 family of standards includes CDMAone, CDMA2000 and UMB. The UMB has been abandoned in favor of LTE. IEEE proposed WiMAX standard for the long range communication in urban scenarios, but, for various reasons, the work group of WiMAX has joined the one of LTE.

The different generations of cellular networks and respective data rates is shown in Table 2-1.

Table 2-1. Different generations of cellular networks and respective data rates

Generation	Protocol	Downlink	Uplink
2G	GSM	9.6 kbit/s	9.6 kbit/s
2.5G	GPRS	9.6-50 kbit/s	9.6-50 kbit/s
	EDGE	384 kbit/s	384 kbit/s
3G	UMTS	384-2000 kbit/s	384-2000 kbit/s
	HSDPA/HSUPA	10 Mbit/s	5 Mbit/s
	HSPA+	100 Mbit/s	23 Mbit/s
3.9G	LTE	300 Mbit/s	75 Mbit/s
4G	LTE Advanced	1 Gbit/s	1 Gbit/s

Although the standards of cellular networks are different, the basic idea is always the same. For cellular networks, the world is divided into different cells. Each cell is served by a base station. A cellphone, properly in a mobile vehicle, connect to the base station serving the cell where the cellphone is located in. Moreover, the cellphone will switch to an appropriate base station when it crosses the boundary of cells. The illustration of cellular network is shown in Figure 2-3.

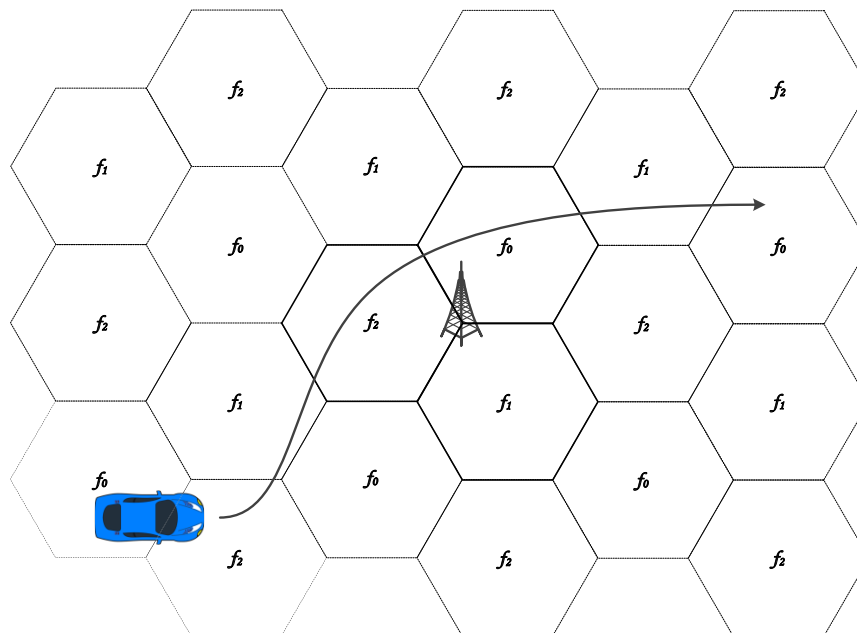


Figure 2-3. Cellular Network

In the last decade, several projects and Field Operational Tests (FOTs) have been performed, from which we can get some useful and inspired information for the implement of cellular networks in VANETs. First of all, the feasibility of cellular networks is proved

by FOTs, which shows that the vehicle at a very high speed, i.e., 290 km/h, can connect to the base station of the cellular network. The signal is only interrupted after a sudden braking behavior for the handover prediction fails. In 2006, CoCar (Cooperative Car) project started to investigate the feasibility of using cellular networks solely for VANETs [15]. The results showed that cellular networks achieve a very good scalability for Traffic Information Systems (TISs). However, the technology is not able to support safety-critical applications, since the delay is on the order of seconds. Following this project, in 2009, CoCarX (Cooperative Car Extended) integrated IEEE 802.11p into the cellular communication system [16]. At that time, an early version of LTE was used in CoCarX project. Therefore, CoCarX builds a completely heterogeneous vehicular network, in which vehicles can exchange messages by IEEE 802.11p in the one-hop neighborhood and send these messages to vehicles or infrastructure far away by LTE. The report showed that the system not only supports the TIS, but also can satisfy some safety applications, e.g., hazard driving warning. The only limitation is the capability of the system. It is still not known whether cellular networks scale well with the increasing number of participating vehicles. However, considering the well implemented infrastructure of cellular networks, this access technology is the most suitable access technology for the early phase of IVC applications since the penetration rate of DSRC devices is still very low.

2.3.2 WiFi

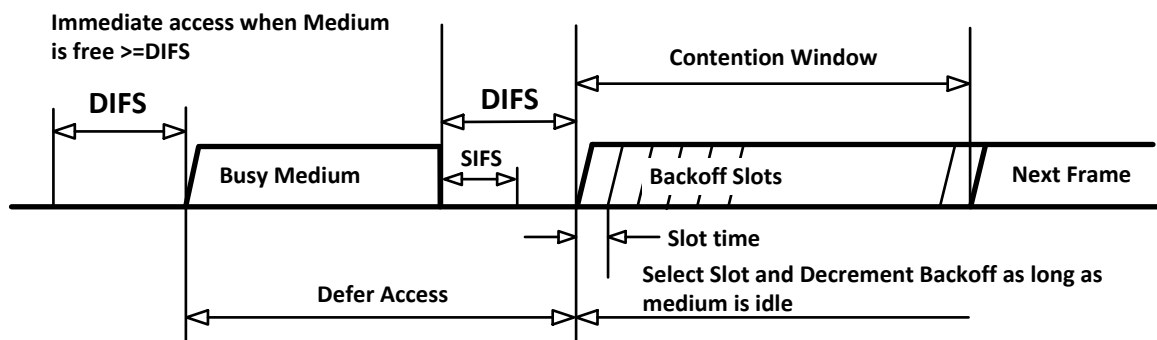


Figure 2-4. The access procedure of the MAC layer of IEEE 802.11

WiFi is an access technology based on IEEE 802.11 that allows communication devices to connect each other in Wireless Local Area Network (WLAN), mainly using 2.4G Hz band. Generously, WiFi and WLAN could be believed to be a synonym, since most WLANs are composed by using IEEE 802.11. In addition, for completeness, WLAN is also the name of IEEE working group of 802.11.

The fundamental access method of the MAC layer of IEEE 802.11 is the Distributed Coordination Function (DCF) known as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), as shown in Figure 2-4 [17]. When stations prepare to transmit frames, they should determine that whether the channel is idle or not in Physical Layer Convergence Protocol (PLCP) sublayer. This function is implemented by Clear Channel Assessment (CCA). The station can transmit a frame only if the channel is clear or idle for at least one DIFS (DCF InterFrame Space). DIFS is calculated by Equation (2-1).

$$\text{DIFS} = \text{aSIFSTime} + 2 \times \text{aSlotTime} \quad (2-1)$$

If a station wants to transmit a frame, it must sense the channel (busy or clear) by performing CCA. If the channel is busy, the station will queue the frame and start to contend the channel by using a *backoff procedure*. It selects a random backoff time (delay) from the pre-configured Contention Window (CW). A timer is triggered to decrement the backoff time if the channel is idle. Before the timer expiring, if the channel turns to be busy again, the timer will be frozen until the channel turns to idle again for at least one DIFS. This backoff procedure also happens after a successful transmission to give other stations a chance to access the channel. To mitigate hidden terminal problems, the MAC layer provides the Ready-To-Send (RTS) and Clear-To-Send (CTS) mechanism.

The Basic Service Set (BSS) is a central concept of IEEE 802.11, in which synchronized stations in the same BSS can communicate with each other. There are two modes of BSS, i.e., infrastructure and ad-hoc. In infrastructure mode, stations connect to the Access Point (AP) and then associate to send or receive data. In the other hand, stations in the ad-hoc mode form an Independent Basic Service Set (IBSS) and then communicate with each other directly.

The utility of WiFi for Intelligent Transportation System (ITS) has been investigated by the early measurement campaigns. The “drive-thru Internet” project investigated the impact of the speed of vehicles on the capability to connect to AP and exchange data [8]. The results showed that the infrastructure mode of WiFi is not suitable to high dynamic and time-sensitive applications of ITS. The reason lies in the long time association process of stations with APs. Moreover, due to the limited communication range, this association process will be happened frequently when vehicle switches connection from one AP to the other.

2.3.3 IEEE 802.11p

Given the drawback of WiFi mentioned in the last section, a new communication technology needs to be developed for ITS. Therefore, in 1999, US Federal Communication Commission (FCC) allocated 75 MHz of dedicated bandwidth in the 5.9 GHz region for ITS applications. Seven 10 MHz channels are provided to serve the communication on the road. These channels are given the specific number ID, as shown in Figure 2-5a, that is, channels 172, 174, 176, 178, 180, 182, 184. Channel 178 is used to transmit and receive control messages, namely Control Channel (CCH). Channels 172 and 184 are reserved for the public safety applications. These dedicated frequency band is called Dedicated Short Range Communication (DSRC) band. In 2008, European Commission and Electronic Communications Committee (ECC) also allocated five channels for ITS, i.e., 172, 174, 176, 178, 180, as shown in Figure 2-5b. To enable the efficient use of the DSRC band, US Department Of Transportation (DOT) developed the standard IEEE 802.11p since 1997 [18]. Currently, the IEEE 802.11p has been integrated into the 2012 version of IEEE 802.11.

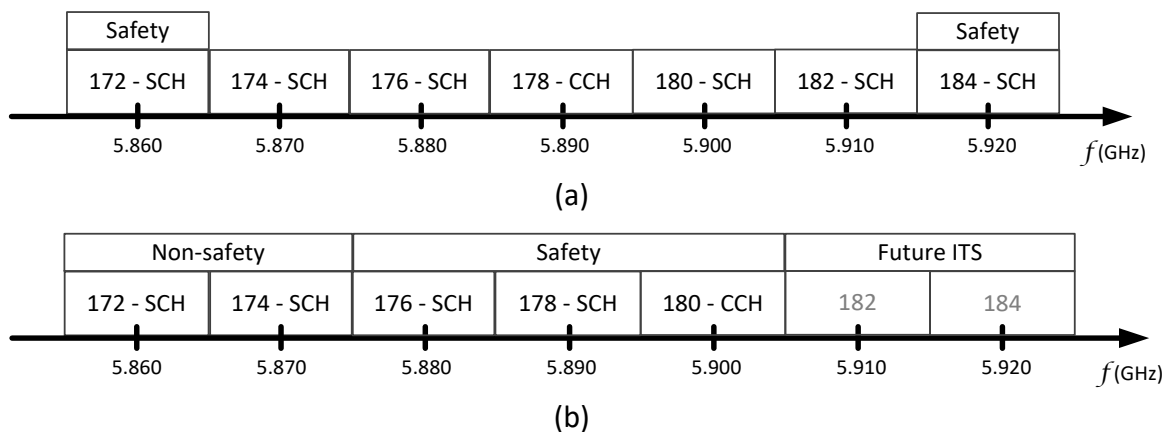


Figure 2-5. Channel Allocation of WAVE (a) and of ETSI ITS (b)

Based on extensive research, testing and feasibility studies, IEEE 802.11p adopted the PHY layer of IEEE 802.11a and the MAC layer of IEEE 802.11e. The necessary amendments were made for the requirement of ITS applications. 10 MHz bandwidth is expected by ITS instead of 20 MHz of the original PHY layer of IEEE 802.11a. Therefore, all symbol times and CCA time are doubled so that the original data rate is cut into half, i.e., 3 Mbit/s, 4.5 Mbit/s, 6 Mbit/s, 9 Mbit/s, 12 Mbit/s, 18 Mbit/s, 24 Mbit/s, 27 Mbit/s. The bright side of this amendment is to significantly decrease the inter-symbol interference, which can make transmissions more robust. For the MAC layer, a new operation mode, i.e., OCB (outside the context of a BSS), is introduced to allow stations to be not necessary to

establish a BSS and also do not perform the authentication, association and data confidentiality service of the IEEE 802.11. The BSS identifier of all frames is set to a wildcard value, which allows all recipients to process the frame. These amendments significantly reduce the transmission delay. In addition, the broadcast and the multicast of IEEE 802.11p do not have the acknowledgment process, the RTS/CTS mechanism and the MAC-level recovery mechanism. As a result, the transmission delay continues to be reduced, but the reliability of transmissions cannot be guaranteed.

IEEE 802.11p uses Enhanced Distributed Channel Access (EDCA) mechanism to perform the channel access procedure. Frames are classified into four Access Categories (ACs), as shown in Table 2-2, providing different priorities for the data from higher layer. That is, the data with a higher priority will be transmitted first.

Table 2-2. Access Categories

AC	Description
AC_BE	Best effort
AC_BK	Background
AC_VI	Video
AC_VO	Voice

In EDCA of IEEE 802.11p, the Interframe Space (IFS) uses a new concept, namely using Arbitration Interframe Space (AIFS) instead of DIFS in WiFi. The AIFS length and the maximum and minimum Content Window (CW) are based on the priority (category) of the data, as shown in Table 2-3. aCWmin and aCWmax are equal to 15 and 1023, respectively.

Table 2-3. Default EDCA parameter set

AC	AIFSN	CWmin	CWmax
AC_BE	9	aCWmin	aCWmax
AC_BK	6	aCWmin	aCWmax
AC_VI	3	$(aCWmin+1)/2-1$	aCWmin
AC_VO	2	$(aCWmin+1)/4-1$	$(aCWmin+1)/2-1$

Here, we will show the access procedure of IEEE 802.11p by using EDCA, as shown in Figure 2-6, including the calculation of AIFS[AC] and the backoff time for different access categories (ACs).

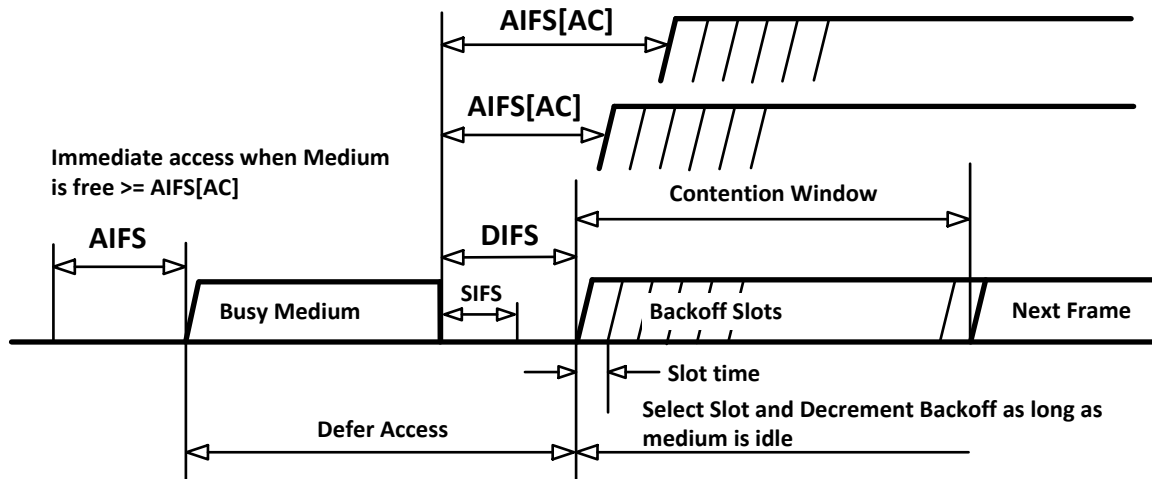


Figure 2-6. The access procedure of MAC layer of IEEE 802.11p

When the MAC layer receives a data from upper layer, the data is stored into respective AC queue according to its priority (AC). EDCA will calculate a $AIFS[AC]$ according to the data's AC by using Equation (2-2).

$$AIFS[AC] = aSIFSTime + AIFSN[AC] \times aSlotTime \quad (2-2)$$

$AIFSN[AC]$ can be obtained in Table 2-3. $aSlotTime$ and $aSIFSTime$ are equal to $13 \mu s$ and $32 \mu s$, respectively.

Before transmitting the data, the station determines the status of the channel at first. If the channel is free for greater than or equal to $AIFS[AC]$, the data will be sent. If the channel is busy when the station wants to transmit the data, exclusive of the $AIFS[AC]$ period, a backoff procedure will be attached. The core operation of the backoff procedure is to obtain a random integer value $CW[AC]$ that represents the content window. The value of $CW[AC]$ is between CW_{min} and CW_{max} .

$$CW_{min} \leq CW[AC] \leq CW_{max} \quad (2-3)$$

$CW[AC]$ can be obtained according to the different events that invoke the backoff procedure. For a clear explanation, a flow chart of the backoff procedure in EDCA is shown in Figure 2-7.

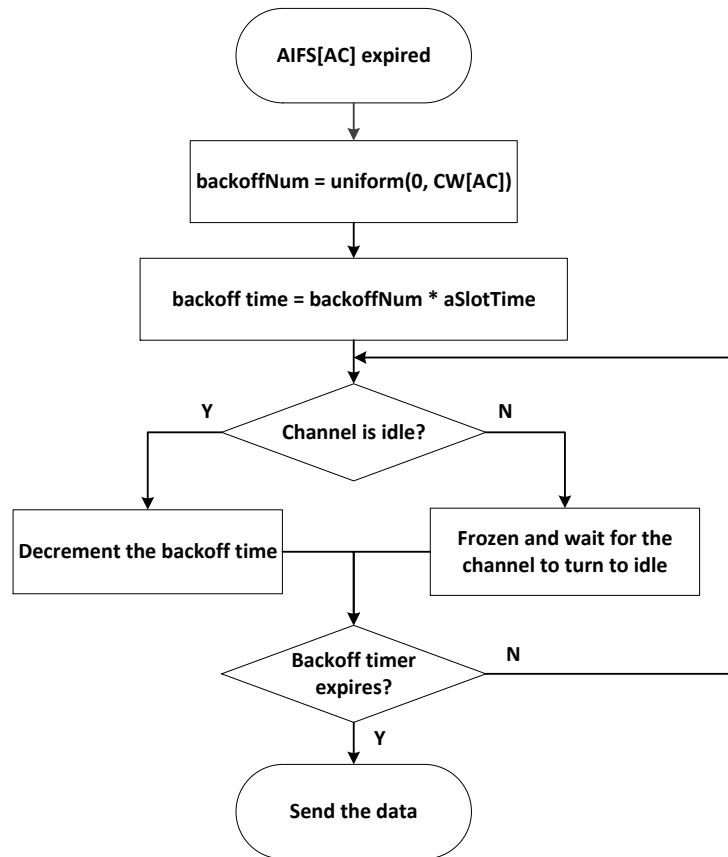


Figure 2-7. The flow chart of the backoff procedure in EDCA

A backoff number, i.e., backoffNum , is selected between 0 and $\text{CW}[\text{AC}]$ following uniform distribution. The backoff time can be obtained by multiplying backoffNum and a slot time, i.e., aSlotTime . Then, the station checks the status of the channel. If the channel is idle, the backoff time will be decremented. Otherwise, the backoff time will be frozen, waiting for the channel to turn to be idle. Once the backoff timer expires, the data will be sent.

2.3.4 WAVE

The USA adopts IEEE 802.11p as the lower layer of its ITS protocol stack that is called Wireless Access in Vehicular Environment (WAVE) protocol stack, as shown in Figure 2-8. This stack also includes IEEE 1609 standard suite, e.g., IEEE 1609.4 for multi-channel operation, IEEE 1609.3 for networking service and IEEE 1609.2 for security service [19].

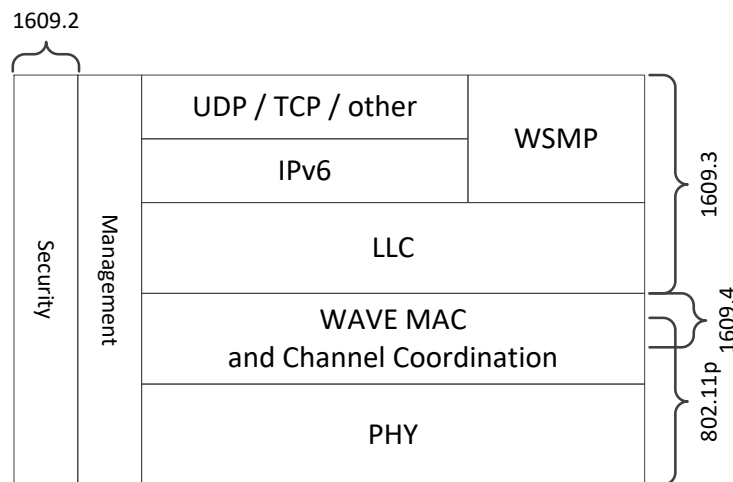


Figure 2-8. Architecture of WAVE

WAVE device is defined to be equipped with one single radio and can communicate on seven channels in 10 MHz DSRC band. In order to synchronize all vehicles on the same channel, IEEE 1609.4 is developed to manage the multiple channels [20]. Since IEEE 1609.4 is an additional MAC layer on the top of IEEE 802.11p, it is also called WAVE MAC. The channel is classified into two parts, i.e., Control Channel (CCH) and Service Channel (SCH). In default “continuous option” of IEEE 1609.4, every part of channel occupies 50 ms and switches between each other. To mitigate the synchronization errors, the first 4ms of each 50 ms time interval is left to be a guard interval. However, a number of transmissions would be triggered at the border of the switch channels, these packets will be suspended until the next time interval of the same channel. As a result, many contentions blow up at the beginning of the time interval so that a large amount of collisions would occur [21].

To notify neighbors the type of services offered on the next SCH, the WAVE station broadcast WAVE Service Advertisements (WSA) on the CCH. This functionality is supported by IEEE 1609.3 [22]. This standard also provides networking services for the legacy IPv6 and a lightweight WAVE Short Message Protocol (WSMP). The IPv6 is mainly used to communicate with the RSUs or future IoT/WoT devices for the non-safety application. The WSMP is responsible for exchanging WAVE Short Messages (WSM) between WAVE stations for the safety application. Moreover, IEEE 1609.2 specifies communications security for WSA and WSM [23].

2.3.5 ETSI ITS

ETSI ITS protocol stack is standardized by ETSI in Europe. The access technology of this stack is also based on IEEE 802.11p, operating 5 GHz frequency band for ITS. Therefore, the access technology is called ITS-G5. However, the ETSI ITS device and stack are different from the ones of WAVE. ETSI ITS device is defined to be multi-radio and multi-channel mode. That means the station should use an exclusive ITS-G5 radio to exchange safety messages on Control Channel, i.e., G5-CCH, and another ITS-G5 radio is responsible for transmitting service messages on Service Channel, i.e., G5-SCH. This mode effectively reduces the synchronized collisions. The architecture of ETSI ITS is shown in Figure 2-9.

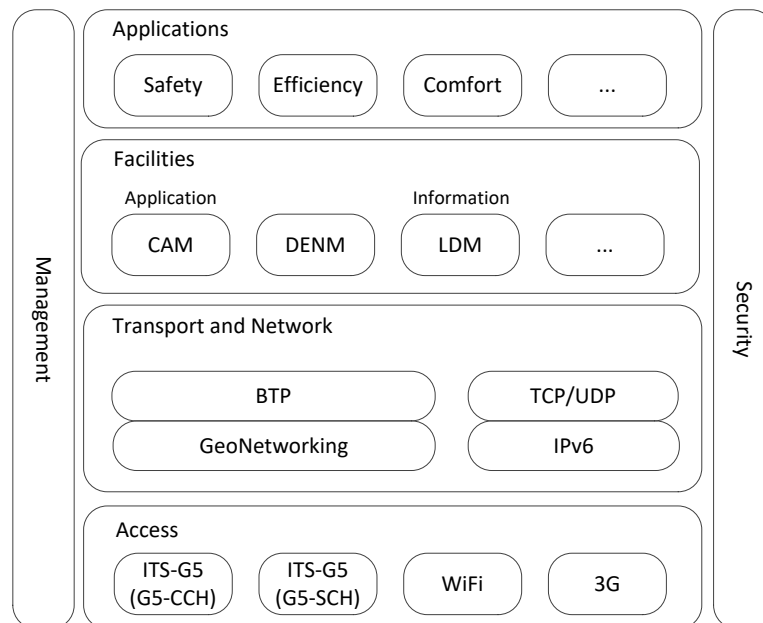


Figure 2-9. Architecture of ETSI ITS

The facilities layer provides several functional messages and information resource, such as Cooperative Awareness Messages (CAMs), Decentralized Environment Notification Messages (DENMs) and the Local Dynamic Map (LDM) [24]. LDM is a database that store information about local neighborhood. The transport and network layer not only supports the TCP/UDP over the IPv6 networking service but also the Basic Transport Protocol (BTP) over the GeoNetworking service. As the WAVE stack, the IPv6 networking service is mainly to communicate with RSUs or the future IoT/WoT devices for non-safety applications, while the GeoNetworking service is responsible for exchange messages between vehicles for safety applications. Especially, ETSI propose a concept of access layer

that adopts WiFi and cellular network along with ITS-G5. ETSI ITS stack intends to abstract the different access technologies and give an identical medium access layer.

2.3.6 NB-IoT

In recent two years, NB-IoT (Narrowband Internet of Things) is invested by many manufactures, such as Huawei, Vodafone, Intel and Nokia, since its unique features and technical feasibility. NB-IoT is a Low Power Wide Area (LPWA) wireless access technology operates in licensed or shared spectrum. Especially, it is able to be deployed over existing mobile network, e.g., LTE. Its characteristics include full coverage, low device and deployment cost, long battery life and supporting for a massive number of IoT devices and so on. 3GPP has adopted NB-IoT feature to specify a new access technology for cellular IoT while was making a full standardization for it. The first commercial trial of pre-standard NB-IoT was completed in November 2015. Huawei and Vodafone have successfully integrated the technology into the operator's existing mobile network in Spain, in which the first NB-IoT message sent to an IoT device. The NB LTE-M, one of cellular IoT access technologies supported by 3GPP, not only can operate in a 200 kHz band refarmed from GSM but also can be able to operate in shared spectrum with an existing LTE network. Therefore, it is recommended by Nokia. The NB LTE-M Rel. 13 version can achieve about 15 km communication range with 150 kbps data rate.

Given the features of NB-IoT, this access technology can bring a great improvement for long range communication, delay tolerant and low data rate IVC applications, such as traffic information system, smart parking, fleet management. NB-IoT will be an important complement to cellular networks for low data rate IVC applications. Since it is still unknown whether cellular networks can scale well with the increasing of participating vehicles, NB-IoT can effectively mitigate the stress of network load for cellular networks. A unique advantage of NB-IoT is that, by using this access technology, a massive number of IoT devices can be connected to vehicles in a long communication range. For the short range communication, WAVE and ETSI ITS stacks have defined respective transport and network layer for IPv6 to connect to IoT devices. We believe that NB-IoT would be a new choice for the long range communication. According the report of Machina Research, the applications about connected car and fleet will take 20% market share in the future cellular IoT connections (Machina Research, May 2015).

2.4 Applications

After discussing the formation, access technologies and standards for VANETs, the IVC applications will be elaborated in this section, aiming to demonstrate the functionality of IVC applications. This thesis will give comments carefully on which technology gains the practical value for current applications, which one can be feasible and potential in the future. Considering different applications use different communication principles, we select three applications that represent the main functionality of IVC, i.e., traffic information systems for non-safety, intersection collision warning system for safety and platooning for transport efficiency.

2.4.1 Traffic Information Systems (TISs)

Navigation service is widely used by drivers through navigation devices, e.g., TomTom and Navigon, or Smartphone APP (application), e.g., Google Map, TomTom and Waze. Those devices utilize the GPS signal and the local installed map to locate vehicles position and calculate the route to the destination. However, the navigation that simply considers the distance from the source and the destination is not satisfied the current requirement of intelligent transport. The future navigation not only can provide the traditional navigation service, but also can provide real-time traffic information about the interested area. This non-safety application system is called Traffic Information System (TIS).

In fact, the first attempt has already been implemented by Google Map, TomTom and Navigon. They use the current navigation information of users to deduce the actual traffic density on the road. But, as mentioned in section 1.1.1, the source data from their users falls far short of the adequate information that can calculate the accurate real-time traffic information, because the number of users for every service is not enough. Moreover, those services have their own servers that cannot share the information between each other. Even so, these commercial implements still proved the possibility and the applicability of the centralized TIS, in which the system aggregates (uplink) the traffic information from infrastructure and vehicles, processes and manages the data, and then disseminates (downlink) to vehicles in the region of interest (ROI). On the other hand, there is an alternative system that resorts to fully distributed data storage in every vehicle rather than in the central server. We will describe the two kinds of TIS system in detail in the following sections.

2.4.1.1 Centralized TIS

The illustration of centralized TIS is shown in Figure 2-10, in which all the traffic information data is aggregated and managed in the central Traffic Information Center (TIC). The data sources come from infrastructure and vehicles on the road. The infrastructure elements include video camera, induction loop, toll bridge and so on. The data from these elements has already existed in TIC. However, the integration of these great amounts of data is still an open research issue. The processing of some data still need human intervention, for instance, the special event, e.g., traffic accident, from the video cameras. Another traffic data source is vehicles themselves, since vehicles become more and more intelligent, which would be equipped multiple sensors, such as ultrasonic, radar and camera. Some vehicles even can recognize their situation automatically. The data from vehicles, e.g., the location of vehicles, is very useful to TIC to recognize the traffic condition in real-time. After explaining the data source, we will discuss, from the networking point of view, how the data can be uploaded from infrastructure and vehicles to TIC and how the data can be downloaded from TIC to vehicles.

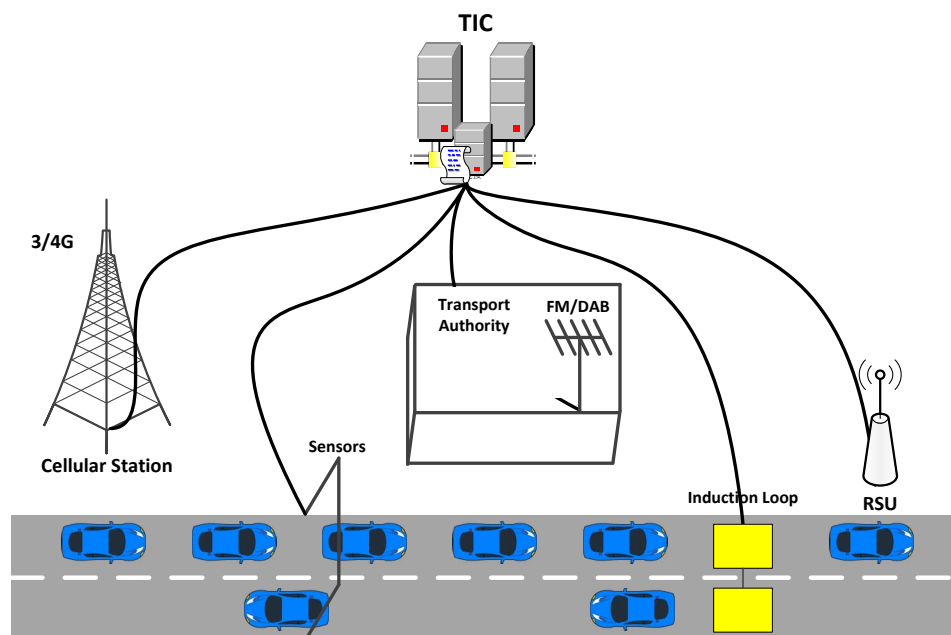


Figure 2-10. Centralized TIS

First, we talk about the uplink channel. Given there have been connections between most infrastructure elements to TIC, the key lies in that how to upload data from vehicles to TIC. The current research and projects mainly focus on using 3G/4G network, WiFi and IEEE 802.11p. The 3G/4G network has enough capacity and scalability to transmit the data from vehicles to TIC, but the cost needs to be considered before the implementation. Moreover,

the influence of participating vehicles on the QoS of cellular network is not clear yet. We also can use roadside unit or APs to connect vehicles into the Internet by using WiFi. But, for this approach, the new APs should be implemented to satisfy the requirement of service. Moreover, the time consumption of association process should be take into account, which would consume several seconds to connect vehicles to the AP. Furthermore, given the limited communication range of WiFi and the highly dynamic of vehicles, the vehicle will switch APs frequently with a long association time. These limitations bring a great challenge. Consequently, we should consider that using which kind of protocol for the challenge, ad hoc routing or broadcasting. If the DSRC device is equipped on vehicles in the future, IEEE 802.11p can be used to transmit data among vehicles. Although IEEE 802.11p does not have the association process as so to achieve a fast connection speed with APs, it also needs to meet the similar problem as WiFi, e.g., the cost of APs and frequent switch between APs.

For the downlink aspect, TIC needs to disseminate the traffic information to vehicles on the road. Except the access technologies used in uplink channel, FM radio and digital audio broadcasting (DAB) are other options to broadcast the data from TIC to vehicles. In fact, FM radio and DAB were the first approach to transmit the traffic information to participating vehicles. This approach has been used for traffic message channel (TMC) that carries the traffic messages to broadcast the vehicles. The message in TMC contains an event code, the position of the event, expected incident duration and other details. The communication range of FM radio and DAB is about 10 km, which is beneficial to cover more vehicles compared with the short range communication technique. However, as all the radio technique, its data rate is very low, e.g., a few hundred bits per second. This problem can be overcome by using 3G/4G network that is a competitive and practical access technology for VANETs. A number of projects are performed to investigate specific technique for cellular networks, such as Cooperative Cars (CoCar) project. The communication capacity of 3G/4G network can well satisfy the requirement of traffic information system. But the challenge mainly lies in the information processing and the cost of implementation. For using WiFi or IEEE 802.11p, except the issues mentioned at uplink aspect, we want to highlight the functionality of Delay Tolerant Network (DTN) routing to collect traffic data from vehicles to RSUs [25], [26]. Given the short communication range of these access technologies, VANETs are not always fully connected. In other words, disconnected networks or the network partition problem are ubiquitous. The DTN routing

uses a Store-Carry-Forward (SCF) mechanism to operate the data dissemination in disconnected networks. If there is no further forwarding route, the SCF mechanism will let the vehicle store and carry the data until meeting a new opportunity to forward. This routing can greatly increase the Packet Delivery Ratio (PDR) and scalability for data collection from vehicles to RSUs, but consuming high delay.

2.4.1.2 Distributed TIS

Now, let us switch to a fully distributed version of TIS, as shown in Figure 2-11, in which vehicles maintain a local knowledge base and exchange its information in the one-hop or multi-hop neighborhood. Obviously, the local traffic information in every vehicle is not enough to reflect the traffic condition in a ROI. Therefore, there will be two main challenges here: How to use IVC to exchange the local information between vehicles, and how to manage the information of vehicles in different areas (near and far). For these two challenges, we give two applications of distributed TIS and then provide respective solutions under the background of specific applications.

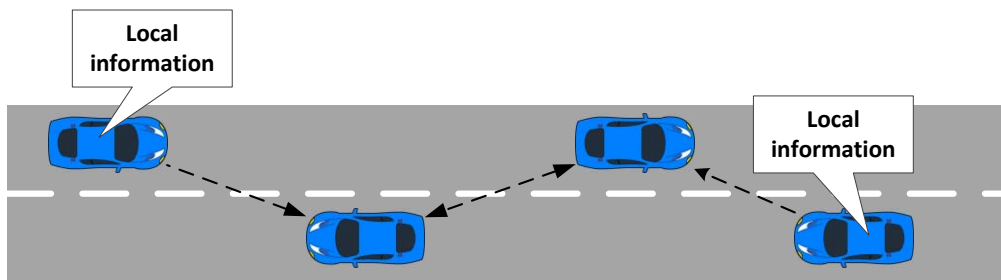


Figure 2-11. Distributed TIS

The Self-Organizing Traffic Information System (SOTIS) was the one of early works that focus on the fully distributed TIS [27], [28]. Vehicles in this system broadcast its local knowledge data in the one-hop neighborhood periodically, e.g., 10 Hz. The vehicle receives a data from its neighbors and then integrates the data with its local knowledge data base. Along the itinerary, vehicles can learn more and more relative information on the road. However, this kind of data dissemination does not guarantee the real-time property. SOTIS operates data aggregation in an intelligent way. The farther the event locates from the local position, the more aggressive the aggregation. Although the fixed periodic one-hop broadcasting is simple and robust, the channel congestion would occur when the vehicular density is high. Moreover, if the vehicular density is low, the frequent transmission rate is not helpful to the data dissemination. For mitigating this issue, two well-known congestion control protocols, PULSAR and LIMERIC, were proposed. Although the algorithms of

these two protocols are different, their objective is the same. They both adjust the transmission rate according to the Channel Busy Ratio (CBR). Therefore, they can guarantee an appropriate low transmission rate when the vehicular density is high, and vice versa. Overall, we suggest using PULSAR and LIMERIC to improve SOTIS, so that the function of the service can be achieved when the vehicular density is low and the channel can be avoided overloading in dense network.

The Peer-to-peer Traffic Information System (PeerTIS) resorts to a different concept, i.e., Distributed Hash Tables (DHTs), to manage traffic information in an optimal manner [29]. PeerTIS develops an efficient DHT algorithm that is so called divide-and-conquer approach. To cut long story short, this approach splits the available map into tiles, and one specific vehicle is assigned to collect and manage the traffic information inside each tile. If a vehicle wants to know the traffic condition on the route provided by the navigation system, it will send a query to the vehicle in the next tile on its route. This query continues to be forwarded vehicle by vehicle on the navigation route. Accordingly, those replies are sent back to the source vehicle in sequence. Normally, the query and the reply are transmitted by 3G/4G network, but the transmissions can also be compatible with short range communication technologies, i.e., WiFi or IEEE 802.11p. While, notice that, 3G/4G network can guarantee the good performance of the reliability and the scalability. Given the advanced Geographic Information System (GIS) and cellular networks, PeerTIS is a practical application that has commercial value.

2.4.2 Intersection Collision Warning Systems (ICWSs)

This section will introduce another category of applications, i.e., safety application. For clearly explaining, a specific application is given, namely Intersection Collision Warning System (ICWS). ICWS aims at avoiding collisions for the vehicles approaching an intersection. Sensors on the vehicles, e.g., ultrasonic, radar and video camera, can be used to assist driver in detecting potential collision with other vehicles. However, the line-of-sight of an approaching vehicle would be blocked by buildings or other objects, thus the sensors above-mentioned cannot discover other vehicles, as shown in Figure 2-12. Therefore, IVC can be considered to fill the gap for this problem.

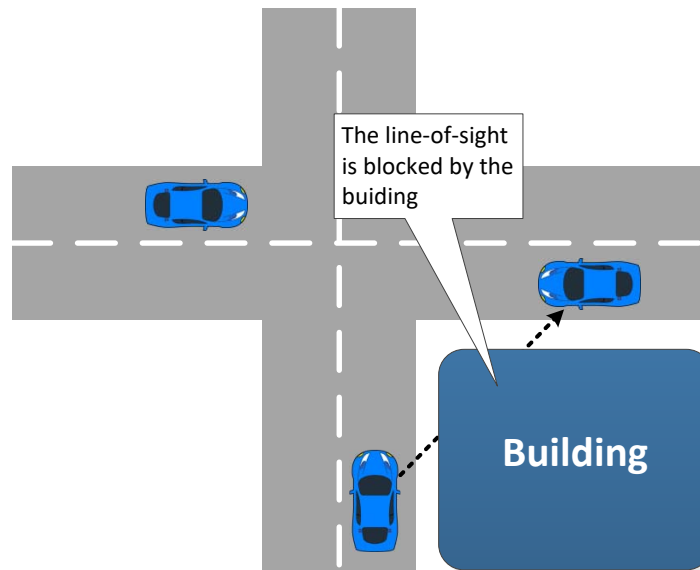


Figure 2-12. Intersection Collision Warning System

The wireless communication of IVC can help a vehicle discover the surrounding neighbors. WiFi, IEEE 802.11p and 3G/4G network can be used for this application. Chen et al. investigated the substantial safety advantage of ICWS and the results showed that intersection crashes could be reduced by 40%-50% [30]. Joerer et al. investigated the potential of beaconing approach for the collision detection. If all the vehicles at an intersection can exchange information periodically, it is very possible to calculate the probability of crash between each two vehicles [31]. Fortunately, even the short range communication technologies, i.e., WiFi or IEEE 802.11p, also can cover the intersection. Thus, it is possible to implement this application at the aspect of access technologies. Next question is how frequent for the beaconing can satisfy the requirement of the service? Joerer et al. reported that static period beaconing with 10 Hz or faster allows vehicles to maintain a reliable collision prediction. But, as mentioned in the section about distributed TIS (section 2.4.1.2), a static transmission rate would lead to an overload channel in dense network. Therefore, we should use the decentralized congestion control (DCC) technique to mitigate this issue. Notice that DCC is an important technique for safety application, which can adjust the transmit power or rate according to the network status.

2.4.3 Platooning

In this section, we talk about an application for transport efficiency and also traffic safety, i.e., platooning or road train, as shown in Figure 2-13. Vehicles in a platoon are connected each other by IVC and drive automatically. A platoon leader vehicle in the front of this

platoon is driven by human, which is responsible for managing the following vehicles. In this way, the group of vehicles can move efficiently, environment friendly and safely, since a smooth travel of platoon can increase traffic flow and decrease the fuel consumption. In the meantime, the safety of passengers is guaranteed because the possibility of the mechanical or electronic fault is much less than the one of human fault.

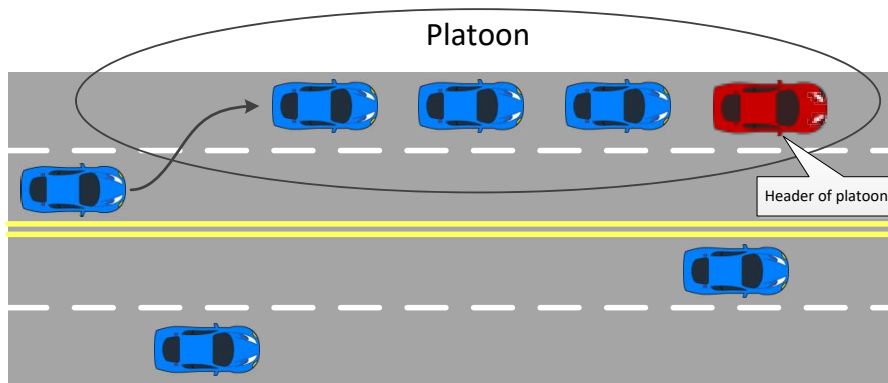


Figure 2-13. Platooning

The key challenge for networking is that IVC should guarantee enough frequent and timely information exchanges between vehicles in the platoon. According to the experiments in the PATH [32] and SARTRE [33], the transmit rate of beacon is required to be about 10 Hz and distance interval between vehicles is 5-7m [34], [35]. Given the local and high frequent data transmission, IEEE 802.11p would be more suitable for this application. At the beginning of implementing this application, several specific vehicles in the platoon will be installed DSRC devices. Since the scale of a platoon is limited, the implementation of DSRC devices is very feasible for some special type of vehicles, e.g., truck or bus. With the increasing of market penetration, more and more vehicles with DSRC devices can join this application.

To simulate the platooning, there is an extension of Veins framework for platooning, i.e., Plexe [36]. Plexe supports the realistic simulation of platooning systems. It features realistic vehicle dynamics and several cruise control models, permitting the analysis of control systems, large-scale and mixed scenario, as well as networking protocols and cooperative maneuvers.

2.5 Open Research Issues

In the last section of this chapter, we will talk about open research issues in VANETs, which also provides the motivation for next chapter, i.e., Data Dissemination Protocol in

VANETs. Only when we make clear the key issues, can we better design IVC protocols to solve existing problems. First, we discuss heterogeneous vehicular networks. As we have known in the description of access technologies and applications, each technology has its own advantages and drawbacks for the specific application. The approach of heterogeneous networks is believed to be a reasonable solution. But, inside the network communication, there are still some issues waiting to be solved. Next, the two main problems for the ad hoc formation of VANETs, i.e., broadcast storm and network partition, are presented for motivating to design data dissemination protocols. Finally, two essential metrics, i.e., reliability and scalability, are discussed.

2.5.1 Heterogeneous Vehicular Networks

Current IVC applications in research or projects trend to use multiple wireless medium access technologies to perform the services. Therefore, the heterogeneous vehicular networks are proposed [37]. The primary reason of using multiple technologies lies in that every access technology has its own unique benefits and unique limitations for the specific application. For clearly explaining, we provide Figure 2-14 to illustrate the classification of IVC applications using respective access technologies.

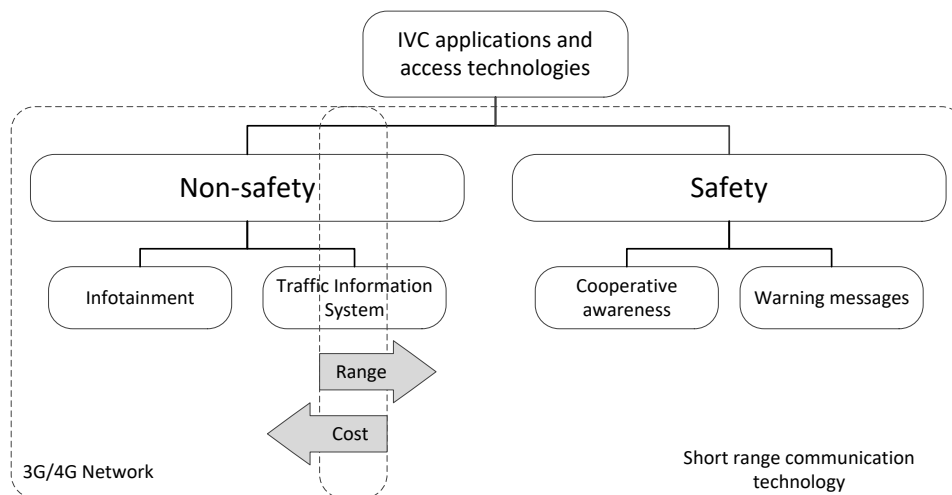


Figure 2-14. The classification of IVC applications and access technologies

IVC applications are classified into two categories, i.e., non-safety and safety. The trade-off between cost and communication range is shown in Figure 2-14. The cellular network can support most of non-safety applications with a good scalability. But the cost is a heavy burden that should be considered in advance. The short range communication technologies, e.g., IEEE 802.11p and WiFi, can provide high data rate and low latency for safety

applications. However, the communication range is limited which would lead to an unstable scalability in the multi-hop communication.

Cellular networks were foredoomed to play a great role for the vehicular network in the initial penetration phase. Currently, most of commercial IVC applications are implemented by using cellular networks. In the future, if the penetration of vehicles equipped DSRC devices achieve an enough proportion, IEEE 802.11p can significantly increase traffic safety by offering cooperative-awareness or warning applications. WiFi also can contribute itself to the downloading of added-value service, which is not only limited to vehicles but also integrate pedestrians and bicycles into the network. However, currently, each IVC protocol is dedicated to support one specific application. In the future, we should pay attention to the issue that: How to design a decision mechanism to schedule multiple protocols or standards for the heterogeneous vehicular network.

2.5.2 Broadcast Storm Problem

Broadcast storm is a main problem to disseminate data under the broadcast paradigm in ad hoc formation of VANETs. The flooding scheme, a basic routing for broadcasting, can disseminate data into a wide area with low delay. But, if the flooding is not controlled properly in dense networks, a great number of vehicles would reply a data simultaneously, enormous amount of collisions will occur, that is called “broadcast storm”. Although the MAC layer of IEEE 802.11 uses CSMA/CA mechanism to mitigate collisions, given so many transmissions are triggered at the same time, this problem still cannot be avoided. Therefore, an efficient routing scheme is required considerably. The relaying scheme is proposed to select the appropriate forwarder to mitigate this problem. Unfortunately, most of relaying schemes exclusively focus on the highway or the urban scenarios. Thus, how to select the suitable forwarders in both highway and urban scenarios is a key open issue.

2.5.3 Network Partition Problem

The distribution of vehicles suffers a large deviation due to the high mobility of vehicles. Moreover, the line-of-sight signal would be blocked because of the existence of buildings or other objects in urban scenarios. There are also many disconnections between vehicular clusters on highway. Consequently, the disconnected network problem is ubiquitous. How to fill the gap between these disconnected networks is a crucial challenge? This problem is investigated widely in Delay Tolerant Networks (DTNs) field. The most commonly used

method is the Store-Carry-Forward (SCF) mechanism. This mechanism treats the vehicle as an information ferry to store and carry data until meet new opportunities to forward. That is, the mechanism uses the temporal delay to complement the spatial partition. However, the delay caused by SCF mechanism is high and difficult to be predicted. To alleviate the issue about latency, the long range access technology can be used. But, again, we should consider the tradeoff between communication range and cost as mentioned at section 2.5.1 (about heterogeneous vehicular networks).

2.5.4 Reliability and Delay

The reliability, described by Packed Delivery Ratio (PDR), is critical to safety applications, especially for the application, e.g., collision warning system, that requires achieving high frequent transmissions in very short time interval, i.e., short inter-packet arrival time. The delay of safety applications is normally from a few hundred milliseconds to tens of milliseconds. The frequent transmissions and short delay would lead to a number of collisions that can influence the reliability of applications. Dedicated algorithms or mechanisms of IVC protocols need to be designed for the qualified reliability. Some safety applications, as the cooperative-awareness, can accept a little weaker requirement on reliability and delay. In the frequent beaconing, the new coming packet can complement the loss of previous one. On the other hand, for non-safety applications, high requirement is not assigned to reliability and delay. These applications are designed for best-effort communications, which is usually very robust to high packet loss and delay.

