Dynamic Wireless Mobile Framework for Distributed Collaborative Real-Time Information Generation and Control Systems

Yueyue Li

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Copyright statement

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Abstract

Intelligent Transportation Systems (ITS) have only recently discovered the exciting possibilities in the nomadic and ubiquitous computing space to build a new generation of information systems by allowing the vehicle to act both as a carrier and consumer of wireless (and thus omnipresent) information. Wide deployment of such ITS systems may eventually allow for more dynamic and efficient transportation systems, which can contribute in several ways towards greater economic growth whilst respecting environmental sustainability. A great number of researchers have dedicated considerable time and resources to tackling traffic related issues by utilising the new wireless capabilities enabled by ITS; such initiatives cover a wide range of applications such as safety, knowledge sharing and infotainment. Indicative of the extent of such efforts is the plethora of research projects initiated by many national and multi-national organisations such as the EU Framework Programme for Research and Technological Development. To achieve their goals, proposed solutions from such organisations depend on the development and deployment of intelligent wireless mobile communication systems, where data dissemination issues make the prospect of efficient and effective communication a challenging proposition.

Presently, Car-to-Car and Car-to-Infrastructure communications are two distinct avenues that make possible efficient and reliable delivery of messages via direct radio links in traffic areas. In all cases, high quality of communication performance is desirable for a communication system composed mostly of roaming participants; such a system needs to be dynamic, flexible and infrastructure-less. Consequently, Mobile Ad hoc Network (MANET)-based networks are a natural fit to ITS.

This thesis establishes a new Collaborative MANET-based Communication Network (CMCN) architecture for the generation and control of distributed collaborative real-time information. In urban traffic scenarios, CMCN nodes are classified as mobile, semi-mobile and static according to their mobility patterns. For a CMCN system, a novel supporting Probabilistic Traffic Message Delivery Algorithm (PTMDA) is designed based on the broadcast characteristics of 802.11p. PTMDA features a set of probabilistic priority events that satisfy efficient and reliable inter-vehicle communications. Further, PTMDA is extensively compared to several existing broadcasting-based routing protocols in realistic urban scenarios based on actual traffic traces from a major metropolitan centre in the UK. The simulation results illustrate that the new routing mechanism and its message dissemination mechanisms enable lower end-to-end delay, larger reachability and higher ratio of successful message transmissions than other state-of-the-art approaches.

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Abbreviations

3G,4G	Third, Fourth Generation of mobile telecommunication technology
3GPP LTE	3rd Generation Partnership Project - Long Term Evolution
AWK	An interpreted programming used to extract simulation data
AODV	Ad Hoc On-Demand Distance Vector Routing
AP	Access Point
BSS	Basic Service Set
C2C	Car-to-Car Communications
C2I	Car-to-Infrastructure Communications
C2X	Car-to-Car/Car-to-Infrastructure Communications
CCH	Control Channel of IEEE802.11p MAC layer
CDMA	Code-division multiple access
CMCN	Collaborative MANET-based Communication Network
CTM	CMCN Traffic Message
DCF	Distributed Coordination Function
DP	Direction-based Priority Scheme
DSDV	Destination-Sequenced Distance Vector Routing
DSR	Dynamic Source Routing
DSRC	Dedicated Short-Range Communications
DSSS	Direct Sequence Spread Spectrum
E2ED	End-to-End Delay (evaluation metric)
E2ERCH	End-to-End Reachability (evaluation metric)
EDCA	Enhanced Distributed Channel Access
FDMA	Frequency-division multiple access
FHSS	Frequency Hopping Spread Spectrum
FNFS	Farthest Node First Send Scheme
GPRS	General Packet Radio Service
GPS	Global Positioning System
IB	Invoked Broadcasts (evaluation metric)
IEEE 802.11	Wireless access standard
ITS	Intelligent Transportation System
I-ROUTE	A type of route provides priority forwarding in CMCN
MAC	Media Access Control
MANET	Mobile Ad hoc Network
NS2	Network Simulator II (version 2.35)
NE2ED	Network End-to-End Delay (evaluation metric)
NON-ACK	Non-Acknowledgement
NRCH	Network Reachability (evaluation metric)
OBU	On-Broad unit

OFDM	Orthogonal Frequency Division Multiplexing
OSI	Open Systems Interconnection model
PHY	Physical Layer of Network protocol stack
PKTD	Packet Drops (evaluation metric)
PTMDA	Probabilistic Traffic Message Delivery Algorithm
R	A language and environment for statistical computing and graphics
RSU	Roadside unit
SB	Sharing-based message
SCH	Service Channel of IEEE802.11p MAC layer
SMS	Short Message Service
SP	High-Speed Priority Scheme
SUMO	Simulation of Urban MObility
TDMA	Time-division multiple access
UMTS	Universal Mobile Telecommunications System
VANET	Vehicular Ad hoc Network
V2V	Vehicle-to-Vehicle communication
V2I	Vehicle-to-Infrastructure communication
WAVE	Wireless Access in Vehicular Environment
WB	Warning-based message
WSA	WAVE Service Advertisement
WSM	WAVE Short Message
WLAN	Wireless Local Area Network

List of Publications

1. Y. Li and E. Peytchev, “Novel ad-hoc wireless mobile communication network routing model for location based sensor networks” in proceedings of International Symposium on LBS & TeleCartography, pp.: 383-396, Guangzhou, China, September 2010.
2. Y. Li, “Study on Test Suite Application of NS-2 Simulation System”, Journal of Communication Technology, vol. 44, no. 7, no. 235, Totally: 39-41, July, 2011.
3. Y. Li, “Embedded Data Communication System based on 4G-Ready”, Journal of Communication Technology, vol. 44, no. 10, no. 238, Totally: 1-3, Oct., 2011.
4. E. A. Gamati, E. Peytchev, R. Germon and Y. Li, “Utilization of Broadcast Methods for detection of the road conditions in VANET” in proceedings of 26th European Conference on Modelling and Simulation, Koblenz, Germany, May, 2012.
5. Y. Li and E. Peytchev, "New Traffic Message Delivery Algorithm for a Novel VANET Architecture" in ICWMC 2012, The Eighth International Conference on Wireless and Mobile Communications, pp.: 395-401, Venice, Italy, June, 2012.
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Chapter 1

Introduction

1.1 Research Project Application Domains – Introduction

Transportation has always played an important role in the economic development of cities. In the age of information technology, the traditional, ever-present transportation of goods, people, and services requires sophisticated approaches. Considerably, the great demand for transportation of information and services is only heightened by fast population growth and may contribute to issues such as environmental pollution and energy shortage. In all concerned social problems, urban traffic control and management is particularly important to promote development of city transportation. Additionally, transportation safety is also of paramount importance considering the substantial increase of traffic accidents (e.g. car crashes in recent times). For instance, [1] indicates that about 6,000,000 accidents occur every year in United States and [1] shows that in the year 2007, there were about thousands of deaths and injuries in mainland China. To solve these problems, a comprehensive system with capabilities of wide, real-time, accurate and efficient transport management is highly desirable in the form of an Intelligent Transportation System (ITS).

ITS, as an exhaustive transportation management system, integrates information, control, communication and sensor technologies into current transport infrastructures and vehicles. All of these are applied in transportation for diverse purposes (Fig. 1.1 [2]). Examples vary from traffic management, such as buses schedules or signal controls, to traffic monitors for road safety or vehicle flows. Further, the system can provide various services to drivers and pedestrians, including vehicle navigation, parking information or environment notice (e.g. weather or slippery) and so on.

Fig. 1. 1 Applications of Intelligent Transportation System [2]

Looking back to the initial driving forces mentioned, such a wide, real-time, accurate and efficient transport control and management system essentially helps to reduce traffic congestions, accidents and improper road use in transportation areas by utilizing safe, convenient and efficient data dissemination. The latter, also referred to as information exchange plays a very important role in ITS applications. It makes it possible for traffic users to request information on road conditions from leading vehicles, or share accident warning cues with vehicles running in the opposite direction.

In the past decades, many communication applications have been designed to assume the presence of infrastructure. Several of these may be seen in Fig. 1.1. In fact, several early ITS applications relevant today require fixed infrastructure. Particularly, the activity of information exchange between vehicles and infrastructure is given a formal term; Car-to-Infrastructure (C2I) communications. While the C2I architecture becomes increasingly mature, several challenges concerning infrastructure deployment, connection, and amount of data emerge. In order to circumvent these, researchers and commercial projects focus on a different type of ITS applications, known as the Car-to-Car (C2C) communications, which focus on message delivery between automobiles without centralized support.

1.2 Scientific Basis to Research Project

1.2.1 Outline of the problems

The overall vision of the proposed research project is to provide innovative strategies to handle various traffic problems in the field of ITS, such as traffic congestions, accidents, regional roadwork and so on. Although previous work in the field has attempted to resolve some of the issues presented here, the schemas included in this thesis advance significantly more comprehensive and efficient solutions than present in the literature so far. To aid discussion, let us review a scenario of interest: A person drives to work and a traffic jam is occurring ahead. Normally, he will not know of that fact until he reaches the area, although it would be clearly desirable for him to know beforehand so he may circumnavigate the area of congestion. Similarly, consider a person driving on the highway at a fast speed when there is a serious accident somewhere along his route. He will not know of it until he is very close to the place of the incident, although advance warning is probably of use in such a situation. The above scenarios are commonplace in daily life and imply that real-time traffic information is important and necessary in order to ensure a safe and efficient traffic environment. To realize the exchange of real-time traffic messages, traffic participants could cooperate by using the C2I and C2C approaches, also known as C2X for both (the X stands for Car or Infrastructure). Consider then, in the previous example, that when the car passes the accident point, it can share information with nearby infrastructure so that incoming cars can download the message. Alternatively, the on-spot car could share the information with cars behind it via a direct radio link and the message could then be propagated backwards in turn.

The common goal of C2X communications, as part of ITS, is to improve the safety and efficiency of transportations in urban and rural areas by providing timely information among people, vehicles, and other traffic participants. Positive outcomes of this include reducing traffic congestions, saving travel time, decreasing traffic accidents, reducing air pollutions, lowering energy consumption and providing information on-demand during travels.

The next few sections will present the relative merits of C2X communications and will justify why it is the technology of focus in this research. From the point of view of communication performance, there are four aspects considered, namely the cost of connections, the speed of links, the volume of data and the locality.

1.2.2 C2C versus C2I communications

1.2.2.1 Cost of connection

An economically viable (i.e. affordable) communications technology is a desirable outcome for any system. Thus, financial reasons become an important driving force behind the development of both communication methods. C2C solutions without the aid of any central control entities have some obvious advantages. C2I applications report traffic information depending on centralized controls. These infrastructures such as roadside units, access points, as well as cellular communication devices are powerful enough to support reliable and secure traffic management and controls, but this comes with massive investments to be installed on all urban roads or along highways [3]. Understandably, mobile phones using cellular infrastructure could be installed and used in cars for communications, but they cost money per minute-use or per byte-transfer and the transmission rate is limited as mentioned previously [4][5][6]. When using Wi-Fi techniques, the access point range is usually setup for a local area radius. Thus a handover technique is considered, coupled with handover delays. Although projects such as [7][8] attempt to improve the connection speed of infrastructure-based communications so that this infrastructure could be used to better effect, the cost of connections will be a limitation for the foreseeable future.

In contrast, C2C solutions were designed to assume no infrastructure. The cost of connection between mobile objects and infrastructures is thus avoided without incurring other costs traditionally related to infrastructure, such as maintenance, re-establishment etc. As a matter of fact, moving vehicles can be regarded as dynamic infrastructure to replace certain functions of fixed infrastructure. Therefore, real-time connections are allowed to occur among wireless communication capable objects anywhere and anytime.

Obviously, C2C applications that do not rely on infrastructure are more economically viable for local network communications compared to C2I. Currently, if C2I solutions use 3G base-stations to support communications, there is substantial cost for every bit of data spent on getting connections between mobile phones or between mobile phones and base stations as well as infrastructure constructions; if using WLAN technologies, expenses are mainly observed on infrastructure deployments, such as constructions, maintenance and replacement of new installations. Considering the above, C2C communications seems to be the better of the two alternatives.

1.2.2.2 Speed of link

The speed of links or transmission rate is a key factor that impacts transmission delays between transmitters and receivers. On this point, C2C solutions provide faster connection speeds than C2I communications.

Most of C2I communications use cell-based technologies, of which the transmission speed is only 400 kbps or lower in General Packet Radio Service (GPRS) or 2.75G networks [9][10][11]. As specified in these studies, high-speed mobility allows only for approximately 144 kbps data rate; even in moderate or low mobility communications, the maximum data rate can be only up to 384 kbps. Certainly, the problem has been improved in the 3G era. The speed of link can be 2Mbps in Universal Mobile Telecommunications System (UMTS) systems and even 3Mbps for downlink and 1.8Mbps for uplink in CDMA2000 systems [9]. However, communications in such networks depend on Infrastructures, then a substantial connection setup time should be considered. Such an overhead is too heavy when an urgent event needs to be communicated to other traffic participants. Moreover, C2I also uses Wireless Local Area Network (WLAN) technologies, namely the infrastructure mode of IEEE 802.11. The transmission speed of WLAN could be faster than cell-based connections, up to dozens of Mbps [10]. For example, IEEE802.11b works under a data rate of 11Mbps while IEEE 802.11a/g provides a data rate of 54Mbps [9]. However, the transmission range is set for local area (e.g. 100 meters) connections only. As stated in [9], as an example, the coverage of communications by IEEE802.11a/g will only 140 meters for outdoor using. In contrast, [12] states that C2C communications present a quick time-critical response which is less than 50ms and high transmission speed between 6 and 54 Mbps by current use of ad hoc WLAN adhering to IEEE 802.11. The term 'ad hoc', generally refers to non-infrastructure and self-organization. Further, direct radio links of C2C communications can reduce time delay in delivering important and urgent messages. Here, a process of infrastructure connection setup is not necessary. Moreover, when Roadside Units (RSU) are introduced into the C2C environments, the communication range is possible to be enlarged.

1.2.2.3 Volume of data

Generally, local traffic information can be accident warning, traffic jam notice, information on the roads ahead, give-way advice, as well as weather information, to name some examples. Taking into account transmission speed, mobiles' velocity and packet length in C2X communications, the amount of data is another critical factor which impacts communication performance and success of transmissions. Transmission speed in both communication approaches is a key factor to deciding the proper size of a packet used during transmissions. This is because there are limited communication durations for each mobile.

In terms of C2I communications, several projects have proposed research on the amount of data. Authors in [13] prove that when a vehicle passes the Roadside Unit (RSU) with fixed data rate 3 Mbps and 80 km/h mobility, the total correct data volume is increased from 6 MB with 200 bytes packet length to approximately 10.5 MB with 1554 bytes packet size. It also proves that although data volume is larger when data rates are higher, the achievable range greatly decreases. Thus, the valid amount of data in C2I communications depends on factors such as transmission rate, achievable range and packet size.

The work presented by F. Schmidt-Eisenlohr [14] defines that in C2C environments, local broadcast capacity means the amount of data allowed for each node in correlations with density (nodes/meter), data rate (bit/s), theoretical awareness range (meter) and required reception probability to the channel usage. When the required reception probability equals 1, date rate b is 3Mbps, 14 nodes per meter and awareness range equals 100m, then the maximum size of data volume is 13,392 bytes/s with 1000 bytes packet size. Additionally, the author considers message sizes in the experiments which influences on communication performance.

Moreover, the capacity of mobiles nodes also impacts on the volume of data. For example, buses as public transportation tools have great responsibility and possibility to maintain and help urban traffic communications. Thus, they can be expected to store more local traffic information than other personal cars. In CPU capacity terms, likewise, public transportation vehicles may be assumed to be better equipped than common cars. Therefore it may be assumed that algorithms and processes operating on public transport vehicles may be more complex and computationally demanding than their car equivalents. Further, the size of data needs to be decided by users' demands. For example, a message involving traffic jam information may be smaller than a message about infotainment.

On the whole, the amount of data transferred in direct link of C2C communications could be larger than C2I solutions based on the same conditions of physical environments. With the same data rate of transmissions, mobile nodes are only given restricted time to pass a fixed infrastructure. And the timeslot depending on the speed of nodes' mobility may or may not support fully transmissions, particularly in a case of large size of messages. Usually, higher speed of mobility causes shorter time communication opportunities between mobile nodes and infrastructure nodes and this may finally result in partly transmissions only. Additionally, data files, which are separated by Short Message Service (SMS), are all routed through any of particular operators in 3G networks; in such a case, these operators enables to control and limit the amount of data depending on security and network conditions [6].

1.2.2.4 Locality

Cellular infrastructure or roadside units are suitable for data disseminations from or to mobile objects in long-distance wireless networks. As discussed above, such infrastructures enable the collection and buffering of information at regular intervals. Additionally, the infrastructure can be a bridge for traffic participants to access the Internet. Therefore, these two types of infrastructure form a system powerful enough to implement a large-scale network communications rather than manage local area events.

On the contrary, infrastructures do not exist in C2C environments. This difference, results in a number of benefits. Firstly, vehicles are mobile and flexible, being able to carry the message to many places, even in sparse networks. Particularly in high-density traffic networks, vehicles are running one after another. The message could be continually propagated along multiple hops to the destination. In another aspect, infrastructures are not essential and proper to be used for solving local problems. Regarding to locality of traffic issues like traffic jams or accident warning etc., using infrastructures, sometimes can lead to resource waste. By way of example, automobiles in a rainy area detect the situation through sharing information on whether their windscreen wipers are active. The information is of value and is actually needed by local vehicles only rather than all participants of the network. Therefore, C2C solutions can be applied without the aid of infrastructure nodes.

Eventually, C2C technologies are more suitable for handling the exchange of regional information. They do not rely on fixed infrastructure to exchange the message, which may lead to discontinuity in communications; instead, mobiles carry the message or intermediate vehicles forward the message to the destinations. Also, in the case of message transmissions for a local area only, C2C provide adequate capability to meet the relevant requirements, coupled with the benefits of cheaper cost of connections, faster speed of connections and larger volume of data.

1.2.2.5 Summary

The cost of connections, the speed of links, the volume of data and the locality are considerations presented in C2X communications. Their combined effect affects ITS applications. For instance, the transmission speed and mobiles' velocity restrict the amount of data. Usually, small transmission speed with high mobile speed will lead to small amount of data exchanges, or vice versa. Also, the amount of data is not an isolated topic. It is also closely related to other considerations such as packet size, achievable range, transmission rate and the inter-distance of two objects. Considering the general discussion above, C2C overall seems to be the better choice.

Indeed, there is not an absolute boundary to state which communication approach is better because the choice will depend on the purposes of networks and various particular cases. In fact, some projects [15] consider the cooperation of C2C and C2I methods. To date, many related projects (e.g. CVIS, SAFESPOT etc.) have contributed more to C2I communications, utilizing current infrastructures, which have been established and pre-exist in some places. Especially, with respect to accuracy and security issues, C2I may present better aspects than that of current C2C applications.

The interest in C2C communications is increasing presently as it is believed that the benefits of C2C applications have not sufficiently been exploited to solve traffic problems in the ITS domain.

1.2.3 Network architectures of C2C communications

Currently, the main vehicle network architectures for wireless communications are based on wireless LAN (WLAN) according to the IEEE 802.11 standards. As indicated in [16], WLAN includes two implementation approaches: infrastructure-based and ad hoc networking. The former is used in C2I communications while the latter is more suitable for C2C communications.

Ad hoc networking, which was aimed at military and disaster relief operations initially, consists of a selection of autonomous nodes capable of connecting to each other via wireless link and linking spontaneously into a network [17]. It appears to replace those infrastructure-based network architectures but may also complement them at particular settings.

Mobile Ad hoc Networks (MANET) consist of nodes that may randomly move and cooperate to provide connectivity and services. This may result in very fast changeable wireless network topology. MANETs are usually considered as a type of independent operation networks; however, they may also be used in tandem with other traditional infrastructure networks and obtain access to the Internet. Due to their

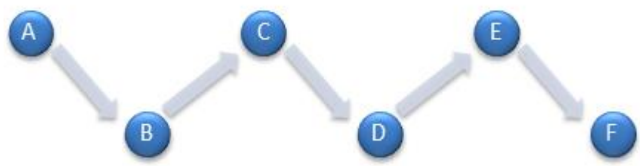


Fig. 1. 2 The multi-hop mode in MANETs

infrastructure-free nature, MANETs implement data transmissions via multiple-hops (Fig. 1.2), which means that the messages will be forwarded through intermediate nodes from source to the destination. Therefore, maintaining a valid transmission route in the rapid changing topology is an important issue.

1.2.4 Research considerations

1.2.4.1 C2C communications in the proposed research

Following the comparison of C2C and C2I communications in Section 1.2.2, it can now be stated that this thesis is originally more inclined to the former. The reasons for this choice may be summed up as follows: Firstly, direct radio links of C2C communications could reduce time delay in delivering important and urgent messages; on the offset, C2I applications usually require time to set up infrastructure network before real message transmissions. Secondly, the cost of connection can be reduced because there is no need for centralized controls in C2C communications. Thirdly, local area information can be well shared by using local vehicles themselves rather than depending on limited amount of infrastructure. Finally, mobile nodes in the system are assumed to have Controller Area Network BUS (CAN-BUS), which collects in-car information, such as traffic route information, ABS active signals etc. Collectively utilizing this information can be very useful in identifying transient local road conditions and the dissemination of such information may intuitively be well met via the use of C2C communications.

MANETs are a natural fit for C2C communications. The main reason is that MANETs allow for the non-existence of infrastructure, flexible network organization and especially high-speed mobility of nodes. Further, vehicles within the wireless connection can be hosts, or routers, or even gateway nodes which communicate with fixed infrastructure to give the vehicle access to the Internet. In such a fashion the role of infrastructure networks may be completely supplanted by ad hoc networking.

1.2.4.2 Protocols in MANET

Considering all the advantages of MANETs, as outlined above, it may be pertinent to outline some other considerations. Typically, fast and unpredictable changing topologies add difficulties into the designs of routing algorithms. Certainly, several MANET routing protocols have been proposed, such as in [16] or [18]. The investigations of communication performance, have not shown MANETs reaching adequate performance in terms of C2C applications in the ITS domain. To implement routing protocol, broadcasting plays an important role. However, conventional broadcasting methods suffer from serious broadcast storms during the transmissions resulting in a large number of packet loss and congestion. This research attempts to ameliorate such concerns by introducing a new broadcasting protocol, in which the route of public transport vehicles is integral to assisting message deliveries.

1.2.4.3 The inclusion of traffic route information

To enhance communication performance in the networks, additional traffic information is highly needed for message delivery. Due to different network purposes, previous work in the literature has proposed the inclusion of particular traffic information in beacon overheads or inside messages, such as the inclusion of the acknowledgements [19] and the inclusion of vehicles' status and surrounding information [20] etc. For this thesis, traffic route information is considered to support the proposed broadcasting schemes. To the best of the current knowledge, inclusion of traffic route information has not been proposed in existing MANET protocols.

Once the additional route information is added for the transmissions, an important prerequisite is considered that the efficiency and reliability of transmissions will not be negatively impacted. On this point, the direct impact factor regarding the data volume displays that too heavy overheads and data reduces communication performance over the networks. At present, while diverse and changeable communication demands and traffic problems occur every day, people expect to know more during the travels. Obviously, this may lead to the increase of data volume as discussed earlier. The argument in favour of including such information – a stance which this thesis adopts - follows: Since the data volume is relatively limited in any kinds of networks, it is required to have maximum and optimum related traffic information in communication protocols rather than in message overheads.