2.5.5 Scalability

The scalability is one of the critical limitations of VANETs. Even in the whole research field of wireless communications, the scalability is also an important issue. One of early works was published by Gupta et al. that identified the upper capacity limits for unicast communication paradigm in fixed wireless ad hoc networks [38]. After that, in MANETs, Grossglauser et al. proposed that the capacity of wireless networks increases if node mobility is taken into account [39]. They also showed that how the mobility can be exploited to improve the data transmissions [40]. However, the mobility model is for MANETs, which is not suitable for VANETs.

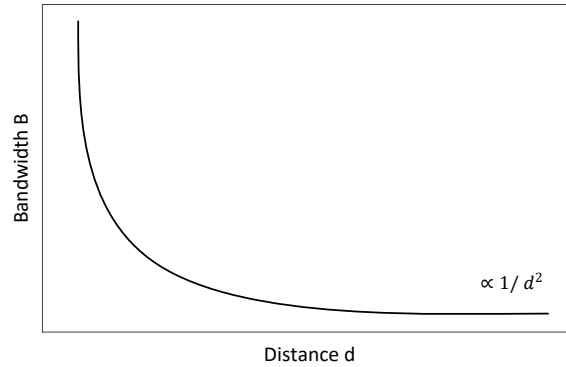


Figure 2-15. The scalability of VANETs

The upper limits of data dissemination in ad hoc formation of VANETs were not fully investigated. One of the most important contributions was published by Scheuermann et al. [41]. This work focuses on the relationship between the dissemination range and the bandwidth occupation. It proposed that the bandwidth must be reduced, by using the aggregation mechanism, faster than a value that is proportional to $1/d^2$, so that the system can be scalable at distance d , as shown in Figure 2-15. In addition, Scheuermann et al. also provided some conclusions and suggestions for designing scalable data dissemination protocols, as follows: Any information has its maximum data dissemination range; with the increasing of distance, the data update frequency is reduced and the data is aggregated exponentially.

Chapter 3 Data Dissemination Protocols in VANETs

3.1 Introduction

After analyzing and summarizing carefully, some practical routing protocols for data dissemination in VANETs have been selected, classified and presented in this chapter. Most of them work in ad hoc formation of VANET using short range communication technology, i.e., IEEE 802.11p. An important assumption is declared here that, for most protocols in this thesis including our protocol proposed in Chapter 5, all the vehicles are equipped with dedicated short range communication (DSRC) device.

First, we will describe MANET routing that include two modes, i.e., topology-based and position-based. The former is usually called *ad hoc routing* while the latter also can be named *geographic routing*. MANET routing has a long history in the domain of mobile wireless networking [42]. In the initial phase of the development of IVC protocols, several MANET routing protocols were adopted for VANETs. MANET routing is believed to be the foundation to understand and design VANET routing. Therefore, we introduce them first and gradually transit to IVC protocols in section 3.3, e.g., from GPSR to GPCR. After analyzing the problems of using MANET routing for VANETs, an important class of IVC protocols, i.e., Geocasting, is elaborated in section 3.5, including efforts of standardization and typical protocols. DTN routing and beaconing also dedicate itself to geocasting, which are described separately. DTN routing is an efficient approach to handle partitioned networks but consuming an additional delay. Beaconing is normally responsible for exchanging local information in the one-hop neighborhood and, therefore, can be used for safety applications. After that, a further introduction is made for the routing with infrastructure in section 3.9. Finally, the key techniques of data dissemination protocols are summarized in section 3.10.

3.2 Topology-based Ad hoc Routing

The MANET routing based on network topology information was first adopted in VANETs in early days. It includes three types of routing protocols, i.e., pro-active, re-active and hybrid routing, as shown in Figure 3-1. This taxonomy also indicates another MANET

routing based on position information, which will be described in next section 3.3. Maybe MANET routing protocols are not suitable for most applications of VANETs, but the basic knowledge of them is the fundament to understand and design routing protocols for VANETs.

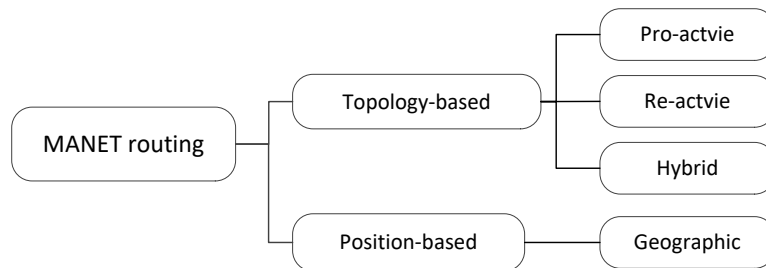


Figure 3-1. Taxonomy of MANET routing

Here, we mainly introduce pro-active and re-active routing, for these protocols is enough to explain the characteristics of topology-based ad hoc routing protocols. Some typical routing protocols are provided for example. The idea of hybrid routing is to combine the two routing to make up for the drawback of each other.

3.2.1 Pro-active routing

The basic idea of pro-active routing is to maintain entire network topology all the time and provide active routes between nodes before a packet is available to send, as shown in Figure 3-2. This principle is similar to the one of classical Internet routing protocols, in which the routing establishment is triggered when the network topology changes. The good thing about this routing is that the full route is available immediately whenever a packet is required to be transmitted. However, this routing will cost tremendous overhead to maintain large scale network topology especially for high dynamic environment, such as VANETs. The network is easy to be overloaded in a density vehicular network. Even if the network resource is assumed to be adequate, the update speed of routing table also cannot satisfy the requirement of IVC applications, especially for the node located in the boundary of a VANET.

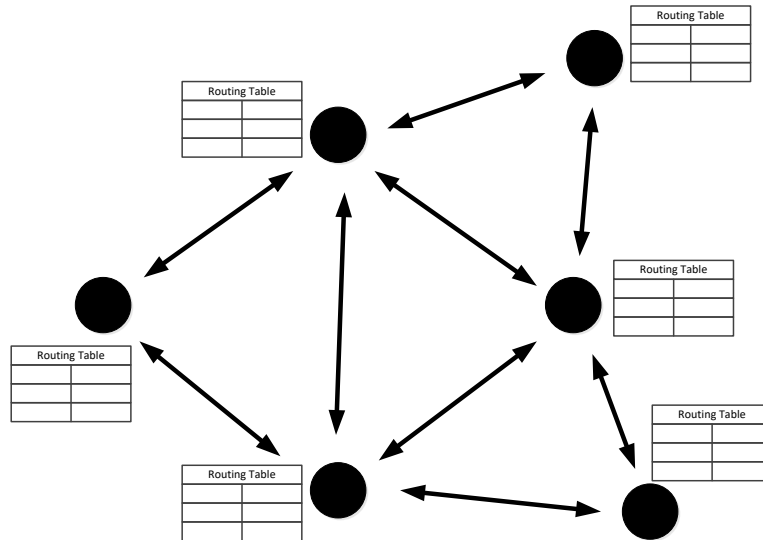


Figure 3-2. Illustration of pro-active routing protocols

3.2.1.1 DSDV

Destination Sequenced Distance Vector (DSDV) protocol is one of the early approaches to pro-active routing in MANETs [43]. DSDV concentrates on the maintenance of a local routing table in every node by exchanging update messages in the one-hop neighborhood. The key idea comes from the Bellman-Ford algorithm which is also used for the Routing Information Protocol (RIP), one of the early Interior Gateway Protocols (IGP) for Internet [44]. The entry of routing table includes information about destination, next hop, distance and sequence number. The distance means the number of hops between a local node and a destination, which is the key metric for the selection of the next hop node. Nodes always choose a neighbor, as the next hop, with the shortest path to the destination. Therefore, DSDV is a *distance vector* routing. The sequence number represents the freshness of the routing table entry, by which the routing loop is prevented. An example is given to explain the operation of DSDV, as shown in Figure 3-3.

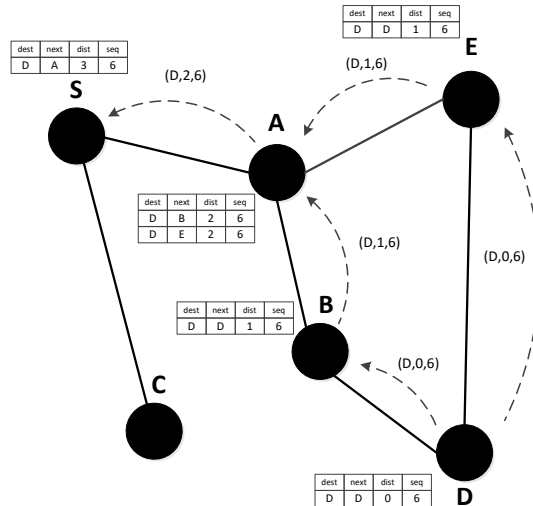


Figure 3-3. Illustration of DSDV operation. The figure shows update messages (destination, distance, sequence number) and routing table entries [destination, next hop, distance, sequence number] related to node D.

Here, we focus on the route towards the node D for example. First, node D sends update messages to each connected neighboring nodes, i.e., node B and E. The update message from node D including information as (D, 0, 6) that can be decoded that: “Node D is the destination”, “There is 0 hop between me (Node D) and the destination” and “The freshness of this update message is 6”. Then, recipients check the freshness of their local routing table and update it according to received messages. After that, these recipients continue to send updated information to their neighboring nodes, e.g., node B tells node A that “You can transmit messages through me to the node D with one hop (distance)”. Finally, every node in the network establishes a route to the node D. For instance, node S known that it can transmit messages to node D through node A as the next hop and the hop number of the entire route is 3.

DSDV would work in some scenarios of MANETs with low mobility or wired networks. On the downside, DSDV is obviously not appropriate to be used as routing for VANETs because the frequent topology changes of VANETs would let DSDV difficult, probably never, to converge and cost a huge number of update messages at the same time.

3.2.2 Re-active routing

In this section, an alternative topology-based routing will be introduced, namely re-active routing (also called *on-demand* routing), which establishes a route to the destination only if there is a packet available to send. That is, a routing discovery process is triggered exactly at the time when a transmission is needed. Otherwise, the re-active routing will do nothing for

the network. This is why the routing is called “on-demand” routing. The essential motivation of re-active routing is to reduce the expensive overhead, i.e., control traffic, in the case of pro-active routing. A price is paid by re-active routing for saving more available network resource, that is, an additional delay is brought by the routing discovery process. To well perform re-active routing, some condition is needed to be satisfied. On the one hand, the network topology should not change frequently. On the other hand, messages should send infrequently or in short bursts multiple packets, moreover, should send to a small subset of destinations. All of these limitations are held to give sufficient time for routing discovery.

In general process of routing discovery, a route request message (RREQ) is broadcast first by the source node to all nodes in the network. Thanks to this flooding, all nodes learn a path to the source node. As soon as the destination node receives the RREQ, it will reply the request by the route reply message (RREP). RREP will be transmitted back to the source node following the shortest route by unicast.

A number of re-active routing protocols have been proposed for MANETs. The well-known examples includes Dynamic Source Routing (DSR), Ad hoc On-Demand Distance Vector (AODV), Dynamic MANET On-demand (DYMO) [45], [46]. We will investigate these protocols to explain the key characteristics of the routing on demand.

3.2.2.1 DSR

Dynamic Source Routing (DSR) is one of the early re-active routing protocols, which was finally standardized by IETF, i.e., RFC 4728 [47]. Its characteristic is that routing information only is contained in the header of data packet, i.e., *source routing*. The data packet can guide itself from source to destination. The overhead of topology maintenance, therefore, is reduced, while additive payload is added to the packet especially in the large scale network. RREQ is also flooded to the entire network, each node received the message adds its address to the routing table in the header of RREQ. If the destination node received RREQ, then the RREP will be replied by unicast to the source node following the routing table in RREQ but in reverse order. An example is shown in Figure 3-4.

the freshness of each routing entry to handle stale routes. The essential intention of AODV is to combine the advantage of DSR and the one of DSDV. That is, AODV not only reduces the overhead of maintaining network topology (overcoming the weakness of DSDV) but also save the payload of data packet (overcoming the weakness of DSR). An example of AODV operation is shown in Figure 3-5.

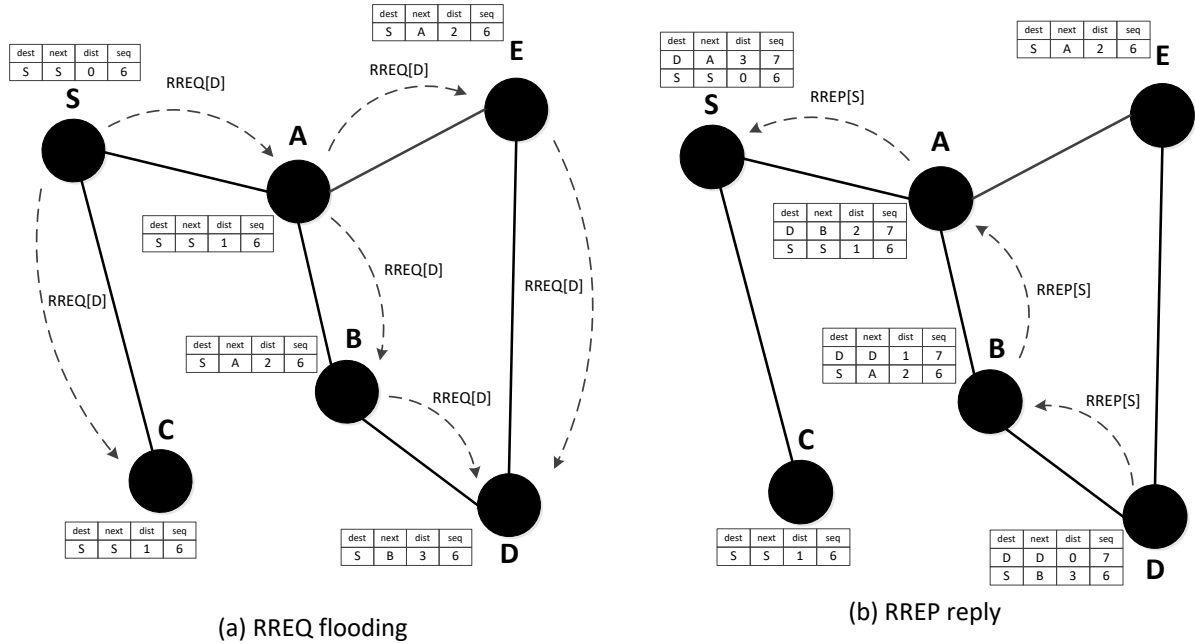


Figure 3-5. Illustration of AODV operation

First, the source node S broadcasts a RREQ into the network to search the destination node D. A routing entry towards the source S is created when intermediate nodes receive the RREQ (Figure 3-5a). The entry includes information about destination, next hop, distance and sequence number, i.e., [dest, next, dist, seq], as shown in Figure 3-5. Once the destination node D received the RREQ, it will reply a RREP by unicast to the source node S according to its routing table. The nodes on the shortest path to the source S are responsible for forwarding the RREP. A routing entry towards the destination D is created when these nodes receive RREP (Figure 3-5b). As soon as the source S receives the RREP, a full path to the destination D has been completed. Therefore, the data packet is enabled to transmit.

An expanding ring search technique is used in the source node to prevent unnecessary network-wide dissemination of RREQs. The route maintenance performs to repair the link failure resorting to RERR messages. Therefore, AODV works well in MANETs with limited mobility. However, for the scenarios in VANETs with high mobility, the control traffic of AODV will increase sharply, for the route is broken frequently and the route discovery often needs to be triggered.

3.2.2.3 DYMO

Dynamic MANET On demand (DYMO) routing protocol was developed to overcome some of the drawbacks of AODV and make it more robust with respect to mobility. Currently, it continues to develop as *AODV v2* [52]. A special improvement is made in the route discovery process. The enhanced RREQ and RREP can save the information of nodes on their forwarding path, which is similar to the source routing. Each node participating in route discovery can exploit more routes that point to all the nodes included in RREQ or RREP. The mechanism sufficiently utilizes control messages, so that the local routing table gets more information compared with AODV. An instance is given to prove this point, as shown in Figure 3-6.

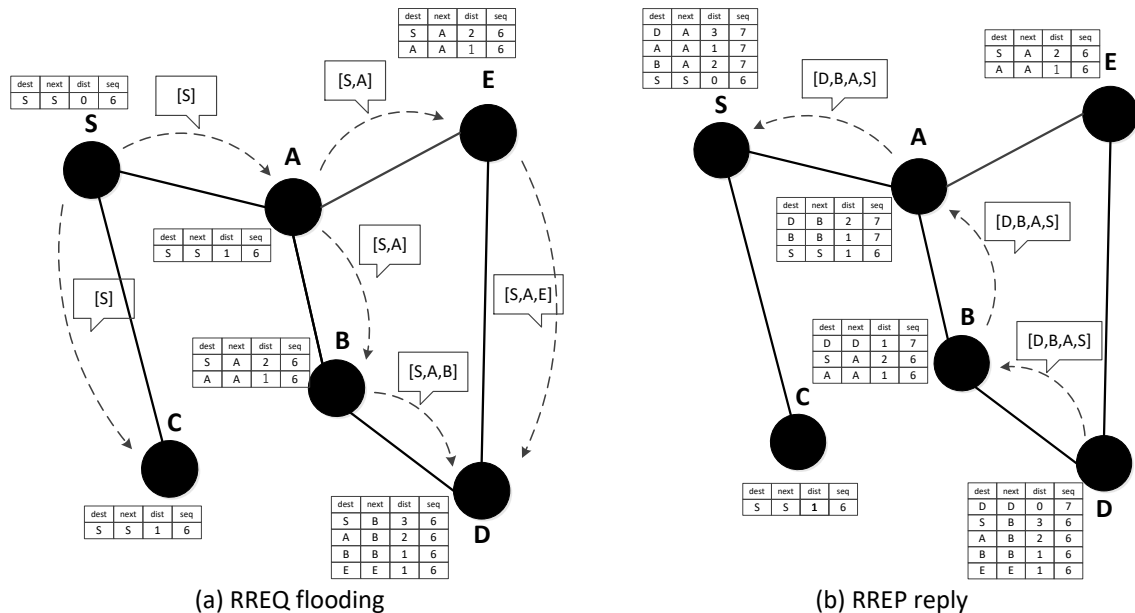


Figure 3-6. Illustration of DYMO operation

First, the source node S broadcasts a RREQ into the network. Every node received the RREQ adds their own address in the message and re-broadcast again. Therefore, nodes can obtain more network topology information. For instance, after RREQ flooding the network, the destination node D gets more routes to nodes A and B (Figure 3-6a) compared with the case of AODV (Figure 3-5a). Similarly, when the source S receives the RREP replied by the destination D, it also gets more routes to node A and B (Figure 3-6b) compared with the case of AODV (Figure 3-5b). Therefore, DYMO can use a few control messages to discovery more network topology information than AODV. This is also the essential different between DYMO and AODV.

3.3 Position-based Geographic Routing

An alternative of MANET routing is geographic routing, which is based on the position of nodes instead of topology information. Greedy forwarding is used to transmit packets to the neighbor closest to the destination in terms of geographic distance. That is, the forwarding is greedy to make a progress towards the destination as much as possible. The routing requires to know the position of source, intermediate nodes and destination in advance. However, obviously, the position of destination is difficult to obtain by the source node in ad hoc network. This is the greatest challenge that has not been addressed by most of geographic routing protocols. Location service is the key technique, in which cellular network can be used if there is infrastructure available. The position of every node can be determined by Global Positioning System (GPS). The granularity and accuracy of GPS is assumed to be sufficient for all the techniques in this chapter.

3.3.1 GPSR

Greedy Perimeter Stateless Routing (GPSR) is one of the best-known geographic routing protocols, which is promising for practical applications of MANETs [53]. The routing uses *right-hand rule* and *perimeter routing* (face routing) to address local maximum problem (dead end), as shown in Figure 3-7.

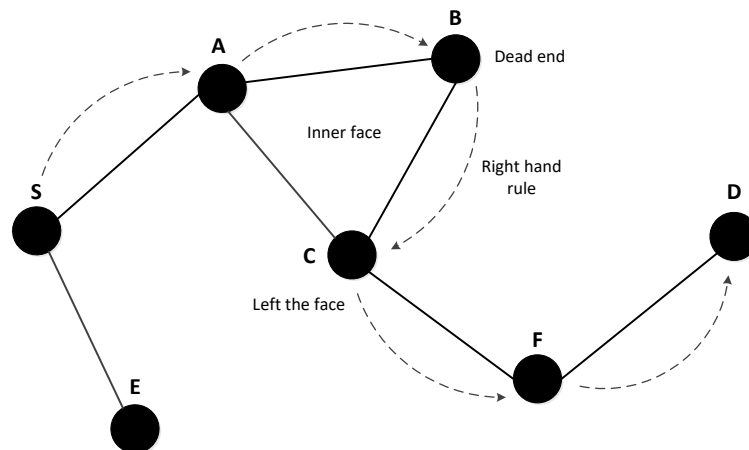


Figure 3-7. Illustration of GPSR operation. Right-hand rule and perimeter routing are employed to overcome local maximum problem.

The source node S intends to transmit packets to the destination node D. The greedy routing manages the packet to make as much progress as possible towards the destination D. However, this simply routing is easy to lead to a dead end, e.g., at node B. That means there

is no more neighbors closer to the destination D than node B itself. In this situation, GPSR uses right-hand rule to escape the dead end. That is, node B selects the node, i.e., node C, at the right side of the forwarding direction from node A to node B. But, a loop will happen when routing follows right-hand rule in an inner face that is composed of nodes A, B and C. To address this issue, perimeter routing uses the position of the entrance of face, i.e., node A, and the destination D to decide when the packet should leave the face. When the packet is forwarded at node C, it has two routing choices, node A and node F. If selecting node A, the packet will go back to the face. If selecting node F, the greedy routing can work again to find the destination node D. Therefore, the packet leaves the face at node C.

3.3.2 GPCR

Intuitively, Greedy Perimeter Coordinator Routing (GPCR) is an improved version of GPSR for vehicular networks in urban scenarios. GPCR also uses greedy routing and right-hand rule. The different point is that GPCR defines a special role, i.e., coordinator, to route messages around the building obstacles. The coordinators are the nodes in the area of a junction or intersection. The main idea of GPCR is to achieve a good Packet Delivery Ratio (PDR) from a source to a destination without using a digital street map while reducing the control overhead. The routing mainly includes two parts: a *restricted greedy forwarding* and a *repair strategy*. First, greedy routing is restricted by using the coordinator. Instead of passing packets through the junction, the coordinator has a high priority to be the next hop to forward the packet, as shown in Figure 3-8.

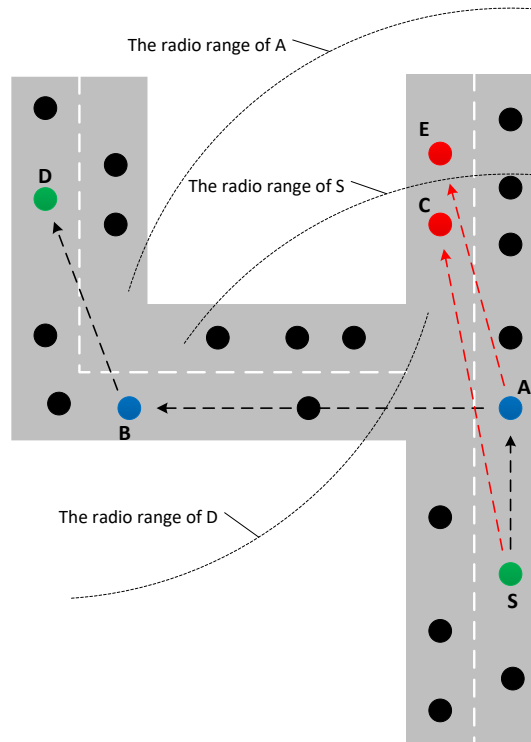


Figure 3-8. Greedy routing vs. restricted greedy routing in the area of a junction.

Normally, node S should forward packets to node C according to greedy routing. This simple routing misses the chance to get a more appropriate route to the destination D. In the case of GPCR, the coordinator A is selected to be the next hop, so that node B can be exploited to route messages to the destination D efficiently. If a local maximum happens, the forwarding of the packet is then switched to the repair strategy. The packet continues to forward along the street until it meets the first coordinator, as shown in Figure 3-9.

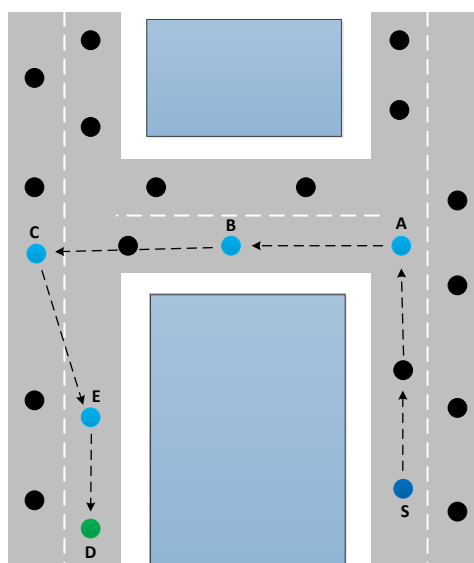


Figure 3-9. Repair strategy: the right-hand rule is used on the level of streets

Node S is a local maximum in its geographic proximity to node D. The repair strategy is triggered to forwards packets along the street to the coordinator A. The right-hand rule is used to select which street the packet should be forward to. Therefore, node B is selected to be the next hop of node A. The right-hand rule is used again at node C to forward the packet to node E. At this time, the distance between nodes E and D is less than the one between nodes S and D, so the routing switches back to restricted greedy forwarding. Finally, the packet reaches the destination D.

A key issue of GPCR is how to determine *whether a node is a coordinator or not*. GPCR proposes two approaches. In the first approach, by employing beaconing (periodic hello messages), a node can know the position of its neighbors and the neighbors' neighbors. The node is considered to be a coordinator, if it has two neighbors that are within transmission range of each other but not list each other as neighbors. This means that the two neighbors are separated by a obstacle and the coordinator in a junction is able to exchange messages between the two neighbors. However, this approach would lead to a wrong determination when the vehicles are in a curve road line. The second approach uses the correlation coefficient to determine the relative position of a node with respect to its neighbors. If the correlation coefficient is close to 1, that means a node has linear position relation with respect to its neighbors, so the node is located in a street. If the value is close to 0, the node is believed to be a coordinator. But, in our simulation experience, this algorithm will make a mistake if a vehicle is approaching to a junction but not reach. At this time, the radio range of the vehicle can also cover vehicles around the junction. As a consequence, the vehicle might be wrongly determined to be a coordinator. We believe that a practical approach is to use the junction list of an urban map that includes every position of junctions in the city. The vehicle is believed to be coordinator when it reaches a small distance with a junction. The efficiency of this method is proved by our simulation in Chapter 5.

3.4 Problems of MANET routing in VANETs and Promising Ideas

It seems unfair to MANET routing protocols to investigate the applicability of them in VANETs, for the design objective of this routing is totally different. But, we will do this to find out the problems of MANET routing in VANETs so as to propose some promising ideas for the development of IVC protocols. That is exactly what researchers did in early

days of VANET field. The different characteristics between MANET and VANET are shown in Table 3-1. Our discussion mainly focuses on the first three properties.

Table 3-1. Different characteristics between MANET and VANET

Characteristics	MANET	VANET
Network Scale	Medium	Large
Topology Dynamic	Low	High
Mobility Pattern	Random	Road Layout
Location Dependency	Low	Very High
Energy	Low	Very High
Computation Power	Low	High
Memory Capacity	Low	High

Topology-based routing protocols attempt to establish a full route between source and destination. However, this objective is difficult to achieve in large scale and highly dynamic networks, i.e., VANETs. On the other hand, the protocols that use flooding scheme do not work well when the network scale is large. Therefore, re-active routing cannot scale well in the route discovery process. Even if the route is established, it will be broken soon because of the highly dynamic topology of VANETs. Although pro-active routing does not resort to flooding, it also cannot scale up to a large scale network either. Because the routing needs to maintain entire network topology in every node by using update messages, consequently, the consumption of control messages will be huge and a large amount of bandwidth is wasted. Moreover, given the highly dynamic topology of VANETs, the routing table cannot be updated quickly enough to adapt to the topology change.

To sum up, it is not worth creating or maintaining a full route between source and destination, since route time to live (TTL) is short due to the highly dynamic network topology. Naturally, geographic routing can be another candidate to VANETs, for it does not need to establish a full route and just manages packets to be forwarded on a hop-by-hop basis. Unfortunately, this routing also cannot be directly applied to VANETs because the mobility pattern is different between MANETs and VANETs. Nodes in MANETs move randomly while vehicles in VANETs travel following specific road layout and traffic rule. But, the basic forwarding approach of geographic routing is an appropriate solution for VANETs. That is, the packet is forwarded hop by hop based on the position of nodes. We can consider related scenarios of VANETs to improve the original geographic routing of MANETs, just like what the authors of GPCR did.

Now, we can imagine some promising solutions according to the above-mentioned problems. First, the road topology should be considered when the packet is forwarded. The building obstacle would block the connectivity between vehicles that are not in line-of-sight even they are in the radio range of each other. Second, broadcast is more applicable than unicast. The reason lies in two points: On the one hand, a full route is very easy to be broken in a highly dynamic network. On the other hand, broadcast communication paradigm can support most IVC applications, such as collision warning and electronic emergency brake. Consequently, the broadcast suppression technique should be carefully designed to prevent broadcast storm problem. Another experience coming from topology-based routing is that, the routing for VANETs should not maintain nonlocal information from nonlocal nodes. The information from surrounding nodes should not be far more than two hops. Last but not least, Delay Tolerant Network (DTN) routing can be chosen to handle sparse or high dynamic scenarios. This routing is based on the principle of Store-Carry-Forward (SCF) mechanism. That is, if a vehicle cannot find any neighbor to transmit messages, these messages can be stored and carried by the vehicle until meet a new opportunity to forward. This sort of operation is very useful for many scenarios in VANETs.

3.5 Geocasting

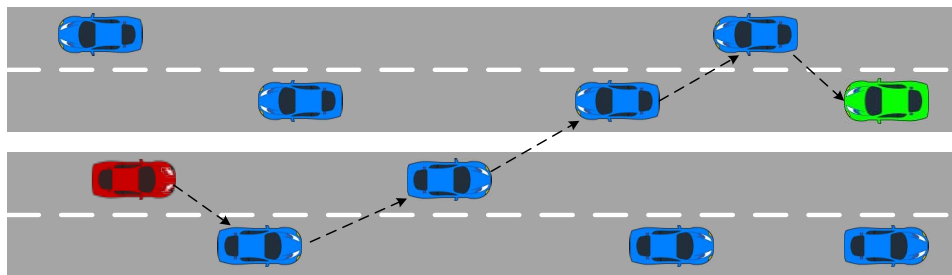
During investigating MANET routing protocols, we have caught a glimpse of adopting geographic routing for VANETs, i.e., GPCR case, and analyzed the problems of applying MANET routing in VANETs. Most protocols we have mentioned perform a service by unicast. However, except some infotainment applications, unicast communication paradigm may be not suitable to most applications in VANETs. An alternative paradigm is *broadcast* that can transmit packets to the nodes in a specific geographic area instead of a specific node. Broadcast has more flexible characteristics and better meets with requirements of data dissemination in VANETs. Therefore, broadcast-based geographic routing is proposed to be used in VANETs, namely geocasting.

In the following of this section, first, we will introduce some standardization efforts made by ETSI for data dissemination in VANETs. Then, several classic geocast routing protocols will be described.

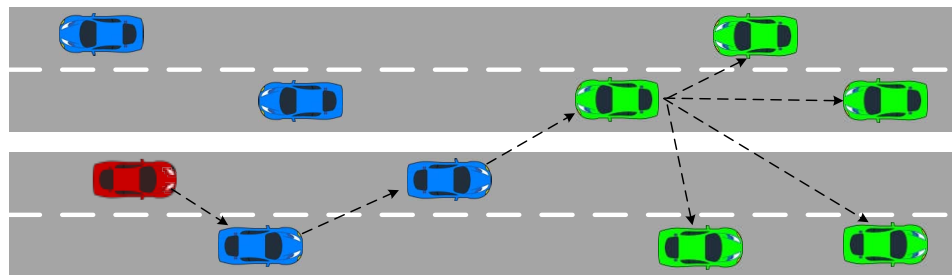
3.5.1 ETSI GeoNetworking

By learning the experience from MANET routing and applying geographic routing to VANETs, ETSI developed GeoNetworking standard to be the network layer of ETSI ITS protocol stack that has mentioned in section 1.1.1 on page 17. The GeoNetworking standard is responsible for organizing wireless communication among vehicles and between vehicles and infrastructure while concentrates on mitigating the issues caused by highly dynamic mobility [54]. A variety of IVC applications are supported by GeoNetworking, from road safety warning messages dissemination by *broadcast* to infotainment application by *unicast*. A number of respects are considered by GeoNetworking, such as scenarios, network architecture, addressing and forwarding, transport protocols and internet integration.

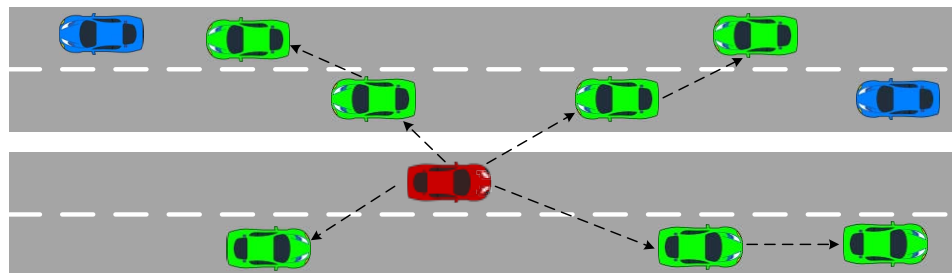
Three forwarding schemes are provided by GeoNetworking, i.e., GeoUnicast, GeoBroadcast and topologically scoped broadcast, as shown in Figure 3-10, which can support to route messages to a specific node or nodes in a geographic area.



(a) GeoUnicast: send a message to a specific vehicle using geographic routing



(b) GeoBroadcast: send a message to vehicles in a geographic area



(c) Topologically scoped broadcast: flood a message to vehicles in the n-hop neighborhood

Figure 3-10. Forwarding schemes of GeoNetworking

GeoUnicast (Figure 3-10a) performs packet delivery between two nodes by multiple wireless hops. Alternatively, GeoBroadcast (Figure 3-10b) provides a method of geographical broadcast, by which a packet is able to be forwarded hop by hop until it reaches the destination area, and then the first reception will broadcast the packet into the destination area. Other nodes in this area would rebroadcast the packet to those nodes beyond the communication range of the previous forwarding node. GeoAnycast is different from GeoBroadcast in that the first reception will not rebroadcast the received packet. Topologically scoped broadcast supports the rebroadcasting of a data packet from a source to all nodes in the n -hop neighborhood, as the case of Figure 3-10c where n is equal to 2.

3.5.2 ETSI DENMs

ETSI published a standard for the notification of traffic-related event in 2013 [55], namely Decentralized Environment Notification Messages (DENMs). The notification messages are triggered by the Decentralized Environment Notification (DEN) basic service and then disseminated to all vehicles in the destination area. This type of message is event-driven instead of periodic transmission, such as road hazard warning. DENMs are configured to disseminate warning messages related to road hazard or abnormal traffic conditions. An unused *action ID* is allocated for each event. If the originating ITS station detects the evolution of an event, the DENM will be updated by the DEN basic service. A new reference time will be allocated for the DENM, but the action ID of the same event remains unchanged. A DENM will be repeated at a pre-defined repetition time, so that new ITS stations entering the destination area during the event validity duration can also receive the DENM. Finally, the event can be terminated by the originating ITS station using *cancellation DENM* or by other ITS stations using *negation DENM*.

A DENM is composed of a common ITS Protocol Data Unit (PDU) header and multiple containers, as shown in Figure 3-11.

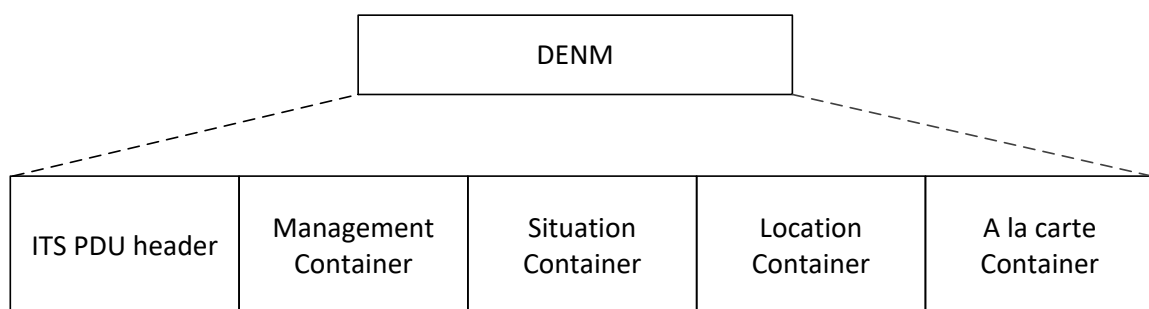


Figure 3-11. General structure of a DENM

The ITS PDU header includes the information of the protocol version, the message type, the ITS station ID and the originating ITS station. The following four containers comprise the DENM payload. The management container contains information related to the DENM management and the DENM protocol, e.g., the action ID, the detection time, the reference time, the DENM type and so on. The situation container includes information that describes the detected event, as shown in Table 3-2. The location container contains information of the event location, and the location referencing. The à la carte container contains specific information for the use case which requires the transmission of additional information that is not included in the three previous containers.

Table 3-2. Selected cause description and cause code assignment for ETSI use case

Cause code description	Cause code	Sub cause code	Sub cause code description
Traffic condition	1	2	Traffic jam slowly increasing
		3	Traffic jam increasing
		4	Traffic jam strongly increasing
		5	Traffic stationary
		6	Traffic jam slightly decreasing
		7	Traffic jam decreasing
		8	Traffic jam strongly decreasing
		Accident	2
Roadworks	3	4	Short-term stationary roadworks
		5	Street cleaning
		6	Winter service
Wrong way driving	14	1	Vehicle driving in wrong lane
		2	Vehicle driving in wrong driving direction
Post crash	92	1	Accident without e-Call triggered
		2	Accident with e-Call manually triggered
		3	Accident with e-Call automatically triggered
		4	Accident with e-Call triggered without a possible access to a cell network.

3.5.3 Geocast Routing Protocols

3.5.3.1 TO-GO

Topology-assisted Geo-Opportunistic (TO-GO) routing protocol incorporates topology assisted geographic routing with opportunistic forwarding to effectively handle unreliable wireless channels [56]. To achieve this aim, two special algorithms are proposed; the *next-hop prediction* algorithm and the *forwarding set* selection. The former is to determine a packet's target node and the latter is to find a set of candidate to forward packets. The *target*

node is the *furthest node* on the current segment or the *junction node* located at the junction, like the coordinator in GPCR.

First, we will introduce *how to predict the target node* and the advantage of this operation. For the selection of target node, there are only two choices: the furthest node or the junction node. To support junction forwarding prediction, except including the basic information of nodes, the hello message is enhanced upon beaconing, so that a node would have a neighbor list that contains the information about neighbors, the furthest neighbors of every neighbor in each road direction, a Bloom filter of neighbors of every neighbor. The Bloom filter is a data structure that enables the construction of neighbors' information, which can keep the broadcast overhead at a minimum. Based on the information from beaconing, the next-hop prediction is performed, as shown in Figure 3-12.

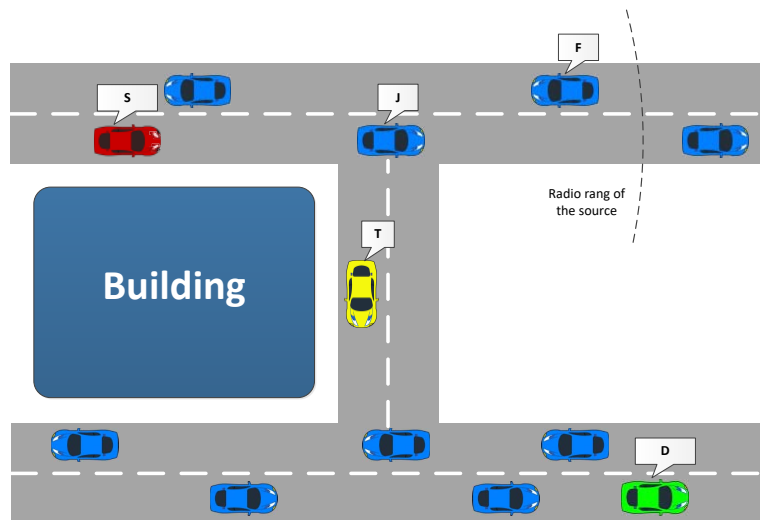


Figure 3-12. Next-hop predication

The source S wants to transmit messages to the destination D, it has two choices for the next hop, i.e., the furthest vehicle F and the junction vehicle J. The algorithm works as follows: If junction node has neighbor that is closer to the destination than the furthest node, the junction node is select to be target node. Otherwise, the furthest node is chosen. In the case of Figure 3-12, the junction vehicle J has a neighboring vehicle T that is closer to the destination D than the furthest vehicle F. Therefore, vehicle J is selected to be the target node to forward the message from vehicle S. The advantage of this approach is that the junction node is not always chosen to forward the packet. If the junction node has no better neighbor to forward the packet, the furthest node of the sending node will be selected. Therefore, TO-GO is more intelligent to route messages than GPCR.

After finding the target node, a set of nodes should be selected to forward the packet, i.e., *forwarding set*. In principle, nodes in the forwarding set can hear each other to prevent hidden terminal problem. But, such a mission is proved to be NP-complete. Thus, TO-GO uses a simplified scheme to estimate an approximate forwarding set. The resulting forwarding set covers the neighbors in the densest area towards the target node. Among the nodes in forwarding set, an efficient and widely used scheme performs to choose one forwarding node. We call it *delay-contention* scheme that organizes nodes to contend for the forwarding of packets based on a distance based timer, i.e., *the further the distance from the sender, the shorter the packet expiration timer*. Upon this delay-contention scheme, the furthest node will rebroadcast the packet first while other nodes hear the redundant packet and cancel the forwarding schedule of the same packet. Notice that this delay-contention scheme is also used in following geocasting protocols. Given that the forwarding node is selected from nodes in the densest area and on the reasonable route towards destination, the reliability of wireless channel is guaranteed.

3.5.3.2 DV-CAST

Distributed Vehicular BroadCAST (DV-CAST) protocol is a distributed geocasting protocol that relies only on local topology information to handle data dissemination in highway scenarios [57]. DV-CAST is one of early works that can mitigate both broadcast storm and disconnected network problem in dense and sparse vehicular networks. Periodic hello messages are used to detect the local topology in the one-hop neighborhood. In dense networks, DV-CAST uses a broadcast suppression technique, i.e., slotted 1-persistence, published by the same research group [58]. Specially, in sparse networks, DV-CAST only resort to three flags that represent the local topology to handle different scenarios of disconnected network problem, as shown in Figure 3-13.

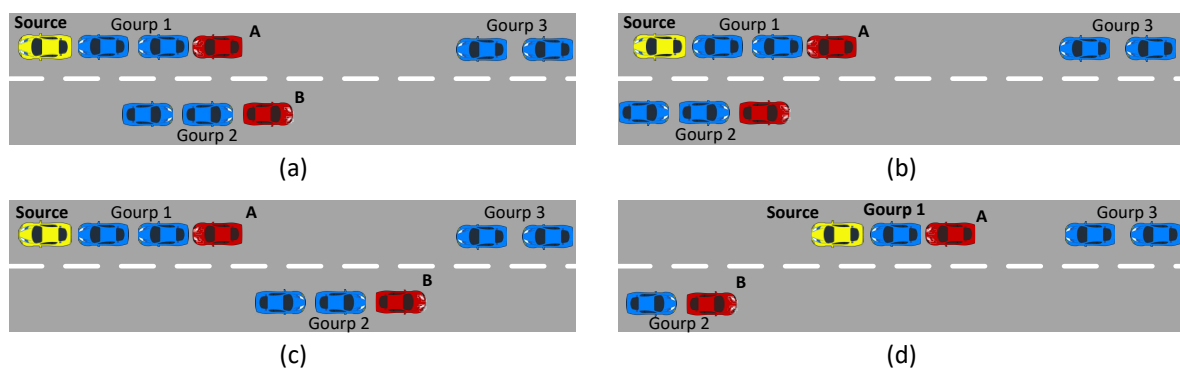


Figure 3-13. The different scenarios of disconnected network problem

In these scenarios, the source vehicle intends to disseminate data to vehicles in rear of it, so that these vehicles can receive the notification about the traffic condition in front of them timely. DV-CAST can recognize the last vehicle of the cluster in the same direction of the source vehicle, i.e., vehicle A, and the first vehicle of the cluster driving against the source vehicle, i.e., vehicle B. The source vehicle transmits data to vehicle A through the members of group 1 constrained by broadcast suppression technique. Then, if vehicle B is not in the communication range of vehicle A, the vehicle A will store and carry the data waiting for the vehicle B by performing a waiting timer. As soon as vehicle B arrives, vehicle A forwards the data to the vehicle B so as to let the data be carried by vehicle B to the group 2. There is another waiting timer in vehicle B to control the effective duration of the data.

However, we found a problem of this protocol during our work. In principle of DV-CAST, the data packet can be transmitted to vehicles in the ROI. But, in practice, given the radio wave characteristic, e.g., fading and shadowing, vehicle A might not always forward the data to vehicle B successfully. As a consequence, vehicles in group 2 would not receive the data. Therefore, the Packet Delivery Ratio (PDR) would be hurt, which will be verified in experiments in 5.4 on page 97.

3.5.3.3 UV-CAST

Urban Vehicular BroadCAST (UV-CAST) protocol is one of early works for data dissemination in infrastructure-less urban scenario, addressing both broadcast storm and disconnected network problem [59]. There are two main mechanisms: One is a broadcast suppression technique that assigns a higher priority to the vehicle located at an intersection to rebroadcast, which can disseminate the data message in more directions and suppress the redundant broadcast. The other is a Store-carry-forward (SCF) mechanism that uses a gift-wrapping algorithm to select boundary vehicles to store, carry and forward messages to fill the gap between different disconnected networks. [59]. The authors also highlight some challenges for broadcast/geocast routing protocols in urban scenarios and gives some helpful and constructive solutions.

1) Selection of SCF-agent Vehicles

The SCF mechanism aims at selecting some vehicles, i.e., *SCF-agents*, to store and carry the data until meet appropriate vehicles to forward. This mechanism is beneficial to improve Packet Delivery Ratio (PDR) while it may trigger more broadcast transmissions. The illustration is shown in Figure 3-14.

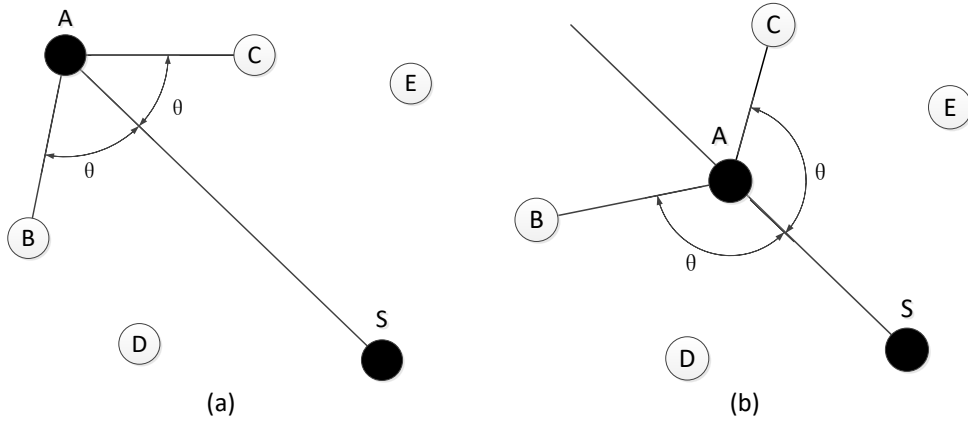


Figure 3-14. The distributed gift-wrapping algorithm

The sender S intends to broadcast data packets to other nodes. Node A is a candidate to be SCF-agent. The gift-wrapping algorithm works as follows: If $|\theta_-| + |\theta_+| < \pi$, node A will be selected. Otherwise, the SCF-agent role will not be assigned node A. The basic idea of this algorithm is to select the vehicles located at the boundary of network to be SCF-agent. Those boundary vehicles will carry data packets and travel out of the network. Therefore, the reception probability of the vehicles located outside of the network can be increased. However, as the authors of UV-CAST admitted, the distributed algorithm may over-select the boundary vehicles to be SCF-agents. Consequently, the number of transmissions would be considerable.

2) Broadcast Suppression

The broadcast suppression technique can constrain the rebroadcast in well-connected network to address broadcast storm problem. It relies on a delay-contention scheme as mentioned in TO-GO on page 47. When a node receives a data message, it calculates the waiting time of rebroadcast according to the distance to the sender. UV-CAST assigns higher priority of transmission to the vehicles located at intersection because these vehicles get more chances to disseminate data messages in all possible road directions. An illustrative formula to calculate a waiting time is shown in Equation (3-1):

$$\tau_i = \begin{cases} \frac{1}{2} \left(1 - \frac{d_{ij}}{R}\right) \tau_{max} & \text{if vehicle } i \text{ is at an intersection} \\ \frac{1}{2} \left(2 - \frac{d_{ij}}{R}\right) \tau_{max} & \text{otherwise} \end{cases} \quad (3-1)$$

τ_i is the waiting time, d_{ij} is the distance to sender, R is the maximum radio range, τ_{max} is the maximum waiting time.

The significance of UV-CAST is that it drafts a unified framework for broadcast/geocast routing in urban scenario. The framework includes a *broadcast suppression mechanism* for

well-connected networks and a *Store-Carry-Forward mechanism* for disconnected networks. Although the specific algorithms in UV-CAST are not outstanding compared with the later IVC protocols, the framework is still being used today.

3.5.3.4 AMD

Adaptive Multi-directional data Dissemination (AMD) protocol is an infrastructure-less data dissemination protocol supporting both highway and urban **scenarios**. As UV-CAST, AMD also includes a broadcast suppression technique and a Store-Carry-Forward (SCF) mechanism. A generalized time slot scheme is used to suppress broadcast, which is based on directional sectors. In the SCF mechanism, a role transition, i.e., from *tail* to *non-tail*, is used to trigger a new broadcast to uninformed vehicles.

1) Broadcast Suppression Technique

This mechanism mainly contains two parts: One is the *directional sector classification* and the other is the *time slot scheme*. The number of directional sector of the sender S is adjusted adaptively between 2 or 4 according to the local road topology and the distribution of neighbors. The illustration of classification is shown in Figure 3-15.

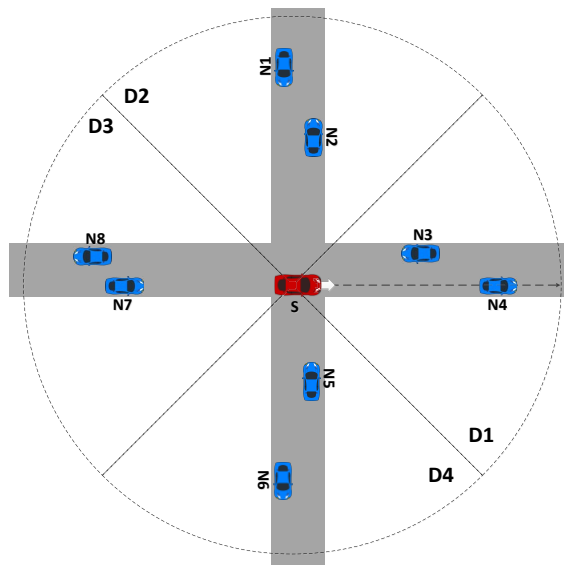


Figure 3-15. The directional sectors of suppression mechanism

In this case, the sender S attempts to classify all its neighbors into respective directional sectors, i.e., D1, D2, D3, D4, that represent the four directions of the orthogonal crossroad. In every directional sector, the slot time scheme is responsible for allocating a waiting time to member vehicles. The formula can be expressed as Equation (3-2):

$$T_{ij} = st \left(\left\lceil \frac{(S_{ij}+1)}{ts_d} \right\rceil - 1 \right) + AD_{ij} \quad (3-2)$$

T_{ij} is the waiting time. $S_{ij} \in [0, n - 1]$ is the priority of vehicles in every sector, n is the number of vehicles in every sector, the furthest car is set $S_{ij} = 0$ and the closest car is set $S_{ij} = n - 1$, i.e., the further distance, the shorter delay, the higher priority. st is the total transmission time that includes medium access delay, propagation delay and transmission delay. ts_d is the number of vehicles in a single time slot, which represents the density of time slot. To prevent timeslot boundary synchronization problem, an additional delay AD_{ij} is attached [60]. Upon the delay-contention scheme, if vehicles hear a redundant message from a member of the same directional sector, they will cancel the rebroadcast schedule of the message.

2) Store-Carry-Forward (SCF) Mechanism

The SCF mechanism casts a *tail* role to the vehicle that has no further neighbor in one of directional sectors. The tail vehicle is assigned the right to store data packets. When the tail vehicle connects new neighbors, it will change its status from tail to non-tail. At this time, a new rebroadcast is triggered to forward the stored data to the new neighbors. To prevent unnecessary rebroadcasts, only the data that neighbors do not hold can be rebroadcast by comparing message list. Notice that SCF mechanism depends on the accuracy of the classification of directional sector. If the classification fails to recognize the irregular road topology, the SCF mechanism will be affected badly.

3.6 Delay Tolerant Network (DTN) Routing

DTN routing mainly resorts to Store-Carry-Forward (SCF) mechanism, by which a vehicle can store and carry data packets until meet a new opportunity to forward. This approach is an efficient way to handle disconnected network problem. Due to the intermittent connectivity in VANETs, there is not always an end-to-end connection between source and destination. DTN routing can enhance PDR by enabling opportunistic transmission in a ROI with a restricted additional overhead. Services or applications using this routing should be delay-insensitive because a great amount of transmission time is used by the vehicle carrying data on the road.

Normally, SCF mechanism is a part of geocast routing as the description of DV-CAST, UV-CAST and AMD in section 3.5.3. A large number of transmissions are triggered on the boundary of ROI, where the vehicle going out of the ROI will forward the stored data to the

vehicle coming into the ROI. Therefore, how to manage these transmissions should be considered carefully when we design the SCF mechanism of IVC protocol.

3.6.1 VADD

Here, we give a typical DTN routing, i.e., Vehicle-Assisted Data Delivery (VADD), to illustrate the basic principle. VADD provides a solution to alleviate the effect caused by high dynamic topology of VANETs. This routing not only uses street map, but also considers traffic density, maximal speed and average speed to calculate the transmission capability of each street [25].

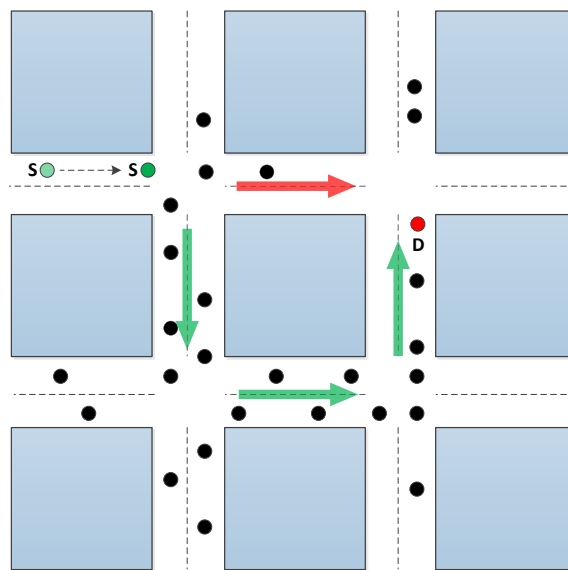


Figure 3-16. Vehicle-Assisted Data Delivery protocol

In Figure 3-16, the dots and the boxes represent vehicles and buildings, respectively. Vehicle S (the green dot) wants to transmit messages to vehicle D (the red dot). But there is no effective connection in the shortest route as shown by the red arrow. So vehicle S carries packet to the intersection and calculates an alternate route to transmit packet to vehicle D, the computing result is shown by the green arrows Figure 3-16. VADD gives several solutions to choose the next relay, but none of them is qualified. The best one is to select more than one next relay nodes, which is a multipath transmission approach. Unfortunately, the overhead of this approach is relatively high. Moreover, the estimation of the up-to-date traffic condition is also a challenge, which is important enough to motivate a specific system, i.e., Traffic Information System (TIS).

3.7 Static Beacons

Beaconing refers to broadcasting Hello message periodically in the one-hop neighborhood. In VANETs, the Hello message usually can be called beacon, which is maybe a little different with the concept of beacon in WSN, i.e., beacon only can be sent by coordinator or router (e.g., ZigBee PRO). Because, normally, vehicles in VANETs are organized by ad-hoc mode, every vehicle can be thought of ‘Coordinator’ even if they are not the case actually. Static beaconing is the periodic, fixed-interval beaconing with constant transmission power. This concept is widely used in IVC protocols to detect the local topology information, which provides geographic position of neighbors for geographic routing. Traffic information also can be piggybacked hop-by-hop by static beaconing as the description about SOTIS system in section 2.4.1.2 on page 22.

3.7.1 ETSI CAMs

Cooperative awareness is a well-known application, using static beaconing, in ETSI protocol suite, by which all road users and roadside unit (RSU) are informed each other’s position, dynamics and attributes [61]. It is worth mentioning that the road users include all vehicles on the road, such as cars, trucks, motorcycle, bicycle, and even pedestrians. For the standardization of this service, the specification of cooperative awareness basic service is defined by ETSI, e.g., protocol and message formation. The protocol is rather straightforward to exchange Cooperative Awareness Messages (CAMs) among road users with a fixed frequency, which does not depend on the current channel status. This protocol can be called *static beaconing* protocol. However, this approach using fixed transmission interval quickly meets the channel congestion problem in dense and dynamic scenarios. This exactly motivated the development of Decentralized Congestion Control (DCC) standard that will be discussed in next section (section 3.8.1 on page 57). ETSI ITS protocol stack, of course, is used to broadcast CAMs on control channel (CCH) by using IEEE 802.11p. Upon receiving CAMs from neighboring vehicles, drivers can learn relative information about surrounding traffic environment. The information is saved in respective containers in the CAM. Finally, we will introduce the general structure of a CAM, as shown in Figure 3-17.

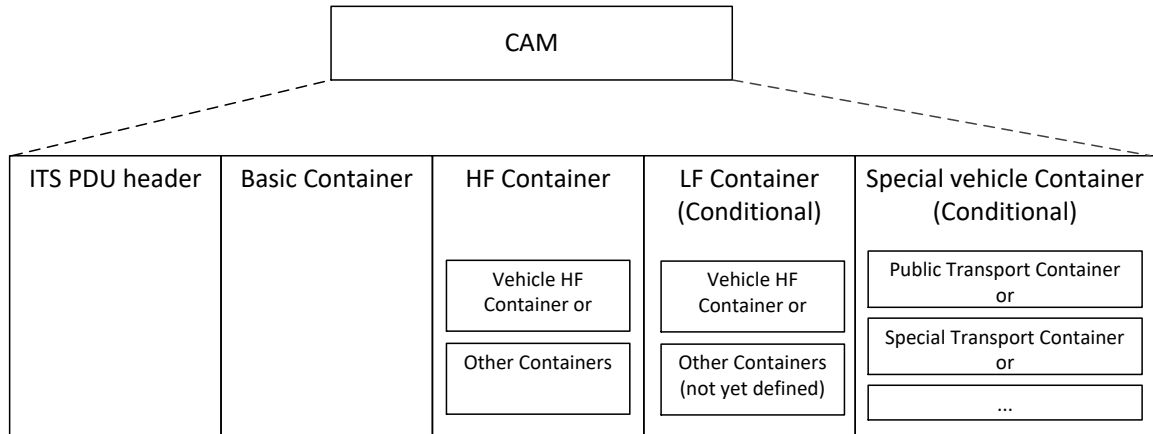


Figure 3-17. General structure of a CAM

Like DENM, CAM also includes the ITS PDU header and multiple containers. According to the standard, a basic container and a High-Frequency (HF) container must be provided in a CAM. The basic container records the vehicle type and the latest geographic position. The HF container includes all highly dynamic information, e.g., heading or speed. In addition, The LF container contains static or slow-changing vehicle data, e.g., the dimension of the vehicle or the status of the exterior lights. In particular, the vehicles which have a special role in road traffic, e.g., public transport, special transport, emergency vehicles and so on, shall provide further status in special vehicle container.

3.8 Adaptive Beaconing

The basic idea of adaptive beaconing is to adapt transmission parameters, e.g., transmit rate or transmit power, according to the current channel condition, while keeping the channel load below predefined thresholds. The objective is to mitigate the channel congestion problem mentioned at last section (section 3.7.1 on page 55). For ETSI CAMs, the congestion on channel has dramatic effect of increasing the CAM loss probability, so that the vehicle is more difficult to sense the potentially dangerous situation in its neighborhood. To address the channel congestion in VANETs, several works have been proposed [62], [63]. In 2011, ETSI also developed a set of Decentralized Congestion Control (DCC) mechanism to mitigate the congestion on CAMs channel [64]. Recently, a new standardization process has been performed and still underway [65]. The ongoing work of DCC mainly lays its foundations into Periodically Updated Load Sensitive Adaptive Rate control (PULSAR) and LInear MESSage Rate Integrated Control (LIMERIC) protocols [12], [13].

3.8.1 ETSI DCC

Here, we will describe the current development of ETSI DCC standard. The DCC access control performs at access layer of ETSI ITS protocol stack for the selected channel from ITS-G5CC or ITS-G5SC. Channel Busy Ratio (CBR) b_t is used to be the key metric that represents the state of channel load. To determine the CBR, the channel is repeatedly probed to check whether it is busy or not. The average power of the channel is compared with the CCA threshold in physical layer. During a sampling interval T_i , the CBR is the ratio between busy time T_{busy} and T_i , as shown in Equation (3-3).

$$\text{CBR} = \frac{T_{\text{busy}}}{T_i} \quad (3-3)$$

Several transmission parameters can be used to tune the channel load. Adaptive transmit rate and power are mostly selected to mitigate the channel congestion. In addition, some adaptations about modulation, carrier sense threshold and transmit queue management are also exploited to control the channel load.

- Transmit Rate Control (TRC): The transmit interval is increased to relax data traffic when the channel load becomes congested.
- Transmit Power Control (TPC): To alleviate the congestion on the channel, the transmit power is decreased so as to reduce the interference range of nodes.
- Transmit Data rate Control (TDC): Data rate is adapted according to the state of channel. Reducing data rate can mitigate the channel congestion while lower data rate support higher reliability.
- DCC Sensitivity Control (DSC): CCA threshold is adapted to resolve local channel congestion. Notice that, for the measurement of CBR, a fixed CCA threshold is still used.
- Transmit Access Control (TAC): This access control is similar to EDCA of IEEE 802.11p, in which the transmit queue is managed to support different message priority.

The access mechanism adapts transmission parameters based on a state machine, as shown in Figure 3-18. There are three states, i.e., *relaxed*, *active* and *restrictive*. b_{min} and b_{max} are the minimum and the maximum of defined channel load. b_{up} is the minimal value of b_t in the last second, b_{down} is the maximal value of b_t in the last five seconds.

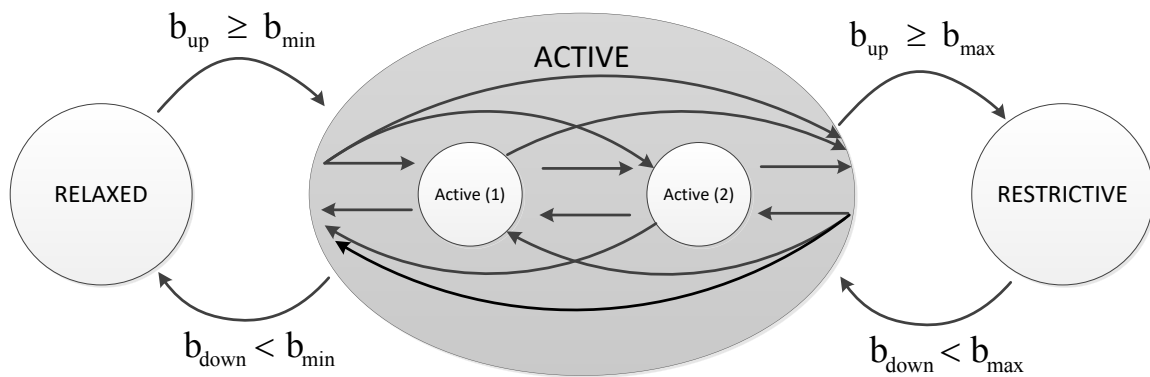


Figure 3-18. DCC access state machine

The state machine manages the change of state when the condition is satisfied. From relaxed state to restrictive state, the minimal CBR in last second b_{up} is compared with the channel load threshold, while, in the opposite direction, the maximal CBR in last five seconds are considered. That means: DCC mechanism is sensitive to tune channel state towards restrictive while being careful to switch state towards relaxed. This approach consists with reason because we should pay attention to a clue of congestion and give a little rescue time to the congestion resolution. The channel state and the corresponding transmission parameters of different access control mechanisms are listed in Table 3-3.

Table 3-3. Transmission parameters corresponding to states of ETSI DCC for CCH

	Relaxed	Active	Restrictive
Channel load threshold	15 %		40 %
TRC: Transmit interval	0.04 s	0.5 s	1 s
TPC: Transmit power	33 dBm	23 dBm	-10 dBm
TDC: Data rate	3 Mbit/s	6 Mbit/s	12 Mbit/s
DSC: CCA threshold	-95 dBm	-85 dBm	-65 dBm

However, the ETSI DCC of 2011 version only uses the CBR information of local node. This mechanism is difficult to handle the scenario: A node with appropriate CBR but contributes to a congestion of its neighboring node. In the perspective of adaptive beaconing, the CBR of local node, 1-hop neighbors and 2-hop neighbors should be taken into account. Tielert et al. [12] proved that the 2-hop piggybacking information can help to achieve a global fairness and support the need of safety application.

3.9 Routing with Infrastructure

Inter-Vehicle Communication (IVC) being available should be supported by two conditions: market penetration and vehicular density. In this thesis, we assume that every vehicle is equipped with dedicated short range communication (DSRC) device using IEEE 802.11p as the underlying layer. Based on this assumption, it is also possible that wireless communication between vehicles cannot be achieved due to a too low vehicular density at certain space or time. Only if the wireless network reaches a sufficient capacity given the two factors, all protocols provided by this thesis can perform their normal operation. Otherwise, the VANET faces major problems. The most straightforward approach is to use infrastructure that can provide long range communication or additional short range communication.

Currently, for IVC applications in the real world, cellular network (in section 2.3.1 on page 8) is the only one practical wireless access technology associated by smartphone or other access devices. A typical early work is the CoCar project for Centralized TIS (in section 2.4.1.1 on page 20). In addition, to integrate with IEEE 802.11p, how to select suitable gateway and control the data flow in a hybrid VANET-cellular system are critical issues [66], [67]. Recently, a new access technology of LPWA network, i.e., NB-IoT (in section 2.3.6 on page 18), can be used for those IVC applications in need of long range and low data rate.

Alternative infrastructure element is the AP-like system beside the road, so-called roadside unit (RSU). A very potential approach is to use WiFi that is the ubiquitous wireless access technology [8]. Several works have already investigated the performance of using WiFi directly for VANETs [68], [69]. IEEE 802.11p also can be implemented in RSUs to communicate more efficiently with vehicles. These RUSs also could be connected with one or more TICs by the backbone network, so that traffic information is able to collected and disseminated more intelligently, as shown in Figure 3-19.

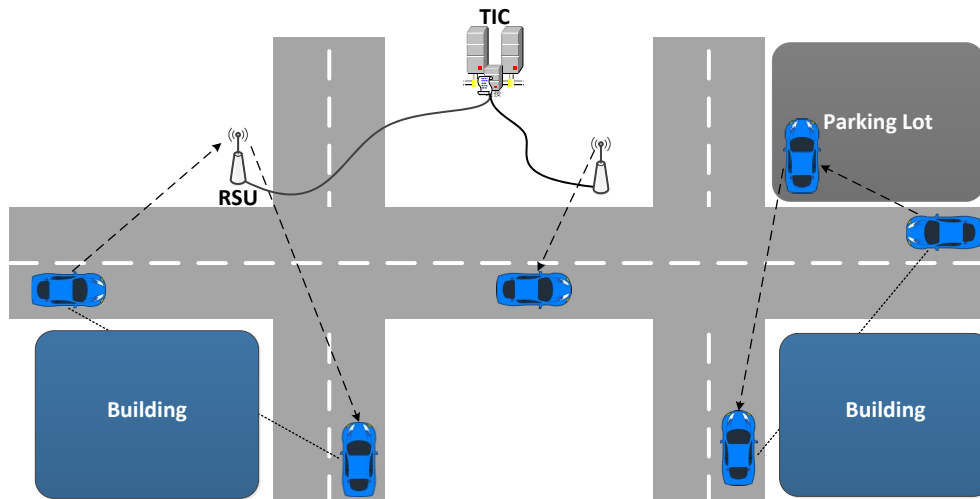


Figure 3-19. Scenarios of RSUs and parked vehicle helping to connect vehicles those are not in communication range of each other or blocked by building obstacles

The RSU at the corner can route messages for vehicles that are blocked by the building obstacle (on the left), but also relay traffic-related messages to an RSU that is geographically suited to disseminate the messages (on the middle). Moreover, Sommer & Eckhoff et al. [9], [70] proposed that the parked cars can improve cooperative awareness and mitigate signal attenuation in VANETs (on the right).

3.10 Key Techniques

After investigating the IVC protocols for data dissemination in VANETs, it is the time to summarize key techniques learned from the survey. Upon understanding these key challenges, we can achieve a better design of the data dissemination protocol.

3.10.1 Broadcast Suppression Technique

The distributed algorithm of broadcast suppression technique is mainly based on the delay-contention scheme that is described in detail at the last paragraph of section 3.5.3.1 on page 49. Although this scheme is simple and efficient, the specific scenarios should be taken into account when we design the specific mechanism. Normally, the original scheme can handle most of highway scenarios except a few special road topologies, e.g., curve road with angle more than 90 degrees, the entrance or exit of the highway. However, many problems arise when IVC protocols perform in urban scenarios. The reason lies in the complex traffic environment of city, e.g., irregular road topology and building obstacle. To transmit messages in different directions, also aiming to handle both highway and urban

scenarios, the radio range is usually divided to several sectors and the delay-contention scheme performs in every sector. As the case of AMD, the protocol divides the radio range into 2 or 4 directional sectors according to the local road topology and the distribution of neighbors. But, due to the irregular road topology, the classification of AMD is not accurate, even not correct sometimes. Therefore, *how to design a classification technique to achieve a high accuracy* is a key issue.

3.10.2 Store-Carry-Forward (SCF) mechanism

SCF mechanism is responsible for filling the gap between disconnected networks. Sometimes the IVC protocol needs this mechanism to guarantee a qualified PDR in sparse and highly dynamic networks. SCF mechanism also helps the vehicle going out of ROI transmit its stored data to the vehicle coming into ROI, so that the valid data can be maintained in the ROI. To prevent the redundant data, *the trigger condition of stored data transmission is a key technique*. DV-CAST and UV-CAST use message list to find which stored data needed to be sent, while AMD resorts to a transition behavior, i.e., from tail to non-tail. Moreover, the new incoming vehicle usually not requires only one stored data, but several. *How to manage the continuous transmissions of stored data* is another issue.

3.10.3 Beaconing

In my point of view, beaconing is a foundation mechanism of IVC protocols. From the perspective of routing protocol, beaconing can provide the local information in the one-hop neighborhood. Furthermore, from the perspective of applications, beaconing also dedicates itself to the cooperative awareness that is the essential safety application. Finally, from the perspective of network load, the adaptive beaconing can mitigate the channel congestion. Therefore, the key technique of beaconing is to design *a strategy that can achieve a fairness of bandwidth utility (local and global) and also satisfy the requirement of safety applications*.

3.10.4 GPS Drift Tolerance

Given geographic routing based on positioning of GPS system, the accuracy of position information is very important to the performance of IVC protocols. However, the GPS system is usually not precise. The average deviation of standard GPS is up to 30 meters [71]. To alleviate the impact of GPS drift, the broadcast communication paradigm is widely used,

like geocasting. But that is not enough, *a dedicated GPS drift tolerance mechanism should be considered.*

Chapter 4 Mobility Model and Realistic Road Traffic Scenarios

4.1 Introduction

In this thesis, we used “Simulation of Urban MObility” (SUMO) road traffic simulator to create road traffic scenarios for the performance evaluation of IVC protocols. SUMO performs the microscopic simulation by which road vehicles, public transport, pedestrians are modeled explicitly. In fact, SUMO is a road traffic simulation suite, in which various supporting tools can be used to import road networks, create traffic routes and perform the visualization. Therefore, SUMO can build the realistic traffic scenarios, where real road map, buildings, present traffic rule and traffic light program are simulated according to the ones of the real world.

At the beginning of this chapter, the main mobility model of SUMO, i.e., Krauss car-following model, is introduced. Then, we will describe how to create road traffic scenarios step by step. In section 4.3, abstract traffic scenarios are given to illustrate how to build some simple scenarios. Based on these scenarios, we provide a special design to use the close circle road traffic to simulate the open circle road traffic. After that, realistic traffic scenarios are elaborated in section 4.4. Three realistic scenarios will be given for the IVC protocols simulations described in Chapter 5, which are also a part of contributions of this thesis. Finally, the bidirectionally coupled simulation is explained, in which a survey of current popular network simulators is presented and SUMO is used for evaluating the performance of IVC protocols in an on-line loop with a network simulator, i.e., OMNeT++.

4.2 Mobility Model

The mobility of vehicles in SUMO is mainly controlled by a car-following model proposed by Krauss [72], [73]. Figure 4-1 shows the class inheritance of car-following models in SUMO source code. Except the Krauss model, there are also other models provided for users to perform their road traffic simulation. The Krauss mobility model belongs to microscopic model of traffic flow that can describe the dynamics of each individual vehicle as a function of positions and velocities of the vehicles in the neighborhood.

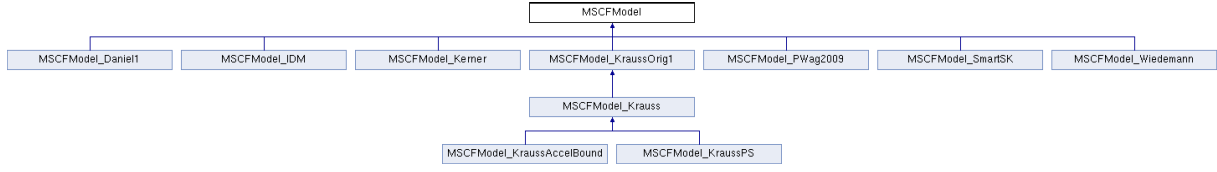


Figure 4-1. The class inheritance of car-following models in SUMO

Here, we will introduce the basic principle of the Krauss car-following model, which shows *how vehicles can avoid collisions between each other during the simulation*. The basic idea of the model is to control the velocity of vehicles below a safe velocity v_{safe} , so that the gap g between the leading and the following vehicle is always larger than a desired gap g_{des} , as shown in inequality 4-1.

$$\frac{dg}{dt} \geq \frac{g_{des} - g}{\tau_{des}} \quad (4-1)$$

τ_{des} is the desired time scale, during which a driver can achieve the desired gap g_{des} . Inequality 4-1 is an abstract expression. Now, let us consider the specific scenario of a leader and a follower with a gap g between them at velocities v_l and v_f , respectively. The road is assumed to be one lane and the reaction motion between vehicles is considered. If the leading vehicle brakes and stops completely, the braking distance is measured to be $d(v_l)$. To make sure that the following vehicle does not collide with the leading vehicle, the inequality 4-2 should be satisfied as follows.

$$d(v_f) + v_f \tau \leq d(v_l) + g \quad (4-2)$$

$d(v_f)$ and τ is the braking distance and reaction time of the following vehicle, respectively. The inequality 4-2 shows that the distance consumed by the following vehicle in braking and reaction behavior of the driver should be less than the braking distance of the leading vehicle plus the gap g . To find the relation between v_l and v_f , Krauss used Taylor series to expand $d(v_f)$ and $d(v_l)$ around the average velocity of the leader and the follower $\bar{v} = (v_l + v_f)/2$, as shown in Equations (4-3) and (4-4).

$$d(v_f) = d(\bar{v}) + d'(\bar{v})(v_f - \bar{v}) + \dots \quad (4-3)$$

$$d(v_l) = d(\bar{v}) + d'(\bar{v})(v_l - \bar{v}) + \dots \quad (4-4)$$

The third and higher order terms of right side of Equations (4-3) and (4-4) are dropped, and then we bring these two equations into inequality 4-2. Therefore, we can obtain the inequality 4-5.

$$d'(\bar{v})v_f + v_f \tau \leq d'(\bar{v})v_l + g \quad (4-5)$$

The derivative $d'(\bar{v})$ is not difficult to be quantified. Considering that a vehicle decelerates from velocity v to velocity 0 with a deceleration rate $-b(v)$, we can obtain the Equation (4-6).

$$d'(v) = -\frac{d}{dv} \int_v^0 \frac{v'}{b(v')} dv' = \frac{v}{b(v)} \quad (4-6)$$

Bring Equation 4-6 into Inequality (4-5), we can get the relation between v_l and v_f as shown in Inequality (4-7).

$$v_f \leq v_l + \frac{g - v_l \tau}{\frac{v}{b(\bar{v})} + \tau} \quad (4-7)$$

Thus, v_f should be less than a safe velocity v_{safe} that is equal to the right side of Inequality (4-7).

$$v_{safe} = v_l + \frac{g - v_l \tau}{\frac{v}{b(\bar{v})} + \tau} \quad (4-8)$$

Moreover, the final desired velocity v_{des} also needs to obey the free motion of a vehicle, that means v_{des} should be less than the maximum velocity v_{max} that is in relation to the desired velocity of the driver. In addition, v_{des} is still limited by the maximum acceleration a of the engine. That is, v_{des} should be less than the velocity $v + a\Delta t$. Finally, we achieve the desired velocity of Krauss car-following model as follows:

$$v_{des} = \min(v_{max}, v + a\Delta t, v_{safe}) \quad (4-9)$$

4.3 Abstract Road Traffic Scenarios

Abstract road traffic scenarios are created by SUMO tools or by hand, which are not converted from the real road map. The road topology of abstract scenarios would be the regular or irregular geometry, e.g., ManhattanGrid and Spider network, but, its every single road section always is straight line. The architecture of abstract scenarios is relatively simple compared with realistic ones, which mainly includes road network and traffic routes, as shown in Figure 4-2.

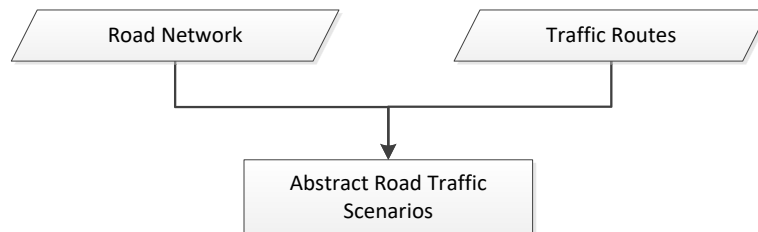


Figure 4-2. The architecture of abstract road traffic scenarios

Abstract scenarios are beneficial to the experimental attempts that can determine whether the new function of our IVC protocols is correct or effective. By using abstract scenarios, the drawback of our new idea would be uncovered more clearly. We could feel confident enough to use our IVC protocol in realistic scenarios only when the protocol passes the performance evaluation in abstract scenarios. Introducing abstract scenarios first is also for providing relatively simple examples to explain *how to create road traffic scenarios*.

4.3.1 ManhattanGrid Scenarios

ManhattanGrid network is created by NETGENERATE, one tool of SUMO suite, which can create some specific type of road networks. We only need to set the length of the road section and the number of the block, the network will be built automatically. Roads of ManhattanGrid network are orthogonal at the intersection and form a closed grid network, as shown in Figure 4-3a. This type of network is called ManhattanGrid because its road topology is similar to the one of Manhattan borough in New York City, USA. The detail of intersection is shown in Figure 4-3b, which is a selected area indicated by the box with green dot line in Figure 4-3a. The red and green bars represent traffic lights. For traffic routes of ManhattanGrid scenarios, we recommend JTRROUTER that can create random traffic routes for specific number of vehicles so as to distribute vehicles into the network uniformly.

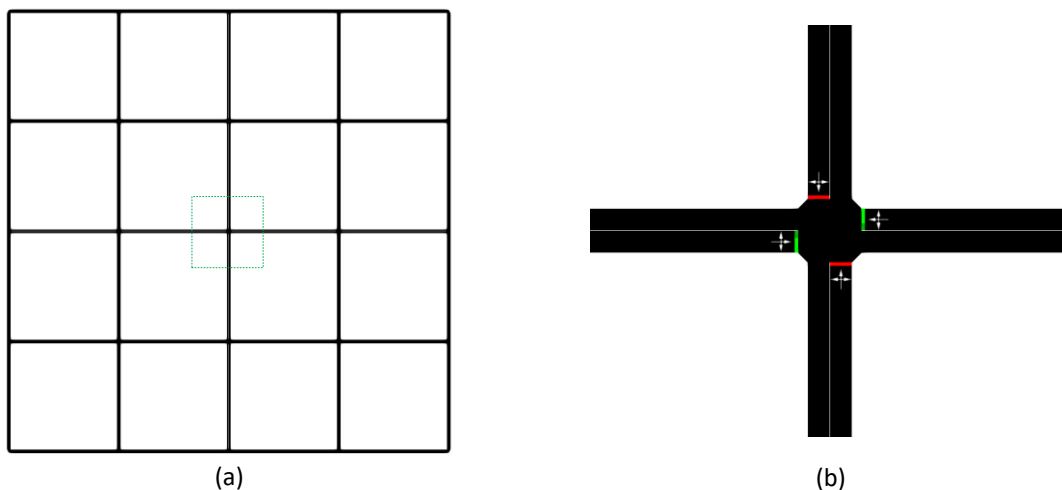


Figure 4-3. ManhattanGrid Scenarios

Data dissemination in ManhattanGrid scenarios is easy to be handled by IVC protocols, since the orthogonal road topology can be recognized efficiently by predesigned algorithms. Therefore, ManhattanGrid scenarios are usually used in the first experiment to verify the validity of our IVC protocol. If an IVC protocol cannot handle ManhattanGrid scenarios, it

will be impossible to handle more complex ones. Moreover, due to the simple road topology of ManhattanGrid scenarios, some design issues can be exposed clearly.

4.3.2 Spider Scenarios

The network and traffic routes of spider scenarios also can be created by the same tools used for ManhattanGrid, i.e., NETGENERATE and JTRROUTER. The spider network, as the name, looks like a spider net as shown in Figure 4-4a. The detail of intersection is shown in Figure 4-4b, which is a selected area indicated by the box with green dot line in Figure 4-4a.

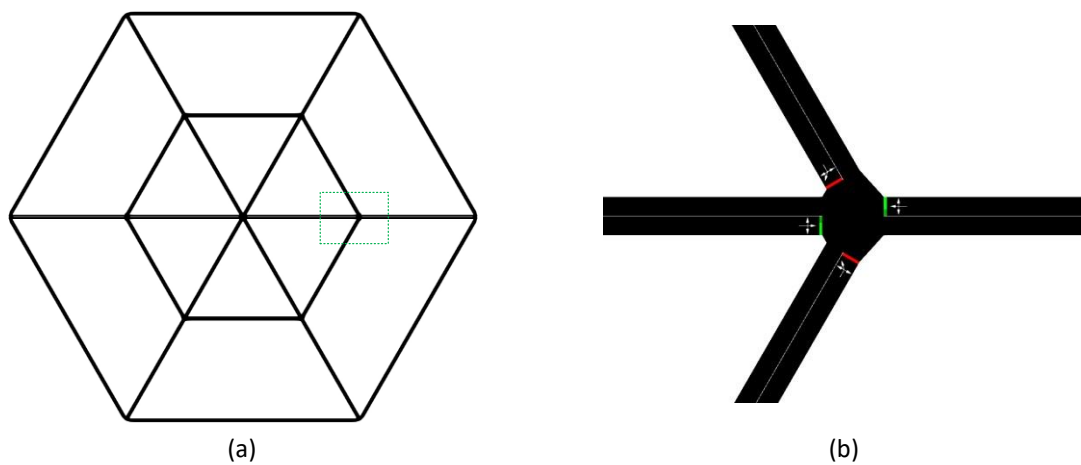


Figure 4-4. Spider Scenarios

Spider scenarios are a little more complex than ManhattanGrid ones. Roads of the spider network are not orthogonal at the intersection. This road topology is similar to some ones in Paris or Rome. Several roads converge at the central intersection of the network. Given this special topology, we had used our protocol in the vehicle located at the central intersection to to develop the directional cluster classification strategy for the key technique ‘broadcast suppression’ mentioned in section 3.10.1 on page 60..

4.3.3 Man-Made Scenarios for Closed Circle Road Traffic Simulation

Although the two scenarios above-mentioned have its own features, the basic topology of them is fixed. It is difficult to edit the networks after they have already created. Therefore, we can also make our own road networks *by hand*, which will satisfy our specific requirements. Moreover, to have further thoughts, the itinerary of a vehicle in the real world is not possible to be random. Alternatively, the vehicle must pass through the map toward a

specific direction. This type of traffic system is an *open circle system* that is difficult to simulate. To achieve the realistic traffic environment, we propose the *closed circle road traffic simulation* to simulate the open circle traffic system. Obviously, the tools using for the above two scenarios cannot satisfy the requirement of the new traffic simulation. Therefore, we exploit other tools of SUMO suite to create the *Man-Made* scenarios, as shown in Figure 4-5. First, we will introduce *how to build the closed circle road traffic simulation* on the Man-Made network, and then the approach about how to create the Man-Made network will be elaborated.

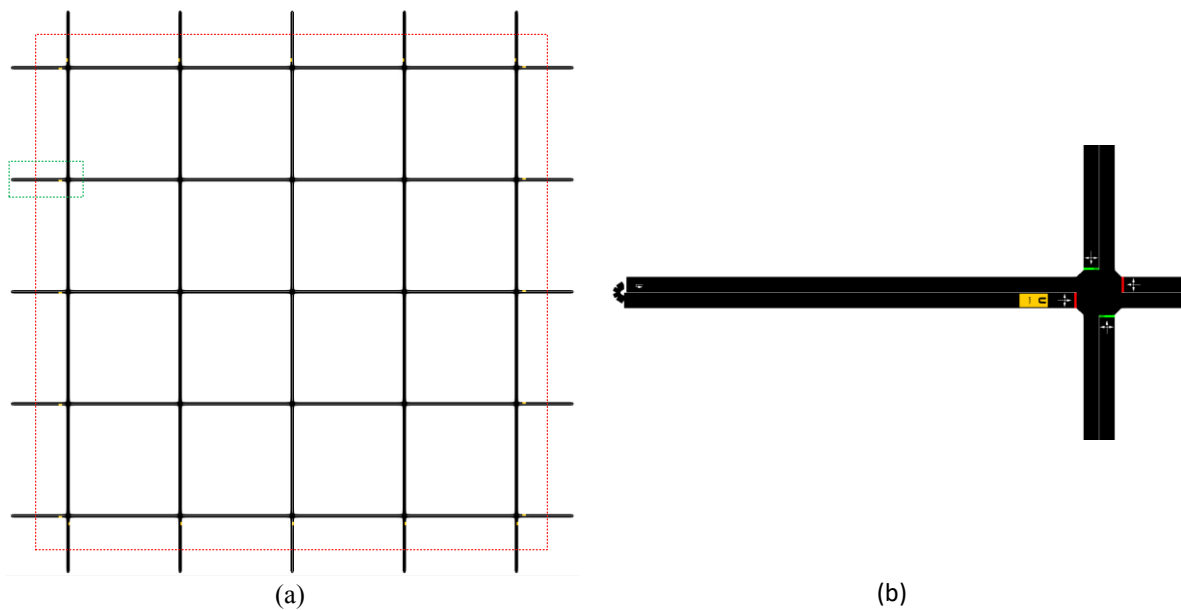


Figure 4-5. Man-Made Scenarios

First of all, a concept should be introduced, namely Reign of Interest (ROI). Because, in ad hoc networks, any information has its maximum data dissemination range, as mentioned in section 2.5.5, an appropriate ROI should be defined for the respective application. In Figure 4-5a, the ROI is indicated by the box with red dot line. In the closed circle road traffic simulation, if a vehicle runs out of the ROI, the data buffer of the vehicle will be cleared. This operation is to simulate the vehicle has left the ROI. Moreover, the Man-Made network provides several branches at the border of the ROI, one of them is shown in Figure 4-5b that is the selected area by box with green dot line in Figure 4-5a. These branches give the leaving vehicle a chance to turn back to the ROI. At that time, the data buffer of the leaving vehicle has been cleared, so that the vehicle can be seen a new vehicle when it comes into the ROI again. We use REROUTER, the yellow symbol in the Figure 4-5b, to control vehicles to turn back to the ROI. The function of REROUTER is that, a new destination will be assigned to a vehicle when the vehicle touches the symbol. So, we only

need to set the destinations of a pair of REROUTER to each other, vehicles will run in a closed loop. Figure 4-6 shows traffic flows in the closed circle traffic simulation. Every red line means a closed loop. Vehicles run between a pair of branches, e.g., W1-E5, connected by the red lines.

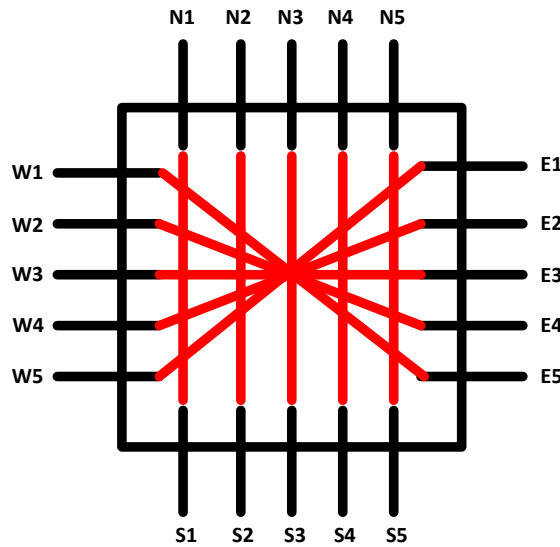


Figure 4-6. Traffic flows in closed circle traffic simulation

At the initial phase of our road traffic simulation, we use DUAROUTER, a tool of SUMO suite, to create a primary route for vehicles to pass through the map, e.g., from W1 to E5, before they touch the REROUTER symbol. When vehicles finish their primary route, they will touch the REROUTER symbol and turn back to the ROI by the branch road. To reduce the time during which all vehicles can be completely distributed on the network, vehicles depart from both branch pair, e.g., from W1 to E5 and from E5 to W1. Notice that the closed circle simulation cannot be performed in ManhattanGrid or Spider scenarios. The reason lies in that these networks do not provide return points for vehicles.

Now, let us talk about *how to create the Man-Made network*. NETCONVERT, a tool of SUMO suite, is used to create the Man-Made network according to four man-made input files, as shown in Figure 4-7. These input files are nodes, edges, type and connections file.

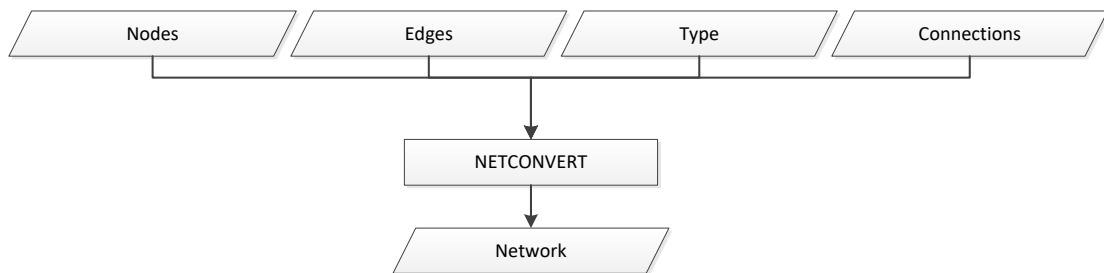


Figure 4-7. Man-Made network creation

Figure 4-8 is given to define the structure of the Man-Made network. The circles represent nodes with the number of row and column that start from 0.

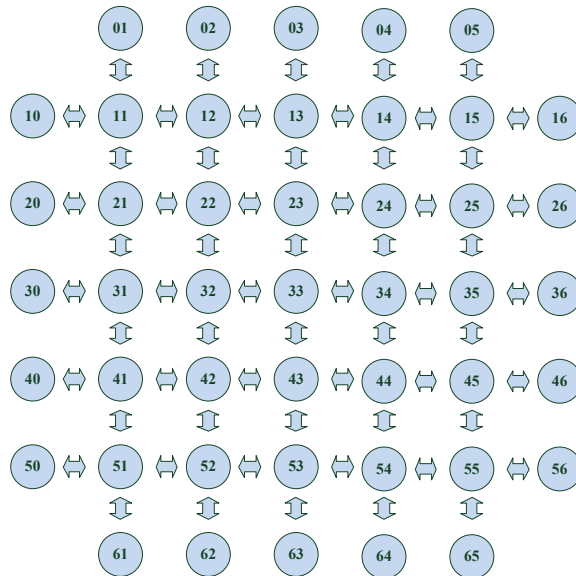


Figure 4-8. The structure of Man-Made network

The nodes file specifies the ID of intersections, i.e., the number of row and column, and the coordinate of these intersections, as shown in Figure 4-9.

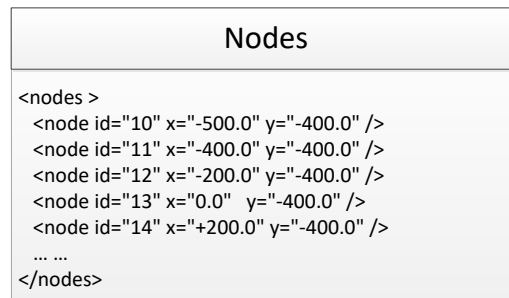


Figure 4-9. Nodes file

The edges file specifies the ID of edges, upstream and downstream nodes and the edge type, as shown in Figure 4-10.

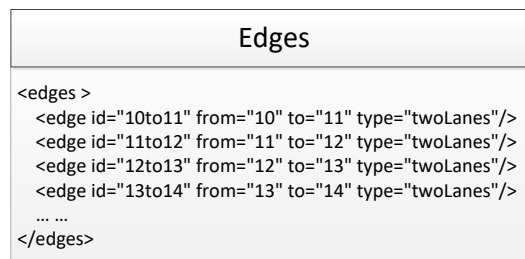


Figure 4-10. Edges file

The type file defines the driving priority based on traffic regulations, the number of lanes and the maximum allowed speed, as shown in Figure 4-11.

Type
<pre> <types> <type id="twoLanes" priority="3" numLanes="2" speed="13.889"/> </types> </pre>

Figure 4-11. Type file

Finally, the connections file regulates the boundary lanes to connect to each other in order to make the network closed, as shown in Figure 4-12. For instance, the first line of connections file, lane “11to10” is towards outside of network while lane “10to11” towards inside. The connections file rules lane “11to10” connects to lane “10to11”, so that vehicles can turn back to the network.

Connections
<pre> <connections> <connection from="11to10" to="10to11" /> <connection from="21to20" to="20to21" /> <connection from="31to30" to="30to31" /> <connection from="41to40" to="40to41" /> <connection from="51to50" to="50to51" /> </connections> </pre>

Figure 4-12. Connections file

To sum up, our special design, i.e., closed circle road traffic simulation, can use the closed circle traffic system to simulate the open circle one. Man-Made scenarios provide the necessary condition for the simulation. Moreover, our closed circle road traffic simulation can also be used in realistic scenarios, only if the realistic scenarios can provide return points which let vehicles turn back to the ROI.

4.4 Realistic Road Traffic Scenarios

In this part, we will introduce *how to create realistic road traffic scenarios* by using SUMO. The realistic scenario includes a map and a number of traffic routes. Therefore, first, we explain how to convert the available geographic data source to SUMO map, and then different types of traffic routes will be designed for respective purposes. Notice that the realistic scenarios described in this section are also used in our IVC simulations in Chapter 5.

4.4.1 Convert OpenStreetMap to SUMO Map

To obtain the realistic map that can be used in SUMO, we selected OpenStreetMap as the geographic data source. OpenStreetMap is an open geographic database [74]. It provides dedicated geographic information, e.g., roads, buildings, rail way, pedestrian way, bicycle way. Moreover, the database also provides the information of traffic rule and traffic light, which is beneficial to create realistic road traffic scenarios. Next, we select the city center of Clermont-Ferrand, France for instance to illustrate the process of creating the realistic SUMO map. The SUMO map includes the road network and the building polygon.

First, we introduce how to obtain the road network from OpenStreetMap, which specifies the shape of roads, traffic rule and traffic lights. NETCONVERT, a tool of SUMO suite, was used to extract road network from OpenStreetMap. Except the OpenStreetMap file, the input files also include a road type file, as shown in Figure 4-13.

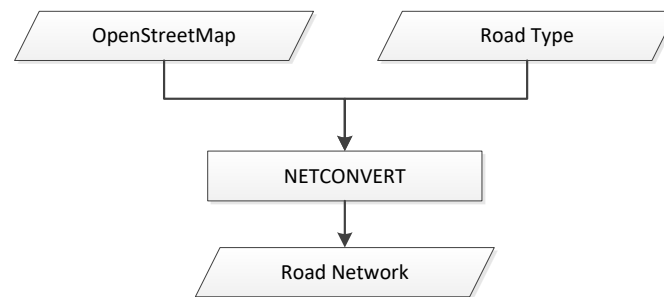


Figure 4-13. SUMO road map creation

The road type file rules the type of roads, the priority, the maximum speed limitation and the default lane number, as shown in Figure 4-14. The tool maps the type of roads with the one in OpenStreetMap and uses the rule to create the road network. For instance, following the French traffic rule, the maximum speed limitation of highway is 36.111 m/s, i.e., 130 km/h and the maximum speed limitation of urban road is 13.889 m/s, i.e., 50 km/h. For the default lane number, it only is used when the OpenStreetMap does not specify the lane number of a road.

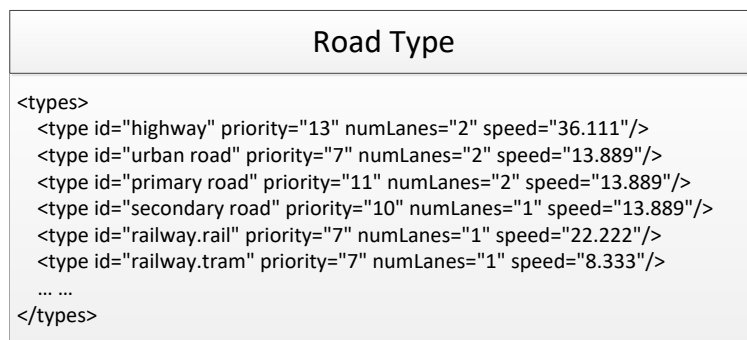


Figure 4-14. Road type file

The OpenStreetMap of the city center of Clermont-Ferrand is shown in Figure 4-15a. After importing these OpenStreetMap and road type files into NETCONVERT, the road network can be obtained, as shown in Figure 4-15b.