An important question which may be raised in the context of this work is on the feasibility to obtain traffic route information for message delivery. With the development of wireless mobile communications, however, it is common that electronic devices such as Global Positioning System (GPS) are installed in most of cars and mobile terminals. A routing algorithm can collect the pre-set route information by these devices directly. Certainly, there is an alternate way to include traffic route information. Some transportation participants have relatively fixed routes (e.g. buses), which could be considered as route information.

1.3 Research Aims and Objectives

The overall target of this project is to establish a novel wireless mobile communication network model based on wireless mobile ad hoc networking for Car-to-Car (C2C) system architecture, consisting of three types of ad hoc nodes – mobile (cars), semi-mobile (buses, cars following sat-nav instructions and so on) and static nodes (bus stops). The network includes traffic route information (present in semi-mobile nodes) into the routing algorithm, which improves the efficiency and reliability of inter-vehicle communications in urban areas.

Several proposals have been investigated for solving an increasing number of problems in the field of Intelligent Transportation Systems (ITS), ranging from traffic jams, slippery road warning, to automobile safety, parking space search, and electronic toll payments. To smoothly process these applications, C2C solutions are the most appropriate for the local information exchanges. The work presented in this thesis mainly focuses on C2C communications and it also provides studies on the essential cases of C2I communications. According to the type of messages, there are difference aspects to consider. For example, a warning message with accident information needs to be delivered to the close areas or coming vehicles in short time. On the other hand, a sharing based message like parking spaces might be targeted to participating automobiles only.

In these cases, C2C approaches can utilize a fast direct radio link and C2I solutions help to further data disseminations and provide the possibility of central controls by related city departments. Certainly, the usage and selections of infrastructure or roadside units are particularly considered in order to save expenses to a certain degree. This project considers bus stops as infrastructure and a number of methods to exploit it are investigated.

As far as data disseminations are concerned, a broadcasting mechanism is implemented in this thesis. Broadcast is considered an intuitive and efficient method to deliver messages over a target area. However, the reliability of message delivery by broadcasting is not very high because of complex city topographies, such as streets and avenues, intersections, traffic density, mobility patterns and others. Some methods have been proposed to improve the reliability of transmissions, such as, for example, using C2I communications. This thesis proposes a Probabilistic Traffic Message Delivery Algorithm (PTMDA) with the inclusion of the traffic route information and adopts various roles of communication nodes to help the development of efficient and reliable multi-hoping broadcast transmissions. Furthermore, influencing factors of communication performance, such as network bandwidth, message size and vehicle speed, are simulated and evaluated.

The inclusion of traffic route information is a novel idea realized in this project. These routes are selected by two methods. Firstly, they may be planned in advance; also, they are identified by semi-mobile nodes. The work presented here uses the former although the latter may also be a viable alternative. The integration of route information into the broadcasting algorithm attempts to improve the efficiency of transmissions.

As a result of the brief discussion above the objectives of this research could be identified as follows:

- Present a design of an architecture where the mobile nodes have distinct movement behaviour – static, semi-mobile and mobile.
- Create a simulation environment for testing and evaluating of the proposed architecture
- Create a communication protocol suitable for the proposed architecture

- Evaluate the communication protocol against other proposed solutions

1.4 Original Contributions

The original contributions of this research are outlined as follows:

1.4.1 Design of Collaborative MANET-based Communication Network (CMCN) Architecture

The architecture (Chapter 3) is designed as a case study proof of concept about anywhere and anytime information generation and transmission. It consists of components found in a real traffic, such as cars, buses, static facilities, and lanes. This is drawn according to examples of a city map of Nottingham. The system will be a platform to use a novel message delivery algorithm and achieve the goals of efficient and reliable message delivery. A certain classification of nodes is assumed to accommodate the original dynamic and uncontrollable topologies. These nodes are mainly distinguished by their mobility patterns (e.g. mobile, semi-mobile or static) and also their responsibilities (e.g. gateway or non-gateway) – their collaborative activity ensures adequate communications performance. Novelties incorporated in the CMCN architecture include:

- **Usage of network layers –** On the basis of Open System Interconnection (OSI) model, the CMCN architecture consists of physical layer, media access control/logical link control layer, network layer, transport layer and application layer. In each layer, the specific protocols are configured to adapt for C2X communications. Generally, messages in the field of ITS are generated at the application layer and finally they are broadcast with a fixed format to the network via IEEE 802.11p.
- **Novel classification of nodes** – An important part of the CMCN system is to specify three types of nodes depending on their speed, direction and position, called mobile, semi-mobile and static nodes in the thesis. The overall aim is to maximize the utilization of network cooperation and make the communication

performance to be the optimization. For all vehicles, they are divided into mobile vehicles and semi-mobile vehicles in the system and the motion path is a main factor to distinguish them. The former generally has unpredictable moving paths while the latter is structured, controlled by the traffic control centre of a city. Meanwhile, semi-mobile nodes are the most frequent and regular group that connect to static nodes in the system. Besides, the third type of nodes is defined as static nodes which are normally placed along the road, also known as roadside units or bus stops in this thesis.

- **Introduction of node gateway function** – In the CMCN system, static nodes (e.g. bus stops) are gateway-enabled. It specially aims to overcome the poor connectivity of fully C2C communications via wireless technology in particular cases, i.e. transmissions at night. Meanwhile, the difficulty of urban traffic control and management due to the arbitrariness of cars also requires a certain degree of traditional wired connections or infrastructure-based solutions. Studies on this point contribute to identify an economical and optimum utilization of infrastructure nodes.

1.4.2 Design of a Probabilistic Traffic Message Delivery Algorithm (PTMDA)

The PTMDA algorithm (Chapter 4) is a new broadcasting protocol designed for the proposed CMCN architecture. Obviously, the algorithm contributes to achieve the goal of message delivery and attempts to moderate the amount transmissions in an efficient and reliable manner by addressing the problem of broadcast storms. To optimize communication performance, the algorithm fully exploits the characteristics of CMCN nodes according to their direction of motion, the position, and the speed of movements. Novelties incorporated in the algorithm include:

- **The inclusion of traffic route information (I-Route)** – It is well-known that connectivity is very important in highly dynamic MANETs. In many urban centres there are certain roads which are used more often than others and for which connectivity is not a problem, i.e. bus lanes. Buses appear on these roads frequently and regularly so that message transmissions are able to last longer than when they depend on cars only. Moreover, these routes are close to infrastructure facilities, such as bus stops, which enable active gateway functions in the CMCN network. The gateway feature makes the utilization of bus lanes and buses more critical to implementing credible message delivery. Hence, these routes could be used as main communication “trunks” and nodes on them are able to forward the message with a top priority. In this case, messages are probably delivered in an efficient and reliable manner. As a result, PTMDA includes the route information, named as I-Routes in this thesis. These routes are pre-set to be bus lanes in an urban traffic scenario. Communication nodes operating PTMDA compare their timely position with route information and decide to carry on next actions via probabilistic priority schemes.

- **Elimination of redundant rebroadcasts –** To alleviate broadcast storms during transmissions, a proper broadcasting protocol needs to control packet collisions and redundant broadcasts. In PTMDA, a probabilistic priority scheme contributes to this goal. The scheme consists of I-Route scheme, Farthest Node First Send (FNFS) scheme, Direction-based Priority (DP) scheme and High-Speed Priority (SP) scheme. The main idea is that a receiving node computes its own probability based on the role (e.g. car, bus and bus stops) and mobility patterns such as position, distance from the sender, direction and speed. The calculated probability is compared with a threshold value. Once the conditions are met, it is regarded as the qualified node and it is invoked to forward the message after a waiting delay. According to different network densities and message sizes, the threshold value could be adjusted. Section 5.3 elaborates on the point.
- **Asynchronous forwarding –** Asynchronous forwarding is implemented by giving a waiting delay. The action aims to avoid simultaneous forwarding, which usually causes packet collisions and degrades communication performance. In PTMDA, the idea cannot be implemented until a node obtains its own probability

value from the first part of probabilistic priority scheme. With the probability result, a qualified node could be given a unique waiting delay for the coming forwarding action.

1.4.3 Metropolitan mobility model study

The evaluation of the proposed communication system in this thesis is based on simulation. Actual implementation trials of this scale were financially infeasible and thus out with the scope of this thesis. Studies on urban traffic mobility by traffic simulators (e.g. SUMO) provide more realistic considerations and results to the experimental evaluations. On the basis of a Nottingham City map, this thesis focuses on a 700m*700m region without infrastructure nodes and a more congested 1164m*905m city centre with a certain number of bus stops. In the first scenarios, the observations are focused on end-to-end communication performance in aspects of delivery delay and delivery successes. On the other hand, experiments based on the city centre scenario mainly evaluate communication performance at all network nodes. Thus, the network transmission delay, message reachability, invoked broadcasts, packet drops as well as the utilization of infrastructures are all considered in depth.

1.5 Thesis Outline

Chapter 1 (this chapter) introduces the research area domain and outlines the research problems that are addressed by this research. It also defines the aims and objectives of this research and lists all major research contributions of this work.

Chapter 2 provides an overview of the related work and essential literature reviews for subsequent chapters. Firstly, C2X studies on completed and on-going projects are reviewed. The advantages of C2C technologies in aspects of the cost of connections, the speed of links, the volume of data and the locality features are assessed by reviewing published works. Additionally, typical wireless mobile network architectures supporting for ITS applications are studied and compared with the focused MANET/VANET networks. Following that, routing approaches, particularly on broadcasting, are discussed. Finally, there are current simulation issues delivered including various simulators and methodology explanations.

Chapter 3 introduces a Collaborative MANET-based Communication Network (CMCN) architecture which is utilized for high quality of message transmissions. The chapter starts with brief reviews of existing C2X-oriented wireless mobile network architectures and their limitations in comparison to the CMCN system towards an in depth study in the area. Then the details of CMCN layer technologies are analyzed. Finally, a section specially focuses on the network components, which are characterized by different functions and responsibilities.

Chapter 4 presents the technical details of a broadcast-based Probabilistic Traffic Message Delivery Algorithm (PTMDA) with a particular emphasis on C2C broadcasting. The chapter starts with a discussion on the category of messages as different levels of transmission capabilities are identified. And then the broadcasting mechanism is described with several events and sub-schemes by means of terminology explanations, procedure definitions and algorithm presentations.

Chapter 5 displays the results of simulative experiments and gives throughout observation analysis for the design presented in the previous chapters so that theoretical concepts are evaluated and discussed in depth. The section emphasizes simulation models of proposed CMCN architecture and the implementations of PTMDA and other protocols based on studies of specific metropolitan mobility models.

Chapter 6 summarizes the primary results and deduced conclusions for the whole research work presented in the previous chapters and proposed avenues for future work.

Chapter 2

Literature Review

2.1 Overview

Intelligent Transportation Systems (ITS) are attracting more attention recently because serious traffic problems are growing to influence our daily lives. Typically, substantive traffic accidents are frequently happening over the world, as example cases in [1][21]. Thus, in diverse ITS applications, the most urgent demand is to establish a broad, real-time, accurate and efficient transport control and management system, aiming to reduce traffic congestion, accidents and improper road uses in the modern transportation area. Timely traffic information essentially helps to achieve these goals. In recent years, there have been many research initiatives and projects dedicated to improve C2X communications and this chapter will provide some examples.

Certain outcomes have been proposed to improve the technologies of infrastructures used in cellular phone networks and IEEE 802.11 WLAN networks. However, the high costs, the low connection speed and the small volume of transmission data shown in infrastructure-based communications have directed this research towards another type of message delivery approach, namely C2C applications.

On the basis of various studies [16][21][22] , Mobile Ad hoc Network (MANET) will be a well-suited framework for supporting C2C communications because MANET architecture is characterized by infrastructure-free technologies such as wireless mobile technologies. As stated in [11][16], the frequent changes in topology and the high mobility of network nodes has made the routing scheme challenging in ad hoc networks; accordingly, several published and ongoing MANET routing and broadcasting designs for message delivery are reported.

This chapter is organized as follows: Section 2.2 starts with a general review of completed and ongoing ITS relevant projects, which place great emphasis on C2I solutions. By assessing the advantages of C2X approaches, this research pays more attention to C2C applications. Section 2.3 mainly covers a most important research topic with regard to the network architecture. Current ITS-suited wireless mobile network architectures and their critical techniques and challenges are observed in depth as they are the important technical basis for the proposed design of Collaborative MANET-based Communication Network (CMCN) architecture (Chapter 3). Section 2.4 discusses ad hoc protocols ranging from general classifications to the particular ones applied in MANETs and VANETs. The broadcasting mechanism of routing protocols is a focal point. Section 2.5 studies the most popular used network simulators and traffic simulators. Finally, Section 2.6 provides a summary of literature review and briefly introduces the relationship between views in the literature and the coming chapters.

2.2 C2X Communications

2.2.1 Related projects

Several completed and initiated projects can be found in the seventh EU Framework Programme [23] for Research and Technological Development. The 60 million EU CVIS (Cooperative Vehicle-Infrastructure Systems) Integrated Project [24] provides smart interactions between vehicles and transport infrastructures for road safety. In 2008, the PRE-DRIVE C2X project started, intending to develop and verify a prototype on the basis of the system of EU-project COMeSafety [25] for future field operational tests. Generally, COMeSafety provides a platform to gather results from various individual projects.

The COOPER (CO-OPerative SystEms for Intelligent Road) project [26] is aimed at cooperative traffic management by exchanging real-time traffic information among travellers and fixed roadside systems to finally enhance road safety on motorways.

The SAFESPOT integrated project [27] facilitates intelligent information exchanges between vehicles and roadside units to realize safe and efficient transportation. Likewise, [22] uses roadside stations as it believes that the infrastructure is a prerequisite for particular transportation monitors, such as speed advisories and route navigation; in addition, the Car-to-Car Communication Consortium (C2C-CC) [28] supports C2I solutions since it particularly emphasizes secure information exchanges based on the support of roadside info-stations.

According to the National Institute of Standards and Technology [29], more than 60 research establishments in the USA contribute to achieve the exchange of real-time traffic information for road safety by applying C2X communication solutions.

While many of above mentioned projects exploit infrastructure-based approaches in the field of ITS, the research on C2C communications is gradually increasing. Typically, the German project FleetNet [30] consisting of many automobile suppliers, car manufacturers and even academic research members, has proved initial feasibility of C2C applications.

2.2.2 Theoretical supports of C2C technology

Although the feasibility of infrastructure-based networks (e.g. 3G and WLAN) for ITS applications have been shown in some research such as [3][31], the limitations of C2I applications in terms of the cost of connections, the speed of links, the volume of data and the locality have been noted recently. Instead, these could be addressed by C2C solutions.

2.2.2.1 Cost of connection

From an economic point of view, infrastructure-based network in ITS is not recommended. First of all, the real life experiences prove that substantial costs are computed every minute if communications depend on traditional infrastructures i.e. base station. Moreover, it is not desirable to spend huge sums on construction, maintenance and, as [3] stated, a surge of new roadside units along roads or highways if there are other choices. It is known that C2C communications occur in an environment without deployment of infrastructures and the connections are established by digital radio. A representative V2V project – FleetNet [32] indicates that periodic information data transmission among automobiles via a cellular method will be costly, but not with a decentralized wireless multi-hop communication network. In other words, expensive infrastructure costs are avoided by C2C solutions. Although the C2I communication is well-known to allow mobiles to access Internet via infrastructure devices, C2C is possible as well through a so-called gateway node or dynamic infrastructure [3], which plays an important role to allow a non-infrastructure network to access Internet services within C2C ranges only.

2.2.2.2 Speed of link

In C2X applications, connection speeds can vary for different network technologies in different mobility situations. Project [3] concludes that the end-to-end delay in C2I is very high even for local area message exchanges. Some of C2I applications are deployed in 3G networks and in-car mobile phones play essential roles to complete data disseminations via established infrastructures. But in high-speed mobile communications, the transmission rate [9][10][11] will be only from 144 kbps as the lowest to 3Mbps as a latest value while WLAN-based networks allow C2I communications by using Access Point (AP) and the speed is faster, up to 150Mbps under 40MHz channel bandwidth. However, [10][11] points out that WLAN presents poor performance in a high-speed mobility environment and cannot guarantee communication security while cell-based networks can. Nevertheless, the SOTIS project in [33] demonstrates that C2C offers direct radio links which provide low delays in the local area. Meanwhile, [12] indicates that C2C communications with the transmission speed between 6 and 54 Mbps via IEEE 802.11 present a quick time critical response that is less than 50 ms. The end-to-end delay of connection is also compared in the paper [3], being lower than that of C2I solutions.

2.2.2.3 Volume of data

The experiments conducted in [13] shows how the total correct received data volume relates to packet sizes and transmission rates between cars and roadside units. In the authors' opinions [13], the total data volume is affected by packet length and the sum of correct received frame in terminals (Equation (2.1)).

$$\text{data\_volume} = \text{packet\_length} * \text{sum of correct received frame} \tag{2.1}$$

Fig. 2.1 [13] depicts a comparison of data volume by changing packet length and data rate respectively. As a conclusion, Fig. 2.1a proves that as the packet length increases, the total data volume increases under the 80 km/h vehicle speed and 3 Mbps transmission rate scenario. It shows that the total volume reaches 6 MB when the packet length is 200 bytes and 10.5 MB for 1554 bytes of packet. Additionally, Fig. 2.1b implies that higher data rates using quadrature phase shift keying (QPSK) modulation based on ½ and ¾ coding rates presents larger data volumes within a boundary value. This example shows the boundary value for both direction tests is 9Mbps. At the point, the maximum data volume for driving to east is 5.4 MB while the opposite direction owns 6.1 MB.

a) 80 km/h, 3 Mbps b) 120 km/h, 200 Byte

Fig. 2. 1 The comparison of total data volume [13]

Comparably, F. Schmidt-Eisenlohr in his paper [14] analyses the data volume in V2V environments. He uses a term 'local broadcasts capacity' to mean the amount of data allowed for each node in correlation with density (nodes/m), data rate (bit/s), theoretical awareness range (m) and required reception probability (p) to the channel usage (Equation (2.2)). When p equals 1, data rate b is 3 Mbps, 0.14 nodes per metre and awareness range r equals 100 m, then the maximum size of data volume can be 13,392 bytes/s and in the worst case 171 bytes/s.

$$C_{LB,\,max}\,(b, d, r, p) = b/2dr \tag{2.2}$$

It then provides closer analyses with regard to the effect of different message sizes on communication performance. Experiments set different packet sizes ranging from 100 bytes to 1000 bytes. Under the same conditions of other parameters, such as data rate, transmission power and modulation category etc., the experiments' results (Fig. 2.2 [14]) show that for all sizes of messages, the successful packet reception ratio (SRRo) decreases with the increasing distance between senders and receivers in both 60 vehicles/km and 140 vehicles/km. Particularly, a larger size of packet (1000 bytes) shows a lower SRRo than that of a smaller size (100 bytes).

a) 60 vehicles/km

b) 140 vehicles/km

Fig. 2. 2 The comparison of successful packet reception ratio [14]

According to the above literature, it is known that the data volume for both C2I and C2C scenarios are commonly affected to data rate, transmission range and vehicle speed. But C2I concentrates more on packet size and the receiving capability of RSU sides (Equation (2.1)); while C2C applications pay more attention to density and probability of message transmitted from nodes within the awareness range (Equation (2.2)) and the packet size.

2.2.2.4 Locality

Infrastructure-based networks support wide area communications [21], seen in [8] that base stations (e.g. in cellular networks) cover several hundred meters or even kilometres. C2I applications, e.g. mobile telephony, can be potentially used for solving problems that occur in inter-city or highway scenarios rather than just local area traffic problems [6]. In contrast, C2C applications are usually designed for solving local area problems, e.g. traffic congestion. The communication range can be short, within dozens of meters. As the FleetNet project [32] proposed, the locality of the data should be exploited. It notes that one of the significant characteristics of Car-to-Car networks is to have data relevance to a particular geographic region. According to the current position, nodes are able to adopt position-based routing for location-based services rather than using IP addressing only. The authors of [32] also show a number of examples in drivers' assistance to prove that the locality of C2C solutions is competent to replace current methods through centric controls. This is the target of the proposed system.

2.3 Typical Network Architecture for C2X Communications

Currently, the most widely used C2X wireless mobile network architectures are cellular networks, WLAN networks and MANETs.

2.3.1 Cellular network architectures for C2I solutions

Cell-based systems developed in recent years such as GPRS, 3G, 3GPP LTE and 4G, have been used to support C2I applications [34][35][36][37]. In terms of ITS services only, for example, K. Trichias (et al.) in the research [36] modeled and evaluated that the latest mobile communication technology such as LTE (Long Term Evolution), which is developed by the 3rd Generation Partnership Project, can meet most requirements as long as the traffic load does not reach its capacity. Moreover, apart from the short-distant transmissions, the feasibility to provide most vehicular services is equivalent in a medium and large scale of information exchanges [7]. While the cellular networks are deployed for ITS applications, the mobile technologies are able to promise the Internet access for communications [36]. The feature, actually, helps to improve the message spreading. Furthermore, [38][39] exploits the feasibility of C2I communications in cellular networks, especially the Universal Mobile Telecommunications System (UMTS). It proves that multimedia broadcast/multicast services (MBMS) are very important for providing efficient C2I communications in the network. In these C2I-suited cellular network architectures, several fundamental techniques are deployed. This thesis focuses on two of them only.

2.3.1.1 Fundamental techniques

Multiple access methods - In the handbook [40], three types of fundamental

MAC protocols are summarized. Frequency-division multiple access (FDMA) differentiates channels by frequency. Once mobile stations generate information, they will be modulated to various carrier frequencies. A base station identifies each target destination according to different carrier frequencies. Time-division multiple access (TDMA) uses time-slots to distinguish channels. TDMA assigns different time-slots to data streams and sends them to receivers with a specific time distribution scheme. Receiving mobile stations can obtain their messages correctly as long as they deal with messages within specific time-slots. Code-division multiple access (CDMA) utilizes code patterns to separate channels and avoid collisions. As long as two different nodes have significant differences of orthogonal codes, transmissions will not suffer interference. Compared with the other two protocols, CDMA requires more complicated and expensive hardware and sophisticated management schemes. There are two types of spread spectrum: Direct Sequence Spread Spectrum (DSSS) and Frequency Hopping Spread Spectrum (FSSS) used in CDMA-based cellular systems. The 3G cellular system is based on CDMA technology (cdma2000).

Handover technology - In order to meet the demands of larger capacity, higher connection speed and more services in cellular systems, therefore, the occurrences of handover face being increased. To reduce handovers, proper algorithms become hot issues in the field.

According to [41], there are hard handovers and soft handovers respectively. The former indicates that one mobile station only can communicate with one base station at a time. An active connection between the mobile station and the old base station may be broken before a new connection is established. Whereas, the latter allows one mobile station to build a connection with a new base station and then disconnect from the old base station. Thus, mobile stations in soft handover can communicate with different base stations at a time.

2.3.1.2 Challenges of cellular phone network in C2X communications

Generally, the specific features of the cellular system can be summarized in the aspects of radio, networking technologies, limited resources and so on [42]. These characteristics, on the other hand, show some weaknesses for C2X communications.

Speed of links – Using research conclusions in [9][10] as reference, cellular networks from the earlier 2G networks to recent 3G mobile networks, the stable data rates for ITS services are relatively low. For example, S. Al-Sultan (et al.) in [9] present that GPRS was standardised to adapt for high bandwidth data transmission, allowing only up to 170 Kbps data rate; 3G networks such as UMTS or CDMA2000 will only support for approximately 1.8 Mbps uplink and 3Mbps downlink respectively. Many studies [9][10][34] [35][36] have proved that such speed of transmissions cannot meet requirements of timely ITS service, such as accident avoidance, emergency rescue and so on, which is one of the most important responsibility of C2X communications.