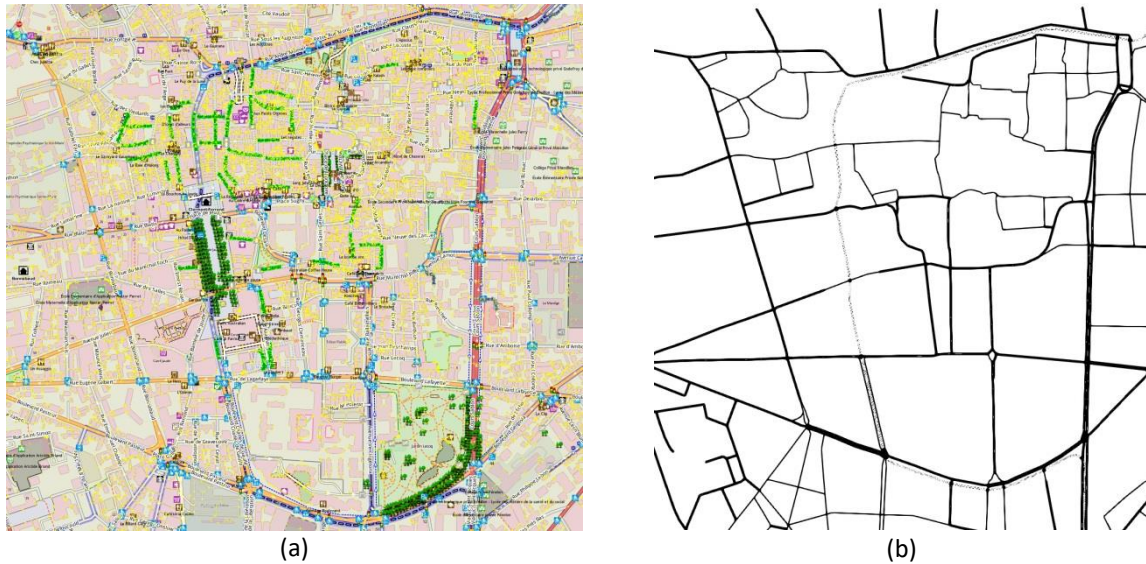


Figure 4-15. OpenStreetMap and road network of the city center of Clermont-Ferrand

Second, we introduce how to extract the building polygon from the OpenStreetMap. In fact, the polygon of SUMO map does not only include buildings, there are also other polygon such as water, park and so on. But the building polygon will be used to be obstacles in our IVC simulations, so we emphasize the building polygon in this section. POLYCONVERT, a tool of SUMO suite, is used to complete this mission. Three files are imported into the tool, as shown in Figure 4-16.

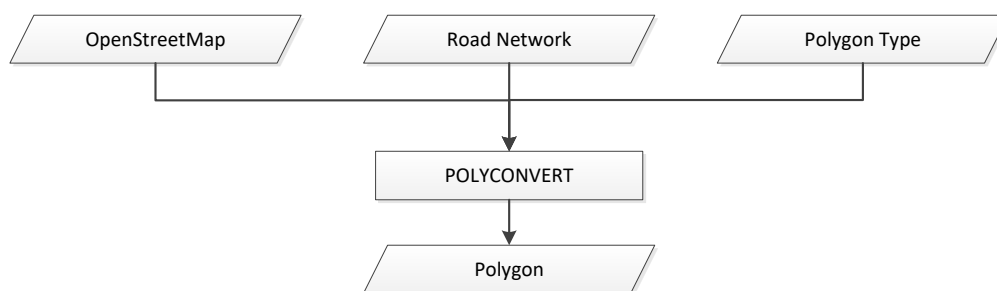


Figure 4-16. Polygon Creation

OpenStreetMap and road network have already got by first step. The polygon type file regulates the polygon ID, the polygon name, the color and the image layer, as shown in Figure 4-17. The ID and name of polygon is used to match the components of OpenStreetMap. If the component is matched, it will be set to the predefined color and image layer for SUMO map. For instance, buildings are shown as the pink color in SUMO map.

Polygon Type
<pre> <polygonTypes> <polygonType id="building" name="building" color="1.0,.90,.90" layer="2"/> <polygonType id="waterway" name="water" color=".71,.82,.82" layer="-10"/> <polygonType id="landuse.park" name="park" color=".81,.96,.79" layer="-11"/> </polygonTypes> </pre>

Figure 4-17. Polygon file

The road network and the building polygon are combined to comprise the SUMO map, as shown in Figure 4-18b. As a reference, the OpenStreetMap is also given in Figure 4-18a.



Figure 4-18. OpenStreetMap and SUMO map of the city center of Clermont-Ferrand

Using the same method, we also created Manhattan scenarios selected from Manhattan borough of New York City, USA and Highway scenarios selected from a section of A711 highway of Clermont-Ferrand, France, as shown in Figure 4-19 and Figure 4-20, respectively.



Figure 4-19. OpenStreetMap and SUMO map of Manhattan borough of New York City

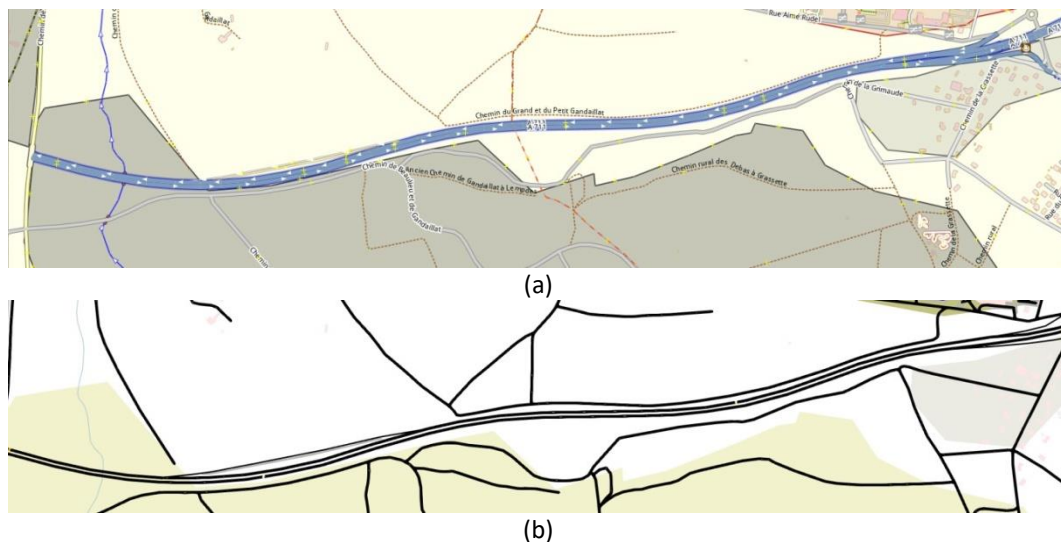


Figure 4-20. OpenStreetMap and SUMO map of A711 Highway of Clermont-Ferrand

4.4.2 Traffic Routes

We still use the closed circle road traffic simulation for realistic scenarios. In this section, we will introduce *how to design traffic routes* on the SUMO map. The basic principle is the same as the one we have described in section 4.3.3 on page 67. Take Clermont-Ferrand scenarios for example, first, we select some branch roads to be the departure points that are also to be the return points in the closed circle simulation, as shown in Figure 4-21a. Then, traffic routes are created between each pair of departure points, as shown in Figure 4-21b.

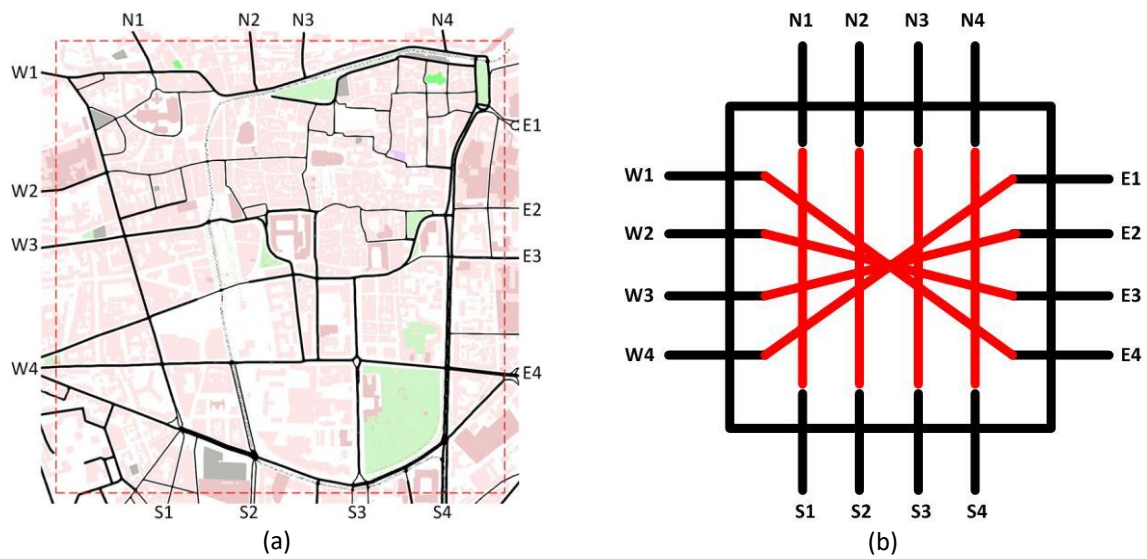


Figure 4-21. Traffic routes in Clermont-Ferrand scenarios

For Manhattan scenarios, we designed two types of traffic routes, i.e., the uniform and the deviated. The purpose of this design is to investigate the impact of different traffic routes on the performance of IVC protocols. The uniform traffic routes of Manhattan scenarios are similar to the ones of Clermont-Ferrand scenarios, which let vehicles move between the top and the bottom half of the map, so that the vehicles can cross the middle line of the map where the source node is located. Therefore, the vehicles get more chance to connect the source node or other vehicles. In Figure 4-22a, macro traffic routes are indicated by blue arrows. The red star is the source node that periodically broadcasts data messages. The red broken line indicates the boundary of ROI. In Figure 4-22b, micro traffic routes are indicated by red lines between departure points.

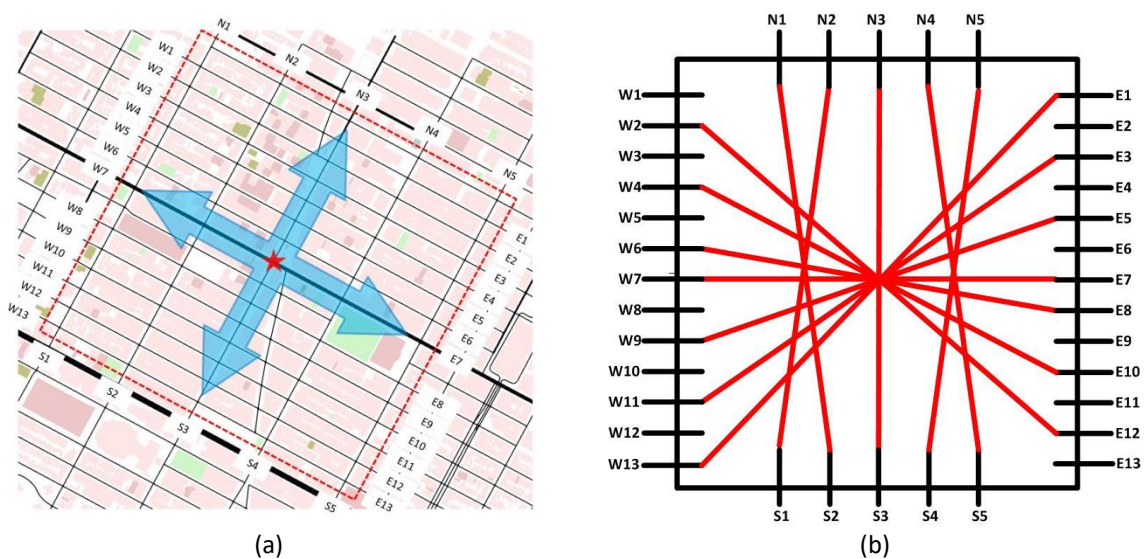


Figure 4-22. Uniform traffic routes in Manhattan scenarios

In the opposite, the deviated traffic routes constrain vehicles inside the top or the bottom half of the map. In this case, only a few vehicles pass by and connect to the source node. Macro and micro traffic routes are shown in Figure 4-23.

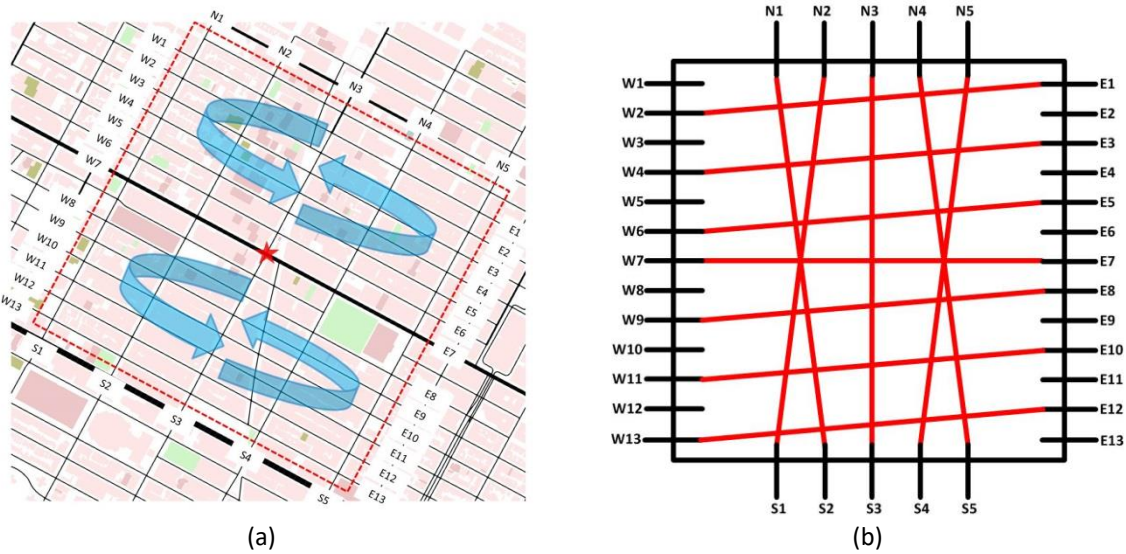


Figure 4-23. Deviated traffic routes in Manhattan scenarios

4.5 Bidirectionally Coupled Network and Road Traffic Simulation

In this section, we will introduce *how to integrate realistic scenarios into IVC simulations*. First of all, it is necessary to investigate the widely used network simulators, then, making a choice among these network simulators for us to support the bidirectionally coupled simulation.

Table 4-1. An overview of simulators and their model libraries

Simulators	Language	Model libraries	Language
OMNeT++	C++	INET	C++
ns-3	C++	ns-3	Python
ns-2	C++	ns-2	OTcl
JiST	Java	SWANS	Java

4.5.1 Network Simulators

In this subsection, four popular open source network simulators will be mentioned, as listed Table 4-1. Every simulator consists of a simulation engine and a simulation model library. Normally, we work on the model library. For the routing protocol, we focus on the

network layer of the model library. Moreover, the mobility module of the library is also important for IVC simulations.

The ns (network simulator) simulator originated from NEST, a network simulator prototype, developed by Columbia University [75]. Later, ns was modified to create the REAL network simulator [76]. The first successful version of ns is ns-2 that has been used widely in networking research field. However, for various reasons, the ns-2 has stopped to officially update since its last version ns-2.35 Released on Nov 4, 2011, even the website of ns-2 is still available on online attached to the sever of Information Science Institute of University of South California when the thesis was writing [77]. The most recent rewrite of ns is ns-3 that become more and more popular than ns-2 in recent years. Notice that, ns-2 and ns-3 have not successive relationship. ns-3 is totally rewritten from scratch by using different language of model library compared with the one of ns-2. ns-3 attempts to mitigate the limitation of ns-2. For instance, ns-2 is often criticized for being hard to learn and offering limited functionalities guide. Therefore, ns-3 changes its model library language to Python and provides dedicated documents. Moreover, since 2009, ns-3 community organized the workshop on ns-3 (WNS3) every year. One thing is worth mentioning that, following the tradition of ns, ns-3 has not IDE and dedicated result analysis tools. In my opinion, this is a weakness of ns-3. The core feature of ns-3 is that it can emulate network facilities as actual testbeds. The status of transmissions during simulation can be inspected by Wireshark. For VANETs, the iTetris simulation platform has been developed for ns-3, in which a central control system, called iCS, is used to manage interacts among ns-3, SUMO and application module [78]. More recently, some works based on JiST simulator begin to emerge. This simulator is developed since 2005 that is relatively late than ns simulator [79]. But, because of its easy-to-use feature, it gets support from researchers and projects. This simulator is selected to be network simulator of VSimRTI framework that uses an advanced concept of decoupling simulation [80].

OMNeT++ is other well-known discrete event simulator with an IDE customized from Eclipse and powerful result analysis tools [81]. Both its engine and model library are developed by using C++. Several dedicated model libraries are maintained by different development groups, in which INET framework is selected as the default model library and maintained by the same group of OMNeT++ [82]. The simulator is easy to use to compose a specific network scenario by using its network description (NED) language. Moreover, it provides detailed document to guide user to grasp the skills step by step. Even for the first

time of using it, from my experience, users can run a demo within one hour. OMNeT++ started in 1992 and has a strong user community. The OMNeT++ community summit has been organized every year since 2014. I have been the first community summit in Hamburg, Germany, in where the new and practical techniques were presented and participators discuss freely together for the current critical challenges and the suggestions for the future development. For VANETs, there is a specific simulation framework developed for OMNeT++, i.e., Veins, that dedicates itself to simulate the WAVE protocol stack. To the best of my knowledge, Veins is the only one framework, with high quality of source code, designed especially for VANETs. It also provides a C++ version interface, i.e., TraCI, for SUMO to support realistic bidirectional coupled simulation. The publications using OMNeT++ and Veins have increased rapidly since 2011. According to the website of Veins, the number of related publications has exceeded 160 per year since 2014. That is why we choose OMNeT++ and Veins to be our research platform.

4.5.2 Bidirectionally Coupled Simulation

In 2011, Sommer et al. [83] proposed a bidirectionally coupled simulation framework, in which a network simulator, i.e., OMNeT++, is associated with SUMO, as shown in Figure 4-24. Therefore, SUMO can provide its scenarios, e.g., abstract and realistic ones, for the network simulator to perform IVC simulations. Since the road topology and building obstacles of realistic scenarios are the same as the ones of the real world, the dependability and the accuracy of IVC simulations have been raised to a new stage.

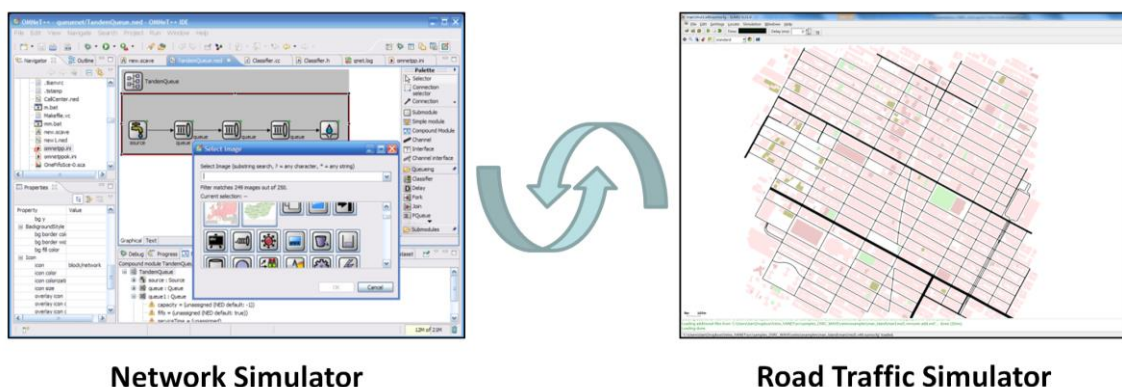


Figure 4-24. Illustration of bidirectionally coupled simulation

OMNeT++ is a discrete event network simulator that provides a mature platform for several simulation frameworks [81], e.g., Veins [84], INET [82]. From our experience, the robustness of this coupled simulation is strong, as we have performed a great number of

simulations without failure and every simulation serial usually run for several hours and days. Detailed techniques will be described in following sections.

4.5.3 Association Process

At the beginning of the coupled simulation, OMNeT++ and SUMO are connected to each other in association process, as shown in Figure 4-25.

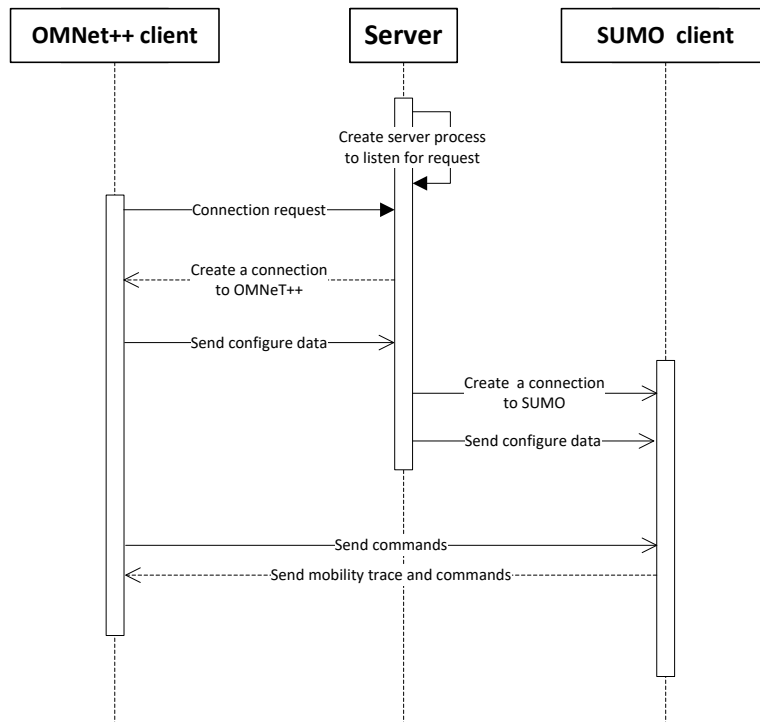


Figure 4-25. Sequence chart of association process

A server proxy process is created for OMNeT++ and SUMO. First, OMNeT++ sends a connection request to the server in order to communicate with SUMO. Then, the server creates a TCP connection to OMNeT++, in which the socket and the address of OMNeT++ are specified. After that, OMNeT++ sends the configuration of road traffic scenarios, e.g., network, traffic routes. When the server receives these configuration data, it will create a new TCP connection to SUMO. Therefore, information can be exchanged between OMNeT++ and SUMO. And even better than that, the coupled simulation supports parallel simulations. That is, if a series of simulations are executed by using multiple process cores of CPU, there are also a series of association processes performed to build multiple TCP connections for parallel simulations.

4.5.4 Information Synchronization and Communication

After association process, information, e.g., commands and mobility traces, begins to be exchanged between OMNeT++ and SUMO. During communications between the two modules, the synchronization of information should be guaranteed. Since OMNeT++ and SUMO are both discrete event simulators, this requirement can be satisfied by the control module, as shown in Figure 4-26. A unified process interval is set for OMNeT++ and SUMO by the control system. Commands arriving in current process interval are buffered until the next time stamp comes. Therefore, the synchronous execution is guaranteed at defined intervals.

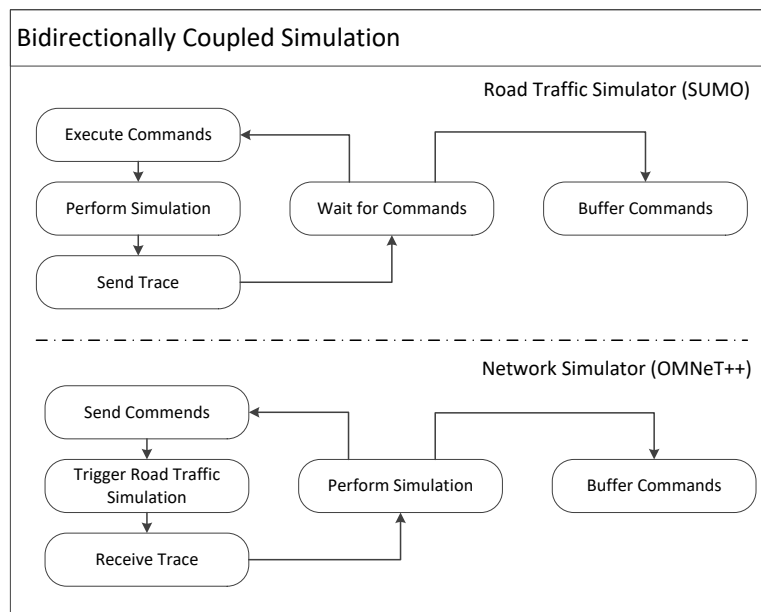


Figure 4-26. State machine of OMNeT++ and SUMO communication modules

At each time stamp, OMNeT++ sends all buffered commands to SUMO and triggers the corresponding road traffic simulation at the same time stamp. Upon completion of the road traffic simulation, SUMO sends the position of participating vehicles and a series of commands back to OMNeT++, which allows OMNeT++ to process vehicles movements and commands according to the received mobility information. After that, OMNeT++ performs the simulation of wireless network, so that the influence of road traffic environment can be brought to the IVC simulations.

4.5.5 Traffic Control Interface (TraCI)

Since the communication of coupled simulation is bidirectional, except SUMO providing mobility trace for the network simulation, OMNeT++ also can send commands back to influence the road traffic simulation by using Traffic Control Interface (TraCI). TraCI is a

dedicated interface of SUMO, which provide a number of functions to manipulate the road traffic. For instance, TraCI can control the speed of vehicles, change the route of a vehicular cluster, and even reschedule the program of traffic lights and so on. Therefore, these operations can make IVC simulations more realistic.

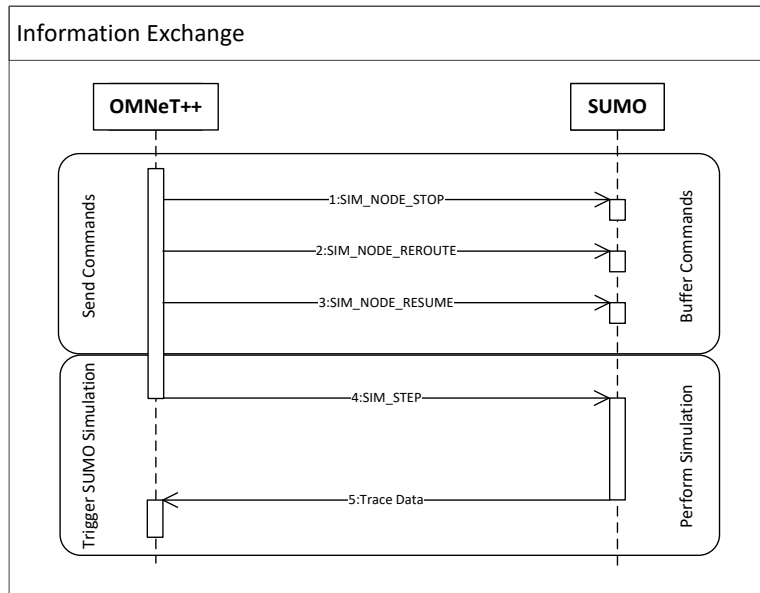


Figure 4-27. Sequence chart of information exchanged between OMNeT++ and SUMO

We can design an artificial traffic accident by using TraCI to stop a vehicle. Then, the vehicle involved in the accident will disseminate warning messages to inform surrounding vehicles. The vehicles moving towards the road where the accident happened receive the warning message and reroute their itinerary. TraCI also can resume the stopped vehicle to solve the accident. The information exchange of the coupled simulation for the scenario above-mentioned is shown in Figure 4-27. The process includes two phase: One is that OMNeT++ sends commands to SUMO to control the behavior of vehicles. The other is that SUMO executes these commands in respective process interval and sends the resulting mobility trace back to OMNeT++.

Chapter 5 TrAD: Traffic Adaptive Data Dissemination Protocol

5.1 Introduction

The economic impacts of road crashes, injuries and the annual congestion are very important, even without considering the impact on the environment [1], [2]. Intelligent Transportation Systems (ITSs) integrate Vehicular Ad hoc Networks (VANETs) with an efficient Inter-Vehicle Communication (IVC) protocol and may help decrease significantly road crashes and road traffic congestion. In fact, VANETs can provide wireless communication technology among vehicles (V2V) or between vehicles and infrastructure (V2I) to support the development of various applications concerning traffic safety, transportation efficiency and infotainment on wheels [85]. Long range communication technologies have been used for most of the non-safety applications. In particular, cellular networks (3G/4G), associated with smartphones, have been investigated to satisfy the requirements of the respective applications [86], [87]. In this chapter, we focus on safety applications, in which the event-driven emergency messages, e.g., traffic accident warnings, must be efficiently disseminated within a specific geographical region [88]. High performance IVC protocols are the key for this requirement, namely data dissemination protocols. However, VANETs offers characteristics that are highly dynamic and data-intensive, spatially and temporally localized, which makes the design of data dissemination protocols a challenging task [89]. To solve these problems, in general a broadcast communication technique is often used to disseminate data packets because it is flexible enough to spread messages to vehicles with high dynamics in a region of interest (ROI) [57], [59], [90]–[92]. In addition, the applicability of disseminating data in both urban and highway scenarios has been proven and evaluated [90], [91].

However, given the nature of vehicular networks and the short range communication issues, there are a number of challenges when designing routing protocols under the broadcast communication paradigm. First, the pure flooding scheme, a basic routing for broadcasts, can disseminate data into a wide area with low delay, but if the flooding is not properly controlled, a so-called “broadcast storm” may occur in dense networks [93]. The relaying scheme proposes selecting appropriate forwarders to mitigate this problem.

Unfortunately, most relaying schemes focus exclusively on the highway or the urban scenario, therefore, how to select suitable forwarders in both highway and urban scenarios is a key open issue. Secondly, the distribution of vehicles suffers a large variability due to the high mobility of vehicles. Moreover, in urban scenarios the line-of-sight signal could be blocked because of the existence of buildings, consequently, the network links are not reliable. Thus, how to efficiently manage the connectivity between these separate vehicular networks is a critical challenge. In addition, the low proportion of Dedicated Short Range Communication (DSRC)-equipped vehicles in the initial market penetration phase is another reason that leads to the above issue. Finally, from a standards point of view, the IEEE 802.11p standard does not establish a Basic Service Set (BSS), which means it is not necessary to perform authentication and association procedures. Furthermore, the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism of IEEE 802.11p does not have an acknowledgment process. These amendments indeed improve the speed of connection process, but lead to unreliable broadcasting connectivity.

In this paper, the Traffic Adaptive data Dissemination (TrAD) protocol is proposed in an attempt to address these problems in both urban and highway scenarios, while simultaneously aiming for high packet delivery ratio, low network overhead and low delay. The main contributions of this paper can be summarized as follows:

- For the broadcast suppression technique, a vehicular cluster classification and a sorting technique were designed to improve the reliability of broadcast transmissions and suppress the broadcast storm problem.
- For the store-carry-forward mechanism, specific vehicles were selected to be data-ferries so as to exchange information between different disconnected networks. Moreover, the redundant transmissions of this process were further suppressed.
- A channel congestion control was designed according to the status of local network traffic.
- A comprehensive performance evaluation was performed by means of realistic simulations. Three classical data dissemination protocols were compared with TrAD in both urban and highway scenarios. Furthermore, the impact of GPS drift on the data dissemination speed was also investigated.

The remainder of this chapter is organized as follows. In Section 5.2, the state-of-the-art in data dissemination protocols are summarized and the issues in need of solutions are highlighted. Section 5.3 presents the TrAD protocol motivated by these challenges, and where every detailed technique or mechanism is elaborated. In Section 5.4, the performance of the TrAD

protocol is evaluated by considering realistic scenarios. In the last section, we establish an assessment of the TrAD protocol and present the future work.

5.2 Related Work

Nowadays, in general, the works of most of data dissemination protocols focus on two main problems. The first challenge is the broadcast storm problem in well-connected networks; the second challenge is the disconnected network (network link reliability) or network partition problem. The broadcast suppression technique is adopted to mitigate the former issue and the store-carry-forward mechanism is designed for the latter one.

5.2.1 Broadcast Suppression Technique

Tseng *et al.* [93] first described the broadcast storm problem, and then proposed three pioneering schemes to mitigate it, *i.e.*, a *counter-based scheme*, *distance-based scheme* and *location-based scheme*. However, all these schemes are specified for Mobile Ad hoc Networks (MANETs) and do not consider the nature of VANETs. Wisitpongphan and Tonguz *et al.* [58] proposed three interesting and influential techniques for VANETs, *i.e.*, *weighted p-persistence*, *slotted 1-persistence*, and *slotted p-persistence*. After that, they went on to propose the Distributed Vehicular BroadCAST (DV-CAST) protocol that resorts to three flags that can provide the necessary knowledge about the local topology to identify the vehicles in well-connected networks. Among these vehicles, the authors recommended the use of the weighted p-persistence technique to suppress broadcast storms [57]. The slotted 1-persistence technique was improved by Schwartz *et al.* [94] for their Simple and Robust Dissemination (SRD) protocol. The optimized slotted 1-persistence defined different priorities in the two directions of the highway. In addition, the Emergency Message Dissemination for Vehicular (EMDV) environments protocol was proposed by Torrent-Moreno *et al.* [62] to improve the reliability of transmissions by using a forwarding area and a contention scheme. However, all the aforementioned efforts focus on one-dimensional highway scenarios.

For two-dimensional urban scenarios, Korkmaz *et al.* [95] proposed the so-called Urban Multi-hop Broadcast (UMB) protocol to address the broadcast storm, hidden node and reliability problems. UMB uses a Request to Broadcast (RTB) and Clear to Broadcast (CTB) handshake mechanism to select the furthest vehicle in a road segment to forward the packet. Moreover, UMB resorts to *repeaters* located at intersections to initialize a new broadcast

according to the final destination. However, the deployment of repeaters will cost enormous financial and human resources, which is the chief stumbling block to implementing the protocol. Fogue *et al.* [96] proposed the enhanced Message Dissemination based on Roadmaps (eMDR) protocol that uses a real urban map and GPS information to identify the location of vehicles to more efficiently perform the data dissemination. The authors of DV-CAST also proposed a broadcast protocol for urban scenarios, Viriyasitavat and Tonguz *et al.* [59] proposed the Urban Vehicular BroadCAST (UV-CAST) protocol where the wait time to rebroadcast is calculated in terms of the location and the distance. A shorter rebroadcast delay is assigned to the vehicles located at an intersection, which intend to disseminate data messages in more directions. Indeed, Fogue *et al.* [97] highlighted that eMDR and UV-CAST should not blindly trust the GPS information that is usually not accurate. Thus, it is important to quantify the impact of GPS drift or error on the performance of IVC protocols.

The Data dissemination pRotocol In VEhicular networks (DRIVE) and Adaptive Multi-directional data Dissemination (AMD) protocols are able to classify neighbors into different quadrants or sectors, which can be used to disseminate data in both urban and highway scenarios [90], [91]. DRIVE partitions the communication area into four quadrants and chooses a sub-area inside each quadrant called *sweet spot*. The vehicles located in the sweet spot have a shorter rebroadcast delay. AMD adaptively divides the vehicle's communication area into two or four equal sectors according to the road topology and the distribution of neighboring vehicles. In fact, in the real world, particularly in European downtowns, the road topology is not always regular as the Manhattan grid-type one. The typical example is the road topology of the "Arc de Triomphe" in Paris, which has twelve roads gathered at a roundabout. The approaches of these two protocols are not flexible enough to recognize the irregular road topology.

5.2.2 Store-Carry-Forward Mechanism

The disconnected network or network partition problem has been extensively investigated in Delay Tolerant Networks (DTNs) to exploit opportunities to complement intermittent connections among mobile devices [98], [99]. However, the data dissemination in VANETs has its own characteristics. The connection of vehicles is easily interrupted due to the high mobility of the vehicles themselves, the building obstacles, the interference and the short range communication [9], [100]. The goal of the data dissemination is to

efficiently inform all vehicles in a ROI about event-driven messages such as emergency messages. Therefore, the Store-Carry-Forward (SCF) mechanism not only needs to organize packets to be exchanged by an end-to-end paradigm in the one-hop range, but also to discover opportunities to start a new dissemination process in a further vehicular network.

Most of literature about the SCF mechanism investigated the selection of *SCF-agent* vehicles that can store and carry the data until they encounter new opportunities to forward it. DV-CAST can recognize two types of vehicles to be selected as the SCF-agent in highway scenarios. One is the last vehicle of a cluster driving in the same direction as the source vehicle, the other is the first vehicle of a cluster moving against the source vehicle [57]. UV-CAST used a gift-wrapping algorithm to select all boundary vehicles to be the SCF-agent. It is to be noted that this algorithm is a distributed version, and the set of SCF-agent vehicles is always a superset of all boundary vehicles. Therefore, UV-CAST would trigger more redundant transmissions. DRIVE did not resort to beaconing, but it only used the vehicles outside the ROI as information ferries to handle the network partition problem. It is obvious that most transmission opportunities would be missed. AMD did not suffer this problem, and it used beaconing to determine whether a vehicle is a *tail* or not. If a vehicle makes a transition from *tail* to *non-tail*, a new broadcast will be triggered. However, the directional sector classification of AMD cannot accurately recognize the irregular road topology. Consequently, it fails to detect some transitions so it misses some opportunities to forward data messages.

5.3 Traffic Adaptive Data Dissemination

The TrAD protocol is based on two main components. The first component adopts the broadcast suppression technique for well-connected networks, and the second one adopts a store-carry-forward mechanism for disconnected networks. Figure 5-1 presents the two running modes of the TrAD protocol according to the network scenarios: connected or disconnected network.

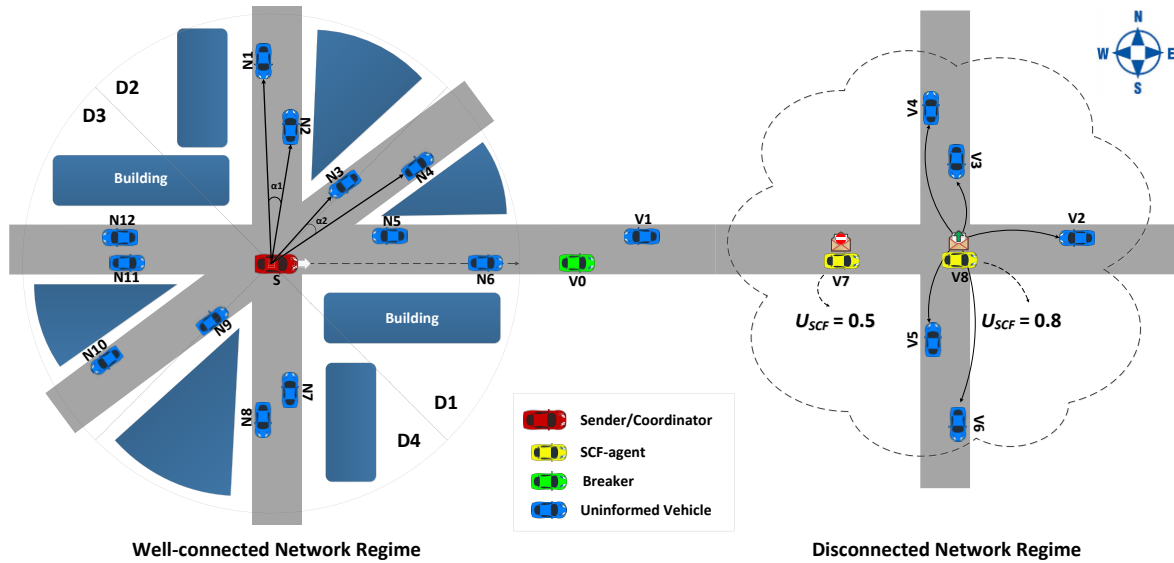


Figure 5-1. Illustration of TrAD protocol.

For a better understanding of this protocol, we define several concepts for TrAD. These concepts will be used throughout the chapter:

- *Directional Cluster C_d* : The directional cluster is a group of vehicles in the one-hop neighborhood of a sender S . Moreover, these vehicles are travelling in a similar direction with respect to the sender S . In an ideal situation, S can accurately classify its neighbors into different directional clusters that match the different road topologies around it. For instance, S classifies its neighbors $N1$, $N2$ into C_1 and $N3$, $N4$ into C_2 as illustrated in Figure 5-1. The two directional clusters are exactly on the roads in two directions.
- *Coordinator*: This concept was firstly defined in the Greedy Perimeter Coordinator Routing (GPCR) protocol [101]. The *coordinator* is the vehicle located at an intersection (e.g., the transmitter S in the Figure 5-1).
- *Breaker*: In a well-connected network, the *breaker* is not only the furthest vehicle in the forwarding direction but also moves towards the outside of the vehicular network (e.g., the green vehicle $V0$ in the Figure 5-1).
- *SCF-agent*: The role of a SCF-agent vehicle is to be responsible for storing and carrying the data messages until it meets opportunities to forward (broadcast) the stored data messages to uninformed vehicles that come from other VANETs.
- *Beacon and Beaconing*: A beacon is defined as a periodic message that is responsible for exchanging the up-to-date status of nodes in the one-hop neighborhood. This periodic exchanging process is called beaconing. The beacon format is defined as following: \langle Beacon ID, Sender ID, Global GPS Position, Heading, Number of Neighbors, Channel Busy Ratio, Message List \rangle .

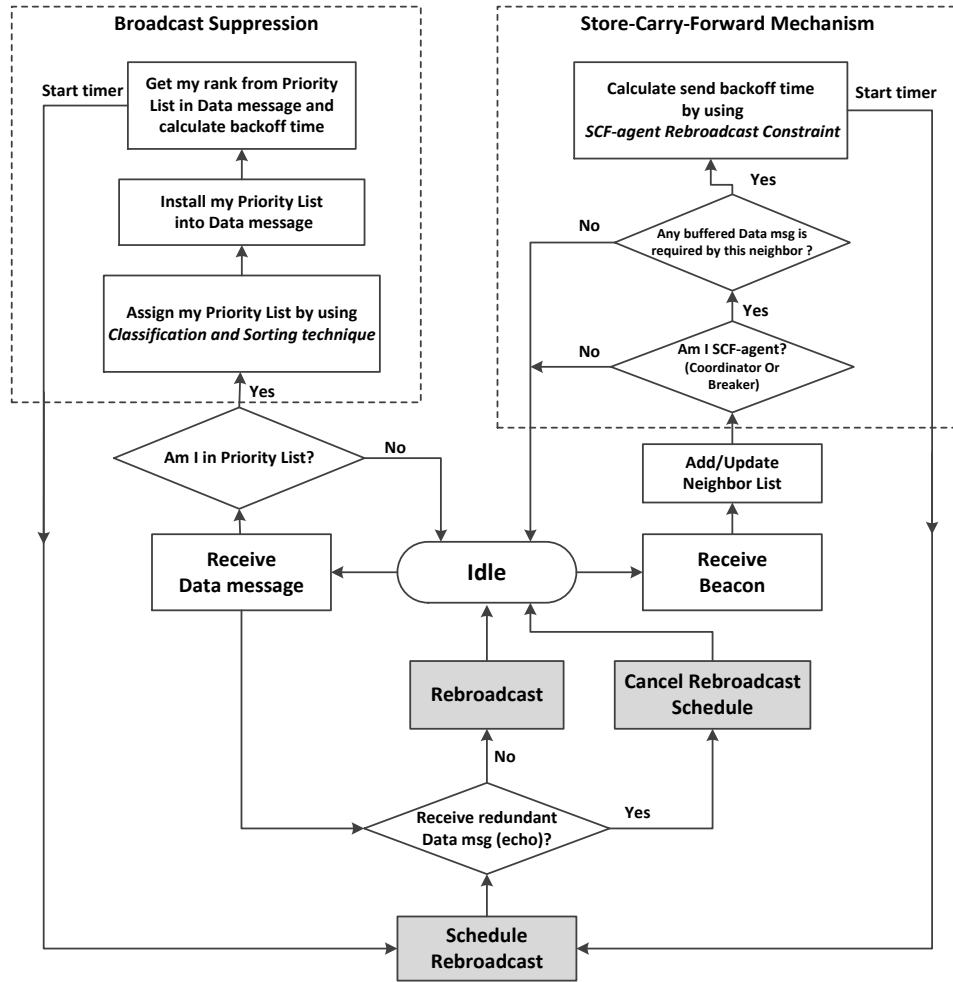


Figure 5-2. The operation of TrAD protocol flowchart.

In this section, the principle of operation for the TrAD protocol is presented as shown in Figure 5-2. TrAD requires that every vehicle send beacons to exchange their up-to-date status in the one-hop neighborhood. The period of beaconing P_b is set to 1 s and the tolerance of beacon equals to $1.5 P_b$ for a rapid reaction to the change of neighbors. The beaconing is another critical research field for safety applications, which includes several congestion control mechanisms, such as transmit power control, transmission rate control and encoding [64], [102]–[104]. However, the adaptive beaconing is beyond the scope of this chapter, we focus on the multi-directional and multi-hop data dissemination protocol. Therefore, we set a fixed beaconing interval for TrAD.

5.3.1 Broadcast Suppression Technique

To mitigate the broadcast storm in well-connected networks, first, a sender uses a classification mechanism to classify its neighbors into different directional clusters. Then, a

sorting technique considers both road traffic and network traffic status to allocate different rebroadcast orders to the neighbors in directional clusters. After that, the sender inserts the rebroadcast order list, i.e., priority list, into the data message and sends it. When the neighbors of the sender receive the data, the *delay-contention scheme* (mentioned in section 3.5.3.1 on page 49) is used to convert the rebroadcast order to the respective delay and perform a rebroadcast schedule. Thus, the neighbors start to contest the opportunity to rebroadcast. A neighbor owning higher order will rebroadcast earlier. If a vehicle receives redundant data (an echo) from a member of the same directional cluster, it will cancel its rebroadcast schedule and switch to an idle state. When the delay timer has expired, if a vehicle does not receive any data or just receive the data from the vehicles of other directional cluster, it will rebroadcast first. Therefore, the suppression technique not only can suppress redundant broadcasts, but also let the data messages be disseminated in all potential directions. Notice that the protocol makes a local centralized decision in the sender to decide the rebroadcast order of neighbors. The reason lies in that the local centralized decision can solve the hidden terminal problem in the multi-directional dissemination [90], [105].

5.3.1.1 Vector-angle-based Cluster Classification Mechanism

A lightweight and flexible classification algorithm is designed, which only utilizes the position information rather than the digital road map. Therefore, it requires less computational power and fits more complex road topologies. The algorithm uses vector angle to identify whether the vehicles belong to a directional cluster or not. Algorithm 5-1 describes the steps used to classify directional clusters.

Algorithm 5-1. Vector-angle-based cluster classification algorithm

Condition: the sender S receives a data message

Input : the position of the sender S and its neighbors $N(S)$

```

1: while  $N(S) \neq \emptyset$  do
2:   for  $i=1$  to  $\text{num}[N(S)]$ ,  $d=1$  do
3:      $N(S) = N(S) - \{n_i\} \leftarrow$  eliminate  $n_i$  from  $N(S)$ 
4:      $C_d \leftarrow n_i \leftarrow$  sort  $n_i$  into directional cluster  $C_d$ 
5:     for  $j=i$  to  $\text{num}[N(S)]$  do
6:       if  $(\widehat{n_i S n_j} < \alpha)$  then

```

```

7:       $C_d \leftarrow n_j \leftarrow \text{sort } n_j \text{ into the same } C_d \text{ of } n_i$ 
8:       $N(S) = N(S) - \{n_j\}$ 
9:      end if
10:     j++
11:   end for
12:   save  $C_d$  into cluster buffer
13:   d++
14: end for
15: end while

```

The cluster classification operation is conducted as follows: In the well-connected network regime of Figure 5-1, the sender or transmitter S extracts the first neighbor $N1$ from its neighbor list and classifies $N1$ into the directional cluster C_1 . Knowing the $N1$ and $N2$ coordinates, the angle α_1 between $\overrightarrow{SN1}$ and $\overrightarrow{SN2}$ can be obtained from their dot product ($\alpha_1 \in [0, \pi]$). The algorithm compares α_1 with a threshold angle α , e.g., $\alpha = 10^\circ$. If the angle α_1 is less than α , the neighbor $N2$ is classified in the directional cluster C_1 . If not, the neighbor $N2$ still remains in the neighbor list for the next step. In the case of Figure 5-1, $\alpha_1 < \alpha$, so $N2 \in C_1$. This process continues until all neighbors have been checked. Therefore, a group of vehicles C_1 that are located in the similar direction as $N1$ is identified. The members of C_1 are saved in a cluster buffer and eliminated from the next classification step. The classification will be carried out in a continuous process until all neighbors have been classified into respective directional clusters.

The classification result of TrAD in the case of well-connected network illustrated by the Figure 5-1 is $C_1 = \{N1, N2\}$; $C_2 = \{N3, N4\}$; $C_3 = \{N5, N6\}$; $C_4 = \{N7, N8\}$; $C_5 = \{N9, N10\}$; $C_6 = \{N11, N12\}$. Vehicles located in the similar direction with respect to S are exactly classified in the same directional cluster. Moreover, the AMD classification result is also illustrated in Figure 5-1. AMD divides the radio range into four equal sectors, *i.e.*, D1, D2, D3 and D4. Notice that the AMD classification result is not accurate. The $C_2 = \{N3, N4\}$ and $C_3 = \{N5, N6\}$ are combined into sector D1, and the $C_5 = \{N9, N10\}$ and $C_6 = \{N11, N12\}$ are mixed into sector D3. Furthermore, the vehicle $N3$ and $N9$ are ambiguous on the boundary of sectors. The result proves that the directional sector classification of AMD is not appropriate for the irregular road topology.