Cost of connections - Cellular networks are not able to operate any transmission operations at no cost [35]. With the increased usage of channels, connections are charged on data transferred. In Finland [6], data upload or download will cost about 1.5 euro every Megabyte of data transmission between mobile devices and infrastructure facilities. C. Peng (et al.) in their research [43] state that cell-based networks, such as 3G, charge the users according to their used data volume. The fees, as in US, vary from 1s to 200s of cents per MB data. According to these examples, there will be a substantial cost for local information exchanges. Moreover, experiments in [43] proved that the charged volume of data in 3G networks is not only for data expected but also for unnecessary waste caused by improper cellular accounting standards currently. Additionally, the central-controlled architecture of cellular networks makes data transmissions carry out with comprehensive designs and costly equipment. For example, a sequence of infrastructures, e.g. base stations, is established within every fixed distance, so that mobile nodes can have normal communications from one place to another further away. Technically, handover and roaming are critically involved.

Limited resources – Nowadays, mobile users are increasing rapidly as more wireless mobile-enabled devices are developed and used in our businesses, studies and entertainment. However, frequency allocations are limited, according to the rules. A potential trend will be found that rising numbers of users and services are allocated a very narrow frequency band, which is very crowded. As [11][38] stated, 3G technologies are picked up to support most C2I applications. But the connection speed is still limited as analyzed in previous paragraphs. On the other hand, operators significantly influence the willing of customers to upload and share traffic information by their pricing policy; meanwhile, they control and limit the connections and data volume due to security and business issues [6].

Locality - [21][44][45] indicate that cellular networks support wide area communications. For example, base stations exert control capabilities within transmission ranges of several hundred meters or kilometres [8]. Such networks are suitable for inter-city communications rather than just local transmissions.

Distortions of radio paths - Mobile nodes move between various buildings and obstacles, which may cause distortions of radio paths. In this case, the final communication quality and reliability will be seriously influenced. To prevent this occurring to a certain degree, research on anti-multipath fading technologies is essential and urgent.

Energy consumptions – While the concept of green wireless communication has been put forward [45], energy consumptions and greenhouse pollution caused by wireless devices are paid more attentions. [45][46][47] state that infrastructures usually provide inefficient energy consumptions due to their power-on mode. In high-load traffic period, the mode offers properly communication services; but it appears a lot of energy waste when there are low traffic loads. Furthermore, as described by P. Serrano (et al.) [45], a part of energy consumptions is rooted in poor-planned deployments of infrastructure and wireless devices. Because of this, particularly in dense transport areas, overprovision or signal overlaps significantly impact communication quality. Rationally, these infrastructure-based networks may face a re-design process to meet requirements of green wireless communications in the future [45].

Based on our life experiences, the 3G system has been broadly used and attracted investment in markets all over the world [38]. Outcomes about using mobile phone systems for vehicular communications have appeared on the market, e.g. infrastructure-based Floating Car Data (FCD) system [48]. However, they do not match the requirements of direct C2C communications [22] to solve ITS problems. In the paper [48], the constraints of such a system are noted. Once the raw data are obtained from mobile terminals, they need to be delivered to the centre controls for interpreting by algorithms. On one hand, the mobile phone system is not good at tracking functions because the speed of links limits its capabilities to return a large number of data for complicated treatment; on the other hand, a useless amount of data reaches the control centre, leading to unnecessary consumption of the channel. Consequently, researchers have become interested in studies on the inter-vehicle FCD system.

2.3.2 IEEE 802.11 network architectures for C2X solutions

Another network architecture that belongs to the wireless mobile system is Wireless LAN (WLAN) with well-known IEEE 802.11 series standards. This is a type of flexible data communication system providing higher speed of transmissions but shorter range (e.g. around 100 meters) compared to cellular networks and MANETs [9][10]. In the field of ITS, WLANs via IEEE802.11 family of standard (e.g. a/b/g/n) [9][10] are able to support C2X applications. Based on [16], there are two operation modes defined in WLANs: infrastructure-based mode and ad hoc mode. The first mode operates by means of access points, which is regarded as a bridge to connect mobile nodes to existing network systems (e.g. the Internet); whereas ad hoc mode is widely used for C2C communications and competes with other suitable architectures of C2C applications.

2.3.2.1 Operation modes

The infrastructure mode of WLAN offers access between nodes and other existing network backbone, both wired and wireless types; conversely, ad hoc operation will only allow information exchanges within local areas and inter-communications are carried out by nodes themselves.

Infrastructure mode - Technically, an infrastructure-mode WLAN is composed of at least one access point (AP) which connects to a fixed LAN and a set of wireless mobile or static end stations. This is a basic building block called a basic service set (BSS) [49]. Once a workstation WS generates an IEEE 802.11-based packet for the destination station DS, the packet has conversations with an AP firstly via a radio frequency which is located between 2 GHz and 5 GHz. For a single-hop [50] BSS, communications between client stations depend on APs. Moreover, devices could download traffic information through APs from other network backbones.

Ad hoc mode - The occurrence of ad hoc mode operation is common in a WLAN when a basic service set (BSS) does not require accessing other networks and they expect to have direct communications by only using IEEE 802.11 network interfaces. Therefore, infrastructure-less and multiple hops are two significant characteristics in the mode. IBSS (independent basic service set), which includes inter-talk by radio waves without APs, is used for naming an ad hoc network with the IEEE 802.l1 standard [51].

2.3.2.2 Fundamental techniques

IEEE 802.11 PHY service - IEEE 802.11 standard is implemented to develop MAC and PHY specifications for wireless connections between static, portable and mobile stations within the local area [11][51]. B. P. Crow (et al.) [51] indicate that twofold purposes of the standard are providing wireless connectivity and standardizing access to frequency bands (e.g. 2.4 GHz, 5 GHz etc.). By referring to [9], [42], [49], [52], [53], [54], [55] and [56], Table 2.1 concludes and compares several well-known IEEE 802.11 standard series in terms of establishment, frequency band, bandwidth, compatibility and modulation.

[51] and [54] describes three implementations in IEEE 802.11 physical layer. They are Frequency Hopping Spread Spectrum (FHSS), Direct Sequence Spread Spectrum (DSSS) and Infrared Spectrum (IR). Additionally, for higher data rate WLANs, there are Packet Binary Convolution Code (PBCC) and Orthogonal Frequency Division Multiplexing (OFDM), complementary code keying (CCK), etc. [42]. The following parts pick up three of these modulation methods from published resources.

Table 2. 1 Typical implemented WLAN IEEE 802.11 standard series [52][53]

	802.11	802.11b	802.11a	802.11g	802.11n
Approval	1997	1999	1999	2003	2009
Frequency (GHz)	2.4	2.4	5	2.4	2.4/5
Bandwidth (Mbps)	1~2	5.5, 11	Up to 54	Up to 54	Up to 150
Compatibility	802.11	802.11/ 802.11g	802.11a	802.11b	----
Modulation	FHSS/ DSSS/IR	DSSS/ CCK	CCK-OFDM	CCK-OFDM/ PBCC	64-QAM, Alamouti, OFDM,CCK, DSSS
MAC protocol	CSMA/ CA	CSMA/ CA	CSMA/ CA	CSMA/ CA	CSMA/CA

FHSS [57] provides a synchronization of unique frequency hopping pattern into senders and receivers at varying timeslots. The term hopping represents constant changes from a frequency to another one, which increases the bandwidth by a length of sequence. In particular, narrowband carriers are used to transmit signals with a speed of 1 Mbps or optional 2 Mbps in a noise-free environment [55].

DSSS divides data stream into small pieces over a frequency channel. A term chipping code is explained in [57] to mean a multiplication of a data signal and a higher data-rate bit sequence. Additionally, the chipping code has the capability to correct damaged data bits without retransmissions. Usually, a longer chipping code leads to increasing throughput of the original data [57]. Compared with FHSS, DSSS offers higher bandwidth, for example, a peak rate of 2 Mbps and 1 Mbps in a noisy environment.

In IEEE 802.11 a/b/g, OFDM is commonly adopted. This is a truly representative of multicarrier technologies. Basically, the idea of OFDM is to separate the channel to be several orthogonal sub-channels. This converts high-speed signals to be parallel low-speed sub-data streams and places them into sub-channels [42]. In the method, against delay spread and against multipath fading are two prominent advantages while the major shortcoming is that OFDM is sensitive pertaining to synchronization errors and frequency offset [42]. For data transmission rate, OFDM supports it up to 54 Mbps.

IEEE 802.11 MAC specifications - The media access control (MAC) layer is responsible for wireless media access, network connection, error checking, the confidentiality of data, etc. [42].

Typical media access methods mainly include Distributed Coordination Function (DCF) and Point Coordination Function (PCF) [42][54]. DCF is utilized for asynchronous data transmissions. In infrastructure networks, DCF is operated independently, or even coexists with the PCF method in the infrastructure modes. In IEEE 802.11 networks, DCF is based on carrier sense multiple access with collision avoidance (CSMA/CA) [42][58]. In particular, R. A. Saeed (et al.) propose a new TDMA method to IEEE 802.11p in [59]. The MAC method simulated with good results. Especially, an enhanced version of the DCF method is called Enhanced Distributed Channel Access (EDCA), which is derived from IEEE 802.11e, being used in IEEE 802.11p V2V applications.

Another function of the MAC layer is to control the scalability of a network. When a workstation powers on, it should first scan whether current workstations or APs can be added. Once it enters a BSS, it will receive Service Set Identifier (SSID), Timer Synchronization Function (TSF), timer value and PHY initialization parameters. Finally, the station can complete network connections. Typically, there are two scanning ways: passive-scanning mode and active-scanning mode [42]

In terms of security, the IEEE 802.11 MAC layer adopts two authentications. open system authentication (OSA) and shared key authentication (SKA) and wired equivalent privacy (WEP) [42]. The first one is a default mode, which contains a client's authentication request and an AP or other stations' authentication responses. Compared with the OSA, the SKA provides better security. In this service, both the client station and the AP agree with a shared key. Besides, there are selectable WEPs defined in IEEE 802.11 standards, which makes wireless networks constitute equivalent levels of security to wired networks.

Handover methods - The Basic Service Set (BSS) is restated in this part to explain the occurrence of WLAN handovers. BSS is made up of mobile nodes (MNs) and APs. One role of AP is a bridge for MNs involved in the WLAN with a certain communication range. When an MN moves from one BSS to another, MAC layer handover processes are taken to avoid disconnections, including detection phase, search phase and execution phase [60]. [61] stated that 85% of total handover duration is used by MNs for detecting the reduction of signal strength or the signal-to-noise ratio (SNR), and 15% of total time for MNs to search a new AP by active scanning method; finally, the execution phase processes an exchange of authentication between the MNs and new APs and associates both devices. As an example of 802.11b WLAN, the process takes 0.1% of total delays [62].

Facing variety of WLAN applications in recent years, researchers continually offer more efficient handover mechanisms. Some proposed handover schemes, e.g. [62][63], focused on the reduction of scanning latency while others may be interested in decreasing delays occurring in the authentication stage, such as [64]. K. Tsukamoto (et al.), in their research [65] regarding communications of a multi-rate WLAN, proposed a new handover method which uses two interfaces (IFs) through the cross-layer between MAC layer and Transport layer. In such a case, two end-to-end links exist at the same time and they could switch the active connection between them at handover. An interesting point is that this handover approach does not need supports of infrastructure. While handover is in process, a mobile node can connect with a new Access Point before the current AP reduces. Additionally, S. Busanelli (et al.) [66] consider a vertical handover method in heterogeneous networks which are composed of Wi-Fi and UMTS technologies.

2.3.2.3 Challenges of WLAN in C2X communications

Cost of connections – Nowadays, WLAN (e.g. Wi-Fi) is a widely deployed networks in many areas [67]. Some public places are even offer free Wi-Fi collections, such as coffee shops, University, Airports and so on. If not free, based on our life experiences, the expense is cheaper than that of 3G networks. For example in Nottingham City Centre, the Wi-Fi charge is no more than £10 per day. The main fees of connections are charged by the use of access point (AP) and network establishments. Access points cover smaller areas than that of base stations, thus, they are normally positioned in a shorter distance and in larger numbers, which means more expenses for constructing, maintaining and repairing them.

Speed of links - Wi-Fi networks could provide communication speeds up to dozens of Mbps, being faster than cellular networks. As stated in [9][10][52][53], the maximum speed of links can be 54Mbps by IEEE802.11a/g; or it can be 72.2Mbps by IEEE802.11n at the same channel bandwidth 20MHz and up to 150Mbps at a channel bandwidth 40MHz. Although ad hoc mode is offered by a WLAN, it cannot support high mobility communications. Related projects such as [7] and [8] have studied improving the connection speed of infrastructure-based communications so that the infrastructures could be used to provide better effect. But how far it can reach is still in doubt.

Locality – A WLAN shows good implementations for local communications in many public and private places [67], such as airports, hotels, coffee shops and so on . Although the ad hoc mode of WLAN brings benefits and possible operations to C2X deployments, it is not the trend of future utilizations for solving ITS problems. The main reason is that this kind of network tolerates low movements (static or minor mobility) of network participants [10], in conjunction with the consideration of connection speed, cost and data amount tolerance.

Energy consumptions – In terms of green wireless communication [45], infrastructure-based WLANs exist with the same energy consumption problems due to unnecessary power-on operation or overlaps of coverage etc. As S.L. Tsao and C.H. Huang [67] surveyed on the issue that many researchers have realized and proposed improved approaches for employing the DCF, PCF, EDCA and so on in WLANs to alleviate inefficient consumptions. The solutions are divided into MAC-layer approaches, such as eliminating contentions or block the acknowledgements [68], and Cross-layer approaches, such as optimizing the energy efficiency of WLAN MAC for Voice Over IP packets [69].

2.3.3 MANET for C2C applications

While C2C communications has attracted more attention to address traffic problems in the ITS domain, there is an important question asked about what kind of network architecture is best suited for applying the technology. As in [16], mobile ad hoc network (MANET) is the one that is critically involved in 4G architecture (Fig. 2.3 [16]).

MANET consists of a group of arbitrary self-organized wireless mobile nodes

Fig. 2. 3 An overview of comprehensive 4G network architecture [16]

with the absence of centralized controls. Mobile objects exist with flexible, dynamic, distributed and self-organization features to collaboratively generate and control transmissions in distributed systems. Such network also provides wide network coverage by multi-hop message forwarding among independent mobiles.

The network is popular for military communications, sensor networks, disaster recovery, e-business, home networking, virtual classrooms, outdoor internet access and location-aware services etc. [4][16]. For further development of mobile networking, a large number of imperative considerations are proposed, such as routing protocols, energy conservations, network security and quality of service (QoS) supports.

2.3.3.1 Topology structure

In line with the logical relationships between mobile nodes (MNs), the authors in [70][71] specify two patterns of MANET topologies: flat structure (Fig. 2.4a) and

a) The flat structure b) The hierarchical structure

Fig. 2. 4 MANET topology structures

hierarchical (cluster-based) structure (Fig. 2.4b).

Flat structure - In a simple flat structure (Fig. 2.4a) MNs are equal to be managed independently or cooperatively. A MANET organized by MNs is also called a peer-to-peer distributed network. In the network, MNs are all able to store and forward active packets without the aid of centralized controls. The topology presents good invulnerability, scalability and flexibility, which are of great benefits to particular application areas, such as urban traffic communications. The work presented in this thesis is based on this structure.

Cluster-based structure - The structure (Fig. 2.4b) distinguishes the role of fair nodes on the basis of cluster concepts. That is, the whole network is divided by different clusters. A cluster consists of a cluster head node (CHN), a cluster gateway node (CGN) and several cluster members (CM) [72]. Furthermore, Y. Y. Jane and P. H. J. Chong [72] indicate that the CHN is determined by preconfiguring or clustering algorithms, being responsible for managing and controlling message exchanges in the cluster. In Fig. 2.4b, the CHN locates one-hop away from the CMs. The CHN is in charge of coordinating local transmission issues, e.g. data forwarding. Many CHNs can be organized to generate higher level networks. Additionally, a CGN works as a coordinator being responsible for transmissions between different clusters. CMs are relatively simple. They play the same role in the cluster to spread information within their cluster only.

In many cases, clustering schemes are generated for MANETs to compensate for some problems brought from flat structures. They do exhibit various advantages as stated in [70]. For example, they can improve system capacity by using multiple channels or strengthen node management by decreasing overheads of exchanges. On the flip side, the hierarchical structure of MANETs may lead to difficult tasks about finding a proper node to be a cluster head, defining hierarchical routing protocols, and etc. or complex network configurations.

2.3.3.2 Vehicular Ad hoc network (VANET)

In terms of C2C applications, many researchers have paidattention to information exchanges in urban traffic. In the area, vehicles are major players to implement wireless mobile communications via modern in-car devices nowadays. Indeed, the system is called vehicular ad hoc network (VANET). It is a special MANET [73], also known as Inter-Vehicle Communications (IVC) system [21][74], supporting both Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications on the basis of a Wireless Access in Vehicular Environment (WAVE) standard which is specially designed for vehicular communications.

Beyond the characteristics of common MANET architecture, the differentiating features of VANET are mainly analysed by the following aspects:

Target applications - MANET was originally designed for military applications. Today, with the increased mobile communication demands by wireless devices, non-military deployments are found in MANET research and projects. There are many commercial and personal applications, such as home and enterprise networking, virtual conferencing and classrooms, outdoor internet access, e-commerce and also emergency services etc. Being different from MANETs, the applications of VANETs concentrate on transportation areas where vehicles are the hosts. That is, driver behaviors are more important, in conjunction with considerations of a cooperative concept among traffic participants. Many VANET applications are studied to address traffic problems, such as route navigation, accident warnings and so on. For example, the TrafficLab [75] provides location-based, traffic-oriented services to drivers based on VANET by using detection technologies and also GPS navigation. In addition, the FleetNet project [32][76] creates advanced applications to improve active safety, distributed floating car data and drivers' comfort communications in VANET. Moreover, an European three-year project CarTALK2000 [77] designed a system based on VANET for driver assistance.

Mobility - There are specific traffic constraints in VANET, including roadways, directions, vehicle speed and intersections etc., which are not big issues in MANETs. These limitations are analyzed in [78]. [21] conducts an in depth study on topology changes due to different mobility features in both networks. MANETs generally consist of mobiles with moderate mobility, but vehicles in VANET can move with high speeds, e.g. on highways. Existing MANET routing protocols, such as Ad Hoc On-Demand Distance Vector Routing (AODV), Dynamic Source Routing (DSR) or Destination-Sequenced Distance Vector Routing (DSDV), lead to point-to-point paths with reasonable delays and occasional repairs. However, reviewed in [79], the time of path discovery by routing protocols should be highly considered because, in VANETs, high-speed vehicles have a very short life duration staying in an area. In order to overcome this situation, one of methods is to enlarge transmission range, but this is set aside because it comes at a high price for communication devices. Therefore, developed message delivery algorithms are required to address this problem.

Energy conservation - This was stated earlier in this chapter and it is a big challenge for mobile ad hoc networks as limited power is provided. Conversely, VANET benefits from its vehicle nodes which can supply enough electric power to in-car devices. It is also discussed in [80] that energy conservation does not really restrict network communications.

Density – In both MANETs and VANETs, nodes are distributed in different areas unevenly. The density of network varies at different times and in different parts of the area, causing fast-changing and unbalanced topologies of networks. [81] considers a well-known design issue, the marginal effect. Hence, considering the density of networks is an important step in investigations of network communication performance.

In conclusion, MANETs and VANETs are based on pure ad hoc networking with differences in some ways and the latter is actually an extension of the former. More challenges of VANETs compared with MANETs have been investigated in [79]. For specific purposes, novel architectures will adopt corresponding technologies in such networks. Overall studies in this thesis are based on urban traffic scenarios, in which the network contains vehicle nodes and non-vehicle nodes, in conjunction with traffic lights, roads, various traffic rules etc. In addition, the mobile nodes are separated into moderate-speed wireless-enabled participants (e.g. buses) as well as high-speed wireless-enabled vehicles (e.g. cars). To consider the universality of the proposed network architecture for future implementations, in this thesis, the concept of MANET and VANET is unified so that the term C2C is regarded as the same as V2V and C2I is the same as V2I or Vehicle-to-Roadside-Units (V2R).

2.3.3.3 Techniques and challenges

The specific mobile ad hoc network issues and constraints exhibit a host of challenges in network designs. MANETs are derivatives of conventional ad hoc networking. In the following part, fundamental technologies utilized in such networks are analyzed.

IEEE 802.11p PHY service - For C2X applications, IEEE 802.11p has been proposed in network architectures. It defines the PHY services and the MAC specifications for vehicle communications, also known as Wireless Access in Vehicular Environment (WAVE) [56]. IEEE 802.11 devices have been considered to operate in the Dedicated Short Range Communications (DSRC) band by using WAVE operation mode to adapt highly mobile vehicular networks. DSRC is specially designed for C2C communications and allocated at 5.9 GHz spectrum. According to [82] and [83], the physical layer of IEEE 802.11p WAVE uses 10 MHz bandwidth for each of seven channels based on OFDM PHY of IEEE 802.11a. As shown in Fig. 2.5 [82], DSRC is not full of WAVE specifications; meanwhile, IEEE 1609 standards are included for upper layers.

Fig. 2. 5 The stack of Wireless Access in Vehicular Environment (WAVE) [82]

F. Schmidt-Eisenlohr [14] argues that modulation mechanism and coding rate are important to determine the appreciable data rate of IEEE 802.11 radios. The former aims to convey information in changing waveforms and the other represents the ratio of total carried bits for real data bits. Table 2.2 [84][14] presents various relevant parameters of modulation scheme in IEEE 802.11p. Particularly, it should be noticed that although a higher data rate is obtained by using better modulation and coding rate, it is more likely to have errors when received in such a frame. Hence, the selection of modulation scheme and coding rate depends on the strength of the received signal.

Table 2. 2 Physical parameters in IEEE 802.11p [84][14] under 10MHz channel bandwidth

Data rate	Modulation Scheme	Coding Rate	SINR Threshold [dB]
3	BPSK	1/2	5
4.5	BPSK	3/4	6
6	QBPSK	1/2	8
9	QPSK	3/4	11
12	16-QAM	1/2	15
18	16-QAM	3/4	20
24	64-QAM	2/3	25
27	64-QAM	3/4	N/A

IEEE 802.11p MAC specifications – IEEE 802.11p MAC, based on IEEE 802.11e, adopts an Enhanced Distributed Channel Access (EDCA) mechanism (Fig. 2.6) instead of rules defined in Distributed Coordination Function [14]. EDCA defines four priorities as access categories: AC_BK, AC_BE, AC_VI and AC_VO [14][85][86]. Fig. 2.6 [14] illustrates that EDCA supports both Control Channel (CCH) and Service Channel (SCH) which are allocated in 5.9 GHz spectrum in C2X communications. Each channel

Fig. 2. 6 IEEE 802.11p enhanced distributed channel access (EDCA) [14]

has four queues which handle their own contention parameters, such as Arbitration Inter-Frame Space (AIFS) and contention window (CW). Consequently, ACs, coupled with CW and AIFS, support data traffic. Basically, a station (SAT) with higher priority traffic could wait shorter time to send its packet when it uses shorter CW and AIFS for its packet [85][86].

In the use of such seven channels (one CCH and six SCHs), safety and control messages are firstly delivered on CCH during CCH intervals and then messages with non-safety data are delivered using remaining time over available SCHs [87]. Once a non-safety CTM message is invoked within the SCH time slot, it then waits to use the SCH within the CCH interval [87]. As stated in [56][87] , it is assumed that CCH and SCH take

50 ms respectively within a fixed 100 ms length of periodic synchronized interval. Using as a reference [88], V. Shivaldova indicated that data rate by IEEE802.11p for C2C communications is ranged from 3Mbps to 27Mbps under 10MHz channel bandwidth. However, if required in the communication systems, the data rate can be increased by merging SCHs to be 20MHz or 30MHz. In such a case, the data rate will be improved.

Hidden-terminal and exposed-terminal - By learning from [16], MANETs usually use broadcasting and shared-media mechanisms to perform data transmissions. However, one of the non-negligible problems, as [16] stated, is data collisions and media contentions, to which the hidden-terminal and exposed-terminal problems are directly related.

Hidden-terminal problem, briefly, implies an occurrence of data collisions between two or more network nodes. As Fig. 2.7 depicted, C locates into both the transmission ranges of A and B while they cannot directly hear each other. If both A and B start sending a message to C at the same time, the hidden-terminal problem occurs at C.

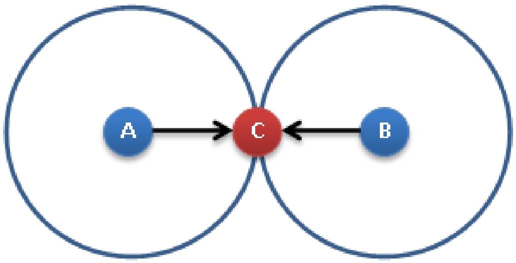


Fig. 2. 7 The hidden-terminal problem

Fig. 2.8 shows the exposed-terminal problem. A, B and C are in the same transmission range (R), where A and C can only talk via B. At time (T), B is sending a message (M1) to A; at the same time, C wants to send a message (M2) to D, which is out of the range R. By Carrier Sense Media Access (CSMA), C first listens to the network and finds the moment when B is communicating with A, so that C has to stop sending anything until the network becomes idle. Visually, C sends the message to D, and there will not be any data collisions occurring at T. However, nodes are forced to obey the rule of CSMA methods, leading to unnecessary loss of throughput.

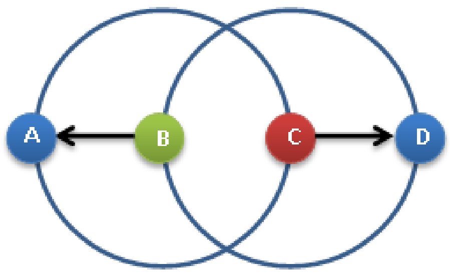


Fig. 2. 8 The exposed-terminal problem

Hidden-terminal and exposed-terminal issues direct conventional MAC methods towards new optimal solutions. As reviewed in literature, a group of developed protocols were designed to solve relevant problems and improve MANET channel performance [16], such as Multiple Access with Collision Avoidance protocol (MACA) [89], MACA with CW optimization (MACAW) [90], Floor Acquisition Multiple Access (FAMA) [91], MACA with Piggy-backed Reservation (MACA/PR) [86], and MACA By Invitation protocol (MACA-BI) [92]. These protocols take advantages of the RTS/CTS mechanism [16], in which Request-To-Send (RTS) packets and Clear-To-Send (CTS) packets are exchanged before a real transmissions between two nodes, aiming to guarantee possible transmission. However, the method is proved by [93] to be unsuitable for heavy traffic conditions. Thus, a set of approaches has been proposed to alleviate these problems.

Backoff mechanism - The backoff mechanism with several collision avoidance approaches is used [93]. The main idea [16] is that a node waits for a random backoff time before any transmissions, even if the network is idle. The backoff duration is tuned by the choice of the contention window and finally handles the network congestion. Certainly, resolutions are not limited by the method only; others have been found recently, such as dual busy tone multiple access (DBTMA) [93].

Routing - One of the big challenges is to manage routings in ad hoc-based networks because of an imperative feature of the networks, namely unpredicted changeable topologies. So far, many routing protocols and algorithms have been designed and published for MANETs and VANETs, aimed at establishing efficient and reliable routes for communicating nodes. The relevant literature is discussed further in Section 2.4.

Handover – A. Böhm and M. Jonsson in their paper [61] described handover methods of vehicular networks. Compared with WLAN, they regard vehicles as mobile nodes and Road-Side Units (RSU) as APs. Due to the nature of high-speed mobility, the handover between vehicles and RSUs has higher requirements.

Generally, a WLAN classifies three handover phases, such as detection, searching and execution, and each phase takes a tolerated time to complete tasks. For VANETs [61], IEEE 802.11p specifies minimized parameters in the execution phase. In this case, vehicles can communicate with RSUs quicker than other IEEE 802.11 versions. However, no association/authentication of IEEE 802.11p handover leads to a difficulty for RSUs to know whether vehicles are in the transmission range or beyond.

[61] classifies four priority applications for different connection setups with RSUs. For example, the highest priority is given to safety-critical C2C alert messages rather than C2I connection set request (CSR), which is assigned as level 2 priority. Following them, periodic C2C cooperative awareness messages are allowed for setups, with greater priority than best effort comfort/entertainment application data.

In real scenarios, RSUs are usually placed along the road, with a certain number to implement handover processes. [61] proposes a proactive handover mechanism to predict the approximate arrival time of vehicles between RSUs.

Energy conservation - At present, a large number of energy conservation strategies have been designed for each network layer. The adjustment of standby in PHY layer, setups of energy conservation channels or improvement of retransmission approaches in MAC layer, and the designs of efficient and reliable routing protocols are the examples of energy conservation. Papers [94] and [95] state that mobile devices rely on battery power, which can be restricting for running algorithms. Therefore, efficient management of power usage is very important in MANETs. As further described in [16], the energy consumption of wireless interface is mostly similar in active states (send or receive) and sleep state. In the sleep state an interface with least influence on sending and receiving operations in cooperative ad hoc networks. VANETs are not significantly considered in the topic. The main reason is that vehicles or other VANET-participants are assumed to produce enough energy during communications, although that is an ideal situation.

Security - As [42] stated, the lack of centralized controls increases the danger that it is possible to access any outside nodes and destroy inside nodes of networks when the firewall technology is not properly used in the networks. Besides, a threat between ad hoc members is considered due to dynamic, flexible and unpredicted topology changes, which also causes uncertain data generations and transmissions.

S. Zhen (et al.) [96] specify five aspects for security designs of ad hoc networks, including information theft attacks, routing protocol security, authentication methods, key management and trust mechanism. Meanwhile, they also present possible challenges of security designs. For example, the limited energy is a focal point in MANETs, and CPU has low-level calculation capability only; additionally, MANETs may contain hundreds of nodes, therefore, the security approaches should be able to adapt for larger scale networks.

Network components lack self-protection ability; thus the security of stored data should be doubted. Although this is an ongoing research area in MANETs, some outcomes are seen in previous work. An authentication method proposed by [97][98] indicates using digital signatures for a message to block malicious or wrong routing and data information. [97] designs specific formats for the message to carry digital signatures. Coincidentally, [99] concerns using a technique that mobile devices trust the source of a secret key and then access control.

QoS - Previous Quality of Service (QoS) solutions for the Internet are no longer satisfactory for MANETs because moderate or high-speed mobile nodes lead to unpredictable changeable topologies [100]. [101] states that the important QoS parts in MANETs are models, MAC, and routing of QoS etc. [102][103] show the outcomes in these areas.

2.3.3.4 Superiority of MANETs for C2C communications

Cost of connections - MANETs are well-known because they are flexible, dynamic and self-organizing. The obvious benefit is the reduced expenses of connections. The direct radio links in C2C or C2I without the aid of compulsory infrastructure devices and multi-hop forwarding methods are applied to complete the transmission. In terms of network construction, the cost incurs by those infrastructures is reduced or even avoided. Road-side units (RSU) may also be needed in particular cases, but the cost will be less than other infrastructure because of simpler techniques.

Speed of links - According to studies such as [82] and [83] etc., C2X communications of MANETs use WAVE standards in Dedicated Short-Range Communications (DSRC) bands to support higher bandwidth and high-speed mobility. In such networks, vehicles in motion can talk with each other via direct links. The method shortens the transmission duration because vehicles need not rely on base stations or APs to forward the packet. Especially in emergency events, the advantages of this aspect can be embodied significantly.

Volume of data - Compared with existing C2I-oriented wireless mobile networks (e.g. 3G), IEEE 802.11p MANETs must admit larger amounts of data. First of all, the communications are established via direct radio link and the transmission rates are totally higher. In addition, the communication range of MANET nodes is determined by multi-hop functions while that in 3G networks, or even WLANs, depends on fixed infrastructures. Moreover, the valid transmission time between vehicles can be relatively long if they keep the relationship in the area. However, this point varies depending on vehicle speeds when they exist within the coverage of infrastructures. That is, if a car moves slowly within the infrastructure transmission range, then it could have a longer message exchange time.

Locality - Non-centric control and direct communications links make the management and control of local events easier. As highly mobility is considered, C2C technologies of MANETs are more suitable for sharing regional information, such as traffic jam broadcasts, accident notifications and so on.

2.4 MANET Protocols

Compared with other types of networks, ad hoc networks with the natures of highly dynamic topologies bring more difficulties and complexities to route messages. Thus, efficient routing protocols, also being directly related to this research, become important in establishing wireless mobile communications [16]. They implement strategies to achieve different applications. The main challenges of ad hoc networks exist in dealing with rapid topology changes, reliable message deliveries and efficient transmission paths.

This section begins with routing protocols in MANETs and focuses on broadcasting approaches.

2.4.1 Ad hoc routing protocol types

According to Fig. 2.9, there are two typical classes of routing protocols which are studied and applied in ad hoc networks, namely, proactive routing protocols and reactive routing protocols [16]. Briefly, the basis of the classification is the form of route generation and maintenance. In other words, proactive routing approaches continually collect routing information and update routing table periodically; while reactive routing algorithms establish routes when nodes require and then update corresponding route entries.

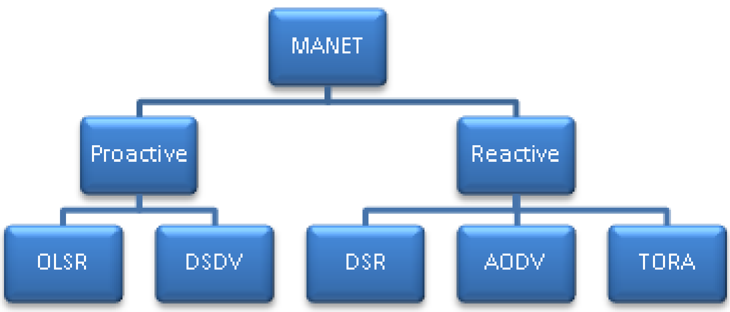


Fig. 2. 9 The taxonomy of MANET routing protocols

2.4.1.1 *Proactive routing protocols*

Proactive routing protocols are known as table-driven protocols [16]. Meanwhile, it was learnt from [104] that each node is responsible for a routing table which records all route information to other nodes. The table will be updated through information exchanges among nodes. Regardless of the states of nodes or network traffic conditions, the updates occur at a certain interval time or when particular events occur, for example, a new link is created or an old link is removed etc. It is worth noting that mobility is a key impact factor on the frequency of even-triggered updates because the speed of motion has an influence on connection changes.

There are several representative protocols, such as Destination-Sequenced Distance Vector Routing (DSDV) [105] and Optimized Link State Routing (OLSR) [106] and so on.

DSDV is a typical distance vector protocol suitable for MANET. DSDV is explained in details in [104][105] stating that each node should periodically broadcast its routing information, including destination's IP address, its sequence number, required hop numbers to the destination and last known sequence number for the destination, to neighbour nodes and also update its own route table when it receives new paths. In order to ensure that the routes are accurate and up-to-date, the broadcast interval should be set properly. Meanwhile, if there is a new entry received by the node, it should increase its sequence number for the route. The sequence number is used to avoid a problem from some distance vector protocols, called counting to infinity [104]. Additionally, if there are two or more paths to the same destination, then message transmission follows a path with the highest sequence number which stands for the most recent route information. According to [104], routing table for each node generally contains five items: destination's IP address, destination's sequence number, next-hop IP address, hop-count and install time.

As proactive routing protocols are not in the scope of the research is routing approach; hence, DSDV will be regarded as a representative one in this part and other related protocols will not be discussed. This research is interested in comparisons of proactive protocols and reactive protocols, which will be analyzed later.

2.4.1.2 Reactive routing protocols

Reactive routing protocols work in an on-demand manner. Different from proactive routing approaches [104], protocols allow nodes to search their routing tables firstly and then decide whether route information needs to be updated. The major method to execute route discovery is flooding the request messages in the whole network. Periodical requests may cause disruption to communication networks; thus, on-demand communications occurring between essential nodes is very important to help efficient route discoveries and updates. As stated previously, reactive routing protocols address the problem of heavy overheads of proactive routing protocols [104].

Typical examples in this area include Ad Hoc On-Demand Distance Vector Routing (AODV) [107], Dynamic Source Routing (DSR) [108] and Temporally Ordered Routing Algorithm (TORA) [109]. AODV is a basic reactive routing protocol used in MANETs so that in this thesis, it is specially evaluated.

Analysis of Ad Hoc On-Demand Distance Vector Routing (AODV) in [16], [104] and [107] indicates that on an on-demand basis, it reduces heavy overheads caused in DSDV. AODV requires each network node to manage a routing table, which includes next-hop routing information and lifetime value. The lifetime period determines whether the route is valid or overdue. The routing approach consists of three parts: route request (RREQ), route reply (RREP) and route error (RERR). Complete procedures are explained in [104] and briefly described as follows:

Assume there is a source node (S) sending a packet (M) to the destination node (D). Reviewing AODV procedures in [104], firstly, S searches whether there is a route to D or not. Only when such a route does not exist, S starts RREQ procedures. Route discovery is a most important step to broadcast the RREQ packet with the information including IP address of D, last known sequence number for D, IP address of S, current sequence number, hop count (from zero) and RREQ ID. In particular, AODV allows periodical broadcast of this Hello message to maintain the relationship with neighbour nodes. Once a neighbour N receives RREQ of S, it creates a reverse route, which stores S as the next hop and hop count increases. Then N continues to check whether it obtains D's route or not. If there is not valid route information to D, then N will rebroadcast the RREQ packet with a new increased RREQ ID, increased hop count value to its own neighbours.

Satisfactory condition is that finally a node N has a valid route for D. RREP packet, including S's IP address, D's IP address, hop count and D's sequence number from the route table entry is generated and unicast back to S. In this moment, a reverse route created in the RREQ step is followed. Each node receives RREP message, creates a forward route for D and uses when S decides to select it for data transmission. It might be a case that more than one RREP received by S. In such a case, the largest value of sequence number and the smallest count of hops help S to choose the most up-to-date short route.

The processes above present an ideal message delivery approach without any abnormalities. However, link interruptions or broken problems need to be considered. AODV allows resolving these problems for active routes by sending RERR messages to related upstream neighbours towards the source. An RERR message contains a list of unreachable destination information. When the source node receives the RERR message, it will repair the route if necessary.

Other reactive routing protocols adopt various strategies to realize message delivery, but the key feature of route discovery is based on the on-demand form.

2.4.1.3 Proactive routing protocols versus reactive routing protocols

The authors in [16] simply compare the above two routing classes. Since nodes' tables hold consistent and up-to-date route information all the time, the biggest benefit of proactive routing protocols (e.g. DSDV) is that they can respond to all transmission requests at the required moment. This leads to a small end-to-end delay in the transmissions, but comes with heavy overheads. The problem is addressed in reactive routing protocols (e.g. AODV), particularly in a small-to-medium size of network with moderate or low mobility, as pointed out in both [16] and [104]. AODV utilizes on-demand route discovery methods to control and limit route broadcasting times, as opposed to managing network-wide routes information periodically as DSDV does. The major weakness of reactive protocols is the latency. That is, an end-to-end transmission delay of a reactive routing protocol including route discovery time coupled with real data communication time, which is normally greater than that of a proactive routing approach.

Furthermore, [110] presents evaluations of common reactive and proactive routing protocol in IEEE 802.11 ad hoc networks that proactive protocols offer lower delays and jitters but they consume more bandwidth; also when the traffic load increases, the delivery ratio decreases by using proactive routing protocols. Similar results are presented in [111]. As a result, proactive routing protocols do not fit within the scope of the proposed research; instead, reactive routing protocols are selected as part of competition testing objects.

2.4.1.4 Protocols for high-mobility environments

Most MANET routing protocols are well suited for nodes having moderate or low mobility. This may demonstrate drawbacks in coping with high mobility communications. To address the problem, some MANET protocols are developed and new routing protocols are designed [76][104][112][113][114][115]. In [112], these protocols are summarized by topology based, position based, geo-cast based cluster based and broadcasting based.

Several geographic routing protocols have been proposed. For example, [76] surveys position-based routing approaches, which include nodes' location information by navigation devices (e.g. GPS) and implement greedy forwarding. In addition, hybrid approaches are referred to in [104]. [113] introduces a routing strategy called Geographic Source Routing (GSR) for VANET in a city scenario, combining position-based routing protocol with topological knowledge.

Mobility based routing protocols are introduced in [112], with focus on the direction of mobility and the lifetime of routes. An instance of this kind of routing protocol, Prediction-based Routing (PBR) [114] believes successful prediction of route lifetime can greatly reduce route failures. Thus it periodically sets route lifetime and creates new routes before existing ones fail. This addresses a problem from some reactive routing protocols with respect to route failures, which may need a long time to repair or reconstruct. As a result, the end-to-end latency is reduced. [116] is an AODV-based protocol created for VANET. This protocol treats movement direction as a primary factor for deciding and maintaining paths, coupled with position and speed.

Some probability-based routing protocols have also been proposed. According to different conditions, the probabilities vary, for example, the probability of reliability between two nodes [117], the connectivity probability of a road segment [118] or the probability of link lifetime [119] etc. Then a decision on the next hop or route is made by such probability computations.

The class of infrastructure-based routing is applied for C2I applications which rely on diverse infrastructures, such as roadside units (RSU), access points, cellular base stations and so on. Given the Differentiated Reliable Routing (DRR) protocol in [115], it relies on robust roadside units to guarantee on-demand communications and extends reactive routing by dividing route discovery into different segments.

Flooding based routing approaches are widely discussed and implemented in ad hoc networks and broadcasting concepts are extensively used in many classes of routing protocols stated above. Particularly, it plays an important role in the proposed research. Therefore, it is necessary to distribute a separate section as 2.4.2 for thorough study.

2.4.2 Broadcasting

Broadcasting is a basic method used in MANET routing protocols. In particular, such schemes are adopted for route discovery in reactive routing protocols. According to [120], the classification of MANET broadcasting protocols could be drawn as Fig. 2.10.

2.4.2.1 Blind flooding

Flooding [121] is the simplest and earliest broadcasting technique [122][123]. Each mobile periodically broadcasts or rebroadcasts a packet to all neighbours which receive the packet for the first time; otherwise, the receiver will discard the packet owing to redundant operations.

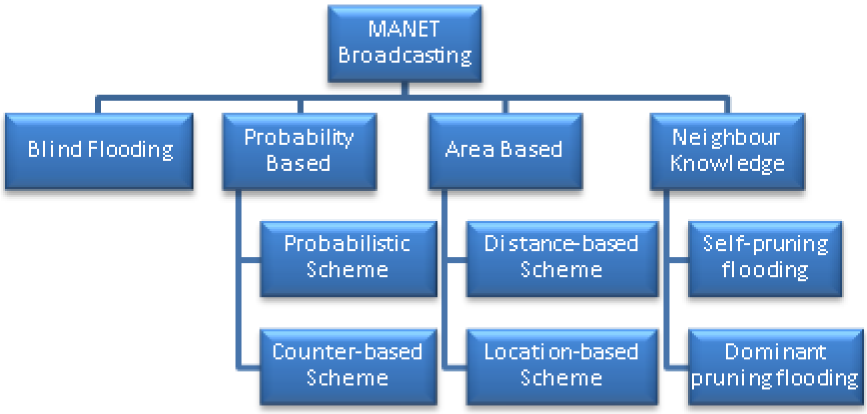


Fig. 2. 10 The classification of the MANET broadcasting protocols

[121] states that the Flooding method provides high reliability, being particularly suitable for high mobility networks. The main problem of simple Flooding, also known as blind Flooding [124], is the high amount of redundant broadcasting messages. This is referred to as broadcast storm.

[125] concludes that a broadcast storm is a phenomenon including redundant rebroadcasts, contention and collision. Redundant rebroadcast occurs when a host resends a broadcast packet to all neighbours whilst they have already received the message. Contention happens when a host's neighbours rebroadcast the packet to their own neighbours, then they contend with others seriously. Besides, back off mechanisms or RTS/CTS dialogue are important to help the avoidance of collision, but they are absent in the blind Flooding approach.

To alleviate the problems, many enhanced Flooding approaches have been proposed to reduce the amount of redundant rebroadcasts or to differentiate the timing of rebroadcasts [125]. The following classes are designed to enhance the pure Flooding method for addressing the broadcast storm problem.

2.4.2.2 Probability-based approaches

The probability-based method is a Flooding technology which can control message floods. Both [120] and [125] introduce the related routing protocols.

In a probabilistic scheme, nodes rebroadcast the received packet depending upon the predetermined probability ($P \in [0,1]$) [126]. The fundamental principle is that each node is given a random probability (rand-P) value and this value is compared with (P). As long as the rand-P is less than P, the node forwards the message immediately; otherwise, it drops the packet. The predetermined probability varies according to the different densities of networks. For example, nodes in dense networks have low probability value, with the result that random nodes do not rebroadcast packets. Thus, it helps to reduce the number of redundant transmissions and mitigate serious broadcast storm by Flooding. In contrast, probability is high in sparse networks as little similar coverage is shared. When the probability reaches 100%, the scheme is identical to simple Flooding. A gossiping-based approach was proposed by [127], stating that it enables nodes to transfer messages relying on the gossiping probability and the network topology. The results proved that high delivery success occurs when the probability is between 0.6 and 0.8.

Another preventative protocol in this area is a counter-based scheme, referred to in [120] and [125]. The major rule of the approach is to use a counter parameter (c) to record the times of broadcast message heard during a random period and compare the c with threshold (C). Once c equals C, then the host is forbidden to rebroadcast the packet and exits. The scheme is simple because nodes do not need to know network structure and they do not need to share knowledge such as reactive routing protocols. As argued in [125], the main problems are that there is a waiting period which may lead to more delays and the threshold is difficult to set up properly. Particularly in dense VANETs, packet collisions cannot be efficiently excluded from the scheme.

2.4.2.3 Area-based approaches

This class of approaches, generally, follows the rules that a node calculates its additional range of area which is used to decide rebroadcast operations [122]. Fig. 2.11 shows the concept of additional coverage area (A). It is obvious that distance from sender (S) to a neighbour (N1) must be shorter than that between S and the other neighbour (N2).

When both neighbours receive the packet from S, the rebroadcast area of N1 almost overlaps the original region of S; whereas the rebroadcast area of N2 is significantly different, e.g. 61% [120][125]. In this example, N1's additional coverage area (A1) is smaller than N2's (A2).