5.3.1.2 Traffic Adaptive Sorting Technique

The algorithm takes into account both road traffic and network traffic status. Three metrics are considered: the number of neighbors N , the distance between a sender and its neighbor D , and the Channel Busy Ratio CBR . The metrics N and D represent the road traffic condition, and CBR reflects the network traffic status. The sender S uses these three metrics to estimate the utility U_{TX} and detects the channel congestion for every neighbor. First of all, the metrics must be quantified for the calculation of utility U_{TX} . The value of all metrics falls in $[0,1]$.

The metric N (Equation (5-1)) indicates the data coverage of potential vehicles in the next transmission:

$$N = \min\left(\frac{\#Neighbor}{max.\#Neighbor}, 1\right) \quad (5-1)$$

$\#Neighbor$ is the instantaneous neighbor number of neighbors in the sender vicinity. For the simulation, $max.\#Neighbor$ is a preset maximum number of neighbors, and it is set to 25. The metric D (Equation (5-2)) represents the distance between a sender and its neighbor. $Dist_{sn}$ is the distance measured between the sender and its neighbor. $max.RadioRange$ is the maximum communication range of the wireless access medium.

$$D = \min\left(\frac{Dist_{sn}}{max.RadioRange}, 1\right) \quad (5-2)$$

The metric CBR (Equation (5-3)) describes the bandwidth occupation in a detection time interval $T_{interval}$, e.g., 1 s. The channel busy time T_{busy} is detected by the Clear Channel Assessment (CCA) in the PHY layer of IEEE 802.11p:

$$CBR = \frac{T_{busy}}{T_{interval}} \quad (5-3)$$

Therefore, we propose an equation (Equation (5-4)) to assign a higher transmission utility U_{TX} to the neighbor that has more neighbors, further distance and free channel load. N and D are of equal importance to represent road traffic status. Finally, the U_{TX} is scaled based on a weight ω_{CBR} that is related to network traffic status, i.e., CBR :

$$U_{TX} = \omega_{CBR} \cdot \left(\frac{N+D}{2}\right) \quad (5-4)$$

ω_{CBR} is defined as a piecewise linear function (Equation (5-5)) in terms of CBR . The mapping of CBR on the ω_{CBR} and the channel status is shown in Figure 5-3. The network load is divided into three levels according to CBR , i.e., free, busy and congestion:

$$\omega_{CBR} = \begin{cases} 1 & 0 < CBR < 0.6 \\ 1 - CBR & 0.6 \leq CBR < 0.8 \\ 0.001 & 0.8 \leq CBR < 1 \end{cases} \quad (5-5)$$

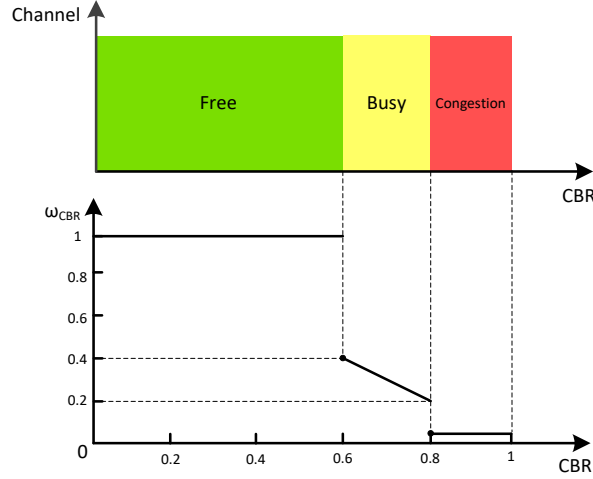


Figure 5-3. The projection of CBR on the weight ω_{CBR} and channel status.

Some well-known studies agreed that the suitable CBR target value for safety applications is 0.6 [12], [13]. Fallah *et al.* identified an appropriate maximum CBR as 0.8 [63]. Therefore, ω_{CBR} does not affect U_{TX} until CBR achieves 0.6. Then, ω_{CBR} decreases with the increasing of CBR , when CBR is between 0.6 and 0.8. If CBR is more than 0.8, a very small value, *i.e.*, 0.001, will be assigned to ω_{CBR} to minimize U_{TX} . Thus, the sender S will sense the congestion of this neighbor and a lowest rebroadcast order is allocated to the neighbor to mitigate the congestion. Moreover, if a sender detected that all the members of a cluster are congested, the cluster will be deleted from the priority list. If the network load of the cluster is alleviated to free or busy level later, the transmission will be recovered.

As stated in Equation (5-4), the neighbors in every directional cluster are sorted in decreasing order in terms of their utility. Then, a round-robin fashion is used to define the final order of vehicles in the priority list [106]. For clear explanation, Figure 5-4 is given to illustrate the process of the sorting technique. The vehicle having the highest U_{TX} in the directional cluster C_1 is put into the first position of the priority list, followed by the vehicle having highest U_{TX} in directional cluster C_2 , *etc.* This method guarantees the fairness for each directional cluster. For instance, we assume that the utility U_{TX} of vehicles is proportional to its ID number in Figure 5-4, *e.g.*, $U_{N2} > U_{N1}$, so after the first round of sorting, the priority list is $\{N2, N4, N6, N8, N10, N12\}$. In the second round, all neighbors are sorted and the final priority list is $\{N2, N4, N6, N8, N10, N12, N1, N3, N5, N7, N9, N11\}$.

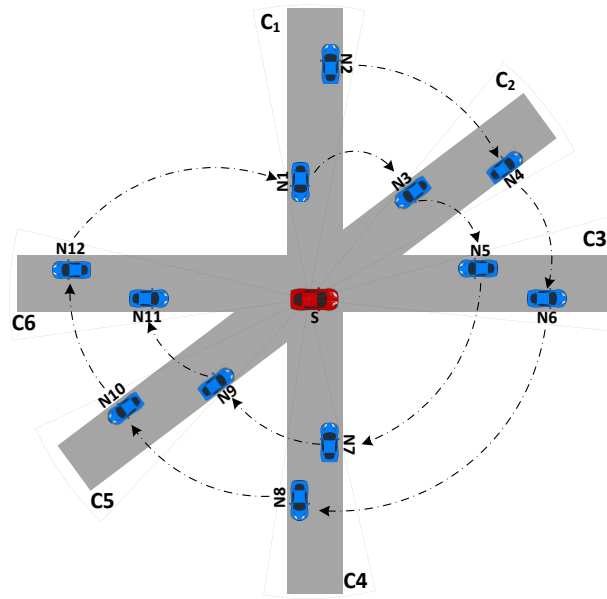


Figure 5-4. The sorting process for priority list.

The sender S inserts the priority list into the header of the data message before transmitting. The header format is $\langle \text{Data ID}, \text{Originator ID}, \text{Sender ID}, \text{Originator Position}, \text{Sender Position}, \text{Priority List} \rangle$. When the recipients receive a data message from S , they extract the priority list and seek out their rank $R \in [0, n - 1]$, where n is the number of neighbors. TrAD gives one time interval t_i between the former transmission and the latter one. t_i includes the total time taken from the transmitter to the recipient, such as medium access delay, propagation delay and transmission delay. The delay (back-off time) of transmissions Delay_{TX} is obtained by using Equation (5-6):

$$\text{Delay}_{TX} = t_i \cdot R \quad (5-6)$$

5.3.2 Store-Carry-Forward Mechanism

TrAD assigns the role of SCF-agent to the vehicles at a specific location in a VANET, which is beneficial to fill the connectivity gaps among vehicular clusters. The SCF-agent stores and carries data messages from one cluster to another, and then it will forward (broadcast) the stored data to the new coming vehicles. That is, TrAD uses the temporal delay to complement the spatial partition. Moreover, we designed a SCF-agent rebroadcast constraint technique that is a particular operation to *further reduce* the redundant broadcasts. In order to avoid data redundancy, the protocol compares the message list of a SCF-agent with its neighbors'. Only the data messages required by the neighbor will be scheduled by using the SCF-agent rebroadcast constraint technique.

5.3.2.1 The Selection of SCF-agent

To facilitate the understanding, we introduce some techniques which enable TrAD to identify the coordinator and the breaker.

- *Coordinator*: After preloading an intersection position list of the urban map into the system; every vehicle will detect the distance between itself and all intersections when the vehicle receives a beacon message. If the distance is less than 20 m, the vehicle is defined as a coordinator.
- *Breaker*: The flow chart of identification of a breaker is shown in Figure 5-5. When a vehicle receives a data message, it will detect and eliminate the possibility of the coordinator role. Then, the vehicle determines whether its moving direction is the same as the data forwarding direction. If so, the vehicle will look up whether there is a further neighbor moving at the front. If not, the vehicle is defined as the breaker. In particular, this procedure is carried out at a continuous process until the boundary of the well-connected network.

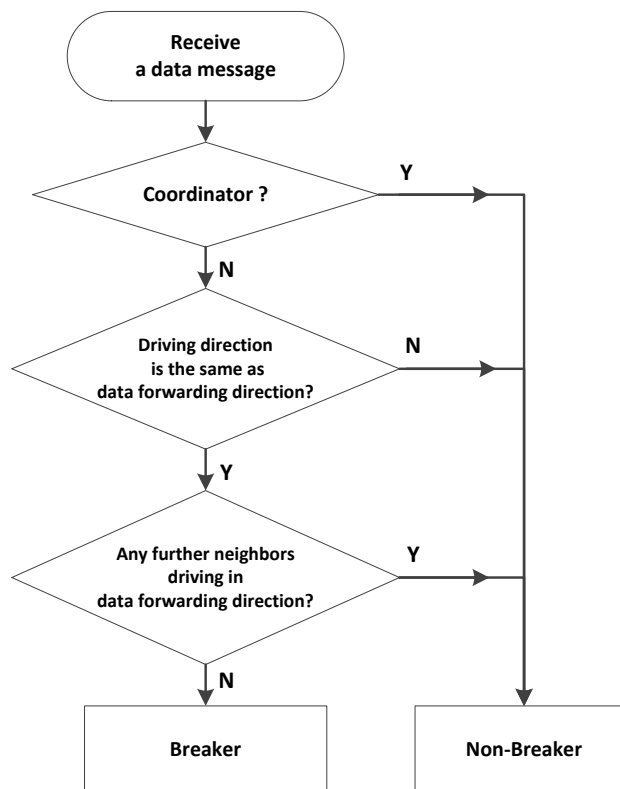


Figure 5-5. The identification of Breaker flowchart.

Vehicles that satisfy any of the definitions of coordinator and breaker are selected to be SCF-agents. This operation is compatible with both urban and highway scenarios. The coordinator is specialized for the two-dimensional topology of urban scenarios. At the intersection, a coordinator obviously has more chances to connect neighbors than the vehicles located between intersections. Therefore, TrAD chooses coordinators to store and

carry the data, which is beneficial to discover more uninformed vehicles. Given that there is no coordinator in highway scenarios, the breaker is defined for both urban and highway scenarios. It can drive towards outside of the well-connected network and transmit the data message into a wider area.

5.3.2.2 SCF-agent Rebroadcast Constraint Technique

The rebroadcast constraint technique aims to avoid redundant rebroadcasts when multiple SCF-agents receive an identical requirement (beacon) simultaneously. If the protocol does not have such a constraint technique, these SCF-agents would transmit the same data messages at the same time, and redundant broadcasts and collisions will be incurred. Thus, we also use the delay-contention scheme to avoid the redundancy. This method can calculate different delays (back-off times) according to the utility U_{SCF} of every SCF-agent. If a SCF-agent receives an echo message (redundant data message) that is the same as the one it is scheduling, the SCF-agent will cancel the forwarding schedule and switch to an idle state. If not, the SCF-agent will transmit first when the timer expires.

Contrary to the utility U_{TX} in broadcast suppression technique, here, a SCF-agent is given a higher utility U_{SCF} when the SCF-agent and an uninformed vehicle are closer. Indeed, a shorter distance is helpful to guarantee a better QoS of consecutive transmissions. Furthermore, since the number of neighbors neither contributes to SCF transmission nor constrains the redundant rebroadcast, U_{SCF} does not consider it. The weight ω_{CBR} , representing network status, is also used to scale U_{SCF} (Equation (5-7)):

$$U_{SCF} = \omega_{CBR} \cdot (1 - D) \quad (5-7)$$

It is to be noted that, in general, a new incoming (uninformed) vehicle does not require only a single data message, but several. Especially at the boundary of ROI, the vehicle going out of the ROI will perform consecutive transmissions to the new vehicle incoming into the ROI. If the protocol does not handle this scenario properly, a burst of transmissions will be incurred. Therefore, TrAD uses Equation (5-8) to calculate transmission delay $Delay_{SCF}$ to solve this problem:

$$Delay_{SCF} = ti \cdot [BurstCount + (1 - U_{SCF})] \quad (5-8)$$

One time interval ti is set between each transmission of required data messages. The *BurstCount* is the transmission order of data messages. A SCF-agent with a higher utility U_{SCF} will fire sooner to transmit the data messages in its transmission queue. The $ti \cdot$

$(1 - U_{SCF})$ part also performs as an additional delay, by which the time slot boundary synchronization problem can be mitigated.

For example, in the disconnected network illustrated by the Figure 5-1, vehicles V7 and V8 are SCF-agents moving from the well-connected network and carrying the same data messages. They received simultaneously the requirement (beacon) from their neighbor vehicles. Since the utility U_{SCF} of V8 (0.8) is greater than that of V7 (0.5), V8 is triggered to broadcast the data messages first. Consequently, V7 hears the redundant data message, and then cancels the respective schedule. Therefore, the redundant transmissions of V7 are suppressed.

5.4 Performance Evaluation

To evaluate the performance of the TrAD protocol, we make an important effort to implement realistic simulations in both urban and highway scenarios. Each simulation *scenario* has a map and traffic routes. The *map* is composed of the road topology and the building obstacles. The *traffic route* defines the planned round-trip route for each vehicle cluster. Notice that several traffic routes comprise the road traffic network on the map. The departure of vehicles follows an exponential distribution law. To perform an objective performance evaluation, the simulation programs are implemented by including three state-of-the-art IVC protocols: Distributed Vehicular Broadcast (DV-CAST) for highway scenarios [57], Urban Vehicular Broadcast (UV-CAST) for urban scenarios [59] and Adaptive Multi-directional data Dissemination (AMD) for both urban and highway scenarios [90].

- *DV-CAST* is a distributed broadcast protocol for highway scenarios with zero infrastructure support. The protocol resorts to neighbor detection to distinguish between vehicles V_s driving in the same direction with respect to the source vehicle and those V_o driving in the opposite direction. If the vehicles V_s are connected to each other, the broadcast suppression technique will be used in multi-hop broadcasts. However, if there are gaps between clusters, the store-carry-forward mechanism will be performed to select some of vehicles V_o to be SCF-agents. In the simulation of this paper, we use the slotted 1-persistence broadcast suppression technique and set the total number of time slots N_{st} to 5, the slot time st to 5ms.
- *UV-CAST* is a distributed broadcast protocol specialized for infrastructure-less urban VANETs. The protocol uses a gift-wrapping algorithm to select boundary vehicles to store, carry and forward messages to fill the gap between different disconnected networks. It also

uses a lightweight suppression technique for well-connected networks. This technique assigns a higher priority to the vehicle located at an intersection to rebroadcast, which can disseminate the data message in more directions and suppress the redundant broadcast. In the simulation of this paper, we set the maximum waiting time τ_{\max} to 500ms that is the same as the simulation setting in the original paper. Furthermore, a position list of intersections is preloaded in the system. If the distance between a vehicle and one of intersections is less than 20m, the vehicle is believed to be at the intersection.

- *AMD* is an infrastructure-less data dissemination protocol supporting both highway and urban scenarios. A generalized time slot scheme is used to suppress broadcasting, which is based on directional sectors. The number of directional sector is adjusted adaptively between 2 or 4 according to the local road topology and the distribution of neighbors. A store-carry-forward mechanism resorts to a role transition, i.e., from *tail* to *non-tail*, to trigger a new broadcast to uninformed vehicles. In the simulation of this paper, The time slot st is set to 5ms and one time slot is assigned to one vehicle, i.e., $ts_d = 1$. Moreover, the additional delay AD_{ij} is set to one DIFS, i.e., 58 μ s. The position list of intersections is preloaded in the system and is operated as the UV-CAST case.

Veins 3.0 framework is used as the basic library to implement the entire wireless communication protocol stack. It is to be noted that the Veins framework is based on two simulators: OMNeT++ 4.4.1, and SUMO 0.23.0. OMNeT++ is an event based network simulator, and SUMO 0.23.0 is a road traffic simulator. The MAC and PHY layer of the DSRC device is based on the IEEE 802.11p standard. The data rate is set to the maximum data rate for broadcasting (6 Mbit/s in IEEE 802.11p), the transmission power is set to 300 mW (the legal power in US is less than 1000 mW). The Friis Free Space Path Loss (FSPL) propagation model is used, in which the exponent α of FSPL is assigned to 3.0, for the value from 2.7 to 5.0 is estimated for the outdoor shadowed urban environment [107]. According to the setting of propagation model, the radio communication range is about 366 m. For the Bit Error Rate (BER) model of 6 Mbit/s data rate proposed by K. Sjöberg, *et al.* is implemented [108]. We adopt the empirical model of IEEE 802.11p radio shadowing in urban environments proposed by Sommer *et al.* [109]. For all simulations, the size of data messages is set to the maximum single packet size allowed by the IEEE 802.11p standard (*i.e.*, 2312 bytes), because we would like simulate the worst case of the network traffic. To be noted that each source node broadcasts periodically the data message every 2 s. The broadcast frequency could be changed to adapt to the requirements of an application. In this work, we use the same broadcast frequency for evaluating all the investigated protocols in

the defined scenarios. Moreover, the size of beacon is set to 378 bytes, where the entry number of message list is set to 40. The beacon sending period is 1 s, and we focus mainly on the simulation of one-hop neighborhood worst case refresh update. The vehicular densities are from 40 v/km² to 160 v/km², the interval is 20 v/km². The simulation setting parameters are summarized in Table 5-1.

Table 5-1. Simulation setting

Physical layer	Frequency band	5.89 GHz
	Bandwidth	10 MHz
	Tx power	300 mW
	Receiver sensitivity	-100 dBm
	FSPL exponent α	3.0
	Thermal noise	-110 dBm
	Radio range (Friis)	~366m
Link layer	Bit rate	6 Mbit/s
	CW	[15,1023]
	Slot time	13 μ s
	SIFS	32 μ s
	DIFS	58 μ s
Data Broadcasting	Broadcast frequency	0.5 Hz
	Data size	2312 bytes
Beaconing	Beacon frequency	1 Hz
	Beacon size	378 bytes
	Message list entries	40
TrAD	t_i	5ms
	α	10°
	$max. \#Neighbor$	25
	$max. RadioRange$	~366m
AMD	st	5ms
	ts_d	1
	AD_{ij}	DIFS
UV-CAST	τ_{max}	500ms
DV-CAST	st	5ms
	N_{st}	5
	WAIT I	120s
	WAIT II	120s

The quantitative analysis considers the following metrics:

- *Packet Delivery Ratio (PDR)*: It represents the average number of data messages received by the vehicles in the ROI as a percentage of the total number of data messages sent by the source node. It also can be called the coverage of data dissemination.
- *Number of Transmissions*: It is the total number of transmissions performed by the vehicles for broadcasting in the ROI during the whole simulation time.
- *Delay*: It is the average time interval between the sending of a data message by the source and its reception by the vehicles in the ROI.
- *Data Dissemination Speed*: This metric represents how fast the data can be disseminated among vehicles in the ROI. To record this metric, the source only sends data message once, and then the simulation computes the increase of data coverage with time. If the data coverage increases greatly in a short time, which means the protocol achieves a high dissemination performance. This metric is mainly used to estimate the impact of GPS drift on the performance of protocols.

To comprehensively evaluate the performance of TrAD, various experiments were designed to analyze the impact of different urban maps, different traffic routes, network density and GPS drift. The geographic data were retrieved from OpenStreetMap (OSM) database. Traffic rules, e.g., the speed limitation and the traffic light, were set according to the real world scenarios. By using the SUMO tool chain, all the geographic and traffic data were converted to the SUMO file format.

5.4.1 Different Urban Maps

For urban scenarios, two maps were created. The first map is a fragment of Manhattan borough in New York City, USA (Figure 5-6a), and the second map is the downtown area of the city of Clermont-Ferrand, France (Figure 5-6b). The ROI size of both two maps is 1 x 1 km². The statistics of maps (Table 5-2) show that the map of Clermont-Ferrand owns more lanes, junctions and shorter street lengths than Manhattan one, which means that the road traffic environment is more complex in Clermont-Ferrand than in Manhattan.

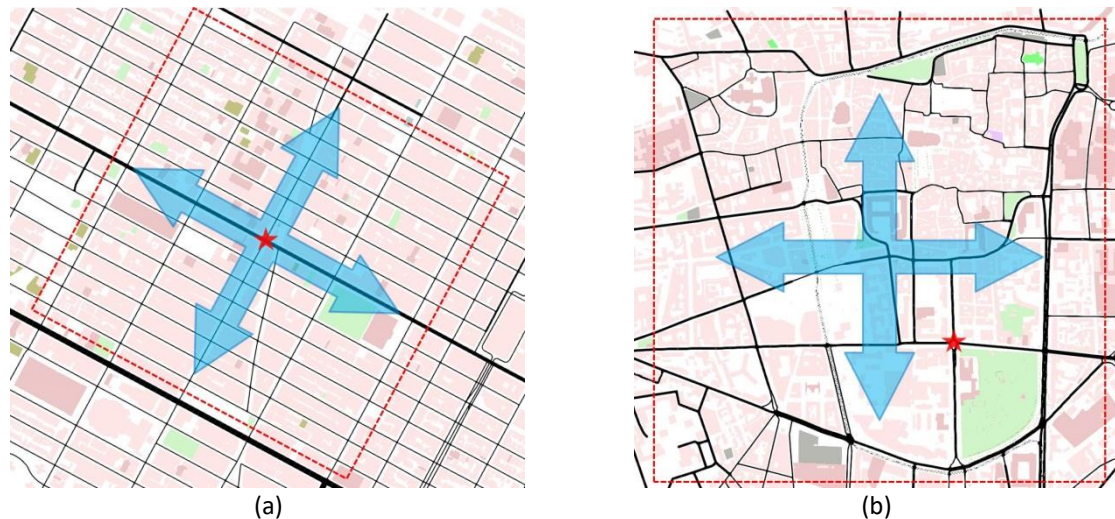


Figure 5-6. Urban Maps: (a) Manhattan borough in New York City (USA). (b) Clermont-Ferrand (France); Traffic routes are indicated by arrows in urban scenarios; The red star is the source node that periodically broadcasts data messages; The red broken line indicates the boundary of ROI.

Table 5-2. Statistics of maps

City Map	Clermont-Ferrand	Manhattan
Total lanes	366	166
Total junctions	137	86
Avg. street length	97.39	151.45
Avg. lanes/street	1.62	1.11

The data messages are generated by a fixed source node located at an appropriate intersection and are collected by all vehicles driving in the ROI. Similar traffic routes were created for two maps, by which vehicles are distributed uniformly in the scenarios. The experiment of each vehicular density is performed for 400s and repeated 10 times with different random seeds. The results with a 95% confidence interval are shown in Figure 5-7 and Figure 5-8. The junction points of the curve are the average values of the metric in repeated simulations. The upper and lower error bar represents the maximum and the minimum, respectively.

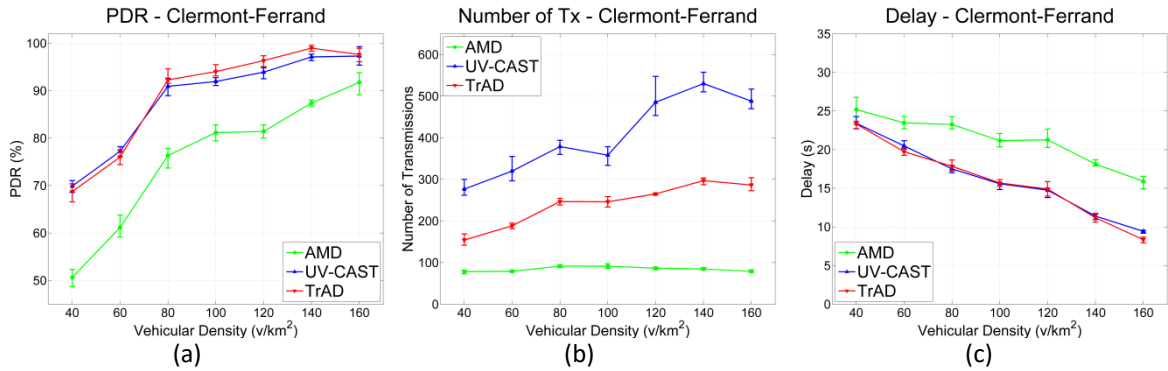


Figure 5-7. Results with a 95% confidence interval in Clermont-Ferrand scenarios: (a) PDR, (b) Number of Transmissions, (c) Delay.

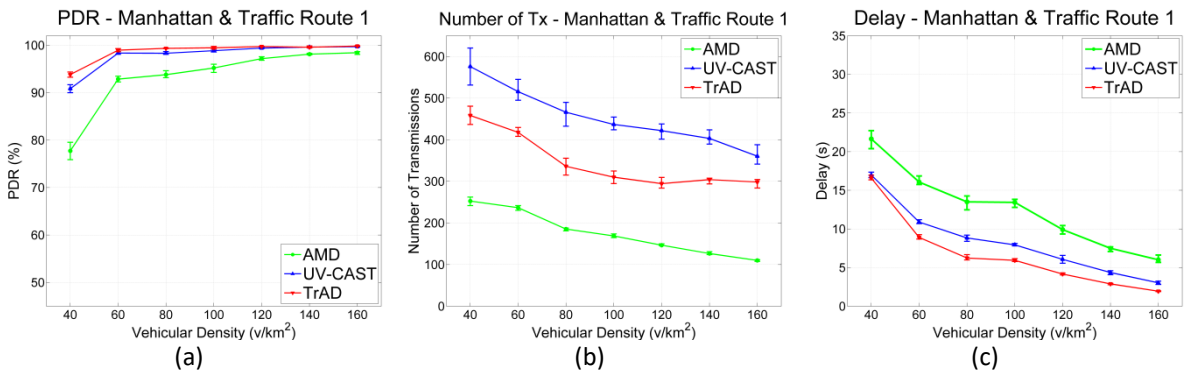


Figure 5-8. Results with a 95% confidence interval in Manhattan scenarios with the traffic route 1 (uniform): (a) PDR, (b) Number of Transmissions, (c) Delay.

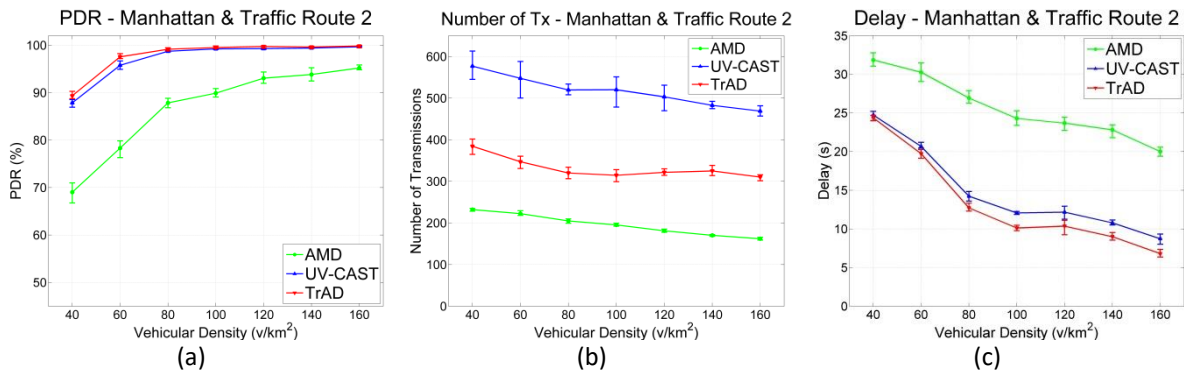


Figure 5-9. Results with a 95% confidence interval in Manhattan scenarios with the traffic route 2 (deviated): (a) PDR, (b) Number of Transmissions, (c) Delay.

As expected, the obtained simulation results show that the different urban maps significantly impact the wireless communication protocols because the scenarios affect the network topology and network link quality, respectively. According to the simulation results of the two scenarios, the Packet Delivery Ratio (PDR) of AMD is the worst in both the Clermont-Ferrand and Manhattan scenarios. Therefore, we compare firstly the performance of TrAD and UV-CAST on different maps.

Figure 5-7a shows that the PDR of TrAD and UV-CAST increases rapidly from about 70% to over 90% when the vehicular density increases from 40 v/km² to 80 v/km², and then continues to gradually reach close to 100%. In case of the Manhattan map (Figure 5-8a), the PDR of TrAD and UV-CAST already achieves over 90% when the vehicular density equals 40 v/km², and then reaches close to 100% when the vehicular density is 80 v/km². Notice that the PDR of TrAD is better than the UV-CAST one (93.82% vs. 90.84%) at the starting point of vehicular densities (*i.e.*, 40 v/km²). The reason for these observations lies in the different complexity of the two maps. The Manhattan map, a regular one, is relatively easy to handle with the protocols. On the contrary, the complex road traffic environment of the Clermont-Ferrand map, *i.e.*, winding and short streets, T style intersections and irregular buildings, leads to intermittent connectivity and increases the complexity of the road topology recognition.

In fact, UV-CAST does not consider the road topology to classify vehicles into different directional clusters. It assigns a high priority to the vehicles located at an intersection to rebroadcast the data messages and use a gift-wrapping algorithm to select the boundary vehicles to be the SCF-agent. As the authors of UV-CAST admitted, the gift-wrapping algorithm would over-select the SCF-agent vehicles. On one hand, it seems that UV-CAST cannot control appropriately the number of transmissions. Thus, the number of transmissions of UV-CAST is much higher than the one of TrAD (Figure 5-7b and Figure 5-8b). On the other hand, TrAD uses the vector-angle-based classification mechanism to sort vehicles into respective directional cluster that matches the road topology. Moreover, TrAD also resorts to the traffic adaptive sorting technique to fairly classify vehicles into the priority list. Therefore, the redundant data message transmissions are canceled appropriately in each directional cluster and, at the same time, the data messages are disseminated more efficiently into every possible direction in the ROI.

Figure 5-7c and Figure 5-8c indicate that the delay of TrAD and UV-CAST in both the Clermont-Ferrand and Manhattan scenarios decreases with increasing vehicular density. Moreover, the delay in the Clermont-Ferrand scenario is higher than the one in the Manhattan scenario for the respective vehicular densities. This shows the side effect of the complex road topology of Clermont-Ferrand scenarios. We also observe that TrAD achieves a similar level of delay as UV-CAST in the Clermont-Ferrand scenarios and gains an advantage over UV-CAST in the Manhattan scenarios. The negative impact of complex

scenarios also influences the PDR of protocols, it narrows the difference of PDR between TrAD and UV-CAST, but UV-CAST consumes more transmissions.

For AMD and TrAD, in Figure 5-7a and Figure 5-8a, the first observation attracting our attention is that the difference of PDRs between AMD and TrAD is greatly narrowed from the Clermont-Ferrand scenarios to the Manhattan cases. That is, AMD fits much better a regular map (e.g., Manhattan) than a complex one (e.g., Clermont-Ferrand). Even so, the PDR and the delay of AMD are still worse than the TrAD ones. However, AMD is suitable to be used as reference, since, like TrAD, it also adopts a directional classification mechanism in the broadcast suppression technique. The difference lies in that TrAD can provide a more precise classification than AMD to handle more complex road topologies. This advantage is proved by the fact that the PDR of TrAD is always better than the one of AMD in both scenarios. Although AMD consumes the least transmissions, TrAD uses a moderate amount of transmissions (a little bit more network overhead) to achieve a better overall performance.

5.4.2 Different Traffic Routes

For urban scenarios, most of previous work used different maps to evaluate the performance of IVC protocols. Notice that the different traffic routes on a same map may impact significantly the performance of IVC protocols. Therefore, we will not only analyze the impact of different maps, but also investigate the impact of different traffic routes.

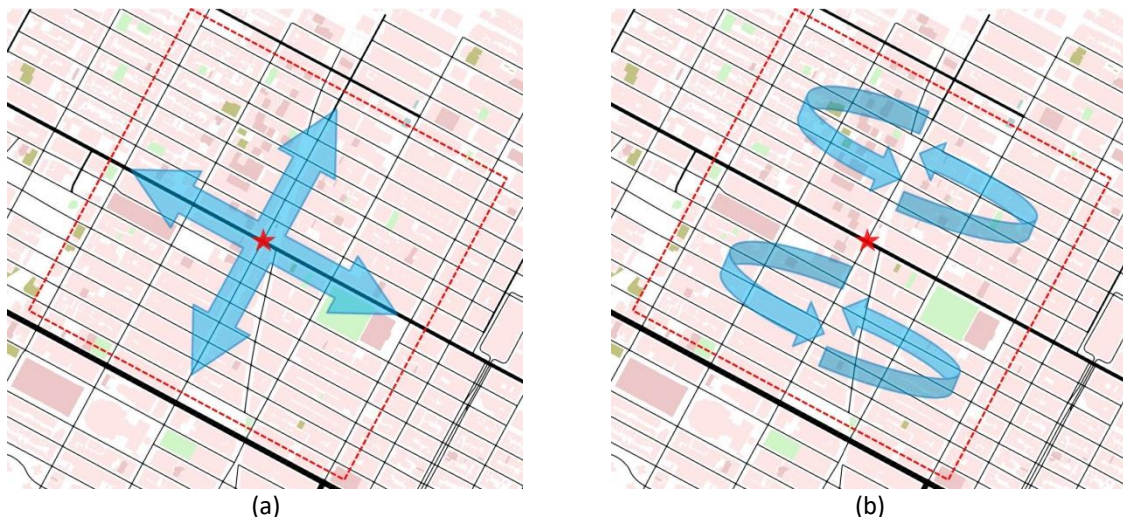


Figure 5-10. Traffic routes in Manhattan scenarios. (a) Traffic route 1 (uniform). (b) Traffic route 2 (deviated); Traffic routes are indicated by arrows in urban scenarios; The red start is the source node that periodically broadcasts data messages; The red broken line indicate the boundary of ROI.

The source node is fixed at the center of the Manhattan map. The simulation of each vehicular density is performed for 400 s and repeated 10 times with different random seeds. We designed two different traffic routes that represent two types of road traffic network, as shown in Figure 5-10. The arrows indicate traffic routes: Traffic route 1 (Figure 5-10a) includes vehicles driving between the top and the bottom half of the scenario, so that they can cross the middle line of the map where the source node is located. Therefore, the vehicles get more chance to connect to the source node or other vehicles. On the contrary, traffic route 2 (Figure 5-10b) constrains vehicles inside the top or the bottom half of the scenario. In this case, only a few vehicles pass by and connect to the source node. That means traffic route 2 creates more disconnected networks than the ones of traffic route 1. Therefore, the design of different traffic routes mainly aims at evaluating the performance of IVC protocols to handle the disconnected network problem. Notice that the scenarios with traffic route 1 (Figure 5-10a) is the same as the Manhattan urban scenario (Figure 5-6a). Thus, the simulation results of these two experiments are also the same. The results of different traffic routes are shown in Figure 5-8 and Figure 5-9.

In Figure 5-8a and Figure 5-9a, it is obvious that the PDR of AMD is significantly affected by the different traffic routes. In scenarios with traffic route 1, the PDR of AMD starts from about 80% at the first vehicular density, *i.e.*, 40 v/km², and exceeds 90% at the second vehicular density, *i.e.*, 60 v/km², finally reaches close to 100%. In the case of traffic route 2, it starts from about 70%, and just achieves 90% at the vehicular density 100 v/km², finally reaches about 95%. These observations reflect that the SCF mechanism of AMD cannot well handle the deviated traffic route or the severe disconnected network. On the other hand, TrAD and UV-CAST are more robust than AMD to the change of traffic routes. Their PDRs only decrease slightly at sparse densities, *i.e.*, 40 v/km² and 60 v/km², in scenarios with traffic route 2 compared with the ones with traffic route 1. Notice that TrAD gains a slight advantage of PDR over UV-CAST at sparse densities in both scenarios.

Although the PDR results of TrAD and UV-CAST are close, the number of transmissions of these two protocols is different. The number of transmissions of TrAD is always lower than the one of UV-CAST in scenarios with both traffic routes, as shown in Figure 5-8b and Figure 5-9b. The reason lies in that TrAD uses the suppression technique in the broadcast and the SCF mechanism to efficiently constrain transmissions. However, the SCF mechanism of UV-CAST selects too many SCF-agent vehicles so as to trigger more redundant transmissions. It is worth mentioning that the difference of the number of

transmissions between TrAD and UV-CAST is enlarged in scenarios with traffic route 2 compared with the ones with traffic route 1. This shows that TrAD gains more advantage over UV-CAST in scenarios with the deviated traffic route. The lowest number of transmissions is achieved by AMD, but the low PDR and the high delay let this advantage completely fade.

Figure 5-8c and Figure 5-9c present that traffic route 2 lets the delay of all protocols increase compared with the one of traffic route 1. Especially, for AMD, its average delay of all vehicular densities increases 13.117 s. The different between AMD and TrAD increases more than twice. In addition, TrAD obtains the lowest delay in both uniform and deviated traffic routes. These observations show that TrAD can handle the deviated traffic route in the Manhattan scenario.

A deviated traffic route, *i.e.*, traffic route 2, indeed influences the performance of IVC protocols significantly. It requires IVC protocol to consume more transmissions to maintain data coverage with high delay. However, TrAD shows an outstanding capability to handle this issue. The experimental observations show that TrAD only consumes a moderate amount of transmissions to handle the disconnected networks to achieve high data coverage with low delay. The reason lies in that TrAD has an efficient SCF mechanism that assigns the role of SCF-agent to the breaker and the coordinator. Furthermore, TrAD also uses a SCF-agent rebroadcast constraint technique to further suppress transmissions. For UV-CAST, the gift-wrapping algorithm triggers more transmissions, which also brings the extra delay. For AMD, although it could recognize the relatively regular Manhattan map, there is a drawback in its SCF mechanism. The SCF mechanism only triggers the transmission of stored data while the transition, *i.e.*, from tail to non-tail, happens, but, due to signal fading or interference, the stored data is not always received, especially in the scenarios with deviated traffic routes. In case a transmission fails, there is not another chance to trigger the SCF-agent to forward the stored data again.

5.4.3 Network Density

5.4.3.1 Urban Scenarios

The obtained simulation results of different maps and different traffic routes in urban scenarios have been analyzed and elaborated. We observe that the network density, the map and the traffic route are the three main parameters which impact significantly the performance of IVC protocol. In general, a lower network density leads to more

disconnected networks, which decreases the overall performance of the IVC protocols: low PDR, high delay and high number of transmissions (network overhead). On the contrary, a higher network density enables the IVC protocols to achieve better overall performance. However, the geographic and traffic environment could also affect significantly the performance of IVC protocols, *i.e.*, the complex road topology, high-rises and the deviated distribution of vehicles. Therefore, to implement a high performance IVC protocol, it is important to consider the abovementioned elements.

5.4.3.2 Highway Scenarios

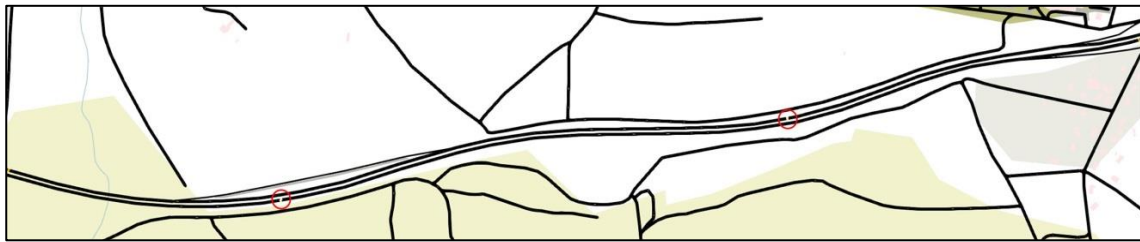


Figure 5-11. A711 highway of Clermont-Ferrand, France.

To implement the highway map, a section of A711 highway located near Clermont-Ferrand airport (Aulnat, France) is modeled, as shown in Figure 5-11. It has two lanes in each direction and has 2 km length. The data message is created by the fixed source node at the west end of the highway and gathered by all vehicles driving in the ROI. To detect the *traffic flow*, induction loop detectors were implemented under each lane as highlighted by the red circles in Figure 5-11. The unit of traffic flow represents the number of vehicles passed the detection point per hour (vph). We set five levels of traffic flow that include 443 vph, 883 vph, 1319 vph, 1764 vph and 2207 vph, which increase linearly. The simulation duration of each traffic flow is 200 s and repeated 10 times with different random seeds. All the obtained simulation results with a 95% confidence interval are shown in Figure 5-12.

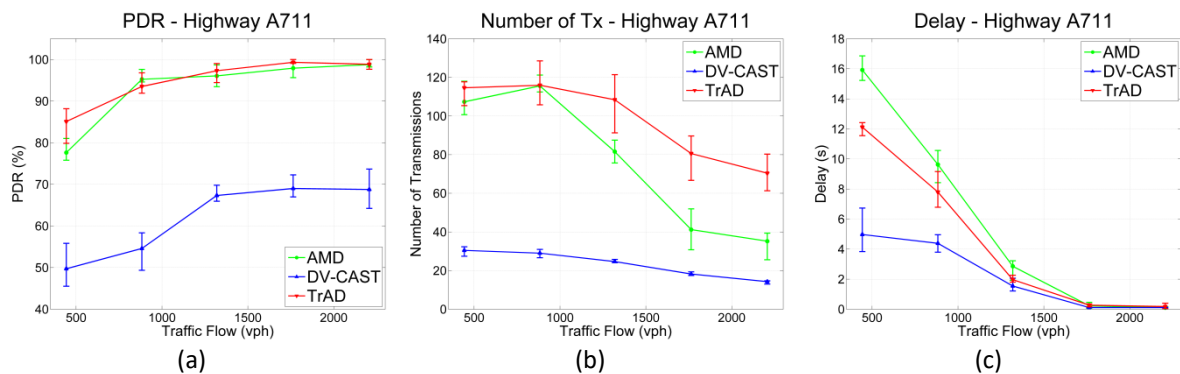


Figure 5-12. Results with a 95% confidence interval in Highway Scenarios: (a) PDR, (b) Number of Transmissions, (c) Delay.

In the case of highway scenarios, AMD achieves high PDRs that are similar as those of TrAD, as shown in Figure 5-12a, due to the relatively simple two-dimensional road topology. The PDR of AMD exceeds 90% since 883 vph and finally reaches close to 100%. However, Figure 5-12a also highlights that the PDR of DV-CAST fails to reach 70% finally. The reason lies in that DV-CAST does not have the rescue mechanism for failed transmissions. Indeed, the transmitter vehicles forward the data message only once, *i.e.*, one-shot deal. Theoretically, the operation principle of DV-CAST guarantees a high data coverage on the highway. However, if a transmission fails, there is no mechanism to trigger the retransmission again. It is possible that the consecutive transmissions would fail due to fading or collisions. Therefore, if a transmission is broken at the middle forwarder, the vehicles in the rear of this forwarder cannot receive the data message.

In addition, TrAD uses the message list in the beacon to detect data messages needed by neighbors, so that the failed transmission can be rescued in the next beaconing process. Since the PDR values of TrAD and AMD are close, it makes sense to compare their number of transmissions and delay, as shown in Figure 5-12(b,c). AMD costs less transmissions than TrAD in dense networks, which is consistent with the result of experiments in [90]. However, the delay of TrAD is lower than the one of AMD. This means that the extra transmissions of TrAD would come from the SCF mechanism in one-hop broadcasting, especially at the border of the ROI. TrAD always employs the breaker going out of the ROI to load data messages to the vehicles just coming into the ROI. That is why the PDR of TrAD gains the advantage over AMD at most of vehicular densities, e.g., 443 vph, 1319 vph and 1764 vph. Although the number of transmissions and the delay of DV-CAST are the lowest, its overall performance is still the worst, because the low transmissions and the low delay exactly benefit from the low PDR.

5.4.4 GPS Drift

Some approaches of TrAD are based on vehicle position. However, the GPS system is usually not accurate, particularly in downtowns. This would be affected by several impact factors, such as satellite position and number, signal attenuation and clocking errors. In particular, in urban scenarios, high towers could obstruct the GPS signal. The average deviation of standard GPS is up to 30 m [71]. Therefore, we investigated the GPS drift in terms of data dissemination speed that was defined at the beginning of this section. Error deviations have been injected into the mobility module of Veins framework. We choose five

options of error deviations, *i.e.*, 0 m, 25 m, 50 m, 75 m and 100 m. The 0 m deviation means the perfect positioning, and other instantaneous deviation values are selected between the plus and minus interval following uniform distribution. For the instance of 25 m deviation, the x axis and the y axis of deviation values are obtained randomly between -25 and 25 and added to the original correct coordinate. To evaluate the impact of GPS drift on the performance of protocols, the moderate vehicle density, *i.e.*, 100 v/km^2 , is used in the Clermont-Ferrand and Manhattan scenarios with traffic route 1 (uniform).

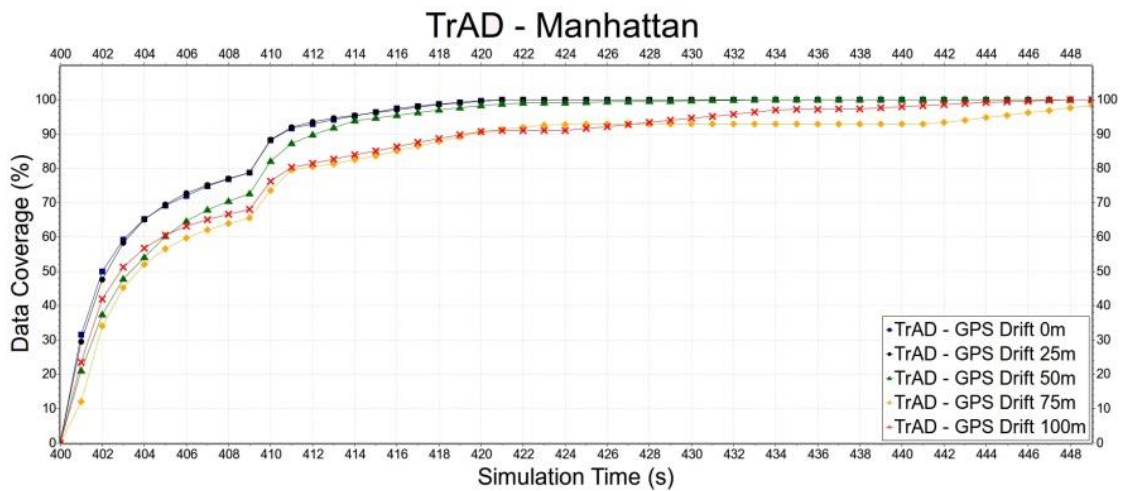


Figure 5-13. The impact of GPS drift on TrAD in Manhattan scenarios.

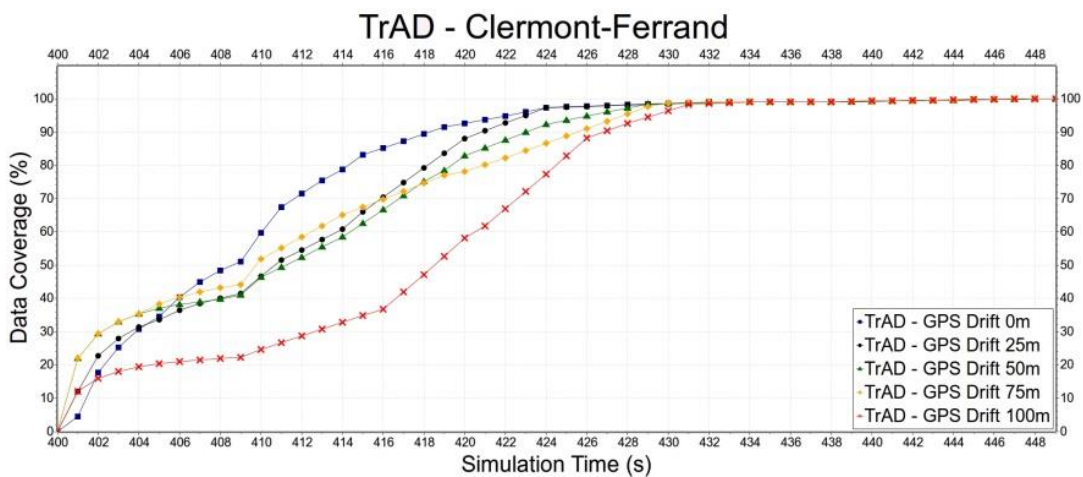


Figure 5-14. The impact of GPS drift on TrAD in Clermont-Ferrand scenarios.

First, the robustness of TrAD to GPS drift is tested in the Clermont-Ferrand and Manhattan scenarios, as shown in Figure 5-13 and Figure 5-14. In Figure 5-13, we can observe that thanks to the regular road topology and building obstacles TrAD maintains a relatively good performance in the Manhattan scenarios except 75 m and 100 m positioning deviations. However, in the case of Clermont-Ferrand, Figure 5-14 presents that the data dissemination speed is slower than the one of the Manhattan scenario due to the complex

nature of the traffic environment. The 25 m, 50 m and 75 m error deviations impact the performance of TrAD, but the data dissemination speed of these deviations still achieves a moderate performance. The result of 100 m deviation is the worst, but its data coverage also reaches 98.3% taking 31 s after the data dissemination has been started.