In [120], two typical schemes are presented regarding the additional coverage area A. The distance-based scheme utilizes the comparison of the distance (d) between senders and receivers with a threshold (D) to decide whether to rebroadcast. When d is greater than D, wider A is implied and the receiver could rebroadcast. Location-based protocols determine to rebroadcast the packet according to accurate location information. The information helps to calculate the A of the node for comparing a threshold value D. If the A is greater than D, then the node needs to rebroadcast the message. The major problem here could be how to set up the threshold value D.

These kinds of routing approaches for VANET are feasible, agreed with [125], because, nowadays, navigation devices (such as GPS) can be installed in vehicles and they help to obtain accurate location information and even distance information etc.

2.4.2.4 Neighbour knowledge approaches

This class of routing protocols makes decisions on rebroadcasts depending on neighbours' information obtained from periodical message exchanges. A critical operation is that the neighbour list of a node is added into a broadcast packet. For example, source S broadcasts a packet with its neighbour list L. When its neighbour N1 receives the packet, N1 compares its own neighbour list L1 with L, dividing the neighbour information into a set of neighbour information the same as L and another set of information different from L. Thus rebroadcasts focus on the second part. [122] indicates that the major problem of this class is caused by send intervals, too short to avoid broadcast storm and to adapt for high mobility.

So far, related works on this as follows: [128] shows the algorithm with directions of local neighbourhood discovery and data broadcasting. It gathers the local topology knowledge and the duplicated information to avoid unnecessary rebroadcasts.

Coincidentally, [129] utilizes neighbour information in two new Flooding methods such as self-pruning and dominant pruning, taking into consideration two-hop coverage. The results are better than blind Flooding. Besides, [130] proposed a mechanism called MPR (multipoint relays), which restricts rebroadcasting to a small group of neighbours rather than to all neighbours in simple Flooding. The set of nodes, as multipoint relays, should be one-hop neighbours directly to the sender and also cover all second-hop neighbours. In addition, Connected Dominating Set (CDS)-based broadcast algorithms are given detailed reviews in [19]. The algorithm allows rebroadcast to be executed in nodes belonging to the CDS. In this way, the non-purpose rebroadcast could be effectively controlled.

2.4.2.5 Other broadcasting protocols for high-mobility communications

Protocols designed based on inter-vehicle communications need to have more consideration of the high speed of cars, the layout of lanes, the density of these lanes and the location of nodes etc. To cope with such features, recent works pay attention to obtaining additional information (e.g. position) from GPS or sensors to help message transmissions, or to include such information in broadcast messages.

[80] presents urban multi-hop broadcast (UMB) protocol which is specifically designed for V2I-based networks. In UMB, nodes do not exchange location information among their neighbours because a set of infrastructures is used to support all the communications, repeaters being used at intersections and also GPS and electronic road maps being fitted in the vehicles, for example. Taking into account the costs of infrastructures, protocols for V2V-based systems are more preferable. [131] provides a fully Ad Hoc Multi-hop Broadcast protocol (AMB) as an extension of the UMB protocol. The protocol enhanced drawbacks of UMB without infrastructures in two parts: directional broadcast and intersection broadcast. Consequently, the paper puts forward a best conception that uses both protocols together in message transmissions with their own functions.

[19] proposes an adaptive broadcast (ABSM) protocol which is good for use in a

wide range of mobility conditions. Based on CDS and neighbour elimination scheme (NES) from [132] and [133], ABSM applies CDS and NES concepts on current local neighbourhood information available. A broadcasting task is performed to obtain local information via periodic beacon messages, where acknowledgements such as sender's position information and neighbour list are included. Simulation results prove that ABSM is a reliable protocol with reduced transmissions, but it does favour low end-to-end delivery delay although it is delay tolerant by nature.

[134] studies 'message ferrying' techniques in inter-vehicle communications, introducing 'bus' as a new concept of the ferry rather than 'car' to be used for traffic message sharing among other vehicles. Similarly, [135] introduces the concept of a mobile gateway to overcome the limitations of infrastructures. Infrastructures can properly provide information exchanges in many cases, but there are limitations existing to cover the whole range of communication areas. Thus, authors specify a certain kind of vehicle - buses - to be mobile gateways because they have fixed routes and the range of transmission could be larger than ordinary vehicles. The paper designs a mobile infrastructure-based VANET routing protocol (MIBR) to use buses for selecting and forwarding messages and it is proved that the protocol improves the delivery ratio and throughput. Nevertheless, on the basis of outcomes of paper [135], [136] believes that buses are not the best choice as mobile gateways because bus journeys are controlled by fixed and regular schedules so that the connectivity of transmissions could be limited. Therefore, the paper proposes another type of vehicle – taxis - as mobile gateways. The mobile gateways routing protocol (MGRP) allows the mobile gateways to use 3G interfaces to connect with the base station by cellular phone technologies and also use IEEE 802.11 interfaces to communicate with normal vehicles in the proposed hybrid network architecture.

2.5 Simulation Techniques

2.5.1 Approaches of system evaluations

As stated in [16], communication system performance can be evaluated by two major approaches so far: real system measurements and simulation techniques.

To the best of my knowledge, very few studies adopt the measurements of real world testbeds, such as typical examples from [137] and [138]. In [137], a testbed Ad hoc Protocol Evaluation (APE) has been proposed by Uppsala University. It intends to evaluate different routing protocols in MANETs and provide proper comparisons. There are several protocols supported by APE, such as AODV-UU, TORA and DSR as well as more new protocols. It is said in [16] that an APE test can accept a scenario with dozens of nodes (e.g. >30 nodes). The testbed operates based on laptops, which offer timely instructions to guarantee repeatable experiments and testing measurements are gathered for further channelling. The overall aim of the APE testbed is to investigate a proper MANET protocol which provides the highest throughput; to judge a protocol that leads to the best path according to changing topology; and to ascertain the main impacts on network performance in various scenarios. Further details of APE can be found in [139].

From the literature [138], Carnegie Mellon University designed and implemented a full-scale physical testbed to evaluate ad hoc network communication performance. There are six mobile nodes and two stationary nodes involved to inter-communications by using DSR routing protocol. All mobiles are supposed to be equipped with GPS so that position information can be provided continually and recorded for replaying afterwards. [137] indicates that the CMU testbed makes it hard to reproduce results owing to the sophisticated processes of hardware configurations. Therefore, repeatability is a challenge of the testbed.

Real world testbeds contribute the first data results to the research but, meanwhile, constructing and maintaining work involves high costs. To construct a real testbed for VANETs requires a number of available vehicles, in-car devices and also devices for real-time data acquisitions. Additionally, repeatability and practicality should be essentially considered. As [16] stated, a real testbed shows great limitations to investigate protocol scalability and mobility patterns because all components are sensitive. Owing to different investigation purposes, objective factors such as network scenarios should be changeable. In terms of ITS only, some researchers focus on a local area but others look at the whole city; some of them need a scenario with traffic jams, but others may need a sparse network environment etc. The testbeds make it difficult to offer appropriate conditions following designers' plans. Hence, because of the economic factor, coupled with considerations of repeatability and practicality, the trend of current network investigations is to use simulation technologies.

In the field of ITS, many simulation outcomes directly related to this research have been proposed. According to the analysis of the literature [16], researchers use diverse simulators to investigate MANET-based networks under all kinds of scenarios, which are organized by the various node numbers and mobility status and so on. With the development of ad hoc routing protocols, new simulation technologies are used to investigate, compare and contrast communication performance between existing and innovative approaches of message delivery. For example, [134] addresses a routing protocol based on the concept of mobile gateway in VANET. It uses a network simulator (NS2) to model and evaluate the relationship between successful delivery rates and the presence of gateway vehicles. Also, a project referred to in [19] uses a microscopic simulation package to evaluate its adaptive broadcast protocol ABSM in highway and suburban scenarios. [140] simulates and compares PBSM (Parameterless Broadcasting for Static to Mobile) with an adaptive protocol VO found in [141] by a simulator developed in Visual C++.

2.5.2 Network simulators for MANET-based networks

Indeed, various simulators have been developed for investigation in academia and industry. The literature [142], [143] and [144] classifies many of them according to the characteristics and the purposes of modelling. [143] provides a comprehensive survey and comparative study for MANET simulators, such as network simulators and traffic simulators. Popular network simulators are NS2 [145], GloMoSim [146], and JiST/SWANS [147]. These are very suitable for MANET research, but also show promise for VANET simulations if there are supports from vehicular mobility generators, such as SUMO [148], STRAW [149] and VanetMobiSim [150] etc. Some simulators which combine technologies of network simulation and traffic mobility generations have also been proposed such as TraNs [151] and GrooveNet [152] etc.

NS2 [145] is one of the most popular tools for both wireless and wired network simulations. It was developed by a research group (VINT) at the University of California and was improved by the CMU Monarch project, which contributed features to simulate MANET communications [142][143]. According to the NS manual [153], NS2 is a complete object-oriented open source simulator, using both C++ and OTcl languages available on multiple platforms. Usually, NS2 is used to model network architectures (e.g. ad hoc networks), design innovative routing protocols and evaluate network performance using various routing protocols etc. Although it is easy to modify existing models in NS2 and to add newly designed models, but it may require a longer execution time than other simulators [142].

GloMoSim [146] provides scalable simulations for both wireless and wired networks. A significant feature of this simulator is its layered approach, which allows quick integration of new models at different layers.

JiST/SWANS [147] consists of two parts: JiST and SWANS. The former, as NS2 and OPNET [154], is a kind of discrete-event simulator, written in Java and running over a Java virtual machine. It enables the conversion between a virtual machine and a simulation platform. SWANS compensates for insufficient functionality in existing simulators by assisting JiST to achieve better simulation performance and lower memory requirements of simulated network applications. As [143] and [155] stated, the principle of this simulator is similar to NS2 or GloMoSim but it especially supports a larger scale of networks on the condition that they use the same time and memory and level of details.

To further highlight the differences among NS2, GloMoSim and JiST/SWANs, [143] considers separately their software and VANET respectively. Software requirements include portability, open source, large networks, GUI, scalability, ease of setup and ease of use and so on while the VANET aspect involves MAC technologies, traffic flow models and obstacles etc. Generally, NS2 is most easy to use and install, which may be difficult in JiST/SWAN. However, there are some drawbacks in NS2, such as the MAC technology not being completely up to date and some features for VANET simulations not having been implemented.

2.5.3 Traffic simulators for MANET-based networks

Regarding [143] and [144], many mobility simulators have been proposed. F. J. Martinez (et al.) indicates that these kinds of simulators aim to adopt existing MANET simulators for use in VANET as well. M. Boban (et al.) note that MANET studies normally adopt the random way point mobility model [156] which is not suitable for real vehicles. Typically, vehicles in VANET move following certain routes, directions and other vehicles. Thus, by using mobility simulators, network simulators can include traffic flows or possible traffic topologies, such as intersections.

Simulation of Urban MObility (SUMO) [148] is a simulation package indicating microscopic road traffic. It is available for a large size of network, e.g. a network with 10,000 streets [143]. The traffic generators provide non-collision movement, multiple vehicle types, streets, junctions and flexible routing.

As mentioned earlier, there are simulators expressly designed for VANET, which combine network simulators (e.g. NS2) and traffic generators (SUMO), such as the Traffic and Network Simulation Environment (TraNS) [151]. TraNS is an open source, being created in Java and C++. By using SUMO, TraNS allows the real map to be integrated, e.g. Manhattan map and NS2 configurations lead to an OTcl script with traffic information.

2.6 Summary

The literature review of this chapter is regarded as a theoretical basis necessary for the work presented in this thesis.

The section on network architecture provides good reference to layers and elements in the proposed MANET-based framework. Three types of nodes are introduced - mobile (cars), semi-mobile (buses) and static nodes (infrastructures). In many published works, vehicles are generally regarded to be fully mobile nodes in MANETs while a few research projects specifically use the functionality of buses, which have pre-set circular routes and travel regularly in urban regions, to enhance inter-vehicle communications. [134] carries out studies in the field. It assumes that buses could store and hold more traffic information in a defined packet - bus packet from surrounding nodes than other types of nodes, and are more likely to continually distribute messages along the road but never out of the area. Likewise, this research considers bus-nodes in the architecture. Being different from [134], buses with routine-run feature are also regarded as normal ad hoc nodes in many cases, that is, cars, other mobile nodes and static nodes communicate with buses by direct radio link as usual. In particular, the bus nodes in the proposed architecture are enabled to receive packets by a top priority compared with other types of nodes.

In addition, the routing and broadcasting approaches, known to be a very difficult research topic, become a core point for the newly designed network architecture presented here. There are no single protocols so far agreed to adapt for MANETs, so that studies on the topic must be further contributed. To achieve better performance of inter-vehicle communications, a new broadcasting protocol, named Probabilistic Traffic Message Delivery Algorithm (PTMDA), is proposed in this thesis, aiming to provide an efficient and reliable method for the proposed architecture. In this protocol, the inclusion of traffic route information is a highlight compared with other MANET protocols.

For example, [19] adds the acknowledgments into the beacon messages, including the information of vehicles' position as well as neighbour information. Also [20] presents a Contents Oriented Communications (COC) system in which the inclusion of vehicles' status and surrounding information is transmitted with the real data, including identifications, locations, directions, speeds and generation time. Unlike above related works, PTMDA, in this thesis, includes a certain number of routes in the protocol without weighting the broadcast overhead of packets. Nodes which apply this algorithm could identify these particular routes and take corresponding action following appropriate procedures for message transmissions.

Chapter 3

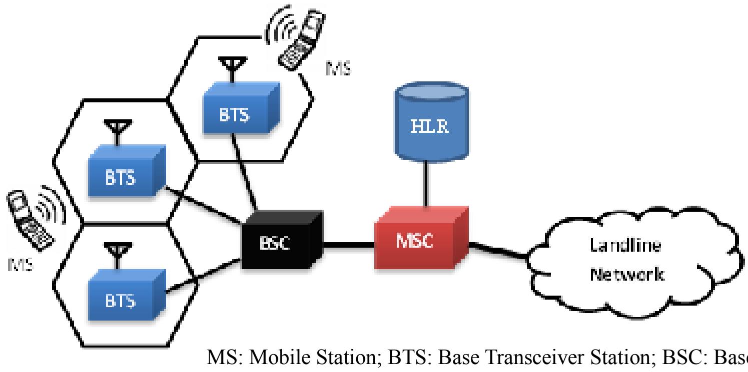
Collaborative MANET-based Communication Network Architecture

3.1 Existing Network Architectures for C2X Implementations

Intelligent Transportation System (ITS) covers a wide range of study topics in academia and industry, such as information technology, computer, control, communication and sensor technology for current transport vehicles and infrastructures. ITS contributes significantly to the improvements of traffic control and management. C2C and C2I solutions are two major approaches that address increasing urban and rural traffic problems. Both are utilized in wireless mobile communication environments to meet particular communication goals. In the field of ITS, the leading architectures of wireless mobile communications are cellular mobile networks (e.g. 3G), WLAN (e.g. IEEE standard networks) networks and ad hoc-based networks (e.g. MANET).

3.1.1 Cellular mobile network

Mobile communication may be described as information exchanges between communication pairs, both or single side in motion [42]. Traditional wired networks are not well suited for mobile communication environment, thus, wireless technologies have been developed to address those. So far, the third generation (3G) of cellular wireless technologies has been widely deployed in many countries. A basic 3G system consists of a mobile station (MS), a base station (BTS) and a mobile switching centre (MSC) (Fig. 3.1). The MS can be an in-car radio terminal or a mobile phone, being in charge of sending and receiving signals. The BTS is a fixed location transceiver, responding to mobile stations. Mobile users are allowed to connect with the BTS at the same time in a two-way manner via different channels depending on communication capacity. MSC is mainly responsible for switching controls, managing mobility of communication mobiles and operating handoff, roaming etc.



MS: Mobile Station; BTS: Base Transceiver Station; BSC: Base Station Controller
HLR: Home Location Register; MSC: Mobile Switching Centre

Fig. 3. 1 Cellular Mobile Phone Systems

Presently, cellular mobile phone networks are used not only for the exchange of information via voice, video, text or other multimedia services, but also the improvement of business management, mobile banking, and traffic navigation etc. These achievements, consequently, make our lives more convenient, efficient and colourful. However, due to problems reviewed in Section 2.3.1.2 regarding radio interference, environment noise, relatively complicated networking technologies and limited frequency resources, cellular mobile systems require more expensive and complex constructions and configurations than other wireless communication forms.

3.1.2 WLAN network

Another important branch of wireless communications is IEEE 802.11 wireless local area networks (WLAN). Generally, WLAN is an evolution of wired local area networks, expecting to reduce the complexity of wiring and allow simpler network installations [42]. At present, WLAN is widely deployed in offices, buildings, supermarkets, campuses, telemetry systems etc. for local area transmissions between static and mobile stations [11][51]. The IEEE 802.11 standard is implemented in WLAN to provide wireless connectivity and standardize access to frequency bands (e.g. 2.4 GHz, 5 GHz) [51]. A general WLAN network (Fig. 3.2) consists of mobile nodes, static stations and access point (AP) routers. APs are utilized to provide Internet access to nodes within the network and support handover between various wireless networks.

Fig. 3. 2 WLAN architecture

With the increasing availability and the decreasing cost of wireless-enabled devices, WLAN adoption has spread in recent years. Moreover, it offers relatively high bandwidth and low cost of connections compared to 3G networks; whereas 3G networks allow wider transmission coverage, higher security and higher speed of network nodes [22].

3.1.3 ITS-oriented MANET-based network

As reviewed in Chapter 2, cellular systems and infrastructure-mode WLANs require infrastructure to implement ITS applications. Again, their limitations become obvious when the cost of connections, the speed of transmissions, the volume of data, and the locality are considered. These limitations expedite open research topics and thus cause research opportunities for designs of new network architectures. Such networks are likely to include:

Flexible organization mode – Components of networks freely join and leave regions anywhere and anytime without sophisticated procedures. It allows dynamic topologies of ad hoc networking.

Infrastructure-free communication operations – There are not any central control entities used in the network to support wireless mobile communications. It is the most potential and economic way to reduce the usage of infrastructure and channel.

Multi-hop forwarding technology – Being both routers and hosts, nodes provide easy approach to deliver messages to destinations from one to the other via direct wireless radio.

Ad hoc networking, as defined by C.E. Perkins [17], allows wireless mobile networks to be independent from costly fixed infrastructures. The network organization is dynamic and flexible. As C.E. Perkins stated, the system is initially used as a tactical network, but has been extended to achieve other wireless communication purposes, in which the infrastructures are expensive or inconvenient to be used [4]. A typical example of ad hoc networks is MANET (Fig. 3.3). This thesis proposes a novel MANET-based network for efficient and reliable traffic message delivery. The network architecture not only inherits traditional ad hoc networking technologies, but also introduces new ideas of broadcasting approaches by utilizing the collaboration of traffic participants.

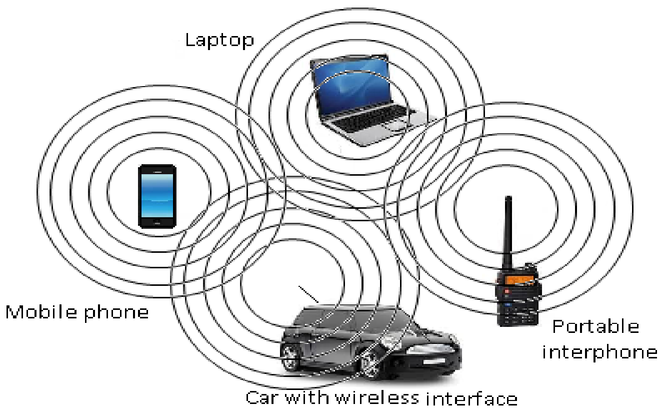


Fig. 3. 3 MANET network architecture

This chapter is structured as follows: Section 3.2 introduces the motivations of the proposed network architecture taking into consideration the cost of connections, the speed of links, the data volume and the locality. Section 3.3 presents the aim of the proposed network, the layer details of the system model as well as the protocols involved.

In particular, collaborative network components such as node type, scenario instance, and their main features in C2X communications are defined. Finally, Section 3.4 provides a brief summarization.

3.2 Motivation for Proposed Network Architecture

With the development of wireless communication technologies, the exchanges of traffic information have become highly demanding for communications between vehicles or between vehicles and static communication facilities. These help to establish safe, efficient and comfortable travels in cities.

It is widely known how important and necessary existing wireless mobile networks (e.g. 3G, WLAN) are in people's daily life and it is especially anxious that these architectures can be also deployed for solving problems in the field of ITS because they have been established and used widely. Nevertheless, this thesis disapproves of the idea. A perspective analysis of existing wireless mobile networks on the cost of connections, the speed of links, the volume of data and the locality convince in depth that a proposed MANET-based network is relatively proper to apply data disseminations.

3.2.1 Cost of connection

The major cost of connections is generated owing to the use of channels and the establishment of infrastructures. The former is popularly seen in our real life that if the transmissions depend on 3G base stations, the cost of mobile data traffic is computed per data transfer byte [5][43][157]. For a transmission with a large data volume, it is not cost-effective to achieve information exchanges by individuals. Meanwhile, the usage-based pricing plan, as analyzed by C. Peng (et al.) [43] and J. Harno [157], is not transparent for users. Apart from the real received data, there are unnecessary amounts of data paid due to any improper processing actions of infrastructures. Furthermore, fixed infrastructure in both 3G networks and WLAN networks is the other factor causing the cost of connections. Firstly, base-stations and access points are established in every fixed distance so that mobile nodes can have normal communication from one place to another further place. The extending problems such as handover and roaming are critically involved. Also, infrastructure-based networks require comprehensive designs, coupled with complicated configurations, frequent maintenance and costly equipment. These constraints cause the relevant technologies in such networks to be laid aside for C2C applications. Although the infrastructure-mode of WLAN depends on AP, which have simpler configured and relatively cheaper than the base-stations, it is popularly used to act on relatively low-speed mobile objects in local area communications. Beside, high requirements of handover mechanism are raised in these networks to tackle communications between regions.

Consequently, C2C communications urgently need a network platform that gets rid of fixed infrastructure equipment so that the cost of connections is significant reduced. On this point, MANETs are preferable. They are flexible, dynamic and self-organized. Wide range transmissions could be handled by multi-hop delivery or managed by C2I via direct radio links.

3.2.2 Speed of link

Although 3G technology has been considered in research [3][31][34][35][36] for C2I communications, it can only support the connection speed within a range of 144 kbps and 3Mbps. Alternatively, Wi-Fi networks support a dozens of Mb per second, such as 150Mbps under 40MHz channel bandwidthto transmit data but they do not suitable for high mobility C2X applications [10].

On this point, conversely, MANETs allow the speed of links to be dozens of Mbps, between 3Mbps and 27Mbps under 10MHz channel bandwidth and even higher data rate if the service channels are emerged [88][158]. The WAVE standard based on 5.9GHz spectrum is used to support high-speed mobility. In such networks, vehicles in motions can talk with each other via direct links. The method shortens the transmission duration because vehicles do not have to rely on base-stations or APs to forward the packet. Especially in emergency events, the advantages on this aspect are considerable. On the whole, MANET-base network architecture meets the demands of connection speed.

3.2.3 Volume of data

Modern communications require adequate information to be delivered via C2X approaches. In another words, the transmission packets are expected to include large capacity knowledge. As proved in Section 2.2.2.3, several factors, such as data rate, density of networks, speed of vehicles, coverage of radios and so on, may constrain volume of data to keep high success rate of transmissions. According to above analysis (Section 3.2.2), available transmission rate of 3G networks is too low and WLAN networks are not good for high-mobility transmissions. Both lack of technical supports to promise a successful large-size transmission, especially in C2I applications. Certainly, if a daily city traffic period is simply divided into peak time and off-peak time, then the possibility of large-size transmissions between cars and infrastructure devices may be only achieved in peak time or a traffic congestion area because vehicles may stay longer in an area.