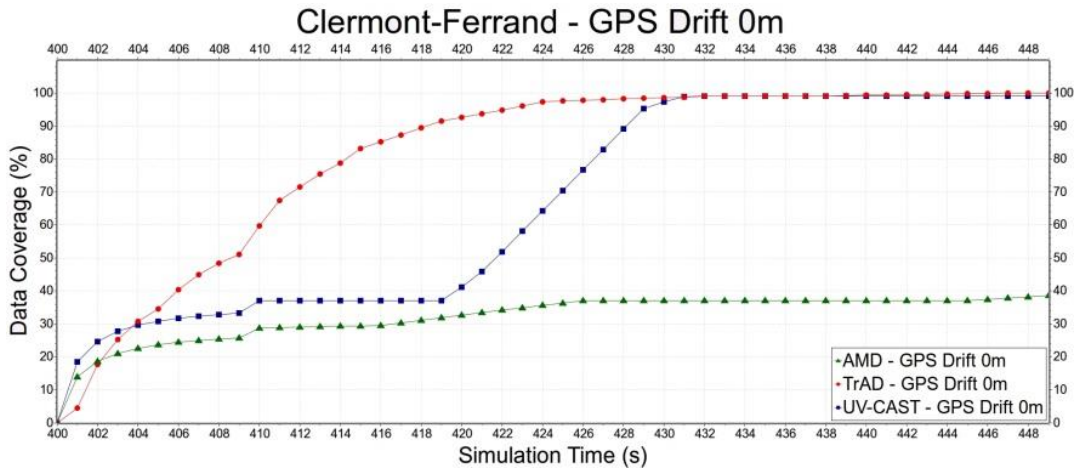


Figure 5-15. The data dissemination speed of TrAD, AMD and UV-CAST with perfect GPS.

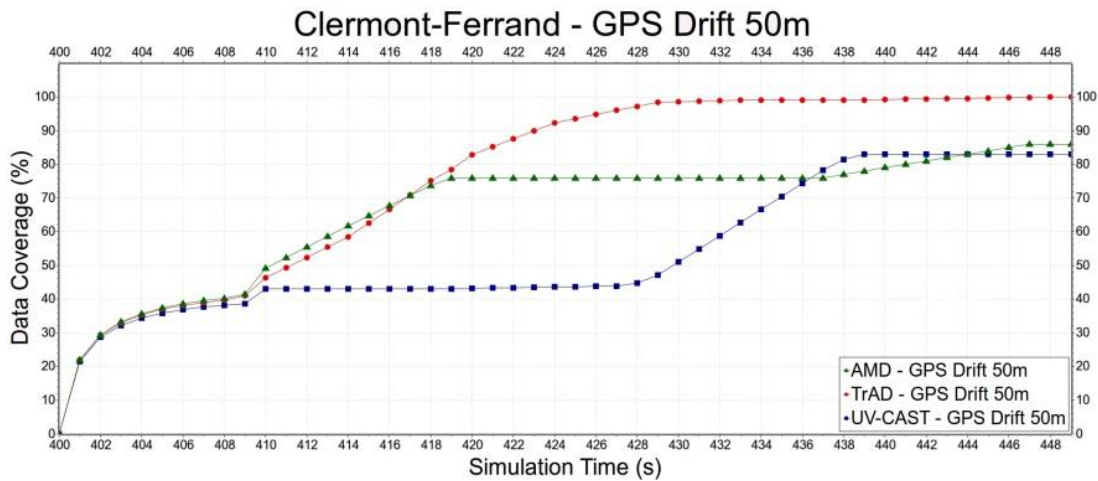


Figure 5-16. The data dissemination speed of TrAD, AMD and UV-CAST with 50m GPS drift.

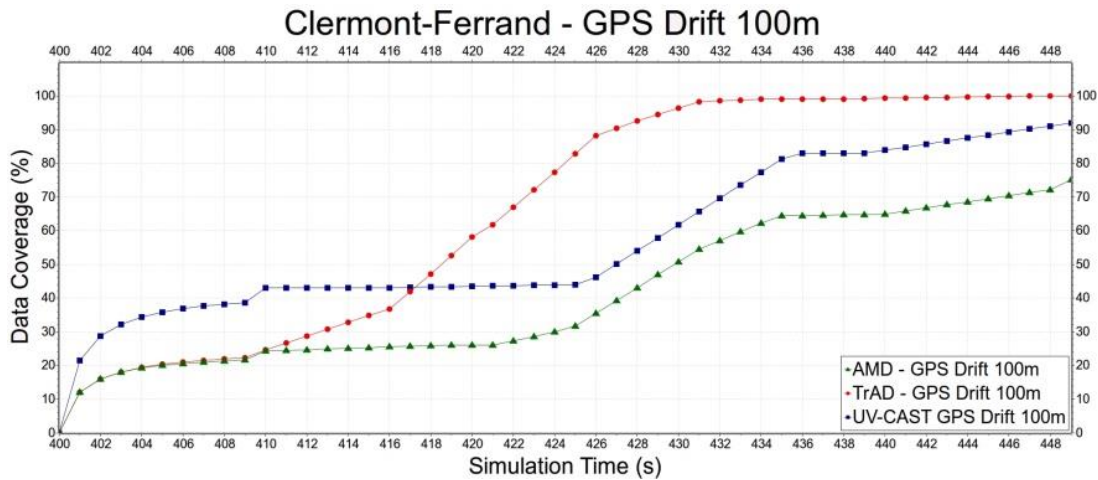


Figure 5-17. The data dissemination speed of TrAD, AMD and UV-CAST with 100m GPS drift.

Second, we select the Clermont-Ferrand scenario to evaluate the robustness of TrAD, AMD and UV-CAST to the GPS drift, since the Clermont-Ferrand scenario has more influence on TrAD than the Manhattan one. Error deviations include 0 m, 50 m and 100 m, as shown in Figures 5-15 to 5-17. In Figure 5-15, the data coverage of TrAD increases rapidly to 100% while the data coverage of UV-CAST climbs up much slower than TrAD and finally reaches 99.1%. In Figure 5-16, TrAD still keeps a good upward trend and reaches 100% data coverage. It is interesting that, in this case, the GPS drift limits the performance of UV-CAST and let its dissemination speed be lower than the one of AMD at most of time. Finally, UV-CAST and AMD achieve 86% and 83% data coverage, respectively. In Figure 5-17, although the large positioning deviation hurts TrAD very badly, the data coverage of TrAD still exceeds the other two protocols 17 s after data dissemination starts and achieves 100% at the end. In this simulation, the dissemination speed of UV-CAST is always better than AMD, which is not the case in Figure 5-16. Finally, UV-CAST and AMD achieve 92% and 75.1% data coverage, respectively. The abovementioned observations reveal that the random GPS drift will cause unreliable results in the protocols with less robustness. Although, for TrAD, the increasing slope of its data dissemination speed gradually decreases with the increasing of error deviations, it always takes the shortest time to reach 100% data coverage.

5.5 Conclusion and Future work

In this chapter, a new adaptive data dissemination protocol named TrAD is proposed for both highway and urban scenarios, taking into account both road traffic and network traffic status. The realistic simulation results show that TrAD outperforms three well-known reference data dissemination protocols in both highway and urban scenarios. On the one hand, TrAD is flexible enough to adapt to irregular road topology and considers both road traffic and network traffic status for the transmission delay-contention scheme and sorting technique. On the other hand, TrAD uses double broadcast suppression techniques to limit data message transmissions. This technique not only performs the broadcast suppression technique in a well-connected network, but also limits the rebroadcast of SCF-agents in disconnected networks. Consequently, TrAD only needs a moderate amount of data message transmissions to achieve high data coverage with low delay. Furthermore, TrAD can alleviate well the impact of GPS drift up to 75 m in a complex traffic environment, e.g.,

the Clermont-Ferrand scenario. In conclusion, TrAD provides good realistic simulation results in terms of PDR, data message transmission and delay, but our next challenge is to implement TrAD in vehicles and to evaluate its field test performance. Moreover, on the one hand, we will investigate the security and privacy issues to improve the TrAD protocol and we know that this will be a big challenge to overcome [110], [111]. On the other hand, how to implement a standard large scale field test of IVC protocol is also still an open research issue.

Chapter 6 Low-cost Tram Simulator based on Specific Mobility Model

6.1 Introduction

This chapter mainly aims to design and to implement the mobility model of the tram simulator for the “TRANSLOHR STE4” tram. This work is a part of the cooperative project between SMIR (Système Multisensoriel Intelligent intégré Réparti) research group of LIMOS (Laboratoire d’ Informatique, de Modélisation et d’ Optimisation des Systèmes) and T2C (Transport en Commun de l’agglomération Clermontoise) company which is the local public transport service provider in Clermont-Ferrand, France.

Tram arose in France in the 1990s. Given the safe, comfortable and environment-friendly transportation, tram has been deployed in many large and medium-sized cities, e.g., Paris, Lyon, Bordeaux and Clermont-Ferrand. With the development of computer science and automotive electronics, vehicular simulator was widely used to train drivers, especially in public transportation. The training simulator can be configured to simulate different scenarios, e.g., traffic accident or mechanical failure. These scenarios are inconvenient and, more importantly, unsafe to be implemented in the real training session [112]. Therefore, by using the driving training simulator, better training effects can be achieved while more traffic resource and training cost are saved [113]. Moreover, the simulator can record accurately the data about operation and driving behavior. Consequently, the wrong operation can be recorded and the driver is able to practice the case repeatedly [114]. In fact, it is not easy, even impossible, to achieve this function in the real training session.

Although current tram simulators are well developed, the mobility model and the cost are still the crucial challenges. The different types of tram, terrain and road will lead to different mobility models. For this problem, we develop a specific mobility model based on the measurement data for the “TRANSLOHR STE4” tram of T2C Company. In addition, the cost of simulator is another issue. In traditional way, the 3D engine is used to show the road traffic scenario. A dedicated 3D scene creation will cause a considerable cost. Therefore, we attempt to use an alternative approach, i.e., video stream, to achieve a low-cost tram simulator. At the same time, the video stream GUI can bring the real-world traffic scenario on the tram line, which cannot be done by 3D graphics.

In this chapter, the state-of-the-art of tram simulator is presented first, that motivated us to develop a new type of low-cost tram simulator dedicated for the specific tram on the specific terrain. Then, the framework of our tram simulator is designed and described. Since we focus on the mobility model in this thesis, only the mobility model and its implementation are presented in detail.

6.2 State-of-the-art of Tram Simulators and Motivation

Table 6-1. Summary of tram simulators

Company	Simulators	Hardware	GUI		Coach Station	Movability	Fault Injection	Functions
			3D	Video				
OKTAL	Micro	Simplified desk; PC; Small sizes touch screens	Yes	No	No	No	No	Refresher and remedial training
	Middle Range	Driving dest with console; PC; Big sizes screen and touch screens	Yes	No	Yes	No	Yes	Refresher and remedial training; Stress management; Response to Emergency situations; Faults troubleshooting; Multi-train training
	Replica	Driving cabin with console; PC; Big Full HD screen and Instruments;	Yes	No	Yes	Yes	Yes	Except the training of Middle Range Simulator, it also includes: Safety Issues; passengers' emergencies; rules and procedures training; maneuvers in depots; accurate stopping on platforms; respect of time schedules
CORYS	Softsim	Normal desk; PC or portable device; Small touch screens	Yes	No	No	No	No	Practice a specific procedure or signal in classrooms
	Compact	Portable driving desk; PC; Middle size screens; Touch screens	Yes	No	Yes	No	Yes	Driving procedures, typical regimes, procedures, etc.
	Desk	Simplified driving desk; PC; Big size screens; Touch screens and interchangeable controls	Yes	No	Yes	No	Yes	Simulate a number of different train models. Ideal for training drivers on diverse or upgraded rolling stock.
	Replica	Driving Cabin; PC and dedicated control system; Big Full HD screen and Instruments;	Yes	No	Yes	Yes	Yes	A high-level training resource, recognising the driving profession and enhancing operators brand image. Drivers have exactly the same desk as they do in real life.

To develop a tram simulator in traditional way, two respects should be designed and implemented, i.e., virtual driving environment and road traffic network. The SCANer™ software tool developed by Renault and OKTAL is dedicated to create virtual driving

scenarios, which includes terrain, vehicle, scenario, simulation and analysis models [115]. Meanwhile, as described in Chapter 4, the road traffic simulator is used to model the road traffic network, and then the modeling results will be installed into the virtual driving scenarios to run the driving simulation.

The French companies OKTAL [116] and CORYS [117] are the leaders in driving simulator field. Normally, their products are classified into three levels, i.e., low, middle and high, as summarized in Table 6-1. With the increasing of the level, the hardware and the software of tram simulators is upgraded. We can notice that the Graphic User Interface (GUI) of all the current simulators resorts to 3D graphics rather than video. Therefore, just imagine if the 3D graphics is replaced by the video shot from the head of tram during driving along the line, the cost of tram simulator will continue to be reduced. Moreover, the smooth motion of tram gives the video approach a chance to achieve a qualified driving training simulator. We can use the saved resource to exploit a more precise mobility model. The only issue is *how to adapt the video smoothly according to the mobility model*. These analyses are the primary motivation of our low-cost tram simulator development.

6.3 Framework Design of Tram Simulator

After analyzing requirements of the tram simulator, we designed four modules to achieve respective functions, i.e., Graphical User Interface (GUI), mobility control, operation console and fault injection, as shown in Figure 6-1 错误!未找到引用源。 .

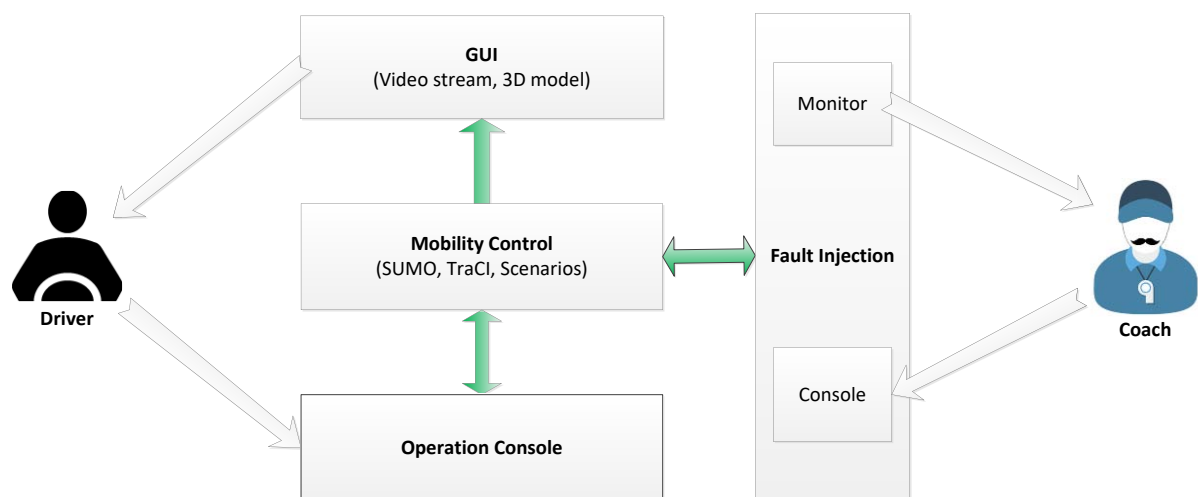


Figure 6-1. The framework of tram simulator

First, on the left, the driver operates the console according to the scenario in GUI. The operation console module transmits the operation commands to the mobility control module. And then the mobility models, introduced in the next section, are used to simulate the motion of the tram. After that, the mobility control module sends commands to update the GUI according to the simulation data from the mobility model. Thereby, the driver can acquire the training in this system cycle. On the right, the coach can watch the driving situation in the monitor and inject various faults, i.e., mechanical failure or electrical failure, into the simulator so as to improve the capability of driver to handle emergency cases.

6.3.1 Mobility Control Module

SUMO is adopted to be the core of the mobility control module because it can support various realistic road traffic scenarios but also provide a powerful interface, i.e., TraCI. The SUMO tool suite can be used to create realistic scenarios related to the training accurately. To verify the accuracy of the digital map, we compare the data from realistic scenarios with the data measured from real-world trails. In these trails, the tram of line A records the distance between one station and another by using intra-vehicle system. The same measurement is carried out in realistic scenarios, in which we program to access TraCI to get the geographic information of the tram. The result, as listed in Table 6-2 [错误!未找到引用源。](#), shows that the deviation of distance between the measurement data and the simulation data is within an acceptable range. We can complement the deviation in the each segment between stations.

Table 6-2. The distance between each tram station of line A

Stations	Measurement data (m)	Simulation data (m)	Deviation (m)
Les Vergnes	0	0	0
Stade G. Montpied	512	516	4
La Plaine	524	519	-5
Champratel	511	518	7
Croix de Neyrat	473	472	-1
Hauts de Chanturgue	405	404	-1
Collège Albert Camus	365	366	1
Les Vignes	536	536	0
Lycée A. Brugière	354	350	-4
Les Pistes	407	406	-1
Musée D'Art Roger Quilliot	679	685	6
Montferrand La Fontaine	408	409	1
Gravière	407	406	-1
Stade Marcel Michelin	363	368	5
1er Mai	455	449	-6

Les Carmes	659	659	0
Delille Montlosier	344	344	0
Hôtel de Ville	439	438	-1
Gaillard	288	293	5
Jaude	327	320	-7
Lagarlaye	390	399	9
Maison de la Culture	365	359	-6
Université	326	326	0
St Jacques Dollet	803	805	2
CHU G. Montpied	395	393	-2
St Jacques Loucheur	444	439	-5
Léon Blum	342	342	0
La Chaux	580	582	2
Cézeaux Pellez	409	408	-1
Campus	576	580	4
Margeride	521	527	6
Fontaine du Bac	274	276	2
Lycée Lafayette	660	658	-2
La Pardieu - Gare	608	601	-7
Total	15149	15153	4

For the simulator, TraCI is an effective way to collect the information from the tram and control the motion of the tram. It can provide the current driving status for the mobility model. The model will calculate the resulting configuration of the next motion according to the operations input and the current driving status. After that, the configuration about the new motion will be transmitted to SUMO. Therefore, the driver can operate the tram in terms of the law we set in the mobility model.

6.3.2 GUI Module

The GUI module provides the road traffic scenarios to the driver. In the traditional way, three dimensional (3D) graphics is created to simulate the realistic scenarios on the road. In our prototype, we intend to use video stream to provide a real view of the traffic environment, as shown in Figure 6-2 错误!未找到引用源。 .



Figure 6-2. The GUI view of real traffic scenarios

The high quality video is provided by T2C Company. The applicability of this approach lies in the mobility feature of tram, i.e., the motion is on the fixed track. It is possible to simulate the real driving scenarios by adjusting the speed of the video according to the mobility model. The individual advantage of the video GUI is that this approach can recreate exactly the real traffic scenarios on the tram line. However, there are also several challenges when we implement this idea in the prototype. The synchronization between the video and the mobility model is a great challenge, for which the frequent pause of video occurred. Moreover, how to insert the traffic event into the video is another issue, e.g., traffic accident.

6.3.3 Operation Console Module

The operation console can be straightforward to know as an interface between the tram and the drive, which provides the drive with various ways to control the tram and shows the information of the tram. In the initial phase of our implementation, the application software of operation console is developed, as shown in Figure 6-3 错误!未找到引用源。 .

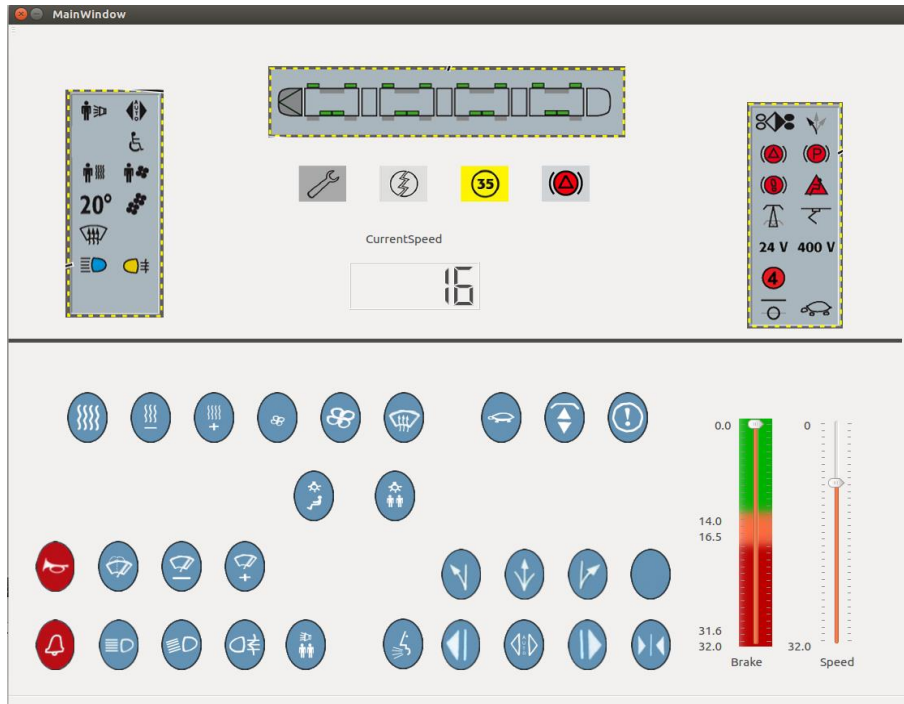


Figure 6-3. Software of operation console

This program can support almost all the functions of the tram, e.g., acceleration, deceleration, open or close door, physical detection and so on. In the near future, the T2C Company will provide the real operation console for the tram simulator, as shown in Figure 6-4 错误!未找到引用源。 .







Figure 6-4. Hardware of operation console

6.3.4 Fault Injection Module

The fault injection module is controlled by the coach, which is used to evaluate the fault treatment capacity of the driver. There are tens of fault signals to inform various faults of the tram. These faults are classified into four categories, as listed Table 6-3 错误!未找到引用源。 .

Table 6-3. Categories of faults

Fault Icon	Introduction
	Minor Fault: It does not affect the operation of the vehicle, does not require an immediate change in operating regime.
	White Fault: It may require a change of operating system.
	Orange Fault: Issue 2 alarm tone remains active until the driver activates the "payment default" button. Automatic speed limit of 35km/h maximum performs. Requires change of operating system.
	Security Brake: It is automatically activated at the first appearance of dangerous failure managing the opening of the security loop.

6.4 Tram Mobility Model

The mobility model is designed according to the measurement data collected from real-world trials that are supported by T2C Company to test the different states of motion. The motion of tram depends on the specification of tram (power unit, weight and payload), the travel route (slope and curve), and the operation of driver (accelerate or decelerate). There are three kinds of motion, i.e., acceleration, deceleration and sliding motion. Normally, the tram is controlled by the driver who operates Power Unit (PU) and Deceleration Control Unit (DCU) while being influenced by geography, friction and air resistance.

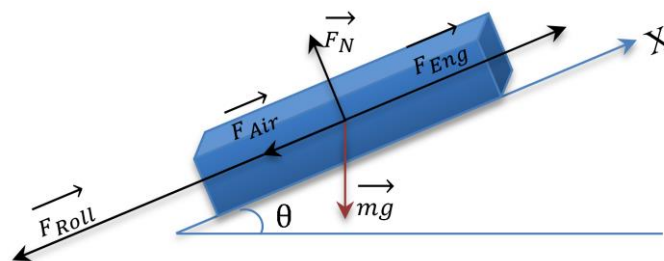


Figure 6-5. Force diagram of tram

In Figure 6-5, the force situation of tram is resolved in horizontal and vertical directions. So, we can obtain the Equation (6-1).

$$\begin{cases} \overrightarrow{F_{Roll}} + \overrightarrow{F_{Air}} + \overrightarrow{F_{Eng}} + \overrightarrow{mg} \sin \theta = m\vec{a} \\ \overrightarrow{F_N} + \overrightarrow{mg} \cos \theta = 0 \end{cases} \quad (6-1)$$

where, $\overrightarrow{F_N}$ is the force from ground; \overrightarrow{mg} is the weight of tram; $\overrightarrow{F_{Eng}}$ is the traction of engine; $\overrightarrow{F_{Air}}$ is the air resistance; $\overrightarrow{F_{Roll}}$ is the rolling resistance; θ is the angle between tram and plane ground; \vec{a} is the acceleration.

In the following sections, based on the force diagram, we will analyze the acceleration model of PU, the deceleration model of DCU and the model of sliding motion without any operation of driver.

6.4.1 Acceleration

Driver uses the accelerator pedal to control the output power of engine. The more the angle of accelerator pedal is pushed, the more the speed of tram is achieved. According to the technical document of tram “TRANSLOHR STE4”, there is an approximation of linear dependency between the angle of accelerator pedal and the maximum speed. Given the angle range of accelerator pedal within 1 degree and 31.8 degrees and the maximum speed of tram forbids to exceed 60 km/h, the relationship of the two factors is shown in Equation (6-2).

$$v = 1.948 \times \alpha \quad (6-2)$$

where, v is the maximum speed; α is the angle of accelerator pedal.

The measurement data of real-world trails about acceleration is listed in Table 6-4. In these experiments, the tram speeds up from the static state to a certain target speed and the time of the acceleration process is recorded. Each experiment is repeated three times.

Table 6-4. The measurement data of acceleration experiment

Target speed (km/h)	Time of experiment 1 (s)	Time of experiment 2 (s)	Time of experiment 3 (s)
10	4.292	3.862	4.282
20	7.784	7.782	7.656
30	11.404	11.304	11.084
40	13.505	14.187	14.955

Therefore, we can obtain the average acceleration of each experiment as listed Table 6-5.

Table 6-5. Average acceleration of each experiment

Target speed (km/h)	Average acceleration A (m/s ²)
10	0.671777
20	0.717811
30	0.739895
40	0.782959

After analyzing the experiment data in Table 6-5, we found that there is a linear relationship between the speed and the acceleration. Therefore, we give a regression equation (Equation (6-3)) to deduce the relationship between target speed and average acceleration by using linear regression.

$$\bar{a}(v) = bv + c \quad (6-3)$$

where, \bar{a} is the average acceleration; v is the target speed; b and c are the parameters of the linear regression equation.

According to the linear regression method, the data in Table 6-5 is fitted by least square estimate so as to minimize the residual sum square between the estimated acceleration \bar{a} and the actual acceleration A .

$$\varepsilon^2 = (\bar{a}(v) - A)^2 \quad (6-4)$$

We take the derivative of the sum of ε_i^2 , i.e., $\sum \varepsilon_i^2$, with respect to b and c and obtain Equation (6-5).

$$\begin{cases} \frac{\partial \sum \varepsilon_i^2}{\partial b} = 2b \sum v_i^2 + 2c \sum v_i - 2 \sum A_i v_i \\ \frac{\partial \sum \varepsilon_i^2}{\partial c} = 2b \sum v_i + 2cN - 2 \sum A_i \end{cases} \quad (6-5)$$

where, N is the number of experiments.

We put the experiment data into Equation (6-5), then obtain the linear equation of the relationship between \bar{a} and v , as shown in Equation (6-6).

$$\bar{a} = 0.012813 \cdot v + 0.639161 \quad (6-6)$$

The measurement data and the line of linear relationship between \bar{a} and v are shown in Figure 6-6.

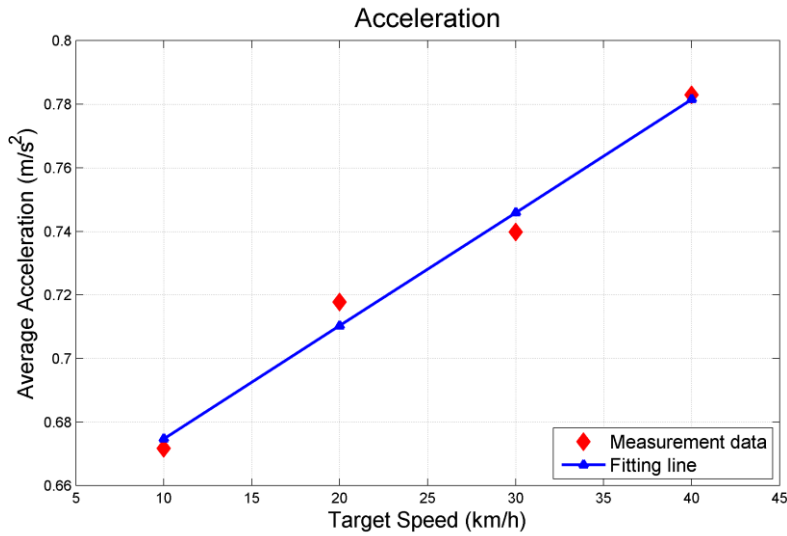


Figure 6-6. The measurement data and its fitting line

We can observe that the fitting line well fit the measurement data. Now, the relationship between the angle of acceleration pedal α and the average acceleration \bar{a} can be built by the target speed v , i.e., Equations (6-2) and (6-6). Therefore, we can obtain the value v and \bar{a} in terms of α , then the mobility model will use the \bar{a} to accelerate the tram until achieve the target speed v .

6.4.2 Deceleration

Driver operates the Deceleration Control Unit (DCU) to perform brake behavior by using brake pedal. The angle range of brake pedal is the same as the one of accelerator pedal. The difference is that the full angle of brake pedal is divided into two parts, i.e., sector A and sector B, as shown in Figure 6-7.

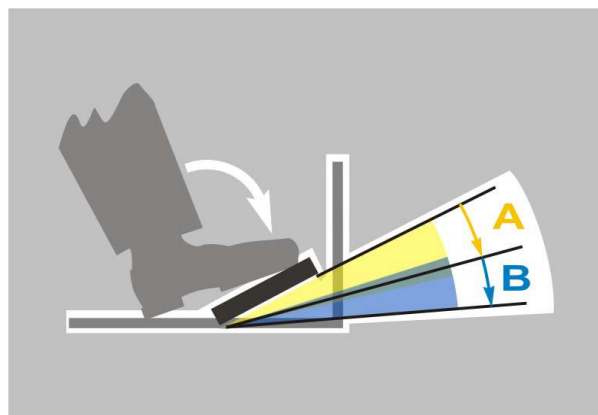


Figure 6-7. The structure of brake pedal

In the sector A, DCU uses the brake-by-wire technology to control brakes through electrical means. During the brake process, the tram can recuperate the electrical energy

created by the brake behavior. In the sector B, DCU switches to the air braking system to perform the brake. In this case, the deceleration is more than the one of the sector A. This sector is used to handle the emergency situation, otherwise the sector A is used to deal with the normal situation.

According to the technical document of tram “TRANSLOHR STE4”, the relational expression between the deceleration and the angle of brake pedal is listed in Table 6-6.

Table 6-6. The relational expression between the deceleration and the angle of brake pedal of tram “TRANSLOHR STE4”

Angle of brake pedal θ (degree)	Deceleration d (m/s ²)
$0 \leq \theta \leq 1$	0
$1 \leq \theta \leq 14$	$d = 0.107\theta - 0.107$
$14 \leq \theta \leq 16.5$	$d = 0.107\theta - 0.107$
$16.5 \leq \theta \leq 31.8$	$d = 0.212\theta - 1.844$

Accordingly, the piecewise line is shown in Figure 6-8.

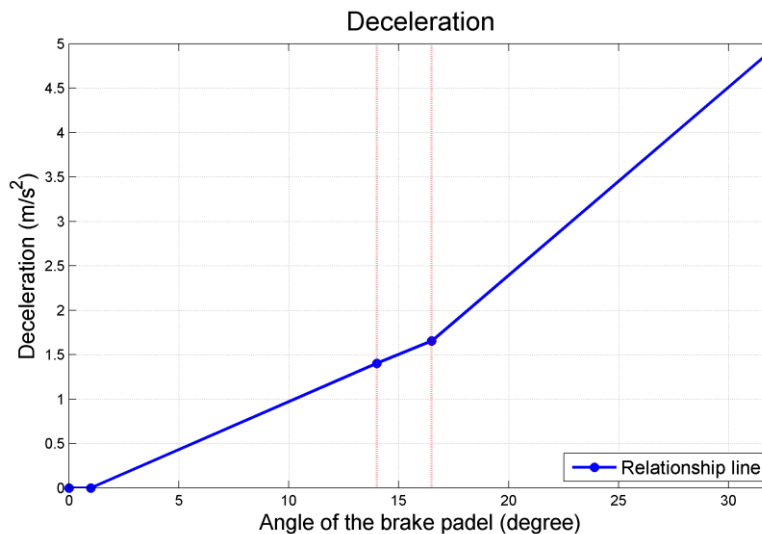


Figure 6-8. Deceleration model with respect to the angle of brake pedal

There is a blank zone from 0 to 1 degree, which is to prevent the wrong operation. The angle range from 1 to 14 degrees belongs to the sector A, in which the deceleration increases gradually with the increasing of the angle of the brake pedal. A buffer zone is set between sector A and sector B from 14 to 16.5 degrees, as the interval between two red dot lines. After the buffer zone, there is the sector B, i.e., the emergency brake phase, where the uptrend of the deceleration is greater than the one of sector A.

6.4.3 Sliding Motion

Sliding motion is the motion of tram without any operations from the accelerator pedal and the brake pedal, tram just sliding according to the effect of inertia. To explore the model of sliding motion, first, we deduce the theoretical model from the force situation of tram, i.e., Equation (6-1). Here, we only consider the sliding motion on the plane ground. That means $\overrightarrow{F_{Eng}} = 0$ and $\theta = 0$. Therefore, the Equation (6-1) is transformed to the Equation (6-7).

$$\overrightarrow{F_{Roll}} + \overrightarrow{F_{Air}} = m\vec{a} \quad (6-7)$$

In this case, the resistance just comes from air and rolling of wheels. So, we investigate these forces respectively. The resistance of air can be expressed by Equation (6-8).

$$\overrightarrow{F_{Air}} = kv^2 \quad (6-8)$$

where, k is the parameter related to the profile of the head of tram.

The moment of rolling friction can connect the roll resistance with the force from ground, as shown in Equation (6-9).

$$M_{Roll} = r\overrightarrow{F_{Roll}} = \lambda\overrightarrow{F_N} \quad (6-9)$$

where, r is the radius of the wheel; λ is the rolling parameter. Since the plane ground is considered, $\overrightarrow{F_N}$ is equal to the weight of the tram, i.e., $\overrightarrow{F_N} = mg$. Therefore, we can obtain the expression of rolling resistance $\overrightarrow{F_{Roll}}$.

$$\overrightarrow{F_{Roll}} = \frac{\lambda}{r}mg \quad (6-10)$$

Substituting Equation (6-8) and (6-10) into Equation (6-7), we can obtain the expression of deceleration, as shown in Equation (6-11).

$$\vec{a} = -\left(\frac{\lambda}{r}g + \frac{k}{m}v^2\right) \quad (6-11)$$

where, we use minus to represent the negative effect of deceleration. The radius r and the weight m can be known in the technical document of the tram. There are only two parameters, i.e., λ and k , needed to be identified. Next, we will use the method of linear regression to estimate these undefined parameters.

According to the type of Equation (6-11), we design the regression equation as Equation (6-12).

$$\bar{d}(v) = bv^2 + c \quad (6-12)$$

where, \bar{d} is the average deceleration; b and c include the undefined parameters. The residual between the estimated deceleration \bar{d} and the actual deceleration D is presented by Equation (6-13).

$$\varepsilon^2 = (\bar{d}(v) - D)^2 \quad (6-13)$$

In least square theory, the fitting curve is optimal when $\sum \varepsilon_i^2$ is minimized. We take the derivative of $\sum \varepsilon_i^2$ with respect to b and c , and then obtain Equation (6-14).

$$\begin{cases} \frac{\partial \sum \varepsilon^2}{\partial b} = 2b \sum v_i^4 + 2c \sum v_i^2 - 2 \sum D_i v_i^2 \\ \frac{\partial \sum \varepsilon^2}{\partial c} = 2b \sum v_i^2 + 2cN - 2 \sum D_i \end{cases} \quad (6-14)$$

Now, we need the sample space of the initial speed v and the actual deceleration D to estimate the desired parameters. To this end, thanks to the cooperation with T2C Company, we carried out several real-world trials. In these trials, the tram speeds up to certain initial speed and begins to slide until it stops. The distance between the start point of sliding and the stop point is measured. According to the theoretical formula (6-15), we can use the initial speed and the sliding distance to calculate the average deceleration.

$$\begin{cases} v(t) = v_0 + Dt \\ x_1(t) = \frac{1}{2}Dt^2 + v_0t + x_0 \end{cases} \quad (6-15)$$

where, v_0 is the initial speed; the final speed is equal to 0; x_0 is the start point of sliding; x_1 is the stop point. Therefore, we can obtain the average deceleration of real-world trails D , as shown in Equation (6-16).

$$D = \frac{-v_0^2}{2(x_1 - x_0)} \quad (6-16)$$

Using the measurement data of the trails and Equation (6-16), we can calculate the value of the actual average deceleration D as listed Table 3-1.

Table 6-7. The average deceleration of real-world trails

Speed v_0 (km/h)	Distance (m)	Average deceleration D (m/s ²)
10	30.4	0.127
19	86.7	0.161
20	88.6	0.174
30	215.1	0.161
32	252	0.157
40	305.8	0.202
42	413.1	0.165

We use the measurement data in the Equation (6-14) to obtain the value of b and c as follows.

$$\begin{cases} b = -\frac{k}{m} = -0.000282 \\ c = -\frac{\lambda}{r}g = -0.144767 \end{cases} \quad (6-17)$$

Naturally, we can obtain the model of sliding motion, as shown in Equation (6-18).

$$\bar{d}(v) = -0.000282 \cdot v^2 - 0.144767 \quad (6-18)$$

Therefore,

$$\begin{cases} \lambda = 0.007913 \\ k = 7.148700 \end{cases} \quad (6-19)$$

The fitting curve is shown in Figure 6-9.

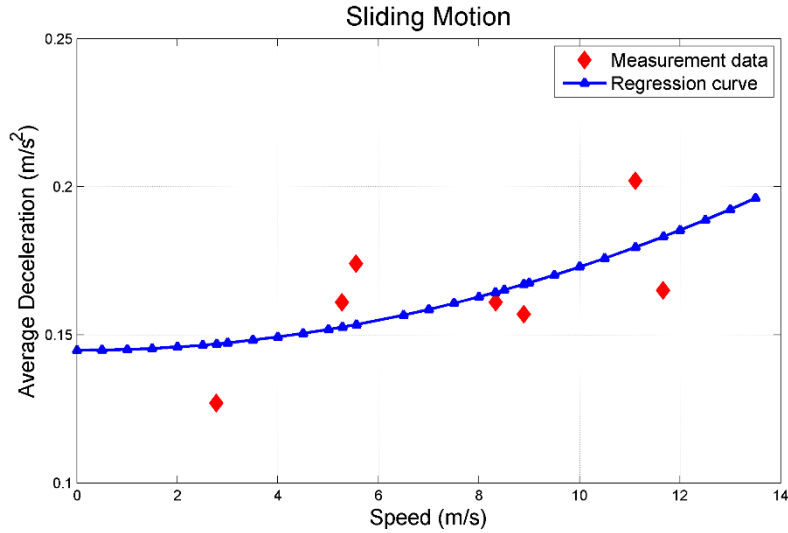


Figure 6-9. The relationship between the deceleration and the initial speed in sliding motion

We observe that the regression curve roughly fits the measurement data, which proves that the model could simulate the actual sliding motion with a qualified performance.

6.5 Implementation of Mobility Control Module

The mobility control module mainly includes two parts, i.e., traffic scenarios and various motion models. The traffic scenarios consist of the SUMO map and the traffic routes, which are related to the traffic line of the tram. The car-following mobility model of SUMO is used, as the engine of the tram, to control the motion of the tram in scenarios in terms of the configuration calculated by the motion models. Therefore, first, we will show the creation of

traffic scenarios. Then, the calculation process of each motion model is present to explain that, how the motion model configures SUMO to control the motion of the tram by using TraCI.

6.5.1 Traffic Scenarios

The implementation of the realistic road traffic scenarios has been elaborated in the section 4.4 on page 71. Thus, here, we do not repeat it and just give the creation result of traffic scenarios, as shown in Figure 6-10.



(a)



Figure 6-10. Implementation of traffic scenarios in the tram simulator. (a) OpenStreetMap; (b) Road network; (c) SUMO map.

In Figure 6-10, there is a fragment of SUMO map that is converted from OpenStreetMap. In fact, we can create the traffic scenarios of most cities in the world. Therefore, the simulator also can be used in other cities, but the mobility models should be investigated again according to the measurement data in the real-world trails as what we have done in section 6.4.

6.5.2 Acceleration

The acceleration process is programmed according to the flow chart in Figure 6-11.

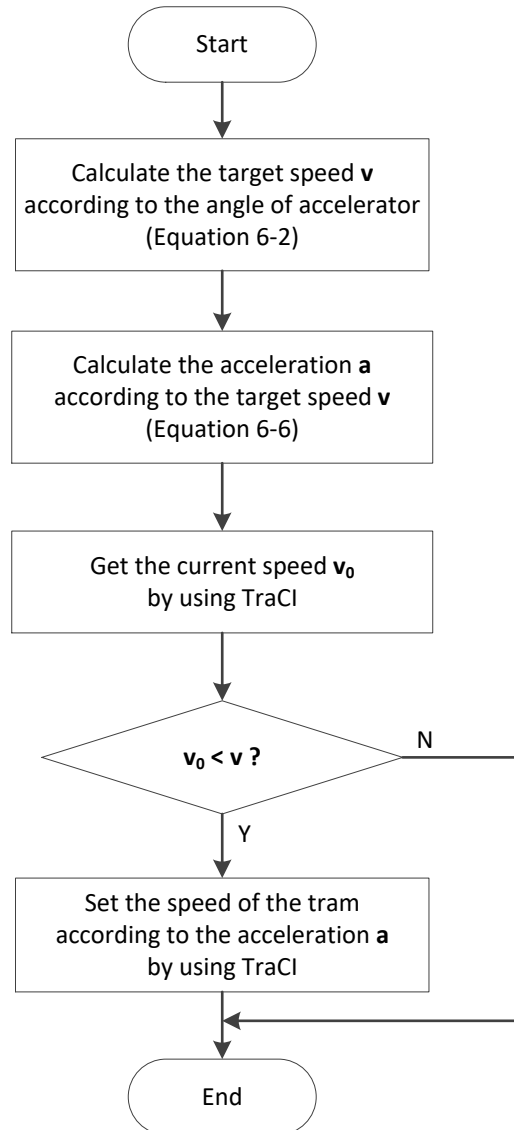


Figure 6-11. The flow chart of acceleration

First, the target speed v is calculated in terms of the angle of accelerator α by using Equation (6-2). Then, the acceleration a is calculated according to the acceleration model, i.e., Equation (6-6). After that, the current speed v_0 is obtained by using TraCI and is compared with the target speed v . If the current speed v_0 does not achieve the target speed v , the tram will be accelerated in terms of the acceleration a by using TraCI.

6.5.3 Deceleration

The deceleration process is achieved according to the flow chart in Figure 6-12.

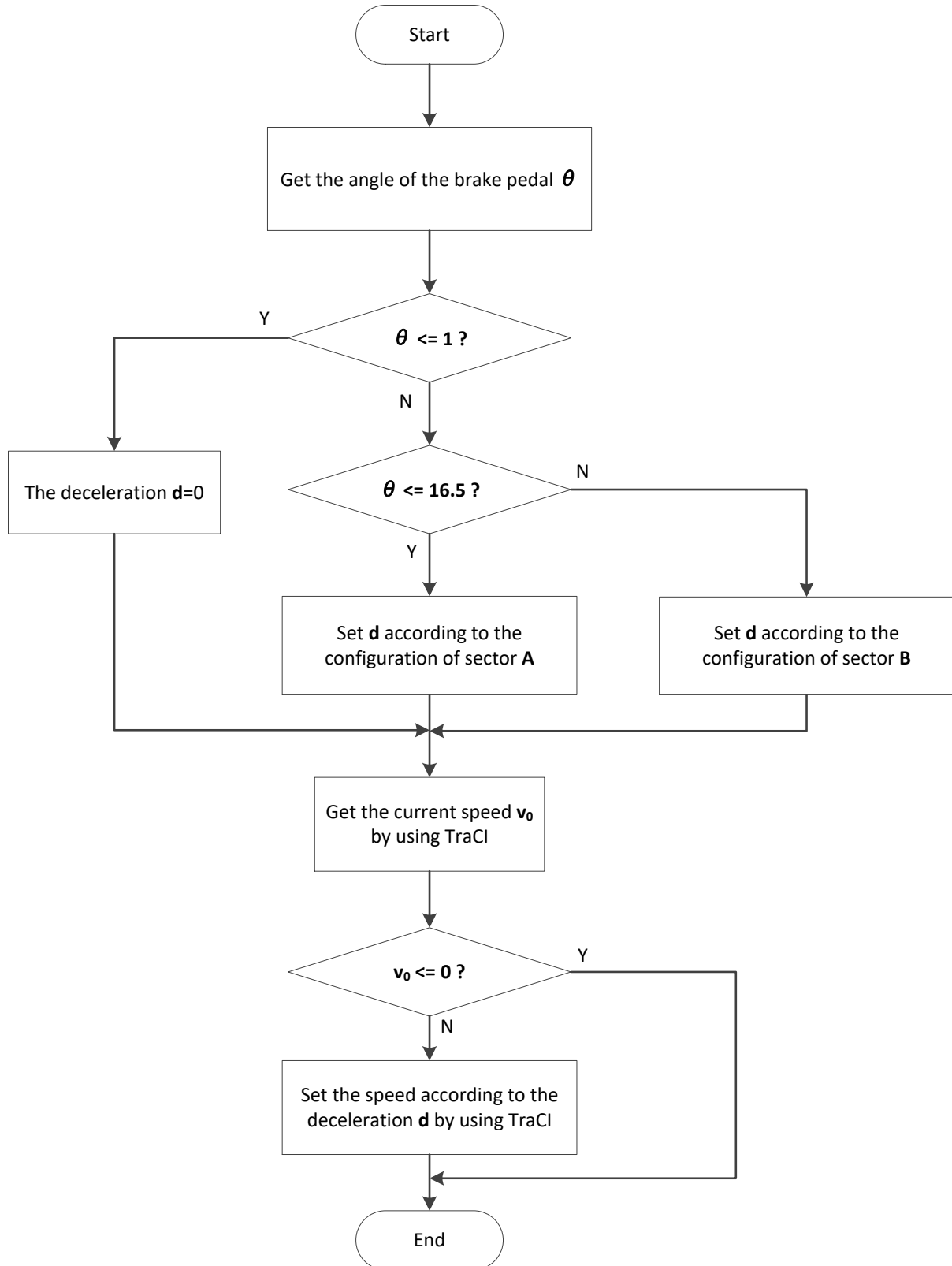


Figure 6-12. The flow chart of deceleration

The angle of the brake pedal θ is obtained in advance. Then, the deceleration d is calculated according to the deceleration model as listed Table 6-6. If the current speed v_0 is

not less than 0, the speed of the tram will be reduced in terms of the deceleration d by using TraCI.

6.5.4 Sliding Motion

The sliding motion process is implemented according to the flow chart in Figure 6-13.

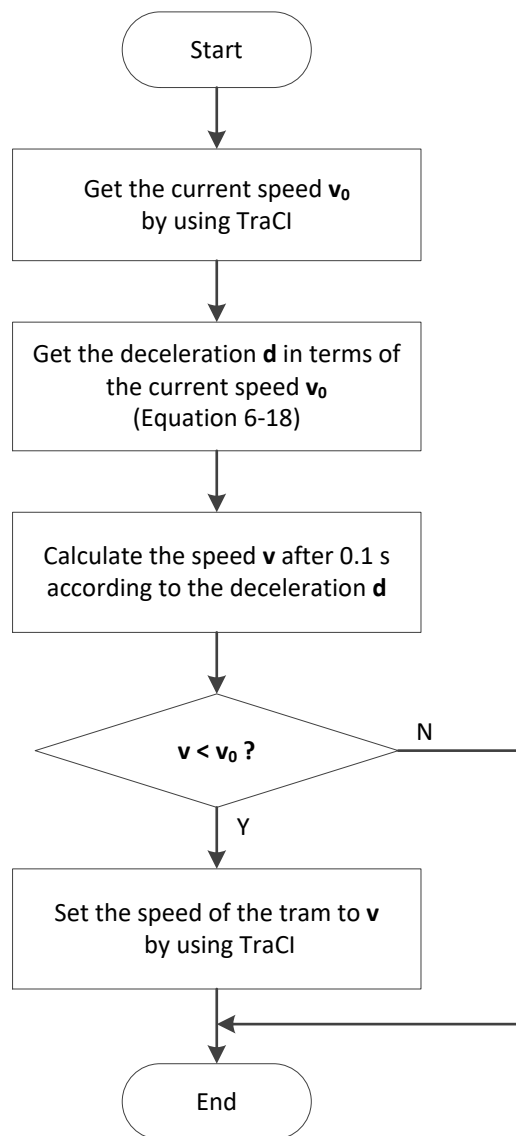


Figure 6-13. The flow chart of sliding motion

The deceleration d is calculated according to the model of sliding motion in terms of the current speed v_0 . Then, the next speed after 0.1s is calculated in terms of the deceleration d . This speed v is checked whether it is less than the current speed v_0 . If the condition is true, the speed v will be set as the next target speed by using TraCI.