On the contrary, in a high mobility environment, MANET-based networks are likely to tackle large size of message delivery timely. A strong reason is the nature of non-infrastructure. Communications are based on direct radio link between nodes so that the total data traffic will not be limited by central entities [6]. Moreover, technically, such networks based on city traffic scenario use WAVE standard which allows high bandwidth and high mobility communications.

3.2.4 Locality

As stated in [8], base-stations enable to control hundred meters and kilometres transmissions. Thus 3G networks are more suitable for inter-city communications than WLANs and MANETs. Indeed, multi-hop operations of the latter are properly used in local message delivery. In this thesis, urban traffic scenarios are concerned which basically needs the transmissions of local information. For this reason, the latter two systems are mainly concentrated on. However, as analysed before, WLANs lack of capability to support high-speed movements of nodes while MANET-based networks are well-known to tackle the problem and manage regional real-time events by means of decentralized and economical C2X methods. MANET-based architecture becomes a first choice not only due to the proper manners of local message delivery but also the advantages in aspects of cost of connections, speed of links and volume of data in comparison with other existing widely used network architectures.

3.3 Collaborative MANET-based Communication Network (CMCN)

As described in the last section, weaknesses with respect to costly hardware construction, strict environment constraints, insufficient channel usage and so on in existing wireless mobile systems gradually become obvious and serious gradually. Hence such systems may not be able to fulfil the high requirements of C2X communications. Generally, different network patterns generally are designed for particular purposes. For example, cellular based networks mostly facilitate to mobile phone services; Wi-Fi networks are usually deployed for AP-based local area issues. These networks provide mature and professional technologies dealing with issues in specific areas. However, these technologies are not particularly suitable for addressing increasing challenges of ITS.

Consequently, this thesis proposes an emerging type of network architecture – Collaborative MANET-based Communication Network (CMCN) – to focus on improvements in traffic control and management, in particular, improving communication performance so that people enjoy safe, smooth and comfortable travels.

3.3.1 Overview of CMCN

In order to provide efficient and reliable data disseminations via C2X communications, we propose a novel Collaborative MANET-based Communication Network (CMCN) architecture which utilizes additional route data available in vehicles such as in-car navigation devices (e.g. Sat Nav), buses on their routes etc. This framework allows participants to access the Internet directly or cooperatively. The focus of this thesis

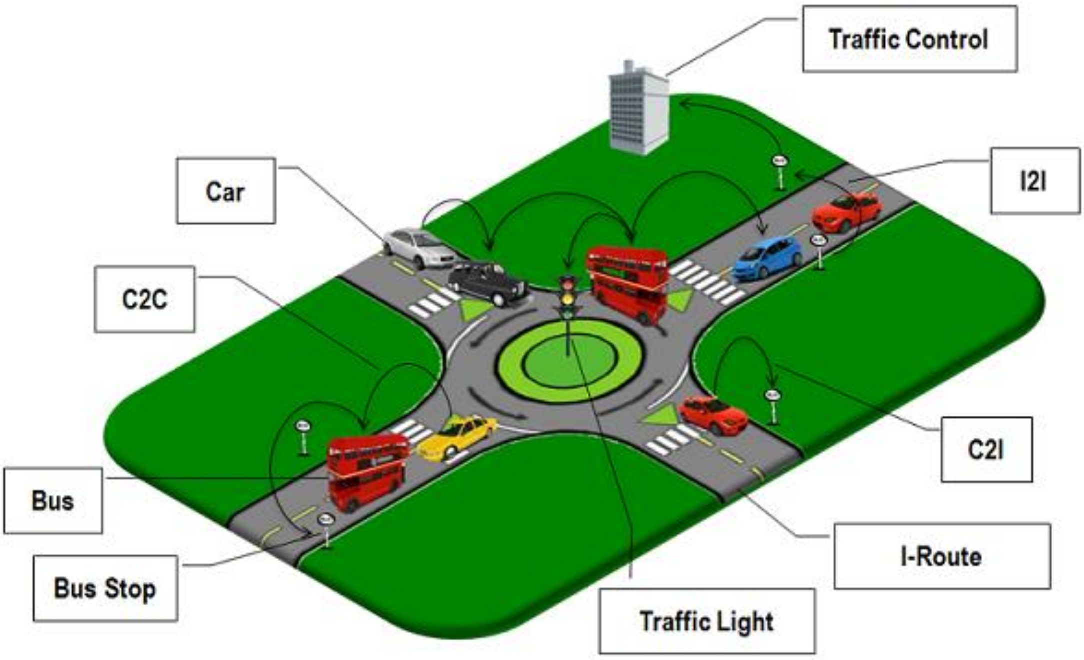


Fig. 3. 4 A vision of the CMCN

is communication performance on urban traffic scenarios (Fig. 3.4), covering vehicles, bus stops, traffic lights, buildings, streets and so on. Specifically, the focal points in the framework are as follows.

Firstly, the types of participants in the system are of significance. Indeed, conventional MANETs do not distinguish the role of nodes. Their equivalence results in simple network organizations but may inhibit the development of highly efficient routing protocols. Facing the dynamic and unpredicted network topology, the designs of routing protocols are still evolving as detailed in Section 2.4. For city traffic scenarios, three types of components (participants) are defined in CMCN, seeking to take advantage of their particular features. For instance, some nodes in CMCN are totally free-roaming while others may have pre-assigned routes and schedules; some may even be immobile (fixed). Full mobility makes it possible to detect immediate traffic events everywhere; structured mobility leads to relatively stable network topologies and transmissions which are less prone to interruption due to unpredictable mobility of free-roaming nodes. The main responsibility of static nodes is to maintain consistent and high-quality message delivery when C2C solutions do not achieve adequate results or do not meet communication demands.

In addition, the proper framework suggests a broadcasting-based Probabilistic Traffic Message Delivery Algorithm (PTMDA) to improve the quality and quantity of message deliveries. Broadcasting schemes of PTMDA adopt non-acknowledge transmissions and probabilistic retransmissions depending on nodes' type, position, distance, speed, and direction. In particular, the protocol introduces a novel idea that traffic route information is involved as a basis of the priority forwarding. The complex descriptions of algorithm will be presented in Chapter 4 and simulation evaluations are carried out in Chapter 5.

3.3.2 System model

CMCN follows a five-layer model (Fig. 3.5), including, in ascending order, Physical layer, Media Access Control / Logical Link Control layer, Network layer, Transport layer and Application layer.

3.3.2.1 Physical (PHY) layer

As an underlying layer, this layer establishes physical connection to wireless channels. The layer is responsible for frequency selection, wireless signal detection, modulation, transmissions, decision of spread spectrum and so on [96]. The CMCN network provides applications involved in vehicular communication environments for which the PHY standard is selected as IEEE 802.11p.

Based on physical specifications of IEEE 802.11a, IEEE 802.11p uses the OFDM modulation technology. According to 2010 amendment IEEE specification [159], the OFDM system allows mandatory data rates of 6, 12, and 24 Mbps for 20MHz channel spacing (IEEE 802.11a) and 10MHz or 5MHz in IEEE 802.11p at 5.9GHz band of operating frequency with one CCH (control channel) and six SCHs (service channel). As specified in [160], the date rate of 6 Mbps is the optimal speed for the safety of C2C communications. It was proved by F. Bai (et al.) in [161] that 6 Mbps (QPSK at 1/2 coding

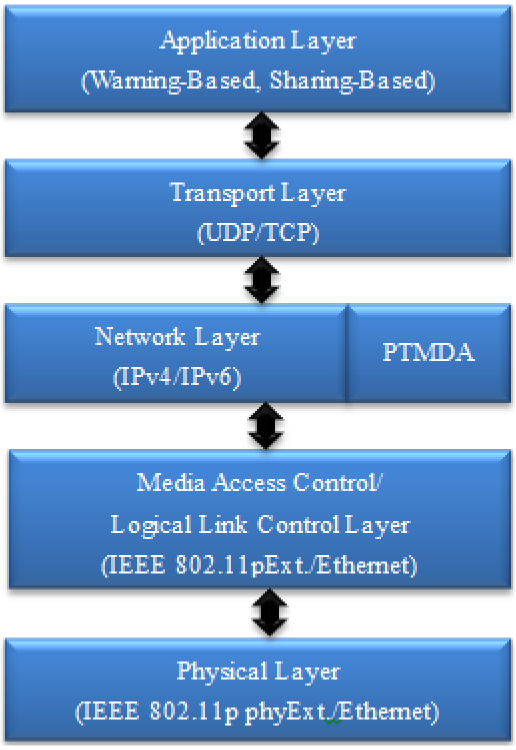


Fig. 3. 5 The CMCN stack

rate) outperforms other modulations in general vehicular environments by providing better Packet Delivery Ratio (PDR). In addition, J. A. Fernandez (et al.) provided similar observations for packet receptions that 6 Mbps of QPSK with 1/2 coding rate shows smaller packet error rate [162]. Therefore, the outcomes are theoretical basis of the CMCN system.

In particular, CMCN static nodes enable to active wired connections thus they may be configured with Ethernet access standard as well. Obviously, C2C communication is a main part in the system and C2I applications are allowed to adapt for particular cases.

3.3.2.2 Media Access Control (MAC) / Logical Link Control (LLC) layer

This layer consists of logic link control (LLC) layer and media access control (MAC) layer. The MAC layer is responsible for wireless channel access defined in IEEE 802.11 standard; while LLC layer manages packet forwarding and error checking.

The MAC layer of CMCN adopts related technologies defined in the MAC layer of common MANET architecture with IEEE 802.11p standard. Based on IEEE 802.11, Enhanced Distributed Channel Access (EDCA) mechanism is used for data traffic. The MAC allows four different priorities as access categories and supports synchronization of the CCH and SCH intervals in C2X communications.

CMCN allows IEEE 802.3 (Ethernet) standard for connections at the layer when the gateway functions are enabled for CMCN static nodes.

3.3.2.3 Network layer

The network layer consists of interconnection processes and routing technologies. To implement seamless interconnections with other types of networks, CMCN uses IPv6 technology, which complies with the trend of future address resources and management. In this thesis, however, IPv4 protocol is used to complete the processes of forwarding, receiving and routing.

In this layer, transmission packets with a unified message format (Chapter 4) are integrated from the upper layer and they are delivered to CMCN nodes in the same layer using an emerging broadcasting protocol – Probabilistic Traffic Message Delivery Algorithm (PTMDA).

3.3.2.4 Transport layer

The main responsibility of the transport layer is to offer reliable end-to-end services to the upper layer. CMCN allows both Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) in C2C communications depending on specific scenarios.

For research purposes, CMCN uses UDP protocol mainly due to the following considerations. Firstly, UDP is a connectionless protocol, which does not require pre-established connection for communications. Thus, there are simple connection procedures implemented to start transmissions so that end-to-end delay will not contain pre-connection durations. Additionally, with lighter overheads, UDP allows delivering instant messages. This feature is particularly beneficial to urgent events that the timeliness is of their especial importance.

3.3.2.5 Application layer

This layer is in charge of event disposal. The events, such as congestion notice, accident warning, local area traffic conditions and so on, are framed using the CMCN message format at nodes and they are broadcast to the network by means of distributed processing. An encapsulated message contains events and other essential delivery information such as IDs, position, directions and timestamps of the nodes. Further details regarding the message format and information types are presented in Chapter 4.

In some cases, traffic control centre need to collect and manage data for traffic controls. In the proposed CMCN, this has been made possible by using its static nodes rather than existing pre-configured infrastructures of 3G or WLAN.

3.3.3 System components

In general, CMCN nodes are similar in function to conventional ad hoc nodes. For example, they may generate and receive information as consumers by direct links and also work as routers to the packets by adopting intelligent routing approaches.

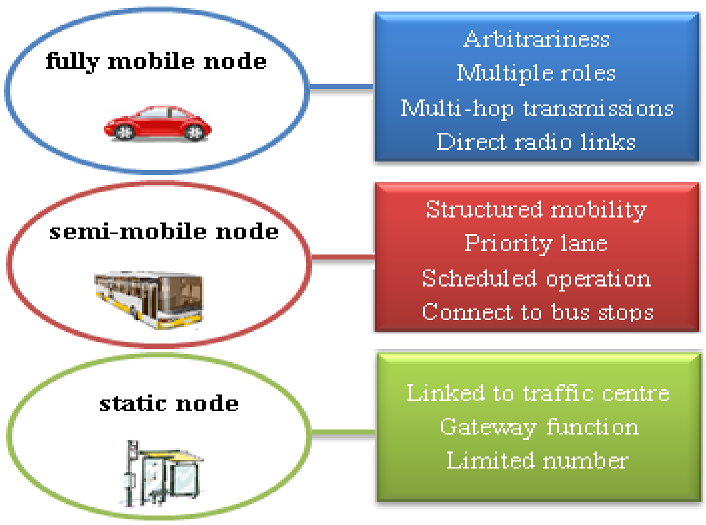


Fig. 3. 6 The type of CMCN components

Clearly, MANET nodes under city traffic scenarios vary according to their velocity, direction, routing, etc. These characteristics lead to completely different communication performance in the same region. Taking into account characteristics of common traffic participants, the network architecture CMCN proposes the taxonomy of network components as shown in Fig. 3.6 and as discussed below.

3.3.3.1 Fully mobile nodes

1) Definition

From a mobility pattern point of view, cars are regarded as fully mobile nodes since their destinations and paths are not controlled by centric control entity as long as they obey traffic rules. This is the largest group of CMCN components, which are basically responsible for real-time information generation and control. Once a message is generated by any fully mobile node, it is framed and broadcast to the network.

2) Main features

Arbitrariness – The main characteristic of fully mobile nodes is their potentially random positions. Furthermore, the random node movements carry and forward the message via direct or indirect forward transmissions. On the other hand, the arbitrariness of motion presents difficulties to manage traffic. Generally, the movement of fully mobile vehicles is a result of planned travels and non-purpose travels. Planned travels occur when drivers equipped with navigation devices or otherwise are aware of their routes to the destination. In such cases, the traffic control centre potentially has the ability to track and predict events such as road congestion during the travel once the data of the planned road trip has been sent to it. On the other hand, non-purpose travels do not involve the pre-determined destination; hence, it is not easy to collect routes information and predict whereabouts in immediate future. For the purpose of traffic control and management, this type of nodes is not always preferable.

Multiple roles – Similar to MANET nodes, CMCN nodes play roles of hosts and routers, allowing broadcasting and forwarding the message via multiple hops.

Direct Links – C2C communications with direct radio links provide efficient end-to-end delays compared to communications between cars and conventional infrastructures devices, as discussed earlier. Vehicles with On-Broad Units (OBU) can simply send and receive timely messages to nearby neighbours without the aid of any infrastructures [163].

3.3.3.2 Semi-mobile nodes

1) Definition

In CMCN, the term ‘semi-mobile’ actually indicates a group of nodes that move according to pre-determined routes and schedules. The bus is a typical instance of this category. As it is an essential public transportation tool, services citizens regularly and frequently. Hence, such a node (bus) (semi-mobile node in general) is controllable and priority-enabled and is capable of timely routing and transmitting messages.

2) Main features

Structured mobility – One of the obvious differences between buses and other vehicles is the predictable mobility of route. As mentioned earlier, cars are generally unrestricted while buses are restricted to specific routes in cities, known as bus-lanes. Although the route flexibility of buses still exists, it is much more limited compared with cars, and therefore, the traffic control centre knows relatively well their location and intention; thus the effect on traffic is predictable.

Priority – In many cities, priority lanes are reserved for buses, which contribute to avoiding traffic jams and allow dealing with emergency events. Fig. 3.7 shows a particular case that a semi-mobile node carries and forwards a traffic congestion notice. In this example, the middle of the lanes is blocked and the problem could be solved after few hours. To avoid heavier traffic congestion, this warning should be urgently shared with coming cars for making new plans so they set alternate routes. As seen in the figure, a bus plays the role of the messenger using its priority lane (bus-lane) to take the message to the coming cars.

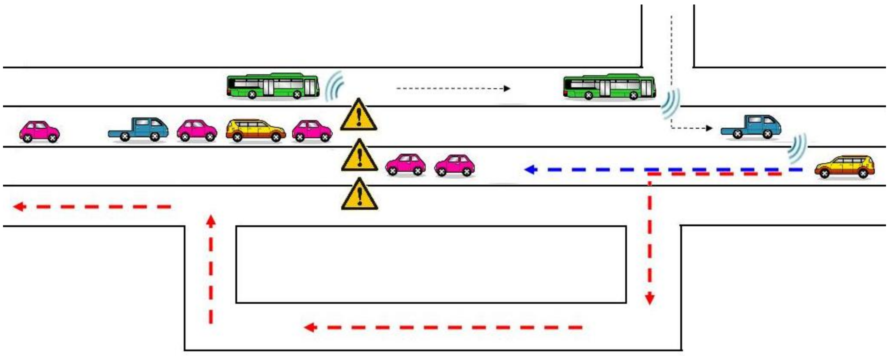


Fig. 3. 7 Scenario: Traffic congestion notice by semi-mobile nodes

Equipped in-car devices – Indeed, many modern electronic devices, such as navigation devices, could be installed in vehicles to provide safe, efficient and comfortable travels by information exchanges. However, those may be infrequently present in private cars due to the economic considerations. Nevertheless, they could be afforded by the government or business companies for bus systems. Such devices are not essential but may be used to enhance C2C communication performance. For example, a larger memory of in-car computer helps to store messages for further transmissions, and an energy-saving on-board unit allows delivering messages with wider transmission coverage.

3.3.3.3 Immobile nodes

1) Definition

Immobile nodes are specially defined in the CMCN to enhance communication quality. They, actually, are also regarded as roadside units in traffic environments. As ad hoc nodes, they may be self-organized accompanying with other ad hoc nodes and, unlike conventional fixed infrastructures, they broadcast packets via direct links. Besides, they work as gateways that may be linked to traffic control centre by wired connections or linked to other nodes by wireless providing the access to various network patterns, e.g. Internet. This thesis takes bus stop as an instance. The reason for the choice is mainly due to a strong relationship between buses and bus stops. Immobile nodes are particularly applied for improving communication performance in the target scenarios when C2C communications between vehicles perform unsatisfactory.

2) Main features

Gateway-function – CMCN static nodes can relay users' data other types of network, such as Internet. The function is analogous to that of base-stations or access points. However, the implementation of C2I communications by the CMCN system, unlike in 3G or WLAN, is based on direct link radio so that the transmissions of real-time information and the wide coverage of message delivery can be achieved economically.

Fig. 3.8 shows a case where mobile nodes access the Internet via CMCN static nodes. A car (C1) gets a traffic jam notice message (M) when it passes an area (A). It carries with M and broadcasts to others. When C1 reaches the coverage of a bus stop (BS1), M is broadcast to the BS1. All bus stops are participants of the Internet and they are connected to each other. Thus, BS2 gains M from BS1 after a certain interval delay. A car (C2) plans to go to A. Suppose that C1 disappears before it meets the car C2, thus, a way for C2 to be aware of the situation in area A is to download M from BS2. Finally, C2 may select other routes to the destination or shares M with other mobile nodes immediately.

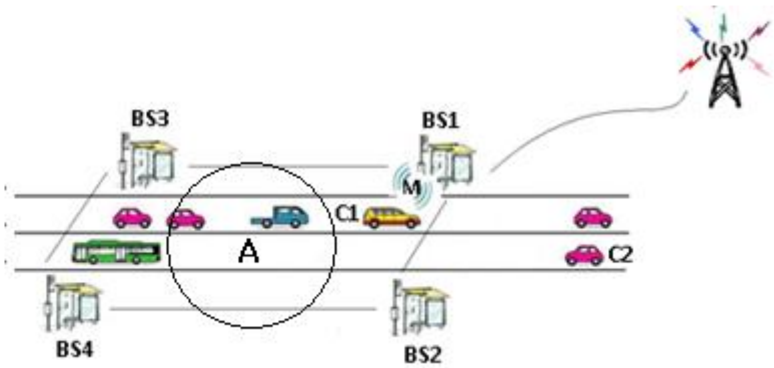


Fig. 3. 8 Scenario: Internet access via the bus stops

Limited number of static nodes – Bus stops are physically placed alongside the bus lanes and they may potentially provide access to Internet. Normally, the physical layout of these static nodes is designed for the convenience of citizens. Based on our experience life, more stops are established, more benefits for people. Despite the static nature of bus stops in CMCN architecture, there are additional costs for configuring, updating, and repairing them. Consequently, as long as static nodes are used, the related expenses are increased. Besides, there is a problem with regard to broadcast storms. Usually, bus stops are allocated beside bus lanes every certain short distance. If all of these static nodes have gateway capability, then they will broadcast a same packet almost at the same time. These behaviours bring heavy rebroadcasts and a huge amount of redundant receptions, resulting in serious packet loss (Fig. 3.9).

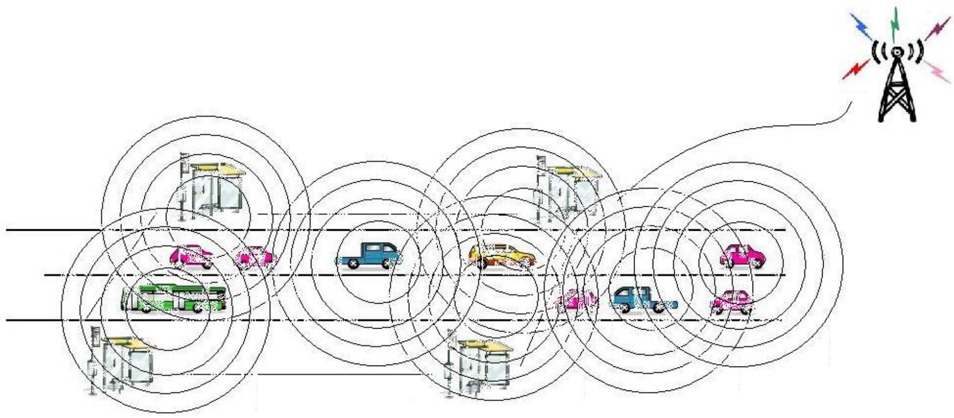


Fig. 3. 9 Scenario: Broadcast storms caused by bus stops

Thus, in order to reduce expenses and alleviate broadcasting problems as much as possible, the amount of bus stops with gateway functions should be restricted. On this point, the experiments in Chapter 5 are designed to investigate and identify a proper number of gateway-enabled bus stops for the best quality of communication performance in CMCN.

3.3.3.4 I-Routes

I-Route is used in the thesis to mean pre-configured urban traffic routes, aiming to improve communication performance in aspects of efficiency and reliability. I-Route information is included in the proposed message delivery algorithm.

As observed above, bus-nodes are capable of maintaining constant or intermittent communications in many cases (e.g. Fig. 3.7) to maintain constant or intermittent communications. This is a main reason why I-Routes largely coincide with bus lanes. The close relation of buses and bus stops in terms of physical position and logical communication may be exploited in depth and used. According to the colour lines in Fig. 3.10, these I-Routes are assigned with various directions, directing the priority delivery towards corresponding directions. In a real communication environment, the I-Route could be fixed as default information in in-car devices or initialized by buses. In the latter case, cars could obtain the I-Route information by communicating with buses and use them in message delivery algorithm.

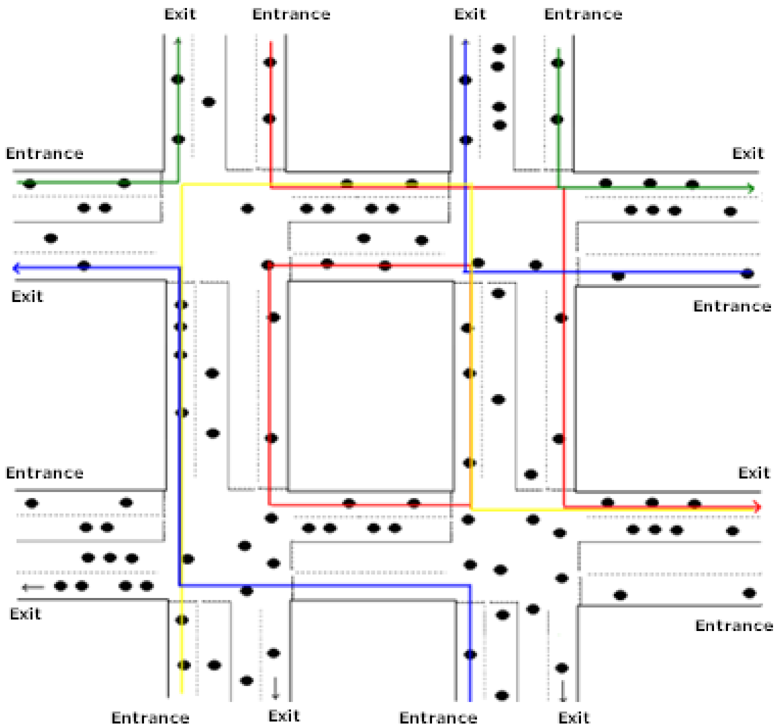


Fig. 3. 10 An overview of I-Routes

3.4 Summary

As a dynamic event oriented wireless mobile network architecture, Collaborative MANET-based Communication Network (CMCN) entails self-organized topology, infrastructure-free communication and multi-hop forwarding which allows distributed, collaborative, and real-time as well as ITS traffic information generation and control. This type of network includes macroscopic and microscopic aspects respectively; the former relates to architecture layers and corresponding protocols while the latter relates to the system components.

Commonly, research focuses on the improvements of layer specifications and protocols for C2X message exchanges but does not exploit characteristics of network components. It may be argued that considerations such as the classification of network nodes increase the complexity of network communications. Nevertheless, this thesis persists pursuing such a research direction as subsequent results indicate that the tradeoffs are largely positive. It is reasonable and feasible to take advantages of their existing roles and utilize them properly to a collaborative message delivery for maintaining safe, convenient and comfortable traffic environments.

Chapter 4

Message Delivery in CMCN

4.1 Overview

CMCN challenges other wireless mobile networks through the nature of dynamic and flexible organization. The characteristics, on one hand, allow non-infrastructure designs to be deployed in modern wireless mobile networks; on the other hand, a comparatively demanding task of efficient and reliable data disseminations faces the network. In recent decades, many effective solutions have been proposed for message delivery in CMCN and well-suited ones, as shown in [120][122][125][126], are designed based on broadcasting mechanism. Broadcasting is a proper technology for C2C communication in CMCN where nodes (hosts, routers, gateways) operate in both one-hop and multi-hop forwarding manners. In other words, messages are exchanged without any centralized controls from one node to another until they reach the destination. But it is worth noting that a primary problem of broadcasting protocol lies in broadcast storms due to redundant rebroadcasts or packet congestions over the network. It may cause significant packet loss or delays during transmissions. Therefore, to control the number of rebroadcasts, to reduce the collisions of packet and to improve the reliability of broadcast become critical tasks when a broadcasting algorithm is designed.

Probabilistic Traffic Message Delivery Algorithm (PTMDA) is a novel broadcasting-based algorithm designed to support efficient and reliable information exchange in CMCN. The algorithm is capable of multi-hop, non-clustered and distributed transmissions with the inclusion of pre-existing route information (I-Routes) for message deliveries in urban traffic areas, no matter they are sparse at night or relatively dense at rush hours. Nowadays, it is reasonable to assume that vehicles and traffic facilities are equipped with various electronic devices. When PTMDA is applied to CMCN communicators, these electronic devices can help to collect geographic information or car-based status. The method makes communication performance more efficient, reliable and accurate.

In terms of PTMDA, it is implemented based on the following criteria:

- **Non-Acknowledgement (Non-ACK) broadcasting**: Considering the efficiency of communications, PTMDA does not use ACKs in the communications. So far, many studies, i.e. [19][164], have been proposed to improve the reliability of transmission by using signals to acknowledge the receipt of data. However, from the efficiency point of view, ACK scheme results in relative longer delay from sources to destinations due to heavy overheads. Additionally, the scheme requires more control mechanism and procedures to handle ACKs.
- **Collaborative CMCN nodes**: PTMDA details individual roles of nodes as they are in real traffic scenarios. For example, the arbitrariness of mobile nodes is regarded as the main sources of message generations. Therefore, CMCN cars exist as ad hoc hosts and routers to process multi-hop C2C communications. The negative part is the disconnection of transmissions because cars are not distributed evenly, particularly in a sparse network. In such case, structured and regular operated CMCN buses help to enhance the connectivity of local transmissions. Besides, CMCN bus stops are used for improving the reachability of messages and widening available coverage of connections, not only in the local area but also among regions.
- **The inclusion of I-Routes**: Due to the priority of buses, bus lanes become very important in city transportation. These roads are frequently and regularly used by buses and they are usually physically close to bus stops. In this thesis, such lanes are called I-Routes. Compared with normal roads, they maintain relatively better connectivity. Therefore, PTMDA rules I-Route nodes to forward the message preferentially. The inclusion of I-Routes in the algorithm, on one hand, provides

a basis to identify the qualification of prior forwarding; on the other hand, lightens the overheads of packet at nodes.

- **Probabilistic priority forwarding**: Focusing on mobile nodes, the probabilistic priority scheme contains a two-step strategy to alleviate packet collisions caused by redundant rebroadcasts and transmission congestions. In the first step, a probability value with regard to the type, position, distance, speed and direction of CMCN senders and receivers is compared with a given threshold value. Once the comparison result meets the requirements, then these nodes are permitted to carry on the next step; otherwise, they drop the packets immediately. In the second step, a waiting delay is assigned to nodes by a calculation relying on the current probability. This action aims to avoid simultaneous forwarding.

This chapter is structured as follows: Section 4.2 introduces the relevant issues of CMCN traffic messages regarding the message format and data characteristics. Section 4.3 presents overall operations of PTMDA at CMCN nodes, covering message encapsulations and broadcast with strategic waiting delays. Section 4.4, 4.5, 4.6 and 4.7 focus on specific sub-schemes of probabilistic priority scheme separately, i.e. I-Route scheme, Farthest Node First Send scheme, Direction-based Priority scheme and High-Speed Priority scheme, providing critical theoretical and mathematical basis of PTMDA broadcasting mechanism. Finally, Section 4.8 gives a summary of PTMDA.

4.2 CMCN Traffic Message (CTM)

4.2.1 Message format

WAVE standard [163], applied in vehicular environments, defines following two types of message formats. WAVE Service Advertisement (WSA) format broadcasts a message, e.g. “Hello” message, periodically to keep track of neighbouring links. Another one is WAVE short message (WSM). It contains broadcasting specifications and timely C2C application data. By default the maximal message size can be 1400 octets. In this thesis, CMCN Traffic Message (CTM) is framed based on WSM format (Table 4.1).

Table 4. 1 CMCN Traffic Message Frame

octet	1	1	1	1	1	1	1	1
Broadcast header	TYPE	OS-ID	B-ID	S-ID	S-MAC			D-ID
	CT	DIR		POS (longitude & latitude)				
	SPD		EXP	Reserved				
CTM data	Warning-based Message/ Sharing-based Message							

Where:

- TYPE: indicates a type of CTM. 1 for warning-based (WB) message with higher priority and 0 for sharing-based (SB) message with lower priority.
- OS-ID: presents originator’s ID.
- B-ID: the broadcast id.
- S-ID/S-MAC: current sender’s ID and MAC address.
- D-ID/D-MAC: destination node’s ID and MAC address. There are two options. If the source and destination has been planned before a broadcast starts, then these sections record predicated destination’s address. Otherwise, it will be filled with -1 and 0 for corresponding parts.
- CT: timestamp when the message is broadcast from a previous sender.
- DIR: it records the direction of the sender at CT.
- POS: geographic position of the sender at CT, consisting of longitude and latitude from GPS.
- SPD: speed of the sender at CT.
- EXP: stores the expiry of a CTM.
- Reserved: a space for essential extensions.
- CTM data: The size of CTM data varies depending on the message type, such as warning message or knowledge sharing message.

4.2.2 CTM data

This part starts with the following assumptions:

Assumption 1 (Fig. 4.1**)**: An unexpected event happened in an area causing a small traffic block. In the opposite road, a passing car (C) detected the events and broadcast a warning message. By means of multi-hop, the message reached at a car coming to the accident area. It is foreseeable that a heavy traffic jam in few minutes can be probably avoided.

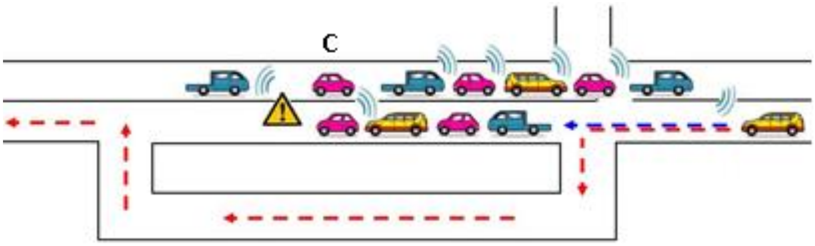


Fig. 4. 1 Assumption 1: Accident message generation and transmission

Assumption 2 (Fig. 4.2**)**: A car C is leaving a parking area in city centre with the knowledge that parking spaces are available. C then broadcasts the message to the traffic environment. Although the information is not very urgent for all cars in the area, it will be desirable information for cars which are searching for the parking places.

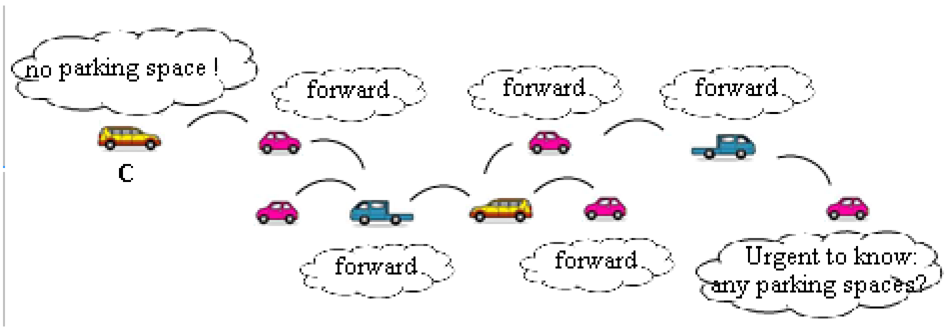


Fig. 4. 2 Assumption 2: Parking spaces message generation and transmission

Fig. 4.1 and Fig. 4.2 intuitively show that transmission data vary relying on communication purposes so that contents and size of CTM data are certainly different. On this point, M. L. Sichitiu and M. Kihl in [21] classify vehicle communications as five kinds of applications with regard to public safety, traffic management, traffic coordination and assistance, traveller information supports as well as comfort applications. According to these classifications, the types of messages are simplified in this thesis as warning-based (WB) message and sharing-based (SB) message.

WB messages require fast formation, small overhead, brief and accurate content. By the literature [21], these messages may concentrate on public safety, traffic coordination and assistance. Fig. 4.1 shows a typical example scenario in which the WB messages are transmitted. Conversely, SB messages, in relation to the traffic control and management, traveller information supports, infotainment and comfort applications, are based on knowledge sharing to meet individual needs. Hence, the accuracy of information and the richness of contents are more considerable rather than the timeliness. For this reason, the CTM data size of SB allows to be larger than that of WB while the latter highly requires faster transmission speed. An example of SB transmission is depicted in Fig. 4.2.

4.3 Probabilistic Traffic Message Delivery Algorithm (PTMDA)

Algorithm 4.1 shows the overall operations of PTMDA. The event-driven method controls the message sending and receiving at nodes. When Event i starts, a sender S broadcasts a packet P to the channel via IEEE 802.11p. The packets are framed according to CTM format (Table 4.1). Event ii occurs when the packet reaches to a receiver R. If the received message is new within the expiry time, R determines to forward or drop packets relying upon the value of probability obtained from the probabilistic priority scheme of PTMDA, such as I-Route scheme (Section 4.4), Farthest Node First Send (FNFS) scheme (Section 4.5), Direction-based Priority (DP) Scheme (Section 4.6) and High-Speed Priority (SP) Scheme (Section 4.7). These schemes are geared to a higher level of C2C communication performance, resulting in faster delivery, less packet loss, and higher reliability.

Algorithm 4. 1 The overall operations of PTMDA

Initialize: S→sender; R→receiver; P→CMCN packet; BRD_Table→a list of receipts P_TH→probability thresholds **Event i: P is transmitted** 1. *S* encapsulates *P* as CTM format; 2. *S* broadcasts *P* via IEEE 802.11p; **END Event i**	**Event ii: P is heard at R** 1. Insert the new broadcast id and sender id to the BRD_Table 2. If {received} then 3. Drop packet; 4. Exit PTMDA; 5. Else 6. If {message valid} then 7. Invoke PTMDA probabilistic priority scheme; 8. If { Prob ≥ P_TH } then 9. Waiting delay assessment by Equation 4.1 10. Else 11. Drop packet; 12. Exit PTMDA; 13. End if 14. End if 15. Implement Event i **END Event ii**

Where:

- Prob: an accumulated probability value based on PTMDA probability schemes, see the first step of Equation 4.1;
- BRD_Table: a table for all receiving information. It is used to avoid redundant operations at nodes.
- P_TH: a probability threshold which is set to adapt for different communication scenarios.

4.3.1 Message encapsulation

When vehicles detect an event, it is encapsulated, coupled with the broadcast headers, to be a CTM frame. The frame (Table 4.1) generally contains broadcasting information such as message type (TYPE), originator id (OS-ID), broadcast id (B-ID), current sender's id (S-ID) and MAC address, destination's id (D-ID), current time (CT), sender's mobility information (DIR, POS, SPD), message expiry (EXP) as well as CTM data with WB or SB information. Once the encapsulated message is ready, it will be broadcast to the network via IEEE 802.11p, as shown in Event i of Algorithm 4.1.

4.3.2 PTMDA broadcast table

A broadcast table (BRD_Table) is integrated into each node for recording the new arrivals of new CTM. Within a certain period, the table information helps nodes to make decisions for dropping or forwarding the packet. Basically, the table contains:

- BRD_ID: represents a broadcast id from the value 0. An original sender corresponds to a single broadcast id.
- S_ID: an identification of a source node.
- D_ID: an identification of a CTM receiver. The field is -1 by default for broadcasting only; otherwise, it stores particular receiving nodes' ID.
- t_EXP: an expiry time used to reset the broadcast table. It helps to clear stale information and avoid the packet to be too heavy during the communications.

4.3.3 Probabilistic priority scheme

In order to limit the amount of rebroadcasts and differentiate the forwarding time, PTMDA adopts a probabilistic priority scheme. It firstly runs probability calculations at intermediate mobile receivers as shown in the first two lines of Equation 4.1. In the equation, the probability depends on the mobility patterns of nodes. Once the average probability is over a pre-set threshold value (P_TH), then the assessment of waiting delay (T_{WD}) is computed by the third line of Equation 4.1.

$$
\begin{aligned}
&\mathrm{Prob} = P_{Node} + P_{POS} + P_{DIS} + P_{DCT} + P_{SP} \\
&\overline{\mathrm{Prob}} = \frac{\mathrm{Prob}}{5} \\
&T_{WD} = \left(1 - \overline{\mathrm{Prob}}\right) \times T_{Interval} \quad (\text{While } \overline{\mathrm{Prob}} > \text{P\_TH})
\end{aligned}
\tag{4.1}
$$

Where:

- $\overline{\text{Prob}}$: a mean of accumulated probability value consisting of node type-based probability, position-based probability, distance-based probability, speed-based probability and direction-based probability.
- P_{Node}: a probability value based on the type of nodes. Semi-mobile nodes and gateway static nodes have higher probability than others, as shown in Equation 4.2.
- P_{POS}: a position-based probability obtained by Equation 4.3. Higher value is given when a node, in conjunction with its sender, are both on the I-Routes.
- P_{DIS}: a distance-based probability obtained by Equation 4.4. Higher value is given to a node that is farthest from the sender.
- P_{DCT}: a direction-based probability obtained by Equation 4.5. Higher value is given to a node which has the same direction as the sender.
- P_{SP}: a speed-based probability obtained by Equation 4.6. Higher value is given to a node which moves with the highest speed.
- $T_{Interval}$: an interval of one-hop sending and receiving operations.

4.4 I-Route Scheme - The Inclusion of Traffic Route Information

In PTMDA, one of the novel mechanisms is the inclusion of traffic route information. This is a key feature distinguishing PTMDA from the other broadcasting protocols. Routes, in this case, can be normal routes pre-configured or can also simply be the bus lanes. In this thesis, they are pre-configured bus lanes. The selection of the routes, in essence, is inspired by the nature of buses and bus stops in the CMCN system. This scheme involves two transmission probability factors that affect overall probability and they are now examined in turn:

1) **Node type-based probability** – This probability is assigned directly depending on a node’s traffic role. For example, cars and buses will have different probability

value as, in this thesis, the latter is always believed to have higher priority. The value will finally contribute to the computations of forwarding delay.

2) **Position-based probability** – This probability depends on the position of senders and receivers. It is a very intuitive way to make differences between I-Route nodes with others.

4.4.1 Node type-based probability

CMCN nodes, generally, may have different transmission capabilities, and PTMDA attempts to take advantages of the fact. From the financial point of view, public transportation facilities – buses and bus stops should be fully exploited because represents an existing investment from governments or companies. Because of this, buses operated in a city have accurate and periodic schedules and priority lanes assigned to them. Moreover, both buses and bus stops are equipped with advanced data acquisition and management modules for message delivery and storage. In addition, bus stops, fixed alongside of the bus lanes, may use wired connections to communicate with a traffic control centre, other wire-connected bus stops or Internet.

Consequently, buses and gateway bus stops are assigned higher transmission probability than cars. The probability (P_{Node}) is given as Equation 4.2.

$$P_{Node} = \begin{cases} 0, & type = \{others\} \\ 1, & type = \{bus \cup gateway\} \end{cases} \tag{4.2}$$

4.4.2 Position-based probability

The main idea of this scheme is to compute a priority probability according to nodes' positioning information. In the day time, I-Routes and common roads of cities are full of vehicles. Particularly in rush hours, message transmissions could experience a high success by C2C communications as the network is connected. However, in the evening, the number of cars is reduced so that network connectivity becomes poor and packet losses increase. To maintain reliable transmissions, a proper solution may involve communications between vehicles and gateway bus stops that propagate the message to other bus stops and thus to the network at large. This idea implies that it is important to deliver a message as fast as possible to bus stops. In other words, vehicles on I-Routes have priority in forwarding because they are close to bus stops. In particular, the probability set for both senders and receivers (Equation 4.3) is:

$$P_{POS} = \begin{cases} 0, & SIR = 0, RIR = 0; \\ 0.5, & SIR = 1, RIR = 0; \\ 0.75, & SIR = 0, RIR = 1; \\ 1, & SIR = 1, RIR = 1; \end{cases} \qquad (4.3)$$

Where:

- SIR: it is a variable indicates whether a sender is on any I-Routes or not. 0 means FALSE; 1 means TRUE.
- RIR: it is a variable means whether a receiver is on any I-Routes or not. 0 means FALSE; 1 means TRUE.

With a high value of P_{POS}, nodes are able to forward the message sooner. However, a special case is considered when all receivers of a sender are on the I-Routes. It can be imagined that if all of them forward with the high position-based probability, the number of invoked broadcasts at that moment will heavily increase. This, as a result, would decrease communication performance. Therefore, more schemes are needed to address the problem immediately. These are presented below.

Fig. 4.3 shows an example scenario based on the I-Route scheme. A sender (S) has seven receivers (R1-R7) which are two buses (R1,R2) and five cars (R3-R7). According to Equation 4.2 and 4.3, R1 and R2 are entitled to forward the message with the highest probability because they are buses, operating on a I-Route (bus lane), and receive a message from the non-I-Route S.

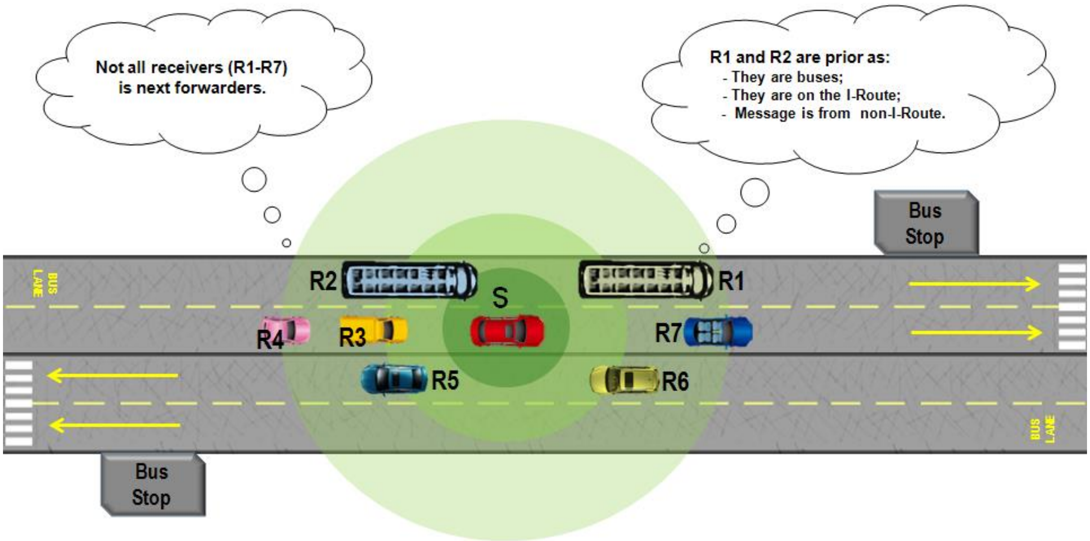


Fig. 4. 3 I-Route scenario:
Sender (S), Receivers (R1-R7); R1 and R2 forward the message with a high priority

4.5 Farthest Node First Send (FNFS) Scheme

Taking into consideration the reality of urban traffic scenarios, the number of vehicles covered by a sender's transmission range varies relying on network density. For example, a kilometre lane distributes 10 cars at an average inter-distance up to be 100 meter; whereas, if the density of lanes increases to be 50 vehicles/km, the inter-distance currently reduces to 20 meters. Therefore, if a CTM is broadcast from the first vehicle with a transmission range of 250 meters, then 2 vehicles from the former case and 12 vehicles from the other case could receive this message. This difference implies a potential problem. It is well known that conventional broadcasting methods allow all vehicles to forward the same message almost at the same time and this obviously causes serious redundant rebroadcasts and packet collisions if there are a lot of forwarders. Thus, under a general broadcasting protocol, the communication performance of a dense network could be very poor.

Such a problem actually motivates the design of FNFS scheme. Within the sender's wireless coverage, the scheme filters out the node that farthest from the sender and provides it a highest probability. In another words, the closer the sender and the receiver are, the smaller the probability of retransmission is.