Chapter 7 Conclusion and Perspective

The main obtained results of my thesis are divided into two parts: TrAD IVC protocol and the mobility model of tram simulator. A new IVC protocol named TrAD protocol focusing on data dissemination was proposed for the former in research aspect while the modeling process was carried out for the latter in practice aspect. Based on the solid simulation platform of vehicular networking, the TrAD protocol dedicated itself to disseminate data from a sender to multi-hop neighboring vehicles in a range of interest (ROI) while considering road traffic and network traffic in both urban and highway scenarios. Results as they used to publish two articles, one in an international journal and the second in an international conference (IEEE) [118], [119].

On the other hand, the tram simulator project has been supported for two years by T2C Company.

The wireless technology advances continuously and significantly driving by mobile network and IoT. It's no doubt, that these advances will impact the paradigm of IVC such as secure and reliable routing technique based on multi-support cognitive radio (IEEE802.11p, NB-IoT, 4G/5G, LoRa, etc.), which will play a key technology to implement V2V, V2I, I2V (e.g., traffic light to vehicle) and V2X (e.g., vehicle to pedestrian).

Beyond that, for the next coming year, I am interested to investigate the distributed congestion control (DCC) in a vehicular cluster. How to adjust adaptively transmit parameters (e.g., transmit rate or power) in the high dynamic vehicular network is a crucial challenge for traffic safety, situational awareness and cooperative awareness. In addition, except ad-hoc formation of VANETs, I want to exploit the infrastructure-based formation of VANETs. The cellular networks, such as 4G or 5G (in near future), will become the most potential wireless access technology for IVC applications, especially in the initial penetration phase of DSRC device. The advanced feature of 5G network can bring a significant improvement for VANETs. After investigating ad-hoc and infrastructure formations, naturally, I expect to explore the cognitive multi-support access technique to improve the reliability and security in heterogeneous vehicular networks.

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Mobilité pour Réseaux Ad hoc Véhiculaires »**

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Mots Clés: Réseaux Ad hoc Véhiculaires; Communication Inter-Véhicule; Data Dissemination Protocol; Scénarios de Trafic Routier Réalistes; Modèle de Mobilité; Simulateur de Tramway

Chapter 1 Introduction

La technologie des Réseaux Ad hoc Véhiculaires (VANET ‘Vehicle Ad Hoc Network’) est l'une des solutions pour améliorer la sécurité routière, l'efficacité du trafic et les divertissements sur roues ‘Infotainment on wheels’, où un grand nombre de messages événementiels doivent être diffusés en temps opportun vers une région d'intérêt (ROI ‘Region of Interest’).

Par rapport aux réseaux sans fil classiques, les VANET disposent d'une topologie de réseau très dynamique et de liaisons peu stable du fait de la mobilité des véhicules et de l'obstacle sur la route (e.g., bâtiments).

De nos jours, le véhicule intelligent devient un sujet brûlant dans l'industrie automobile et la communauté scientifique. Beaucoup d'essais dans le monde réel sont effectués par des entreprises ou des universités, comme Google Car et Tesla Motors.

La communication entre les véhicules intelligents s'appuie sur le VANET. Cependant, il y a encore des défis à résoudre dans la communication inter-véhicules (IVC), tels que le passage à l'échelle, la robustesse et la qualité de service (le délai et la sécurité).

Par conséquent, cette thèse contribuera à développer des protocoles IVC pour les VANET, en particulier en mettant l'accent sur les protocoles de diffusion de données au sein de VANETs. De ce fait, pour évaluer objectivement la performance des protocoles IVC, un scénario de trafic routier proche de la réalité doit être modélisé, mis en œuvre et couplé au simulateur de réseau de véhicules.

Pour assurer que les résultats de la simulation sont fidèles à la réalité, le modèle de mobilité des véhicules est également étudié. Grâce à la maîtrise des modèles de mobilité, un projet de collaboration avec le T2C pour réaliser une nouvelle génération de simulateur de TRAM a été mis en place.

Chapter 2 Communication Inter-Véhicule et VANETs

2.1 Introduction

La communication inter-véhicule (IVC ‘Inter-Vehicle Communication’) effectue l'échange d'informations entre les véhicules ou entre les véhicules et l'infrastructure. Les véhicules et les infrastructures sont reliés par des moyens de communication sans fil, qui forment des réseaux VANETs (VANET: Vehicular Ad hoc Network’).

Généralement, les VANETs sont classées en deux formations, basées sur l'infrastructure et ad hoc. Les éléments d'infrastructure incluent principalement les stations de base du réseau cellulaire (3G/4G), les véhicules ou unités routières (RSU : ‘Roadside Unit’) utilisant la norme WAVE ou le WiFi ou le ZigBee ou le Bluetooth. La formation ad hoc des VANET est principalement centrée pour des applications de sécurité routière. En utilisant la norme IEEE 802.11p, les véhicules pourraient se coopérer ensemble et connaissent leurs véhicules voisins situés dans la même région, atteignables par un saut ‘hop’, de sorte que l'événement d'urgence peut être informé à l'avance à chaque véhicule. Donc, le plus grand avantage de cette formation est le service en temps réel. En résumé, les VANET visent à améliorer les activités de transport incluant la sécurité routière, l'efficacité du transport et l' « infotainment on wheels ».

Ce chapitre présentera une introduction aux concepts de base de la CIV ‘communication inter-véhicule et VANETs, qui fournissent les connaissances nécessaires et une base théorique pour les chapitres suivants.

2.2 Technologies sans fil

Un médium d'accès sans fil adapté peut améliorer considérablement les performances des applications de communication inter-véhicule. Aujourd'hui, pour les VANETs, il existe deux principaux types de technologies sans fil, c'est-à-dire les technologies de communication sans fil à longue et à courte portée. La première se réfère principalement aux réseaux cellulaires (e.g., 3G/4G) et la deuxième comprend principalement le WiFi et le standard IEEE 802.11p. Dans le cadre de cette thèse, nous ne décrivons pas chaque technique spécifique en détail, mais nous étudierons le médium sans fil qui est, ou n'est pas, adaptée aux applications CIV. Par conséquent, nous pouvons avoir une compréhension générale de chaque technologie d'accès.

Le WiFi est le médium d'accès sans fil le plus populaire dans notre vie quotidienne, et qui est basé sur la norme IEEE 802.11. Il permet de réaliser aisément un réseau local sans fil (WLAN) à travers un point d'accès sans fil. L'IEEE802.11 utilise principalement la bande 2.4 GHz. L'IEEE 802.11p est la première norme officielle de communication sans fil pour les VANET.

L'IEEE802.11p est une extension de la norme WiFi adaptée à la communication inter-véhicule en réduisant considérablement le délai de transmission. Pour ce faire, dans la couche MAC, un nouveau mode de fonctionnement, c'est-à-dire OCB (en dehors du contexte d'un BSS), a été proposé pour permettre à chaque nœud (véhicule équipé de

l'IEEE802.11p) de fonctionner en mode sans infrastructure et n'effectue pas non plus le service de confidentialité, d'association et de confidentialité des données imposé par la norme IEEE 802.11.

En outre, la diffusion et la multidiffusion de l'IEEE 802.11p ne nécessitent pas le processus d'accusé de réception (acquiescement après avoir reçu un message), le mécanisme RTS / CTS et le mécanisme de la retransmission en cas d'erreur au niveau de la couche MAC. En conséquence, le délai de transmission est réduit, mais la fiabilité des transmissions ne peut pas être garantie.

L'IEEE 802.11p utilise le mécanisme EDCA (Enhanced Distributed Channel Access) pour gérer les accès au canal. En effet, quatre niveaux de priorité sont attribués aux messages de données pour ordonnancer les transmissions.

Les réseaux cellulaires permettent une bonne évolutivité pour les systèmes d'information routière (TIS 'Traffic Information Systems'). La faisabilité des réseaux cellulaires est prouvée par les tests opérationnels de terrain (FOTs 'Field Operational Tests'), qui montrent qu'un véhicule roulant à une vitesse très élevée, c'est-à-dire 290 km / h, peut se connecter à la station de base du réseau cellulaire.

Cependant, la technologie cellulaire n'est pas en mesure de prendre en charge les applications critiques pour la sécurité, car le délai est de l'ordre de quelques secondes. Ainsi, en 2009, le projet CoCarX (Cooperative Car Extended) a été réalisé pour intégrer l'IEEE 802.11p dans le système de communication cellulaire pour créer des réseaux hétérogènes de véhicules, dans lesquels les véhicules peuvent échanger des messages en utilisant uniquement l'IEEE 802.11p pour communiquer avec leurs voisinages et envoyer les Messages à des véhicules ou des infrastructures lointaines par LTE.

Le rapport du projet CoCarX a montré que le réseau hétérogène (IEEE802.11p et cellulaire) améliore non seulement le TIS, mais peut également satisfaire certaines applications de sécurité, par exemple, avertissement de conduite dangereuse. La seule limitation est la capacité du système car on ne sait toujours pas si les réseaux cellulaires s'adaptent bien au VANET lorsque le nombre de véhicules est important. Néanmoins, à ce jour, cette technologie d'accès est encore la technologie d'accès la plus appropriée pour la phase initiale des applications IVC puisque le taux de pénétration des dispositifs DSRC est encore très faible.

2.3 Applications

Nous considérons que les différentes applications de CIV adoptent différents concepts de communication. De ce fait, nous sélectionnons trois applications qui représentent la principale fonctionnalité de CIV, c'est-à-dire les systèmes d'information pour la circulation non-sécurisée, le système d'avertissement de collision au carrefour et le suivi de convoi pour l'efficacité du transport.

Dans les systèmes d'information routière, les données relatives à la circulation des véhicules sur la route sont agrégées au CIT (Centre d'Information sur le Trafic (TIC 'Traffic Information Center')). Au CIT, le trafic routier est optimisé. Ensuite, la solution est renvoyée aux véhicules par diffusion de messages.

Le système d'avertissement de collision au carrefour (ICWS '*Intersection Collision Warning System*') vise à éviter les collisions pour les véhicules qui approchent d'un carrefour (intersection). Des capteurs sur les véhicules, par exemple des ultrasons, des radars et des caméras vidéo, peuvent être utilisés pour aider le conducteur à détecter une collision potentielle avec d'autres véhicules.

Chen et al. a évalué les performances du système d'avertissement de collision au carrefour et les résultats ont montré que les accidents de collision au carrefour pourraient être réduits de 40% -50%.

Le convoi ou un peloton de de véhicules est un groupe de véhicules qui se suivent et se déplacent vers la même direction derrière un véhicule leader sur une route. Un véhicule leader à l'avant de ce peloton est conduit par un conducteur, tandis que les autres véhicules suiveurs sont en mode de conduite automatique (sans intervention humaine). Grâce à cette application, le groupe de véhicules peut se déplacer en toute sécurité efficacement et respectueux de l'environnement, car une conduite en douceur du peloton peut augmenter globalement le trafic routier et diminuer la consommation de carburant. De plus, la sécurité des passagers est garantie parce que les erreurs de conduite en mode automatique est beaucoup moins que celles des conducteurs humains.

2.4 Les défis

Dans la dernière section de ce chapitre, nous présentons des défis de VANET, qui correspondent également aux motivations du chapitre suivant, à savoir, le Protocole de Diffusion de Données dans VANETs. Il est important de clarifier les questions clés pour mieux concevoir des protocoles CIV qui permet de résoudre les problèmes existants.

Premièrement, nous présentons des réseaux hétérogènes de véhicules. Comme nous l'avons vu dans la description des technologies de médium sans fil et des applications CIV, chaque technologie de médium sans fil a ses propres avantages et inconvénients pour une application spécifique de CIV.

L'approche des VANETs hétérogènes est considérée comme une solution raisonnable. Mais, il y a encore quelques problèmes à résoudre pour améliorer la performance de communication au sein de VANET. De plus, il y a au moins deux principaux problèmes à surmonter tels que la tempête de radio diffusion 'Broadcast storm' et la partition de réseau au sein d'un VANET.

Le premier est un problème majeur pour diffuser des données sous le paradigme de la radiodiffusion au sein d'un VANET, qui peut engendrer un grand nombre de véhicules de radio diffusion et de réponse simultanément des mêmes données redondantes. Dans ce cas, il y aura beaucoup de collisions de données et de congestions de canaux à cause de la grande mobilité des véhicules et des obstacles des bâtiments. Pour ces raisons, le VANET est souvent partitionnée en plusieurs sous-réseaux.

Enfin, il existe deux métriques essentielles pour qualifier la performance d'un VANET, c'est-à-dire la fiabilité et l'évolutivité. La fiabilité est un enjeu clé pour la QoS des applications de CIV, pour lesquelles le réseau cellulaire et le mécanisme Store-Carry-Forward seraient utilisés pour obtenir une connectivité fiable.

L'évolutivité est la principale limitation d'un VANET, car toute diffusion d'un message a sa portée maximale.

Chapter 3 Protocole de Dissémination de données au sein VANET

3.1 Introduction

Certaines classes de protocoles de routage pour la diffusion des données au sein d'un VANET seront présentées dans ce chapitre. Ces protocoles de routage de VANET utilisent la technologie de communication à courte portée, c'est-à-dire l'IEEE 802.11p.

Tout d'abord, nous allons décrire les protocoles de routage MANET qui comprennent deux types, c'est-à-dire, le premier est basé sur la topologie de réseau et le deuxième s'appuie sur la position de chaque véhicule. Le premier type de protocoles est généralement appelé protocole de routage ad hoc alors que celui du deuxième peut également être nommé protocole de routage géographique.

Le protocole de routage MANET a une longue histoire dans le domaine du réseau sans fil mobile. Dans la phase initiale du développement des protocoles IVC, plusieurs protocoles de routage MANET ont été adoptés pour les VANET.

Le protocole de routage de MANET est considéré comme élément de base pour comprendre et concevoir le protocole de routage de VANET. Par conséquent, nous présentons d'abord le protocole de routage MANET, puis progressivement par la suite les protocoles de CIV. Une classe importante de protocoles CIV, c'est-à-dire le protocole de routage basé sur la position géographique 'Geocasting', est mise en évidence dans ce chapitre, y compris les efforts de normalisation. Le protocole de routage DTN et balisage 'beaconing' se consacrent également au 'Geocasting'. Le protocole de routage DTN est une approche efficace pour gérer les réseaux partitionnés mais il induit un délai supplémentaire. Le balisage est normalement responsable de l'échange d'informations locales dans le voisinage à un seul saut 'hop' et peut donc être utilisé pour des applications de sécurité. Enfin, les techniques clés des protocoles de diffusion des données sont résumées.

3.2 Protocole de routage ad hoc basé sur la topologie

Le protocole de routage de MANET basé sur l'information de topologie de réseau a d'abord été adopté dans VANETs dès les premiers jours. Il comprend trois types de protocoles de routage, c'est-à-dire un routage pro-actif, réactif et hybride. Les protocoles de routage de MANET ne seraient pas adaptés à la plupart des applications des VANET, mais leur connaissance de base s'avère indispensable pour comprendre et concevoir des protocoles de routage pour les VANET.

L'idée de base du protocole de routage pro-actif est de maintenir la topologie du réseau tout le temps afin de fournir des routes à jour entre les nœuds. De ce fait, l'envoi d'un message entre deux nœuds est immédiat, car le chemin de routage est connu. Ce principe est similaire à celui des protocoles de routage Internet classiques, dans lesquels la mise à jour de la table de routage 'routing table' est déclenchée lorsque la topologie du réseau change.

L'avantage du protocole proactif est que la route complète est disponible immédiatement chaque fois qu'un paquet doit être transmis. Toutefois, pour un réseau à grande échelle et en

particulier dans un environnement dynamique élevé, ce type de routage augmente significativement le trafic du réseau 'network overhead' car il faut maintenir périodiquement la topologie, ce qui est le cas des VANETs. Le réseau est facilement surchargé dans un réseau où le nombre de véhicules est important.

Même si les ressources du réseau sont supposées adéquates, la vitesse de mise à jour de la table de routage ne peut pas satisfaire aux exigences des applications CIV, en particulier pour les nœuds situés sur la bordure d'une VANET.

Le routage réactif (également appelé routage à la demande) établit un itinéraire vers la destination uniquement si un paquet doit être envoyé. Autrement dit, un processus de découverte de chemin de routage 'route request' est déclenché avant l'envoi d'un message. C'est pourquoi le protocole de routage réactif est aussi appelé protocole de routage "à la demande". La motivation essentielle du protocole de routage réactif est de réduire le trafic du réseau, par rapport au protocole de routage proactif. L'inconvénient du protocole de routage réactif est l'augmentation de délai de l'envoi d'un message car à chaque envoi, le processus de découverte de chemin de routage doit être effectué.

Une alternative de routage MANET est le routage géographique, qui est basé sur la position des nœuds au lieu des informations de topologie du réseau. Le routage nécessite de connaître à l'avance la position du nœud source (émetteur), des nœuds intermédiaires et du nœud destination.

Cependant, il est évident que la position du nœud destination est difficile à obtenir par le nœud source dans des réseaux ad hoc. C'est le plus grand défi du routage géographique dans les VANETs, qui n'a pas été abordé par la plupart des protocoles de routage géographique. Le service de localisation est la technique clé pour laquelle le réseau cellulaire peut être utilisé s'il existe des infrastructures disponibles. La position de chaque nœud peut être déterminée par le système de positionnement global (GPS). La granularité et la précision du GPS sont supposées être suffisantes pour toutes les techniques de ce chapitre.

3.3 Protocole de routage géographique 'Geocasting'

Lors de l'étude des protocoles de routage MANET, nous avons entrevu l'adoption du protocole de routage géographique pour les VANET et analysé les problèmes du protocole routage MANET en vue de la réalisation d'une application dans les VANET. La plupart des protocoles que nous avons mentionnés est basé sur l'unicast. Cependant, à l'exception de certaines applications d'« infodivertissement », le paradigme de communication unicast peut ne pas convenir à la plupart des applications des VANETs. En effet, il existe une autre technique dénommée radiodiffusion 'broadcast' qui permet de transmettre des paquets aux nœuds dans une zone géographique spécifique au lieu d'un nœud spécifique. La radiodiffusion a des caractéristiques plus souples et répond mieux aux exigences de diffusion des données dans les VANET. Par conséquent, le protocole de routage géographique basé sur la radiodiffusion est proposé pour être utilisé dans les VANET, à savoir le « Geocasting »

Des efforts de normalisation ont été réalisés par l'ETSI pour la diffusion des données dans les VANET. La norme ETSI « GeoNetworking » est développée pour être utilisée dans

la couche de réseau de la pile de protocoles ETSI ITS. La norme « GeoNetworking » est chargée d'organiser la communication sans fil entre les véhicules, et entre les véhicules et l'infrastructure tout en se concentrant sur l'atténuation des problèmes causés par la mobilité très dynamique des véhicules.

Une variété d'applications CIV sont supportées par GeoNetworking, depuis la diffusion de messages d'avertissement de sécurité routière par diffusion vers une application d'« infodivertissement » par l'unicast. Un certain nombre d'aspects sont pris en compte par « GeoNetworking », tels que les scénarios, l'architecture du réseau, l'adressage et la transmission, les protocoles de transport et l'intégration à l'Internet. Trois systèmes d'acheminement sont fournis par « GeoNetworking », c'est-à-dire « GeoUnicast », « GeoBroadcast » et une diffusion à portée topologique. En outre, l'ETSI a publié une norme pour la notification des événements liés à la circulation en 2013, à savoir les messages décentralisés de notification de l'environnement (DENM : Decentralized Environment Notification Messages).

Les messages de notification sont déclenchés par le service de base Décentralised Environment Notification (DEN) et ensuite diffusés à tous les véhicules dans la zone de destination. Ce type de message est axé sur les événements plutôt que sur une transmission périodique, comme un avertissement de danger routier.

3.4 Protocole de routage à tolérance de délai (DTN : delay Tolerant Network)

Le protocole de routage DTN repose principalement sur le mécanisme de stockage-transfert (SCF : Store-Carry-Forward), grâce auquel un véhicule peut stocker et transporter des paquets de données jusqu'à ce qu'il rencontre une nouvelle opportunité de transmission. Cette approche est un moyen efficace de gérer le problème de réseau déconnecté. En raison de la connectivité intermittente dans VANETs, il n'y a pas toujours une connexion de bout en bout entre le nœud source et le nœud destination. Le protocole de routage DTN peut améliorer le PDR (Packet Delivery Ratio) en permettant des transmissions opportunistes, mais l'inconvénient est l'augmentation du délai de transmission. Les applications utilisant ce type de routage doivent être tolérantes au délai de transmission car un retard important de temps de transmission est causé par le véhicule transportant des données sur la route.

3.5 Balisage Statique

Le balisage se réfère à la diffusion de message (hello()) périodiquement dans la zone de couverture radio à un saut. Le balisage statique est l'émission périodique d'une trame spécifique à intervalle fixe avec une puissance d'émission constante. Comme ce balisage est facile à mettre en œuvre, il est largement utilisé dans les protocoles de CIV pour détecter la position géographique des nœuds voisins pour le routage géographique.

3.6 Balisage adaptatif

L'idée de base d'un balisage adaptatif consiste à adapter les paramètres de transmission, par exemple la vitesse d'émission ou la puissance d'émission, en fonction de l'état actuel du canal, tout en maintenant la charge du canal en dessous de seuils prédéfinis.

L'objectif est d'atténuer la congestion des canaux. Pour les ETSI CAM, la congestion du canal a un effet dramatique car elle augmente la probabilité de perte CAM. De ce fait, le véhicule est plus difficile à détecter la situation potentiellement dangereuse dans son voisinage. Pour résoudre la congestion des canaux dans les VANET, l'ETSI a mis au point un ensemble de mécanismes de contrôle de la congestion décentralisée (DCC) pour atténuer la congestion du canal CAM.

Récemment, un nouveau processus de normalisation a été initialisé et est toujours en cours. Les travaux en cours de DCC reposent principalement sur les protocoles de contrôle de la vitesse adaptative à la charge périodiquement mis à jour (PULSAR : Periodically Updated Load Sensitive Adaptive Rate control) et LInear MESSage Rate Integrated Control (LIMERIC).

3.7 Techniques Clés

Après avoir étudié les protocoles CIV pour la diffusion des données dans les VANET, il est temps de résumer les principales techniques étudiées. À la compréhension de ces défis clés, nous pouvons réaliser une meilleure conception du protocole de diffusion des données. Tout d'abord, dans les réseaux bien connectés, la technique de suppression de diffusion est la clé pour diffuser les données dans toutes les directions routières possibles tout en atténuant le problème des tempêtes de radiodiffusion.

Pour atteindre ces objectifs, la portée radio est généralement divisée en plusieurs secteurs en fonction de la topologie de la route et l'état de trafic de chaque secteur. Mais, en raison de la topologie des routes irrégulières dans les scénarios urbains, la classification n'est pas précise. Deuxièmement, dans les réseaux déconnectés, le mécanisme SCF est chargé de combler le gap entre les réseaux séparés. Dans certaines applications, ce mécanisme est utilisé pour obtenir une PDR qualifiée dans des réseaux clairsemés ou très dynamiques. Mais, le mécanisme SCF a souvent déclenché plus de transmissions. Par conséquent, comment gérer la transmission des données transportées est un défi.

Chapter 4 Modèle de Mobilité et Scénarios de Trafic Routier Réalistes

4.1 Introduction

Dans cette thèse, nous avons utilisé le simulateur de circulation routière "Simulation of Urban MObility" (SUMO) pour créer des scénarios de trafic routier afin d'évaluer des performances des protocoles CIV. SUMO effectue la simulation microscopique par laquelle les véhicules routiers, les transports publics, les piétons sont modélisés explicitement. En fait, SUMO est une suite de simulation de trafic routier, dans laquelle différents outils peuvent être utilisés pour importer des réseaux routiers, créer des itinéraires de trafic et effectuer la visualisation.

Par conséquent, SUMO peut construire des scénarios de trafic très réalistes, où la carte routière réelle, les bâtiments, la règle de circulation et les feux de circulation sont simulés selon ceux du monde réel. Dans ce résumé, le contenu le plus important, c'est-à-dire les scénarios de trafic routier réalistes et la simulation couplée avec le simulateur de réseau (OMNET++), sont présentés brièvement. Le contenu détaillé de ceux-ci et d'autres contenus, par exemple le modèle de mobilité de SUMO et les scénarios abstraits de trafic routier, sont élaborés dans la version complète du manuscrit.

4.2 Scénarios réalistes de Trafic routier

Le scénario routier réaliste comprend une carte et un certain nombre de routes de circulation. Tout d'abord, nous expliquons comment convertir la source de données géographiques disponibles en carte SUMO, puis différents types d'itinéraires de trafic seront conçus à des fins respectives. Notez que les scénarios réalistes de trafic routier décrits dans cette section sont également utilisés dans nos simulations CIV au chapitre 5.

Pour obtenir une carte de trafic routier réaliste pouvant être utilisée dans SUMO, nous avons utilisé OpenStreetMap comme source de données géographiques. Nous sélectionnons le centre-ville de Clermont-Ferrand, en France, par exemple pour illustrer le processus de création de la carte SUMO. La carte comprend le réseau routier et le polygone des bâtiments.

Tout d'abord, nous introduisons comment obtenir le réseau routier à partir d'OpenStreetMap. Le réseau routier spécifie la topologie routière, la règle de circulation et les feux de circulation. NETCONVERT, un outil de la suite SUMO, a été utilisé pour extraire le réseau routier d'OpenStreetMap. De plus, un fichier de type routier est également inclus dans lequel sont définis le type et la priorité des routes, la limitation de vitesse maximale et le numéro de voie par défaut.

L'OpenStreetMap du centre-ville de Clermont-Ferrand est représenté sur la Figure 4-1a. Après avoir importé ces fichiers OpenStreetMap et Road Type dans NETCONVERT, le réseau routier peut être obtenu, comme le montre la Figure 4-1b.

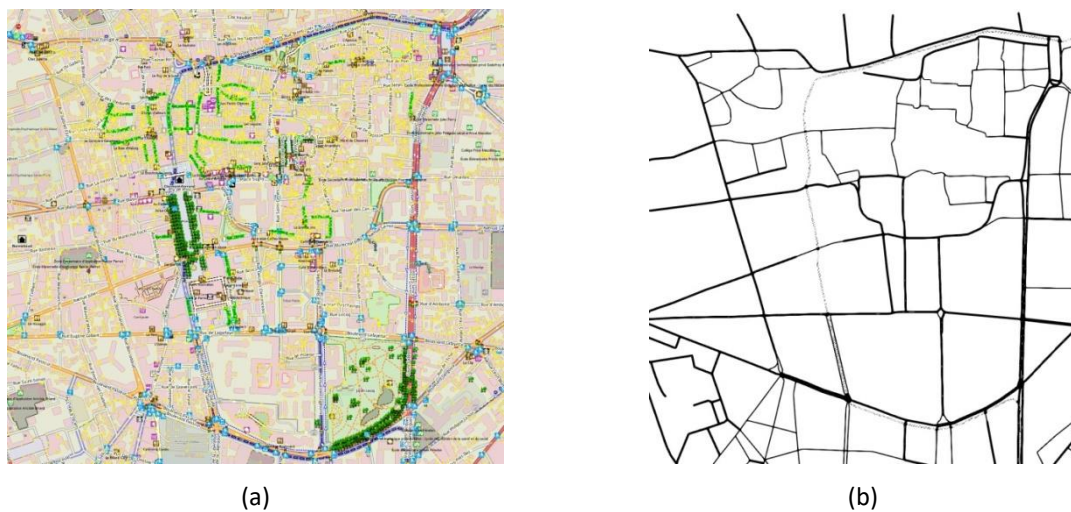


Figure 4-1. OpenStreetMap et réseau routier du centre-ville de Clermont-Ferrand

Deuxièmement, nous présentons comment extraire le polygone de bâtiment de l'OpenStreetMap. Le polygone de bâtiment sera utilisé comme obstacles dans nos simulations CiV. POLYCONVERT, un outil de la suite SUMO, est utilisé pour compléter cette mission. Un OpenStreetMap, un réseau routier et un fichier de type polygone sont importés dans l'outil. L'OpenStreetMap et le réseau routier représentent la première étape. Le fichier de type polygone comporte l'ID de polygone, le nom de polygone, la couleur et la couche d'image. L'ID et le nom du polygone sont utilisés pour matcher avec les composants d'OpenStreetMap. Si le composant est apparié, il sera assigné par la couleur prédéfinie et la couche d'image pour la carte SUMO.

Le réseau routier et le polygone de construction sont combinés pour comprendre la carte SUMO, comme le montre la Figure 4-2b. A titre de référence, l'OpenStreetMap est également illustré par la Figure 4-2a.



Figure 4-2. Cartes de OpenStreetMap et de SUMO du centre-ville de Clermont-Ferrand

4.2.1 Trafics Routiers

Nous utilisons encore la simulation du trafic routier à boucle fermé (close loop) pour des scénarios réalistes. Dans cette section, nous allons présenter comment concevoir des itinéraires de circulation sur la carte SUMO. Prenons des scénarios de Clermont-Ferrand par exemple, tout d'abord, nous sélectionnons des embranchements comme les points de départ qui sont aussi les points de retour du boucle fermé de la Simulation, comme le montre la Figure 4-3a. Ensuite, des itinéraires de circulation sont créés entre chaque paire de points de départ, comme le montre la Figure 4-3b.

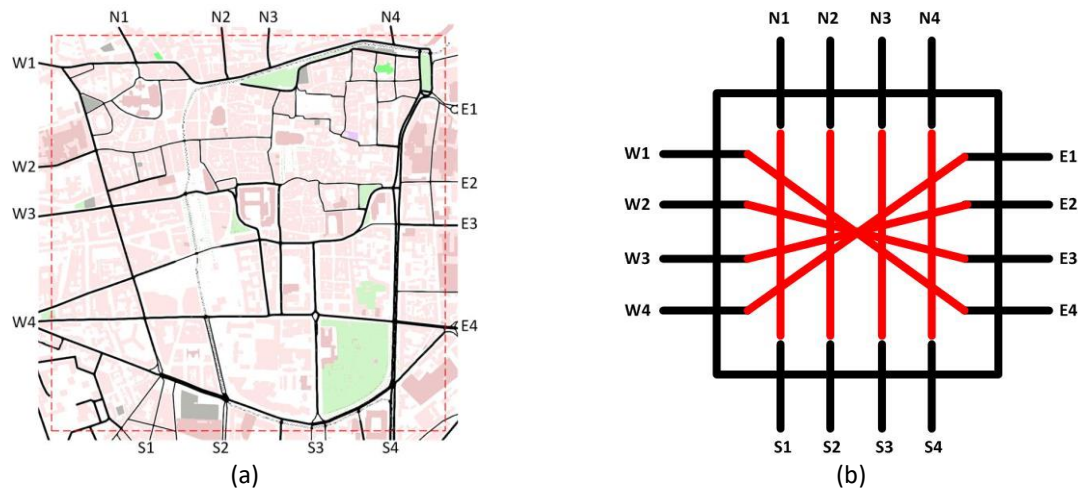


Figure 4-3. Traffic routes in Clermont-Ferrand scenarios

4.3 Simulation du réseau routier et du trafic routier bidirectionnel

Dans cette section, nous allons présenter comment intégrer des scénarios réalistes dans des simulations CIV. En 2011, Sommer et al. a proposé un cadre de simulation couplé bidirectionnellement, dans lequel un simulateur de réseau, c'est-à-dire OMNeT ++, est associé à SUMO, comme le montre la Figure 4-4. Par conséquent, SUMO peut fournir des scénarios réalistes pour le simulateur de réseau pour effectuer des simulations CIV. Étant donné que la topologie de la route et les obstacles de construction des scénarios réalistes sont les mêmes que ceux du monde réel, la fiabilité et la précision des simulations CIV ont été portées à une nouvelle étape.

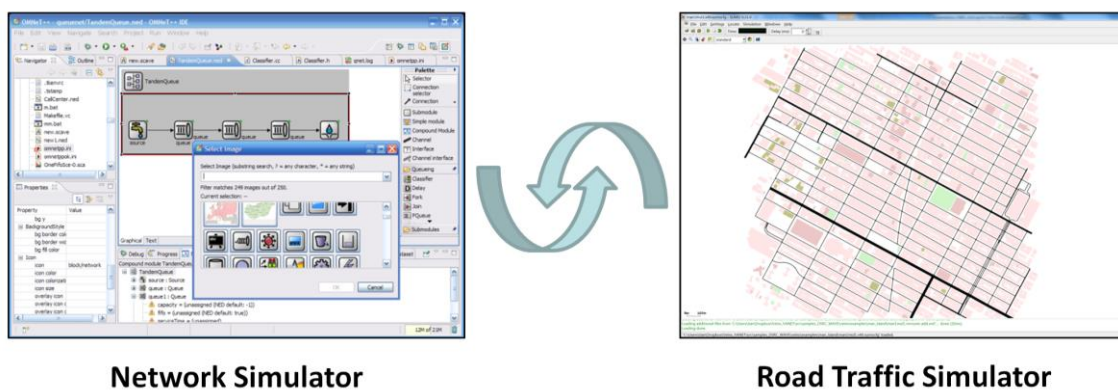


Figure 4-4. Illustration de la simulation couplée bidirectionnellement

OMNeT ++ est un simulateur de réseau d'événements discrets qui fournit une plateforme mature pour plusieurs plateformes de simulation, par exemple Veins, INET. De notre expérience, la robustesse de cette simulation couplée est forte, car nous avons effectué un grand nombre de simulations sans échec et chaque série de simulation fonctionne pendant plusieurs heures et jours. Les techniques détaillées seront décrites dans les sections suivantes.

Chapter 5 TrAD: Traffic Adaptive Data Dissemination Protocol

5.1 Introduction

Les VANETs peuvent fournir une technologie de communication sans fil entre les véhicules (V2V) ou entre les véhicules et l'infrastructure (V2I) pour soutenir le développement de diverses applications concernant la sécurité routière, l'efficacité du transport et l'« infotainment on wheels ». Dans ce chapitre, nous nous concentrons sur les applications de sécurité, dans lesquelles les messages d'urgence axés sur les événements, par exemple les avertissements d'accidents de la circulation, doivent être diffusés efficacement dans une région géographique spécifique. Les protocoles CIV haute performance sont la clé de cette exigence, à savoir les protocoles de diffusion de données.

Cependant, les VANETs ont des caractéristiques très dynamiques et intensives en données, spatialement et temporellement localisées, ce qui rend la conception des protocoles de diffusion de données une tâche difficile. Par conséquent, un protocole de diffusion de données adaptative au trafic (TrAD) est proposé pour résoudre ces problèmes dans les scénarios urbains et routiers, tout en visant simultanément un ratio de livraison de paquets élevé, un faible trafic de réseau et un faible délai.

Les principales contributions de ce document peuvent être résumées comme suit :

- Pour la technique de suppression de radiodiffusion, une classification des clusters de véhicules et une technique de tri ont été conçues pour améliorer la fiabilité des transmissions de radiodiffusion et supprimer le problème de la tempête de radiodiffusion.
- Pour le mécanisme de transfert de données sauvegardées, des véhicules spécifiques ont été choisis pour être des retransmetteurs de données afin d'échanger des informations entre différents réseaux déconnectés. De plus, les transmissions redondantes de ce processus ont été supprimées.
- Un contrôle de congestion de canal a été conçu en fonction de l'état de trafic du réseau local.
- Une évaluation globale du rendement a été effectuée au moyen de simulations réalistes. Trois protocoles classiques de dissémination des données ont été comparés à ceux du TrAD dans les scénarios urbains et routiers. De plus, l'impact d'erreur du GPS sur la vitesse de diffusion des données a également été étudié.

5.2 Diffusion des données routières adaptatives

Le protocole TrAD est basé sur deux composantes principales. La première composante adopte la technique de suppression de radiodiffusion pour les réseaux bien connectés, et la seconde adopte un mécanisme de « store-carry-forward » pour les réseaux déconnectés. La Figure 5-1 présente les deux modes de fonctionnement du protocole TrAD selon les scénarios des réseaux : réseau connecté ou déconnecté.

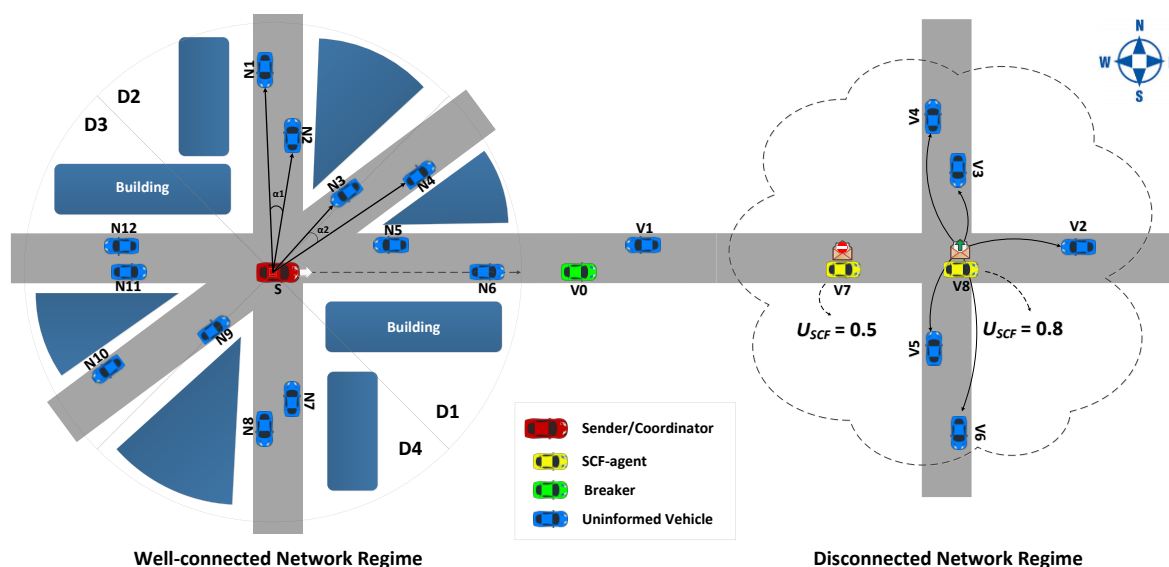


Figure 5-1. Illustration du protocole TrAD.

Pour une meilleure compréhension de ce protocole, nous définissons plusieurs concepts pour TrAD. Ces concepts seront utilisés tout au long du chapitre :

Cluster directionnel Cd: Le cluster directionnel est un groupe de véhicules dans le voisinage à un seul saut de l'émetteur S. De plus, ces véhicules se déplacent dans une direction similaire à celle de transmetteur S. Dans une situation idéale, S peut classifier avec précision ses nœuds voisins dans des clusters directionnels différents qui correspondent aux différentes topologies routières qui l'entourent. Par exemple, S classe ses nœuds voisins N1, N2 en C1 et N3, N4 en C2 comme illustré sur la Figure 5-1. Les deux clusters directionnels sont exactement sur les deux différentes directions.

- Coordinateur : Ce concept a d'abord été défini dans le protocole Greedy Perimeter Coordinator Routing (GPCR). Le coordinateur est le véhicule situé à un carrefour (par exemple, l'émetteur S dans la Figure 5-1).

- Disjoncteur : Dans un réseau bien connecté, le disjoncteur est non seulement le véhicule le plus éloigné dans le sens d'acheminement mais se déplace également vers l'extérieur du réseau de véhicule (par exemple, le véhicule vert V0 de la Figure 5-1).

- Agent SCF : Le rôle d'un véhicule agent SCF est d'être responsable du stockage et du transport des messages de données jusqu'à ce qu'il rencontre des opportunités d'acheminer (diffuser) les messages de données stockées vers des véhicules non-informés provenant d'autres VANET.

- Balisage et balisage : Un balise est défini comme un message périodique qui est responsable de mise à jour les états des nœuds se trouvant dans le voisinage à un seul saut. Ce processus d'échange périodique est appelé balisage. Le format de la balise est défini comme suit : <ID de Balise, ID d'Expéditeur, Position GPS Globale, En-tête, Nombre de Voisins, Ratio d'Occupation de Chaîne, Liste de Messages>.

TrAD exige que chaque véhicule envoie des balises pour échanger leur état dans la zone à

un seul saut. La période de balisage P_b est fixée à 1 s et la tolérance de balise égale à $1,5 P_b$ pour une réaction rapide au changement de voisins.

5.2.1 Technique de suppression de radiodiffusion

Pour atténuer la tempête de radiodiffusion dans les réseaux bien connectés, d'abord, un émetteur utilise un mécanisme de classification pour trier ses voisins en différents clusters directionnels. Ensuite, une technique de tri considère à la fois le trafic routier et l'état du trafic réseau pour allouer différents ordres de rediffusion aux voisins dans des clusters directionnels.

Ensuite, l'émetteur insère la liste de commande de rediffusion, c'est-à-dire la liste de priorités, dans le message de données et l'envoi. Lorsque les voisins de l'émetteur reçoivent les données, le délai d'attente de contention est utilisé pour établir l'ordre de rediffusion respectif et la planification de radiodiffusion.

Ainsi, les nœuds voisins commencent à chercher une opportunité pour rediffuser le message. Un voisin possédant une priorité supérieure rediffusera plus tôt le message. Si un véhicule reçoit des données redondantes (un écho) issues d'un membre du même cluster directionnel, il annule sa planification de rediffusion et passe à un état inactif. Lorsque le temps d'attente a expiré 'time-out', si le véhicule ne reçoit de message du même cluster ou ne reçoit que les données des véhicules d'un autre cluster directionnel, il rediffuse en premier.

Par conséquent, la technique de suppression appliquée permet non seulement de supprimer les émissions redondantes, mais aussi de diffuser les messages de données dans toutes les directions possibles. Notez que l'émetteur adopte une décision locale centralisée et assigner l'ordre de rediffusion des nœuds voisins. La raison en est que la décision centralisée locale peut résoudre le problème terminal caché dans la radiodiffusion multidirectionnelle.

5.2.1.1 Mécanisme de classification des clusters à base d'un angle vectoriel

Un algorithme de classification simple et flexible est conçu, qui utilise uniquement l'information de position plutôt que l'itinéraire numérique. Par conséquent, il nécessite moins de puissance de calcul et s'adapte à des topologies de routes plus complexes. L'algorithme utilise un angle vectoriel pour déterminer si les véhicules appartiennent à un cluster directionnel ou non.

L'opération de classification de cluster est conduite comme suit : Dans le réseau bien connecté de la Figure 5-1, l'émetteur S extrait le premier voisin N1 de sa liste de voisins et classe N1 dans le groupe directionnel C_1 . Connaissant les coordonnées N1 et N2, l'angle α_1 entre $\overrightarrow{SN1}$ et $\overrightarrow{SN2}$ peut être obtenu à partir de leur produit scalaire ($\alpha_1 \in [0, \pi]$). L'algorithme compare α_1 avec un angle de seuil α , par exemple, $\alpha = 10^\circ$.

Si l'angle α_1 est inférieur à α , le voisin N2 est classé dans le cluster directionnel C_1 . Sinon, le voisin N2 reste dans la liste des voisins pour l'étape suivante. Dans le cas de la Figure 5-1, $\alpha_1 < \alpha$, donc $N2 \in C1$. Ce processus se poursuit jusqu'à ce que tous les voisins

aient été classés. Par conséquent, un cluster de véhicules C1 qui sont situés dans la direction similaire à N1 est identifié. Les membres de C1 sont enregistrés dans une mémoire tampon de cluster et éliminés de la prochaine étape de classification. La classification sera effectuée en continu jusqu'à ce que tous les nœuds voisins aient été classés dans les clusters directionnels respectives.

Le résultat de la classification de TrAD dans le cas d'un réseau bien connecté, est illustré par la Figure 5-1 est $C1 = \{N1, N2\}$; $C2 = \{N3, N4\}$; $C3 = \{N5, N6\}$; $C4 = \{N7, N8\}$; $C5 = \{N9, N10\}$; $C6 = \{N11, N12\}$. Les véhicules situés dans la même direction par rapport à S sont exactement classés dans le même cluster directionnel. De plus, le résultat de la classification AMD est également illustré par la Figure 5-1. AMD divise la portée de radiodiffusion en quatre secteurs égaux, c'est-à-dire D1, D2, D3 et D4. Notez que le résultat de la classification AMD n'est pas exact.

Les $C2 = \{N3, N4\}$ et $C3 = \{N5, N6\}$ sont combinés dans le secteur D1, et les $C5 = \{N9, N10\}$ et $C6 = \{N11, N12\}$ sont mélangés dans le secteur D3. De plus, les véhicules N3 et N9 se trouvant à la frontière des secteurs sont ambigus. Le résultat prouve que la classification sectorielle directionnelle de l'AMD n'est pas appropriée pour la topologie routière irrégulière.

5.2.1.2 Technique de tri adaptée aux trafics routier

L'algorithme tient compte à la fois du trafic routier et du trafic de réseau. Trois paramètres sont pris en considération : le nombre des nœuds voisins N, la distance entre un émetteur et son voisin D, et le ratio d'occupation du canal (CBR 'Channel Busy Ratio'). Les métriques N et D représentent la condition du trafic routier et CBR reflète l'état du trafic réseau. L'émetteur S utilise ces trois paramètres pour estimer l'utilité U_{TX} et détecte la congestion de canal pour chaque voisin. Tout d'abord, les paramètres doivent être quantifiées pour le calcul de l'utilité U_{TX} . La valeur de toutes les paramètres, est de [0,1].

Le paramètre N (équation (5-1)) indique la couverture de données des véhicules potentiels dans la prochaine transmission :

$$N = \min\left(\frac{\#Neighbor}{\max.\#Neighbor}, 1\right) \quad (5-1)$$

$\#Neighbor$ est le nombre de nœuds voisins instantanés à un saut de l'émetteur. Pour la simulation, $\#Neighbor$ est un nombre maximal prédéfini de voisins, et il est initialisé à 25. Le paramètre D (équation (5-2)) représente la distance entre un émetteur et son voisin.

$$D = \min\left(\frac{Dist_{sn}}{\max.RadioRange}, 1\right) \quad (5-2)$$

$Dist_{sn}$ est la distance mesurée entre l'émetteur et son voisin. $\max.RadioRange$ est la portée maximale du support d'accès sans fil.

Le paramètre CBR (équation (5-3)) décrit l'occupation du canal sans fil dans un intervalle de temps de détection $T_{interval}$, par exemple 1 s. Le temps d'occupation du canal T_{busy} est détecté par le mécanisme « Clear Channel Assessment (CCA) » dans la couche PHY de l'IEEE 802.11p :

$$CBR = \frac{T_{busy}}{T_{interval}} \quad (5-3)$$

Par conséquent, nous proposons une équation (Équation (5-4)) pour déterminer un critère de transmission prioritaire U_{TX} lorsqu'il a plus de voisins, une longue distance et une charge de canal moins occupée (libre). N et D ont un poids égale pour représenter la circulation routière. Enfin, l' U_{TX} est mis à l'échelle sur la base d'un coefficient ω_{CBR} qui est lié à l'état de trafic réseau, c'est-à-dire CBR :

$$U_{TX} = \omega_{CBR} \cdot \left(\frac{N+D}{2} \right) \quad (5-4)$$

ω_{CBR} est défini comme une fonction linéaire par morceaux (équation (5-5)) en fonction de CBR. La charge du réseau est divisée en trois niveaux selon CBR, c'est-à-dire libres, occupés et encombrés :

$$\omega_{CBR} = \begin{cases} 1 & 0 < CBR < 0.6 \\ 1 - CBR & 0.6 \leq CBR < 0.8 \\ 0.001 & 0.8 \leq CBR < 1 \end{cases} \quad (5-5)$$

Les voisins dans chaque cluster directionnel sont triés par ordre décroissant en termes d'utilité. Ensuite, on utilise une méthode de tourniquet «round robin» pour définir l'ordre final des véhicules dans la liste des priorités. Pour une explication claire, la Figure 5-2 illustre le procédé de la technique de tri.

Le véhicule ayant la plus grande valeur de U_{TX} dans le cluster directionnel C1 est placé dans la première position de la liste prioritaire, suivi par le véhicule ayant la plus grande valeur de U_{TX} dans le cluster directionnel C2, etc. Cette méthode garantit l'équité pour chaque cluster directionnel.

Par exemple, on suppose que l'utilité U_{TX} des véhicules est proportionnelle à son numéro d'identification. Dans la Figure 5-2, par exemple, $U_{N2} > U_{N1}$, donc après le premier passage de tri, la liste de priorité est {N2, N4, N6, N8, N10, N12}. Au deuxième passage, tous les voisins sont triés et la liste finale des priorités est {N2, N4, N6, N8, N10, N12, N1, N3, N5, N7, N9, N11}.

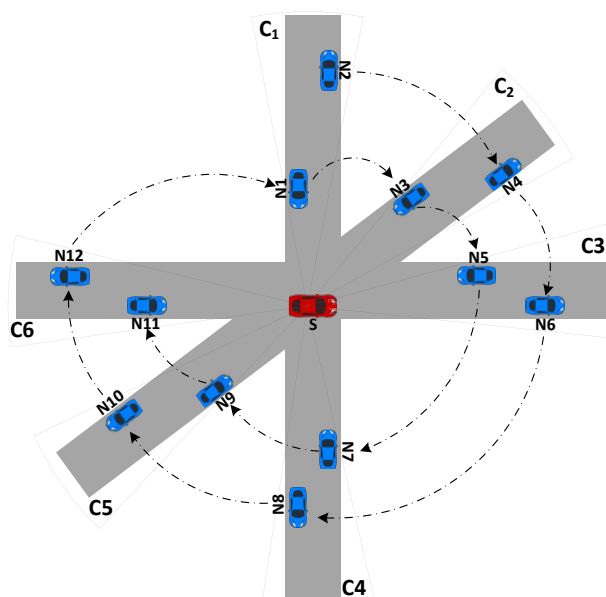


Figure 5-2. Le processus de tri pour établir la liste de priorité

L'émetteur S insère la liste de priorités dans l'en-tête du message de données avant la transmission. Le format d'en-tête est <ID de données, ID d'origine, ID d'expéditeur, Position d'expéditeur, Position d'expéditeur, Liste de priorité>.

Lorsque les destinataires reçoivent un message de données de S, ils extraient la liste de priorité et recherchent leur rang $R \in [0, n-1]$, où n est le nombre de voisins. TrAD donne un intervalle de temps t_i entre deux transmissions (la précédente et la dernière transmissions). t_i comprend le temps total pris de l'émetteur au récepteur, tel que le temps d'accès au support sans fil, le temps de propagation et le temps de transmission. Le temps (temporisation) des transmissions $Delay_{TX}$ est obtenu en utilisant l'équation (5-6) :

$$Delay_{TX} = t_i \cdot R \quad (5-6)$$

5.2.2 Mécanisme de stockage et retransmission

TrAD attribue le rôle de l'agent SCF aux véhicules à un emplacement spécifique dans un VANET, ce qui est bénéfique pour combler les lacunes de connectivité entre les clusters de véhicules. L'agent SCF stocke et transporte des messages de données d'un cluster à un autre, puis il transmet (diffuse) les données stockées aux nouveaux véhicules à venir. C'est-à-dire que TrAD utilise le délai temporel pour compléter la partition spatiale.

De plus, nous avons conçu une technique de contrainte de rediffusion d'agent SCF qui est une opération particulière pour réduire davantage les émissions redondantes. Afin d'éviter la redondance des données, le protocole compare la liste des messages d'un agent SCF avec ceux de ses voisins. Seuls les messages de données requis par le voisin seront planifiés en utilisant la technique de contrainte de rediffusion de l'agent SCF.

5.2.2.1 La Sélection de SCF-agent

Afin de faciliter la compréhension, nous présentons quelques techniques qui permettent à TrAD d'identifier le coordinateur et le disjoncteur.

- **Coordonnateur** : Après avoir préchargé dans le système une liste de position de carrefours de la carte urbaine ; Chaque véhicule calcule la distance entre lui-même et toutes les carrefours lorsque le véhicule reçoit un message de balise. Si la distance est inférieure à 20 m, le véhicule est défini comme un coordonnateur.

- **Disjoncteur 'Breaker'** : L'organigramme d'identification d'un disjoncteur. Lorsqu'un véhicule reçoit un message de données, il détecte et élimine la possibilité du rôle de coordonnateur. Ensuite, le véhicule détermine si sa direction de déplacement est la même que le sens d'acheminement des données. Si c'est le cas, le véhicule vérifiera si un autre voisin se déplace à l'avant. Sinon, le véhicule est défini comme le disjoncteur. En particulier, cette procédure est effectuée en continu jusqu'à la limite du réseau bien connecté.

Les véhicules qui satisfont à l'une quelconque des définitions de coordonnateur et de disjoncteur sont sélectionnés pour être des agents SCF. Cette opération est compatible avec les scénarios urbains et routiers. Le coordonnateur est spécialisé dans la topologie bidimensionnelle des scénarios urbains. Au carrefour, un coordonnateur a évidemment plus de chances de connecter aux voisins que les véhicules situés entre les intersections.

Par conséquent, TrAD choisit des coordonnateurs pour stocker et retransmettre les données, ce qui est bénéfique pour atteindre les véhicules non informés. Étant donné qu'il n'y a pas de coordonnateur dans les scénarios routiers, le disjoncteur est défini pour les scénarios urbains et routiers. Il peut conduire vers l'extérieur du réseau bien connecté et de transmettre le message de données dans une zone plus large.

5.2.2.2 SCF-agent Rebroadcast Constraint Technique

La technique de contrainte de rediffusion vise à éviter les rediffusions redondantes lorsque plusieurs agents SCF reçoivent une contrainte identique (balise) simultanément. Si le protocole ne comporte pas une telle technique de contrainte, ces agents SCF transmettront les mêmes messages de données en même temps et des émissions et collisions redondantes seront importantes. Ainsi, nous utilisons également le temps d'attente de contention pour éviter la transmission redondante.

Cette méthode permet de calculer différents délais (temps de retrait 'back-off times') en fonction de l'utilité U_{SCF} de chaque agent SCF. Si un agent SCF reçoit un message de données identique à celui qu'il planifie, l'agent SCF annule la planification de renvoi et passe à un état inactif. Si ce n'est pas le cas, l'agent SCF transmettra le message lorsque le temporisateur expire.

Contrairement à l'utilité U_{TX} dans la technique de suppression de radiodiffusion, ici, un agent SCF reçoit une utilité U_{SCF} plus élevée lorsque l'agent SCF et un véhicule non informé sont plus proches. En effet, une distance plus courte est utile pour garantir une meilleure QoS de retransmissions consécutives. En outre, étant donné que le nombre de voisins ne contribue pas à la transmission de SCF et ne limite pas la retransmission redondante, U_{SCF} ne la considère pas. Le coefficient ω_{CBR} , représentant l'état du réseau, est également utilisé pour estimer U_{SCF} (Equation (5-7)) :

$$U_{SCF} = \omega_{CBR} \cdot (1 - D) \quad (5-7)$$

Il est à noter que, en général, un nouveau véhicule entrant (non informé) a besoin plusieurs messages de données. Surtout à la limite du ROI, le véhicule sortant du ROI effectuera des transmissions consécutives au nouveau véhicule entrant dans le ROI. Si le protocole ne gère pas correctement ce scénario, une rafale de transmissions sera effectuée. Par conséquent, TrAD utilise l'équation (5-8) pour calculer le délai de retransmission $Delay_{SCF}$ pour résoudre ce problème :

$$Delay_{SCF} = t_i \cdot [BurstCount + (1 - U_{SCF})] \quad (5-8)$$

Un intervalle de temps t_i est établi entre chaque transmission des messages de données requis. Le BurstCount est l'ordre de transmission des messages de données. Un agent SCF avec une utilité U_{SCF} la plus élevée déclenchera plus rapidement une transmission des messages de données dans sa file d'attente de transmission. Le $t_i \cdot (1 - U_{SCF})$ ajoute un délai supplémentaire, ce qui permet d'atténuer le problème de synchronisation des intervalles de temps.

Par exemple, dans le réseau déconnecté illustré par la Figure 5-1, les véhicules V7 et V8 sont des agents SCF se déplaçant dans un réseau bien connecté et transportant les mêmes messages de données. Ils ont reçu simultanément une trame balise de leurs véhicules voisins. Comme l'utilité U_{SCF} de V8 (0.8) est supérieure à celle de V7 (0.5), V8 est déclenchée pour diffuser les messages de données en premier. Par conséquent, V7 reçu le message de données redondant, puis annule la planification de transmission respective. Par conséquent, les transmissions redondantes de V7 sont supprimées.

5.3 Evaluation de Performance

Pour évaluer la performance du protocole TrAD, nous nous efforçons de mettre en œuvre des simulations réalistes dans les scénarios urbains et routiers. Pour réaliser une évaluation objective de la performance, les programmes de simulation sont mis en œuvre en incluant trois protocoles CIV de référence : DV-CAST pour les scénarios routiers, UV-CAST pour les scénarios urbains et AMD pour les scénarios routiers.

L'analyse quantitative tient compte des paramètres suivants :

- Ratio de livraison des paquets (PDR '*Packet Delivery Ratio*') : Il représente le nombre moyen de messages de données reçus par les véhicules dans le ROI en pourcentage du nombre total de messages de données envoyés par le nœud source. Il peut également être appelé la couverture de la diffusion des données

- Nombre de transmissions : C'est le nombre total de transmissions de message effectué par les véhicules pour la diffusion dans le ROI pendant toute la durée de la simulation.

- Délai : C'est l'intervalle de temps moyen entre l'envoi d'un message de données par le nœud source et sa réception par les véhicules dans le ROI.

- Vitesse de diffusion des données : ce paramètre représente la vitesse à laquelle les données peuvent être diffusées parmi les véhicules du ROI. Pour quantifier ce paramètre, le nœud source n'envoie qu'un seul message de données, puis la simulation calcule l'augmentation de la couverture des données avec le temps. Si la couverture des données augmente considérablement en peu de temps, ce qui signifie que le protocole atteint une

performance de diffusion élevée. Cette métrique est principalement utilisée pour estimer l'impact de la dérive GPS sur la performance des protocoles.

Pour évaluer de manière exhaustive les performances de TrAD, diverses expériences ont été conçues pour analyser l'impact de différentes cartes urbaines, différentes voies de circulation, la densité du réseau et la dérive GPS.

5.3.1 Différentes cartes Urbaines

Deux cartes ont été créées pour les scénarios urbains. L'une est un fragment de l'arrondissement de Manhattan à New York, aux États-Unis (Figure 5-3a), et l'autre est le centre-ville de la ville de Clermont-Ferrand, en France (Figure 5-3b). La dimension du ROI des deux cartes est de 1 x 1 km². Les chiffres montrent que la carte de Clermont-Ferrand possède plus de voies, de jonctions et de longueurs de rue plus courtes que celle de Manhattan, ce qui signifie que le trafic routier est plus complexe à Clermont-Ferrand qu'à Manhattan.

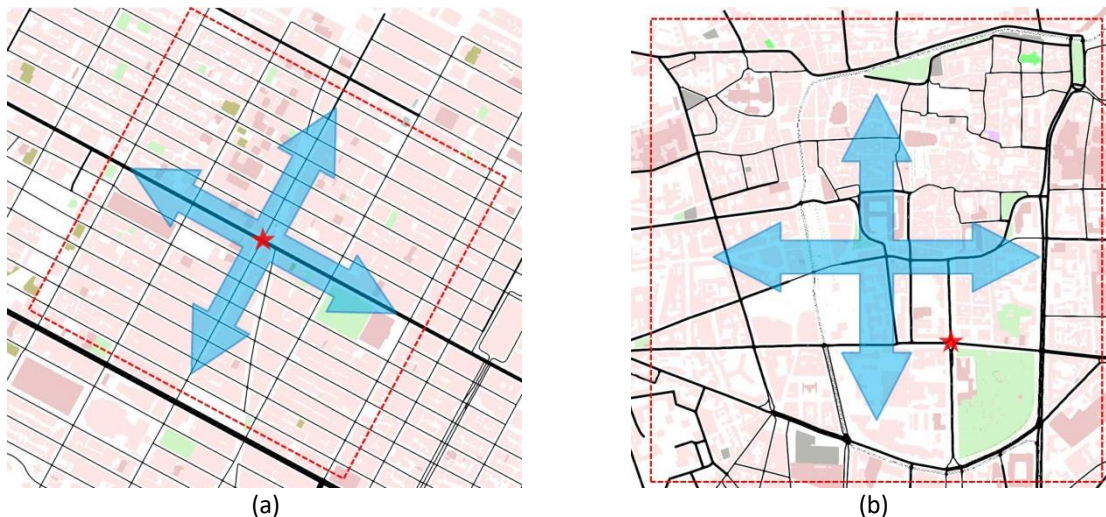


Figure 5-3. cartes urbaines : (a) Arrondissement de Manhattan à New York (États-Unis). (b) Clermont-Ferrand (France) ; Les itinéraires de circulation sont indiqués par des flèches dans les scénarios urbains ; L'étoile rouge est le nœud source qui diffuse périodiquement des messages de données ; La ligne rouge discontinue indique la limite du ROI

Les messages de données sont générés par un nœud source fixe situé à une intersection et sont collectés par tous les véhicules circulant dans le ROI. Des itinéraires de trafic similaires ont été créés pour les deux cartes, par lesquelles les véhicules sont uniformément répartis dans les scénarios. Chaque densité de véhicule est simulée pendant 400s et répétée 10 fois avec différentes données aléatoires. Les résultats avec un intervalle de confiance de 95% sont montrés dans la Figure 5-4 et la Figure 5-5. Les points de jonction de la courbe sont les valeurs moyennes de la métrique dans des simulations répétées. Les barres d'erreur supérieure et inférieure représentent respectivement le maximum et le minimum.

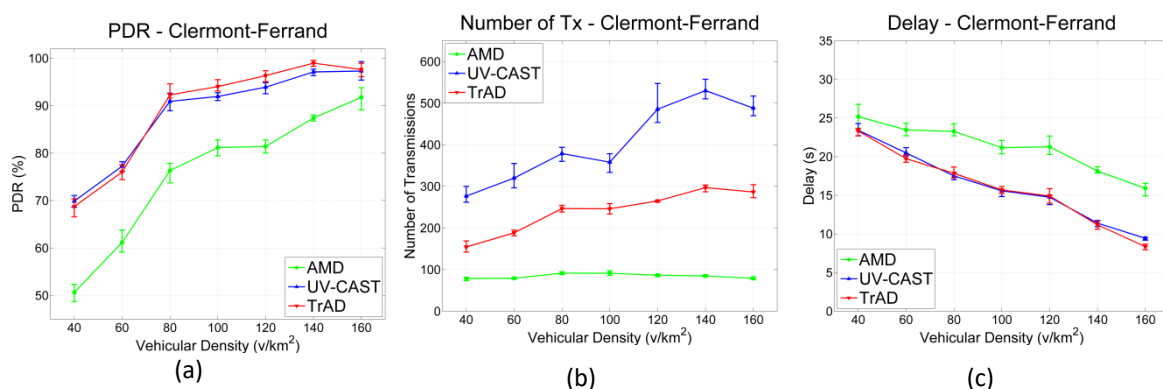


Figure 5-4. Résultats avec un intervalle de confiance de 95% dans les scénarios de Clermont-Ferrand : (a) PDR, (b) Nombre de Transmissions, (c) Délai.

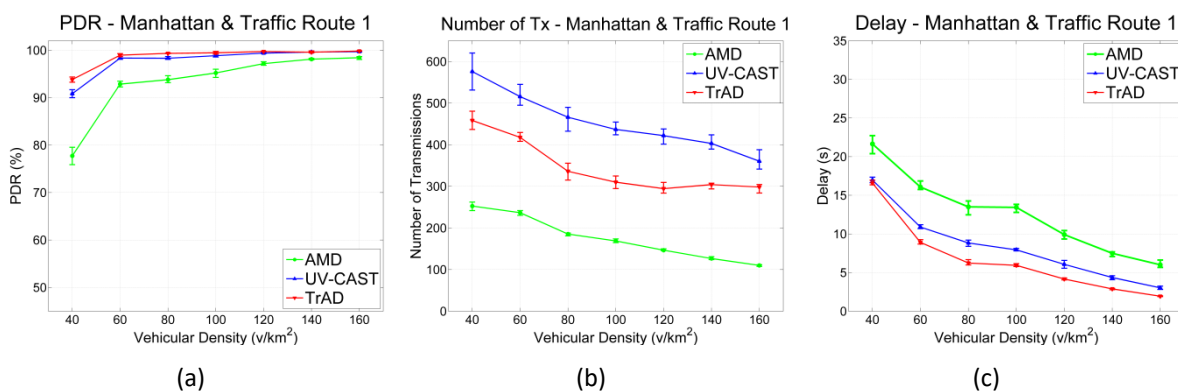


Figure 5-5. Résultats avec un intervalle de confiance de 95% dans les scénarios de Manhattan avec la route de circulation 1 (uniforme) : (a) PDR, (b) Nombre de Transmissions, (c) Délai.

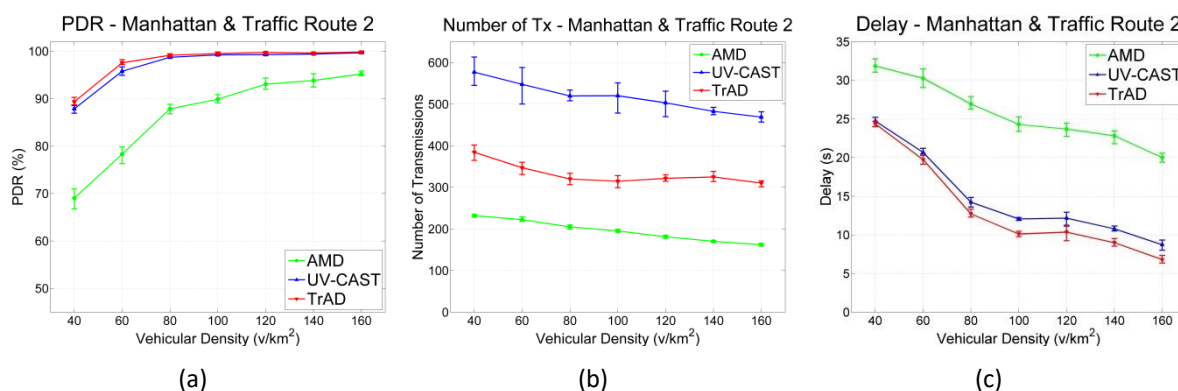


Figure 5-6. Résultats avec un intervalle de confiance de 95% dans les scénarios de Manhattan avec la route de trafic 2 (déviée) : (a) PDR, (b) Nombre de Transmissions, (c) Délai.

Comme on pouvait s'y attendre, les résultats de simulation obtenus montrent que les différentes cartes urbaines ont un impact significatif sur les protocoles de communication sans fil car les scénarios affectent respectivement la topologie du réseau et la qualité des liens du réseau. Dans le scénario de Clermont-Ferrand, le PDR et le délai de TrAD et UV-CAST sont similaires et meilleurs que ceux de l'AMD. UV-CAST effectue plus de transmissions tandis que TrAD effectue modérément les transmissions. Bien qu'AMD

effectue moins de transmissions, elle réalise le PDR et le délai sont les plus défavorables. En comparant les résultats de simulation de Clermont-Ferrand avec ceux de Manhattan, nous pouvons constater que le PDR et le délai de chaque protocole à Manhattan sont meilleurs en raison de la topologie de route régulière du scénario de Manhattan. Mais, il est à noter que TrAD effectue modérément des transmissions pour obtenir un PDR élevé et un faible délai. En outre, le délai de TrAD à Manhattan est le meilleur que les deux autres protocoles.

5.3.2 Différents Trafics Routiers

Pour les scénarios urbains, la plupart des travaux antérieurs ont utilisé des cartes différentes pour évaluer la performance de leurs protocoles CIV. Notez que les différents trafics routiers sur une même carte peuvent également avoir un impact significatif sur la performance des protocoles CIV. Par conséquent, nous analysons non seulement l'impact de différentes cartes, mais nous étudions aussi l'impact des différents trafics routiers.

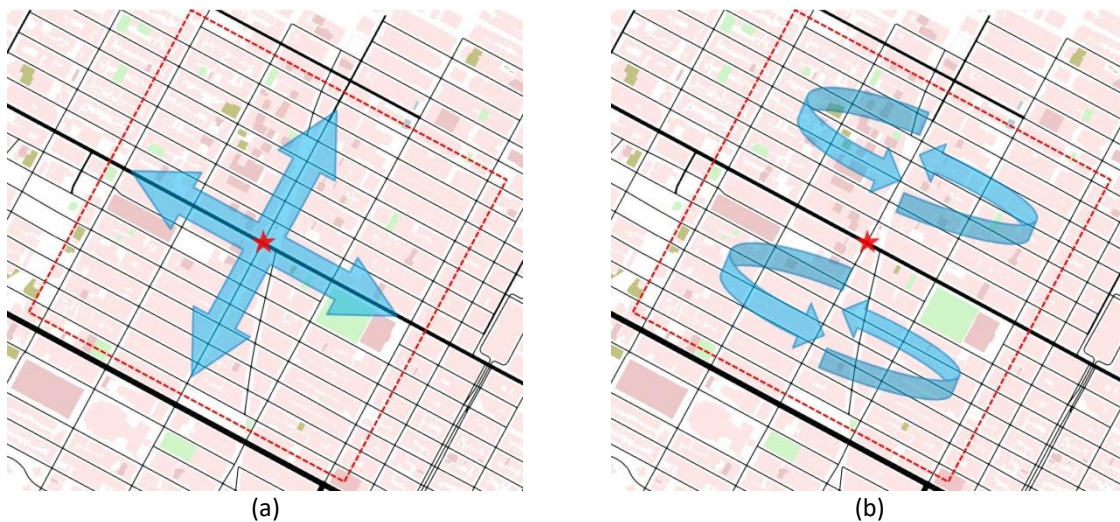


Figure 5-7. Trafic routier dans les scénarios de Manhattan. A) Trafic routier 1 (uniforme). B) Trafic routier 2 (déviée) ; Les itinéraires de circulation sont indiqués par des flèches dans les scénarios urbains ; L'étoile rouge est le nœud source qui diffuse périodiquement des messages de données ; La ligne rouge discontinue indique la limite du ROI.

Le nœud source est fixé au centre de la carte de Manhattan. La simulation de chaque densité de véhicules est effectuée pendant 400 s et répétée 10 fois avec différentes données aléatoires. Nous avons conçu deux voies de circulation différentes qui représentent deux types de réseau routier, comme le montre la Figure 5-7.

Les flèches indiquent les itinéraires de circulation : Le trafic routier 1 (Figure 5-7a) comprend les véhicules circulant entre la moitié supérieure et la moitié inférieure du scénario, afin que les véhicules aient plus de chance de se connecter au nœud source ou à d'autres véhicules. Au contraire, la trafic routier 2 (Figure 5-7b) limite les véhicules à l'intérieur de la partie supérieure ou de la moitié inférieure du scénario. Dans ce cas, seuls quelques véhicules passent et se connectent au nœud source.

Cela signifie que le trafic routier 2 crée plus de réseaux déconnectés que ceux du trafic routier 1. Les résultats des différents trafics routiers sont montrés sur la Figure 5-5 et la Figure 5-6.

Comparons les résultats de simulation du trafic routier uniforme avec ceux du trafic routier dévié, nous observons que le trafic routier dévié abaisse la performance de chaque protocole. Une exception à ces résultats est que le PDR de TrAD et UV-CAST n'est pas très impacté. Cela signifie que les deux protocoles sont robustes à l'égard des itinéraires de trafic routier. Dans les deux scénarios, TrAD effectue également des transmissions modérées pour atteindre un PDR élevé et le délai le plus faible.

5.3.3 Scénarios d'autoroute

Pour mettre en œuvre la carte routière, une section de l'autoroute A711 située près de l'aéroport de Clermont-Ferrand (Aulnat, France) est modélisée. Il a deux voies dans chaque direction et a 2 km de longueur. Le message de données est créé par le nœud source fixe à l'extrémité ouest de l'autoroute et recueilli par tous les véhicules circulant dans le ROI. Nous établissons cinq niveaux de flux de trafics routiers qui comportent 443 vph, 883 vph, 1319 vph, 1764 vph et 2207 vph, qui augmentent linéairement. La durée de simulation de chaque flux de trafic est de 200 s et répétée 10 fois avec différentes données aléatoires. Tous les résultats de simulation obtenus avec un intervalle de confiance à 95% sont présentés par la Figure 5-8.

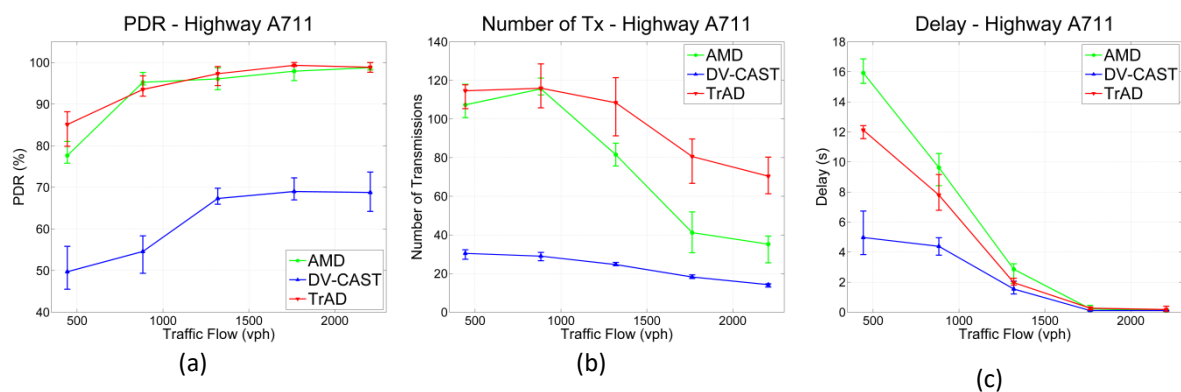


Figure 5-8. Résultats avec un intervalle de confiance de 95% dans les scénarios routiers : (a) PDR, (b) Nombre de transmissions, (c) Délai.

Dans ces résultats de simulation, nous pouvons constater que AMD réalise un PDR élevé comme TrAD. C'est parce que le scénario routier a une topologie routière relativement simple qui peut être prise en compte par AMD. En outre, AMD utilise également moins de transmissions que TrAD. Cela réside dans le fait que TrAD pourrait classer les voisins dans un sens de la route en deux ou plusieurs clusters directionnels en raison de l'existence de virages de la route. Mais, le délai de TrAD est meilleur que celui de l'AMD. Pour DV-CAST, bien qu'il utilise moins de transmissions et son délai est le plus court, ces réalisations n'ont aucun sens car le PDR de DV-CAST est le pire.

5.3.4 Erreur de GPS

En général, le système GPS civil standard n'est pas précis dans le monde réel, en particulier dans les centres-villes. Cela serait affecté par plusieurs facteurs, tels que la position et le nombre de satellites, l'atténuation du signal et les dérives d'horloge. En

particulier, dans les scénarios urbains, les grandes tours pourraient obstruer le signal GPS. L'erreur moyenne du GPS civil standard est de 30 m. Par conséquent, nous avons étudié la dérive GPS en termes de vitesse de diffusion des données. On choisit cinq options d'écart d'erreur, c'est-à-dire 0 m, 25 m, 50 m, 75 m et 100 m.

Pour évaluer l'impact de la dérive du GPS sur la performance du protocole TrAD, la densité moyenne des véhicules, c'est-à-dire 100 v / km², est utilisée dans les scénarios de Clermont-Ferrand et de Manhattan avec le trafic routier 1 (uniforme). Dans les résultats de la simulation obtenus, nous pouvons observer que grâce à la topologie de la route régulière et les obstacles de bâtiment TrAD maintient une performance relativement bonne dans le scénario de Manhattan. Cependant, dans le cas de Clermont-Ferrand, la vitesse de diffusion des données est plus lente que celle du scénario de Manhattan en raison de la nature complexe de l'environnement de la circulation.

Nous choisissons également le scénario de Clermont-Ferrand pour évaluer la robustesse de TrAD, AMD et UV-CAST face à la dérive GPS, puisque le scénario de Clermont-Ferrand a plus d'influence sur TrAD que celui de Manhattan. Dans les résultats de simulation, nous constatons que TrAD obtient toujours le meilleur résultat de la couverture de données et sa performance est diminuée avec l'augmentation de la dérive GPS.

5.4 Conclusion

Dans ce chapitre, un nouveau protocole de radiodiffusion adaptative de données, appelé TrAD, est proposé pour les scénarios routiers et urbains, en tenant compte à la fois du trafic routier et du trafic de réseau. Les résultats de simulation réalistes montrent que TrAD surpasse trois protocoles de référence bien connus de dissémination de données dans les scénarios urbain et routier. D'une part, TrAD est assez souple pour s'adapter à la topologie routière irrégulière et considère à la fois le trafic routier et le trafic de réseau pour le temps d'attente de transmission et la technique de tri.

D'autre part, TrAD utilise des techniques de suppression de radiodiffusion redondante pour limiter les transmissions de messages de données. Cette technique est adaptée non seulement à la technique de suppression de radiodiffusion dans un réseau bien connecté, mais également à la rediffusion d'agents SCF dans des réseaux déconnectés. Par conséquent, TrAD limite le nombre de transmissions de messages de données pour atteindre une couverture de données élevée avec un faible délai. De plus, le TRAD peut atténuer bien l'impact de la dérive de GPS jusqu'à 75 m dans un environnement de trafic routier complexe.

Chapter 6 Simulateur de Tramway à Faible Coût basé sur un Modèle de Mobilité Spécifique

6.1 Introduction

Ce chapitre vise principalement à concevoir et à mettre en œuvre le modèle de mobilité du simulateur de tramway «TRANSLOHR STE4». Ce travail fait partie du projet de coopération entre le groupe de recherche SMIR (Système Multisensoriel Intelligent intégré Réparti) du laboratoire LIMOS (Laboratoire d'Informatique de Modélisation et d'Optimisation des Systèmes) et la société T2C (Transport en Commun de l'Agglomération Clermontoise) qui est le fournisseur de services de transport public local à Clermont-Ferrand, France.

Bien que les simulateurs de tramway actuels soient bien développés, le modèle de mobilité et le coût restent des défis cruciaux. Les différents types de tramways, de terrain et de route mèneront à différents modèles de mobilité. Pour ce problème, nous développons un modèle de mobilité spécifique basé sur les données de mesure pour le tramway «TRANSLOHR STE4» de la société T2C. En outre, le coût du simulateur est un paramètre important. De façon traditionnelle, le moteur 3D est utilisé pour générer le scénario de la circulation routière. Une création de scène 3D dédiée entraînera un coût important. Par conséquent, nous essayons d'utiliser une autre approche, c'est-à-dire un flux vidéo, pour obtenir un simulateur de tramway à faible coût. En outre, l'interface graphique vidéo peut amener le scénario de trafic réel sur la ligne de tram, ce qui ne peut pas être réalisé par le moteur graphique 3D.

6.2 Conception de la plateforme du simulateur de Tram

Après avoir analysé les exigences du simulateur de tramway, nous avons conçu quatre modules pour réaliser les fonctions respectives, c'est-à-dire l'interface utilisateur graphique (GUI), la commande de mobilité, la console de commande et l'injection de défauts, comme le montre la Figure 6-1.

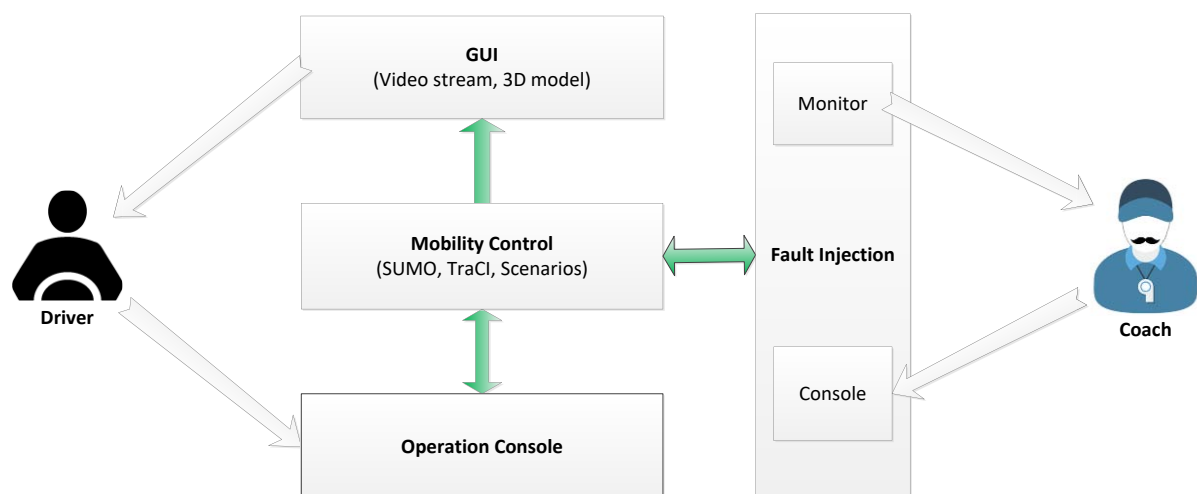


Figure 6-1. La structure du simulateur de tram

Tout d'abord, sur la gauche, le conducteur inter-réagit avec la console selon le scénario défini par l'interface graphique. Le module de console de commande transmet les commandes d'opération au module de commande de mobilité. Et puis les modèles de mobilité, introduits dans la section suivante, sont utilisés pour simuler le mouvement du tram.

Après cela, le module de contrôle de mobilité envoie des commandes pour mettre à jour l'interface graphique selon les données issues du modèle de mobilité. Ainsi, le conducteur peut acquérir la formation à travers ce simulateur. Sur la droite, le moniteur peut surveiller le déroulement de la conduite. De plus, le moniteur peut injecter dans le simulateur divers défauts, c'est-à-dire une défaillance mécanique ou une défaillance électrique, afin d'améliorer la capacité du conducteur à gérer les dysfonctionnements d'un tram.

6.3 Modèle de mobilité de Tram

Le modèle de mobilité est conçu en fonction des données de mesure recueillies à partir des essais du monde réel effectués en collaboration avec la société T2C avec un vrai tram pour tester les différents états de roulement. Le mouvement du tramway dépend de la spécification du tramway (unité motrice, poids et charge utile), de l'itinéraire de déplacement (pente et courbe) et des actions du conducteur (accélérer ou décélérer). Il existe trois types de mouvement, c'est-à-dire l'accélération, la décélération et le mouvement de glissement. Dans les sections qui suivent, sur la base du diagramme de force, nous allons analyser le modèle d'accélération de PU 'Power Unit', le modèle de décélération de DCU 'Deceleration Control Unit' et le modèle de mouvement glissement sans aucune action de pilote.

6.3.1 Accélération

Le conducteur utilise la pédale d'accélérateur pour contrôler la puissance de sortie du moteur. Plus l'angle de la pédale d'accélérateur est grand (pédale fortement appuyé), plus la vitesse du tram est rapide. Selon le document technique du tramway "TRANSLOHR STE4", il existe une approximation linéaire entre l'angle de la pédale d'accélérateur et la vitesse désirée. Étant donné la portée angulaire de la pédale d'accélérateur à 1 degré et 31,8 degrés et la vitesse maximale du tramway supérieure à 60 km / h, la relation des deux facteurs est indiquée dans l'équation (6-1).

$$v = 1.948 \times \alpha \quad (6-1)$$

Où v est la vitesse désirée; α est l'angle de la pédale d'accélérateur

Après analyse des données expérimentales, nous avons constaté qu'il existe une relation linéaire entre la vitesse et l'accélération. Par conséquent, nous proposons l'équation (6-2) pour déduire la relation entre la vitesse désirée et l'accélération moyenne en utilisant une régression linéaire.

$$\bar{a}(v) = bv + c \quad (6-2)$$

Où \bar{a} est l'accélération moyenne; v est la vitesse désirée ; b et c sont les paramètres de l'équation de régression linéaire.

Selon la méthode de la régression linéaire, l'estimation des moindres carrés est utilisée pour minimiser le carré de somme résiduel entre l'accélération estimée \bar{a} et l'accélération réelle A .

$$\varepsilon^2 = (\bar{a}(v) - A)^2 \quad (6-3)$$

Nous prenons la dérivée de la somme de ε_i^2 , c'est-à-dire $\sum \varepsilon_i^2$, par rapport à b et c et obtenons l'équation (6-4).

$$\begin{cases} \frac{\partial \sum \varepsilon_i^2}{\partial b} = 2b \sum v_i^2 + 2c \sum v_i - 2 \sum A_i v_i \\ \frac{\partial \sum \varepsilon_i^2}{\partial c} = 2b \sum v_i + 2cN - 2 \sum A_i \end{cases} \quad (6-4)$$

Où N est le nombre d'expériences. Nous mettons les données de l'expérience dans l'équation (6-4), puis obtenons l'équation linéaire de la relation entre \bar{a} et v , comme le montre l'équation (6-5).

$$\bar{a} = 0.012813 \cdot v + 0.639161 \quad (6-5)$$

Les données de mesure et la ligne de relation linéaire entre \bar{a} et v sont représentées sur la Figure 6-2.

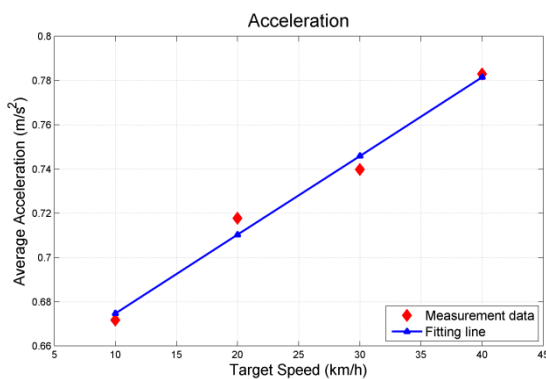


Figure 6-2. Les données de mesure et leur courbe de régression linéaire

Nous pouvons observer que la courbe de régression linéaire correspond bien aux données de mesure. La relation entre l'angle de la pédale d'accélération α et l'accélération moyenne \bar{a} peut être construite par la vitesse cible v . Par conséquent, on peut obtenir la valeur v et \bar{a} en fonction de α , alors le modèle de mobilité utilisera \bar{a} accélérer le tramway jusqu'à atteindre la vitesse cible v .

6.3.2 Décélération

Le conducteur actionne l'unité de commande de décélération (DCU) pour observer le comportement de freinage en utilisant la pédale de frein. Selon le document technique du tramway "TRANSLOHR STE4", la relation entre la décélération et l'angle de la pédale de frein est modélisée, comme le montre la Figure 6-3.

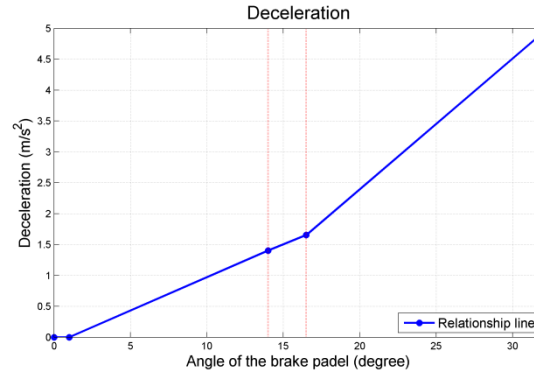


Figure 6-3. Modèle de décélération par rapport à l'angle de la pédale de frein

6.3.3 Mouvement de glissement

Le mouvement de glissement est le mouvement du tram sans aucune action de la pédale d'accélérateur et de la pédale de frein, le tram glisse selon l'effet de l'inertie. Pour explorer le modèle du mouvement de glissement, on déduit d'abord le modèle théorique de l'équilibre de force du tramway.

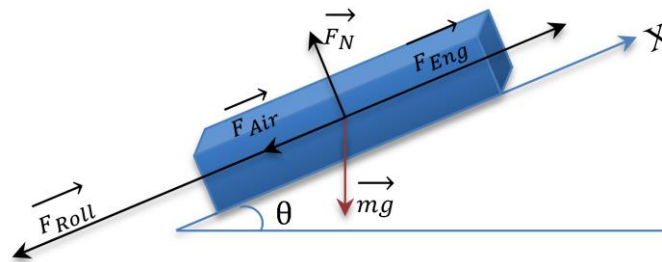


Figure 6-4. Force diagram of tram

Sur la Figure 6-4, l'équilibre de force du tram est établie dans les directions horizontale et verticale. Ainsi, on peut obtenir l'équation (6-6).

$$\begin{cases} \overrightarrow{F_{Roll}} + \overrightarrow{F_{Air}} + \overrightarrow{F_{Eng}} + \overrightarrow{mg} \sin \theta = m\vec{a} \\ \overrightarrow{F_N} + \overrightarrow{mg} \cos \theta = 0 \end{cases} \quad (6-6)$$

Où, $\overrightarrow{F_N}$ est la force de réaction au sol ; \overrightarrow{mg} est le poids du tramway ; $\overrightarrow{F_{Eng}}$ est la traction du moteur; F_{Air} est la résistance de l'air; F_{Roll} est la résistance au roulement; θ est l'angle entre le tram et la masse plane; \vec{a} est l'accélération.

Ici, nous considérons seulement le mouvement glissement sur le sol plat. Cela signifie $\overrightarrow{F_{Eng}} = 0$ et $\theta = 0$. Par conséquent, l'équation (6-6) est transformée en l'équation (6-7).

$$\overrightarrow{F_{Roll}} + \overrightarrow{F_{Air}} = m\vec{a} \quad (6-7)$$

Dans ce cas, la résistance provient uniquement de l'air et du roulement des roues. Donc, nous étudions ces forces respectivement. La résistance de l'air peut être exprimée par l'équation (6-8).

$$\overrightarrow{F_{Air}} = kv^2 \quad (6-8)$$

Où k est le paramètre relatif au profil de la tête de tram.

Le moment du frottement de roulement peut relier la résistance au roulage à la force de la réaction du sol, comme indiqué dans l'équation (6-9).

$$M_{\text{Roll}} = r\overrightarrow{F_{\text{Roll}}} = \lambda\overrightarrow{F_N} \quad (6-9)$$

Où r est le rayon de la roue ; λ est le paramètre de roulement. Étant donné que le sol plat est considéré, $\overrightarrow{F_N}$ est égale au poids du tram, c'est-à-dire $\overrightarrow{F_N} = mg$. Par conséquent, on peut obtenir l'expression de la résistance au roulement $\overrightarrow{F_{\text{Roll}}}$.

$$\overrightarrow{F_{\text{Roll}}} = \frac{\lambda}{r} mg \quad (6-10)$$

En remplaçant l'équation (6-8) et (6-10) par l'équation (6-7), on obtient l'expression de décélération, comme le montre l'équation (6-11).

$$\vec{a} = -\left(\frac{\lambda}{r}g + \frac{k}{m}v^2\right) \quad (6-11)$$

Où, on utilise le signe moins pour représenter l'effet négatif de la décélération. Le rayon r et le poids m peuvent être connus dans le document technique du tramway. Il n'y a que deux paramètres, à savoir, λ et k , qui doivent être identifiés. Ensuite, nous utiliserons la méthode de la régression linéaire pour estimer ces paramètres non définis.

Selon le type d'équation (6-11), nous concevons l'équation de régression comme l'équation (6-12).

$$\bar{d}(v) = bv^2 + c \quad (6-12)$$

Où \bar{d} est la décélération moyenne; B et c comprennent les paramètres non définis. Le résidu entre la décélération estimée \bar{d} et la décélération réelle D est présenté par l'équation (6-13).

$$\varepsilon^2 = (\bar{d}(v) - D)^2 \quad (6-13)$$

Dans la théorie du moins carré, la courbe d'ajustement est optimale lorsque $\sum \varepsilon_i^2$ est minimisé. On prend la dérivée de $\sum \varepsilon_i^2$ par rapport à b et c , puis on obtient l'équation (6-14).

$$\begin{cases} \frac{\partial \sum \varepsilon^2}{\partial b} = 2b \sum v_i^4 + 2c \sum v_i^2 - 2 \sum D_i v_i^2 \\ \frac{\partial \sum \varepsilon^2}{\partial c} = 2b \sum v_i^2 + 2cN - 2 \sum D_i \end{cases} \quad (6-14)$$

Nous utilisons les données de mesure dans l'équation (6-14) pour obtenir la valeur de b et c comme suit.

$$\begin{cases} b = -\frac{k}{m} = -0.000282 \\ c = -\frac{\lambda}{r}g = -0.144767 \end{cases} \quad (6-15)$$

Naturellement, on peut obtenir le modèle de mouvement de glissement, comme le montre l'équation (6-18).

$$\bar{d}(v) = -0.000282 \cdot v^2 - 0.144767 \quad (6-16)$$

Donc,

$$\begin{cases} \lambda = 0.007913 \\ k = 7.148700 \end{cases} \quad (6-17)$$

La courbe de regression linéaire est illustrée par la Figure 6-5.

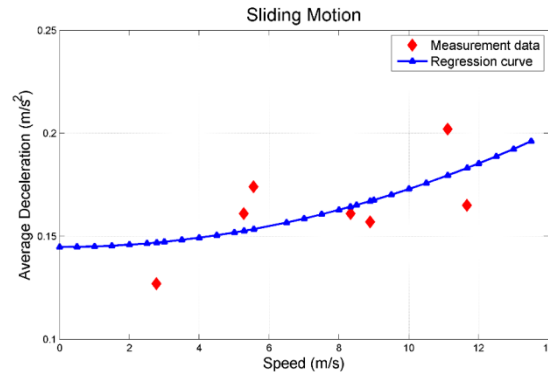


Figure 6-5. La relation entre la décélération et la vitesse initiale dans le mouvement de glissement

Nous observons que la courbe de régression linéaire correspond approximativement aux données de mesure, ce qui prouve que le modèle pourrait simuler le mouvement de glissement réel avec une performance acceptable.

6.4 Implementation of Mobility Control Module

Le module de contrôle de mobilité comprend principalement deux parties, c'est-à-dire des scénarios de trafic et divers modèles de mouvement. Les scénarios de trafic se composent de la carte SUMO et des itinéraires de circulation, qui sont liés à la ligne de trafic du tramway. Le modèle de mobilité automobile de SUMO est utilisé comme moteur du tramway, pour contrôler le mouvement du tram défini par le scénario, calculé par les modèles de mobilité. Par conséquent, tout d'abord, nous allons montrer la création de scénarios de trafic, comme le montre la Figure 6-6.

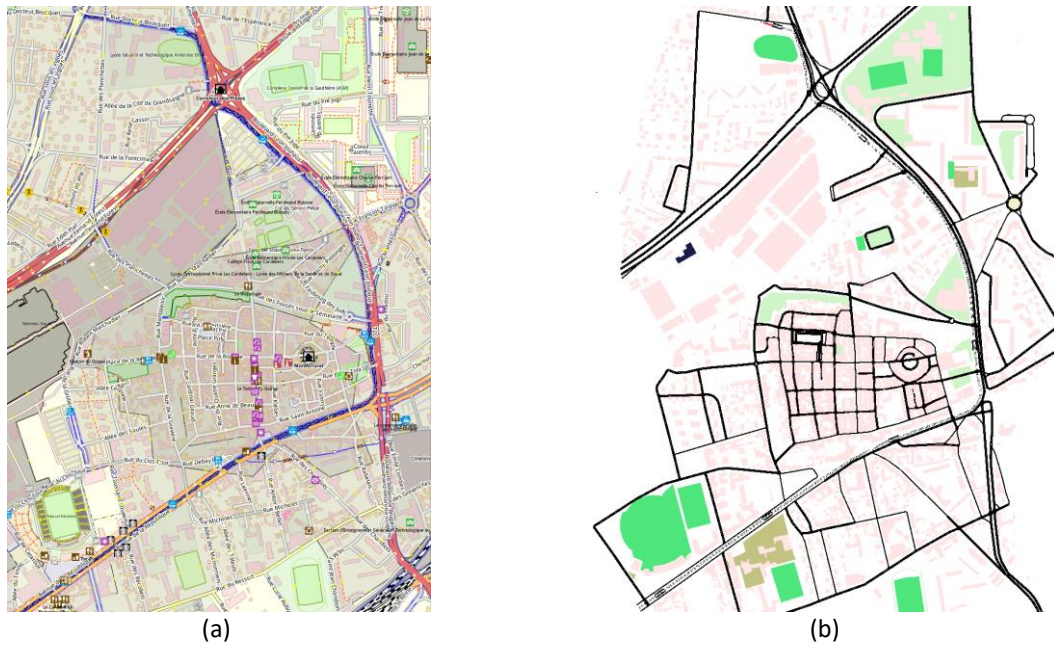


Figure 6-6. Implementation of traffic scenarios in the tram simulator. (a) OpenStreetMap; (b) SUMO map.

Dans la Figure 6-6, il y a un fragment de la carte de SUMO qui est converti à partir de OpenStreetMap. En fait, nous pouvons créer les scénarios de trafic de la plupart des villes dans le monde. Par conséquent, le simulateur peut également être utilisé dans d'autres villes, mais les modèles de mobilité devraient être étudiés à nouveau en fonction des données de mesure de terrain du monde réel. Dans le scénario de trafic réaliste, des modèles de mobilité sont utilisés pour contrôler la mobilité du tramway.

Chapter 7 Conclusion and Perspective

Les principaux résultats obtenus de ma thèse sont divisés en deux parties : le protocole TrAD CIV et le modèle de mobilité du simulateur de tramway. Un nouveau protocole CIV nommé Protocole TrAD axé sur la dissémination des données a été proposé dans le cadre de recherche alors que le processus de modélisation a été réalisé pour ce dernier aspect en pratique. Basé sur la solide plate-forme de simulation de la mise en réseau des véhicules, le protocole TrAD s'est engagé à diffuser des données d'un expéditeur à des véhicules voisins multi-hop dans un intervalle d'intérêt tout en tenant compte du trafic routier et routier dans les scénarios urbain et routier. Les résultats de ses travaux ont été validés par les publications de deux articles, l'un dans une revue internationale et le second dans une conférence internationale (IEEE).

D'autre part, le projet de simulateur du tram a été soutenu pendant deux ans par la société T2C.

La technologie sans fil progresse de façon continue et significative tiré par le développement de réseau sans fil et IoT. Il est certain que ces avancées auront un impact sur le paradigme de CIV, comme la technique de routage sécurisée et fiable basée sur la radio cognitive multi-support (IEEE802.11p, NB-IoT, 4G / 5G, LoRa, etc.), qui est la clé pour mettre en œuvre les communications : V2V, V2I, I2V (par exemple, le feu de circulation au véhicule) et V2X (par exemple, véhicule à piéton). Au-delà de cela, pour la prochaine année à venir, je suis intéressé à étudier le contrôle de congestion distribué (DCC) dans des clusters de véhicules. La façon de régler les paramètres d'émission adaptative (par exemple, la vitesse de transmission ou la puissance) dans le réseau de véhicules hautement dynamique est un défi crucial pour la sécurité routière en prenant en compte le contexte collaboratif.

En outre, mis à part la formation ad hoc des VANET, je veux exploiter la formation basée sur les infrastructures des VANET.

Les réseaux cellulaires, tels que 4G ou 5G (dans un futur proche), deviendront la technologie d'accès sans fil potentielle et importante pour les applications CIV, en particulier dans la phase de pénétration initiale du dispositif DSRC. La fonctionnalité avancée du réseau 5G peut apporter une amélioration significative pour les VANET. Après avoir étudié des formations ad-hoc et des infrastructures, je m'attends naturellement à explorer la technique d'accès multi-support cognitif pour améliorer la fiabilité et la sécurité dans les réseaux de véhicules hétérogènes.