4.5.1 Definition of farthest node

The word 'farthest' depends on the wireless transmission range of CMCN nodes. Indeed, a valid transmission range depends on the signal propagation model as assumed as well as the transmission power and the sensitivity of the receiver. According to Two-Ray-Ground radio propagation, a default transmission range is setup as 250 meters while this project considers the farthest covering distance to be 150 meters. Two points should be outlined now.

Firstly, the density of traffic areas varies in different regions. Generally, a city centre has shorter inter-car distances than those of other areas. This thesis mainly studies on city traffic scenarios in which the density could be both high and low. As discussed above, many receivers and thus many forwarders are not always preferable and narrowing the transmission radius could effectively solve the problem. Review the example at the beginning of Section 4.5, where a case with 12 receiving vehicles could be improved to have 8 recipients if the transmission range has been reduced to 150 meters.

Additionally, the overlaps may be more when the transmission range is set larger for the same layout of vehicles in a street, as shown in Fig. 4.4. Clearly, the possibility of collisions decreases if the wireless coverage of nodes is reduced to 150 meters.

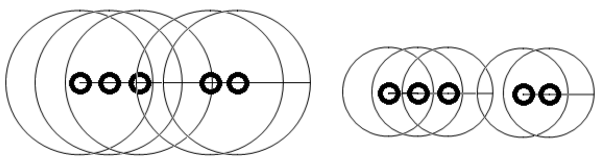


Fig. 4. 4 The overlapped area of different transmission ranges

4.5.2 Distance-based probability

Here the mechanisms used to compute distance-based probability are outlined, as shown in Algorithm 4.2; which consists of two parts:

1) Collect required information – According to Algorithm 4.2 (line 1-line 2), receiver R firstly unpacks the encapsulated message. This is the only way in the CMCN for receivers to learn any information about their neighbours as they read in senders' information from the packets; senders, on the other hand, do not have information on the receivers.

2) Compute distance-based probability (P_{DIS}) – Once obtained information is enough for distance calculations, a mathematical method is followed as shown in Equation 4.4. The probability presents as the distance $DIS_{<S,R>}$ over the maximum value transmission range. For example in Fig. 4.5, four vehicles (R1-R4) receive a message from a Sender (S) and the distances between each receiver and S are d1, d2, d3 and d4 separately. At the moment, the relationship of values is d2<d3<d1<d4. According to Equation 4.4, the farthest receiver R4 gets the highest probability and vice versa.

Algorithm 4. 2 Farthest Node First Send - FNFS

Event: Return the *P_{DIS}* to R
Initialize: S→sender; R→receiver; P→CMCN packet; CT→current time;
$\underline{DIS_{<S,R>}}$ → the distance between S and R; MAX_TRANS = 150;

1. R splits P and reads in S's (X, Y) coordinates
2. R reads in its (X, Y) and CT from the GPS
3. R invokes Equation 4.4
4. Return *P_{DIS}* to Equation 4.1

END Event

$$\begin{aligned} \Delta X &= X_R - X_S; \\ \Delta Y &= Y_R - Y_S; \\ DIS_{<S,R>} &= \sqrt{\Delta X^2 + \Delta Y^2}; \\ P_{DIS} &= \frac{DIS_{<S,R>}}{MAX\_TRANS} \end{aligned} \tag{4.4}$$

Where:

- ΔX, ΔY: the differences of X or Y between S and R, contributing to the computation of $DIS_{<S,R>}$;

- MAX_TRANS: a max value of transmission range of CMCN nodes. The default value is set as 150. It could be different by configurations.

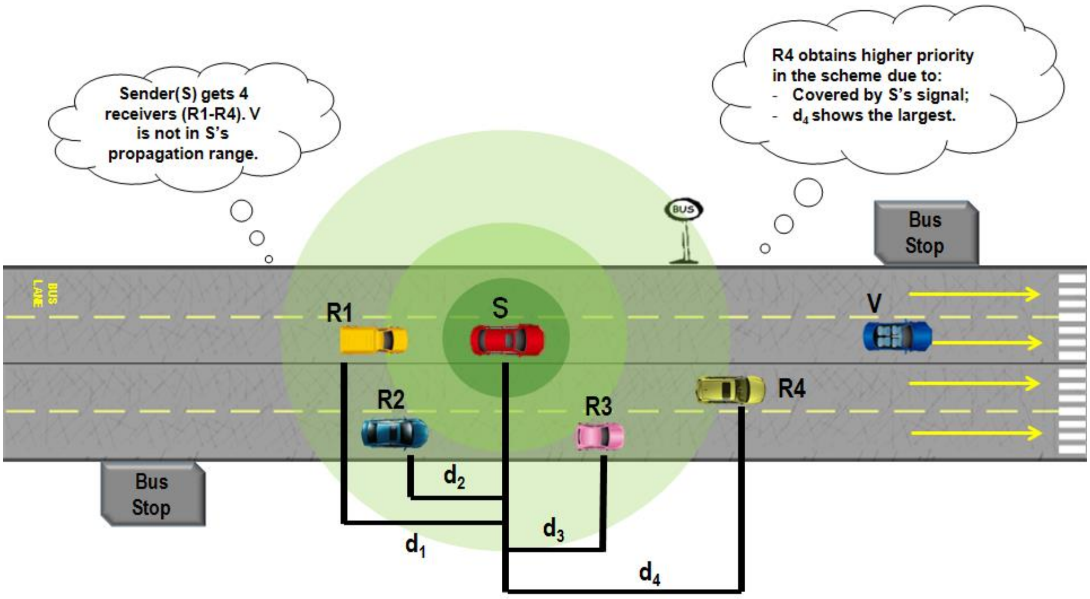


Fig. 4. 5 Distance between a sender and its covered receivers: R4 forwards the message with a high priority

4.6 Direction-based Priority (DP) Scheme

The main idea of this scheme, coupled with the other probabilistic priority sub-schemes, is to lower the risk of collisions when qualified nodes intend to transmit the same CTM simultaneously.

In urban traffic scenarios, the directions of motion of nodes vary depending on the layout of traffic roads. Typically, if two nodes are both moving in east-west lanes, they could move towards the same way or be in opposite directions with different values of direction vectors. In PTMDA, a receiver's direction is compared with the sender and follows techniques outlined in Algorithm 4.3. If a sender S and a receiver R move in the same direction, the direction-based priority is high as a consequence of Equation 4.5.

In a graphical example (Fig. 4.6), six vehicles (R1-R6) receive a message from a sender (S) and the direction vectors of these receivers are θ_1 for R6, θ_2 for R1, R2 and R5, and θ_3 for R3 and R4. According to Equation 4.5, R1, R2 and R5 are given the highest direction-based priority probability.

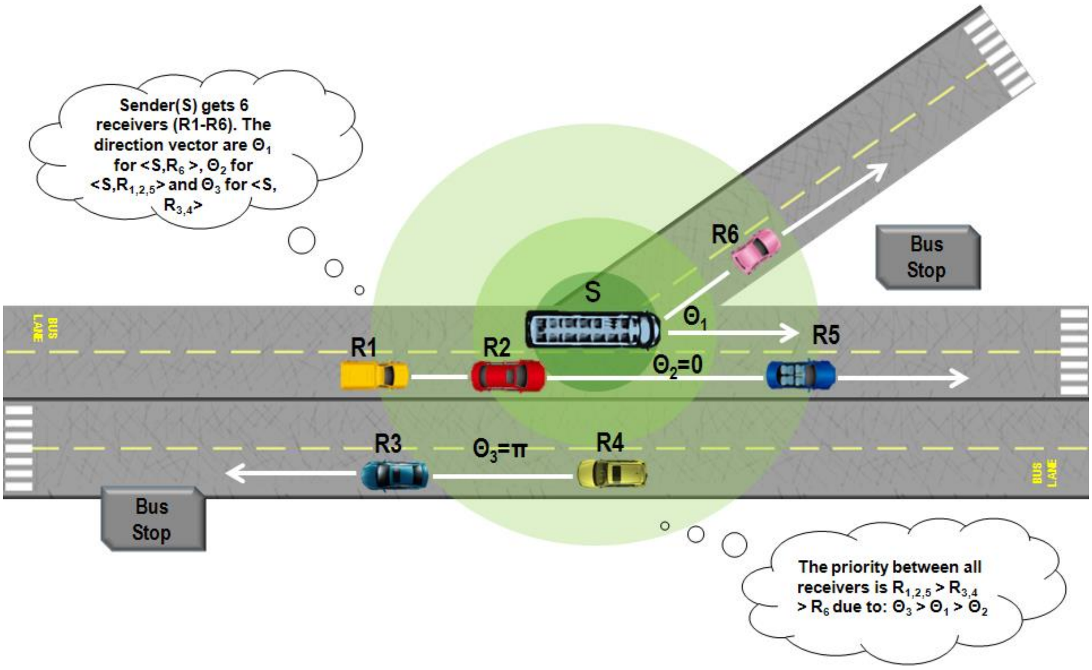


Fig. 4. 6 The directions of vehicles in motion:
R1, R2 and R5 forward the message with a high priority

Algorithm 4. 3 Direction-based Probability

Event: Return the P_{DCT} to R
Initialize: S→sender; R→receiver; P→CMCN packet; CT→current time;

$\vec{S}$ →direction vector of S; $\vec{R}$ →direction vector of R; $\overrightarrow{SR}$ → the difference of $\vec{S}$ and $\vec{R}$

1. R splits P and reads in S's (X, Y) coordinates
2. R reads in its (X, Y) and CT from the GPS
3. R invokes Equation 4.5
4. Return P_{DCT} to Equation 4.1

END Event

$$\overrightarrow{SR} = \left|\vec{S} - \vec{R}\right|$$
$$P_{DCT} = \frac{\pi - \overrightarrow{SR}}{\pi} \qquad (\pi = 180^{\circ}) \tag{4.5}$$

Where:

- $\vec{S}$, $\vec{SR}$, $\overrightarrow{SR}$: direction vectors for senders, receivers and their differences.

4.7 High-Speed Priority (SP) Scheme

While the network density is changeable in a city area, the speeds of vehicles are different. Generally speaking, a fast moving vehicle provides more opportunity to deliver CTM packets to farther areas with smaller delays. This is a reason to consider the SP scheme in PTMDA. Algorithm 4.4 shows the concept in detail. Once the receiver R gets the sender's speed from the packet P and its own speed from GPS, it calculates the difference of speed ($\text{Speed}_{<S, R>}$). Following that it computes a probability by comparing the occupancy of $\text{Speed}_{<S, R>}$ with a threshold value (MAX_DIFF). This threshold is set based on the speed limit of vehicles in urban traffic scenarios. The lowest probability is generated when S is a car with 40 km/h speed and a vehicle R is close to 0 km/h (i.e. when bus pulls in), or vice versa. This idea is not applied in static nodes.

Algorithm 4. 4 Speed-based Probability with respect to I-Route Node

Event: Return the P_{SP} to R
Initialize: S→sender; R→receiver; P→CMCN packet; MAX_DIFF = 40;

$Speed_{<S,R>}$ → the different speed between S and R;

1. R splits P and reads in S's (X, Y) coordinates
2. R reads in its (X, Y) and CT from the GPS
3. R invokes Equation 4.6
4. Return P_{SP} to Equation 4.1

END Event

$$Speed_{<S,R>} = |S_S - S_R|$$
$$P_{SP} = 1 - \frac{Speed_{<S,R>}}{MAX\_DIFF} \tag{4.6}$$

Where:

- S_S, S_R: the speed of a sender and a receiver respectively;
- Speed $_{<S, R>}$: a difference of sender and receiver's speed at receiving time.
- MAX_DIFF: a threshold value compared with the speed difference between S and R. If their speeds are similar, the proportion is small and the speed-based probability is high.

Fig. 4.7 explains the scheme by an intuitive graphical example that two vehicles (R1 and R2) receive a message from a sender (S) and the speeds of them are V1 (km/h) and V2 (km/h) respectively. In the example, V1 is greater than V2 so that, by Equation 4.6, R1 gets the higher speed-based probability.

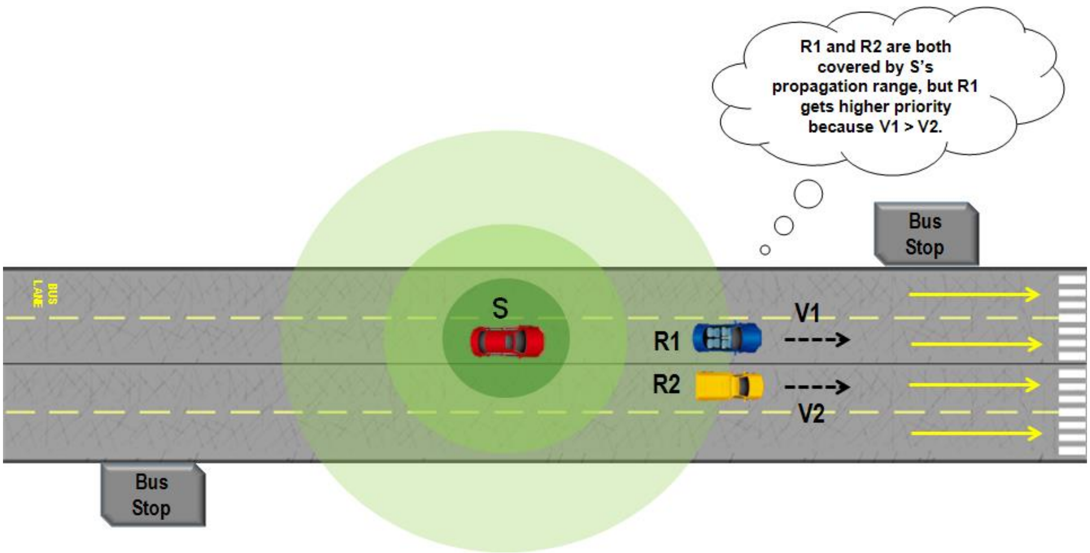


Fig. 4. 7 The speed of vehicles in motion:
R1 forwards the message with a priority

4.8 Summary

Applications in the field of Intelligent Transportation System require a network architecture supporting smooth, reliable and comfortable communications. C2C methods can be the basis of a primary solution while C2I solutions can also aid in that task for particular demands.

To achieve the above stated requirement, this work establishes a Collaborative

MANET-based Communication Network (CMCN) as a basis to implement a new broadcasting-based Probabilistic Traffic Message Delivery Algorithm (PTMDA). The algorithm adopts probabilistic priority scheme for eliminating a certain number of rebroadcasts and differentiating transmission to achieve greater network performance. Following two aspects are mainly concerned in this thesis.

- Efficiency: It indicates achieving lower end-to-end delay from an originator to available packet-reaching destinations. The delay of transmissions becomes lower by using efficient broadcasting methods.
- Reliability: The concept of reliability implies maximising the overall reachability of a broadcast, enlarging the coverage of data disseminations, and implies a high ratio of successful point-to-point deliveries. Adverse impact factors contributing to transmission failures are mainly broadcast storms and network disconnections due to mobility.

Chapter 5

Simulations and Evaluations

5.1 Overview

Real test beds or simulations are two available tools to evaluate the proposed concepts of the research. The former validate investigations on real wireless communications hardware such as in-car devices, urban traffic facilities and so on, while the latter enable all these to be virtually configured based on current academic or commercial study data and results. Generally, the most popular selection for research purposes is simulation technology.

From a financial point of view, introducing real hardware into the experiments causes continuing expenses with regard to installation, maintenance and replacement; on the other hand, simulation software can set up essential devices in simulation programmes to avoid prohibitive costs. Besides, as new technology is created, its specific parameters need to be considered while extensive tests are performed for various possibilities so that the effectiveness of new concepts could be evaluated and proved. In terms of reutilization, simulations are preferable to testbeds. By using real test beds, any changes of the parameters may impact on hardware configurations and this requires more human and material resources. This study investigates message delivery based on urban traffic scenarios, in which a large number of transmissions are involved. Simulations are chosen to use as they allow different environment parameters to be simply configured and modified according to our specific research purposes. There are three main to the investigation:

- **Establishing CMCN architecture** – This section introduces a simulation model based on the Collaborative MANET-base Communication Network (CMCN) architecture, including three types of CMCN nodes, urban scenarios, motilities, protocols and C2X communications.
- **Implementing PTMDA algorithm** – This section presents a Probabilistic Traffic Message Delivery Algorithm (PTMDA) into the CMCN simulation model to investigate the effect of new broadcasting mechanism.
- **Evaluating C2X communication performance** – This section outlines extensive experiments which help observe C2X communication performance and outline C2X potentials.

This chapter is set as follows: Section 5.2 describes as chosen simulation methodology including CMCN network model and urban traffic mobility models. The simulation configurations and theoretical evaluation details on the protocols evaluated, the performance metrics and mathematical methods are also thoroughly analysed. Sections 5.3, 5.4 and 5.5 provide experimental investigation and evaluation of the performance of PTMDA. Finally, Section 5.7 provides a summary of conclusions with regard to the efficiency and reliability of C2X communications in the proposed system.

5.2 Simulation Methodology

5.2.1 Architecture of CMCN simulation and evaluation

The methodology used in CMCN simulation and evaluation is shown below in two main building blocks: simulation model and evaluation model (Fig. 5.1).

Simulation contains a mobility model (red part of Fig. 5.1) and a networking model (green part of Fig. 5.1). A city map is selected as the basis of a simulation scenario. The realistic mobility patterns of Scenario I (Fig. 5.2) and Scenario II (Fig. 5.3) are exported by a Java-based simulator (SimDev) [165] and the SUMO traffic simulator [148] respectively. The outputs are in the form of Tcl scripts in that they are imported to the

Network Simulator II (NS2) [153]. The networking model configures fundamental

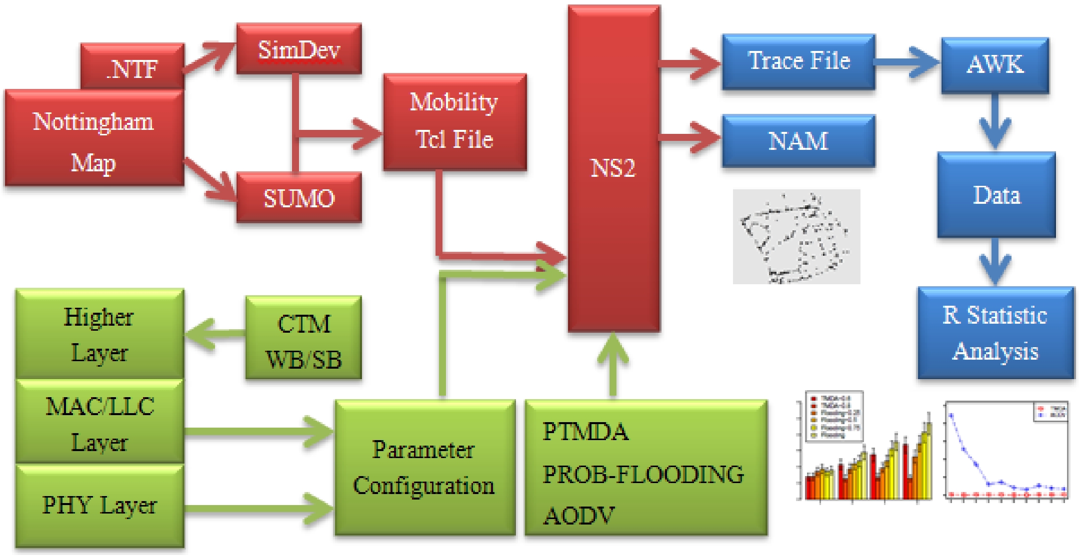


Fig. 5. 1 The architecture of CMCN Simulation and Evaluation

parameters of system layers (Table 5.1, Table 5.2, and Table 5.3). Meanwhile, the routing and broadcasting protocols written by C++ are integrated into the model to complete message delivery.

The evaluation model (see Fig. 5.1: blue part) contains methodology of data analysis using programs designed based on AWK language and R language. Once outputs are generated from the simulation model, trace files are appropriate for statistical analysis, containing much information such as simulation events (e.g. send/receive events), simulation time, node's IP and MAC address, position, layer traces and so on. AWK programmes read in trace files from the simulation stage and then convert them to human-readable results. Meanwhile, the statistical analysis tool R exports these results to comprehensive graphs. Additionally, NS2 offers the Network Animator (NAM) (Fig. 5.5b and Fig. 5.6b) which allows tracing network status and real world packet delivery.

5.2.2 Simulation model details

As introduced above, the simulation model is based on urban traffic scenarios where C2X communications are applied and observed. In this context, two main topics are considered: scenario and mobility.

5.2.2.1 Scenario pattern

City scenarios mainly consist of lanes and intersections which could be created based on an artificial map or a real city map. Certainly, a custom scenario design includes many idealized simulation elements. For example, there are only main roads and intersections; also the paths of mobility are set up to be simple and controllable. On the contrary, real urban traffic conditions are usually much more complicated, including main roads linked to many non-trunks, several roundabouts and intersections (Fig. 5.2 and Fig. 5.3).

In this work, two scenarios based on Nottingham (UK) city traffic areas are selected for different investigation and evaluation purposes.

Scenario I: 700m*700m Nottingham (UK) Region – This scenario (Fig. 5.2) displays relatively simple traffic flows with approximately 65 vehicles in day time. The maximum speed of vehicles is set to 40 km/h. In the scenario, only CMCN mobile nodes and semi-mobile nodes are considered so that pure C2C communications are investigated. Furthermore, the I-Routes are selected as the red lines in Fig. 5.2a). This implies that the message transmissions on these routes should follow the direction of arrow.

The evaluation in this scenario focuses on paired end-to-end C2C communications

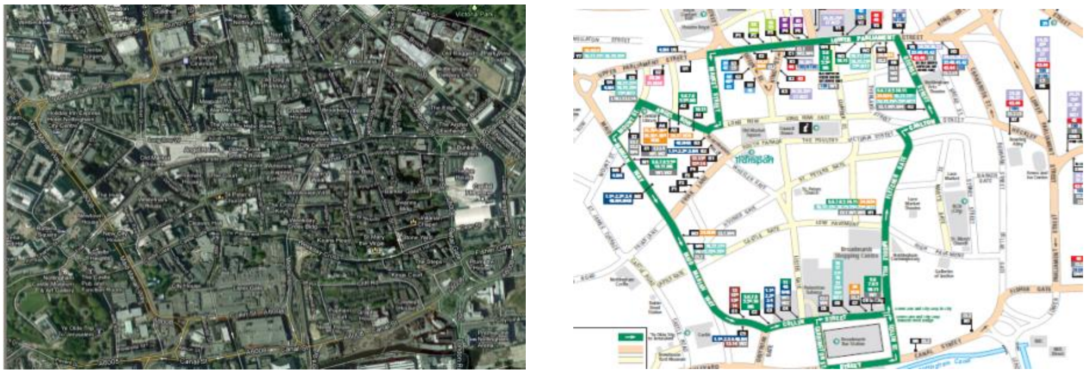
a) Satellite Map

b) I-Route map

Fig. 5. 2 Scenario I: 700m*700m Nottingham (UK) Region

(Fig. 5.4). The communication pairs are generated from 65 vehicles and any sources that could detect and broadcast a warning-based (WB) message or sharing-base (SB) message. Each source of communication pairs knows the ID of destination node, which is integrated into the CTM packet, and then the source broadcasts this CTM to its predetermined receiver as shown in Fig. 5.4a via one-hop and multi-hop modes. Obviously, there could be different messages transmitted by corresponding sender-receiver pairs over the network at the same time.

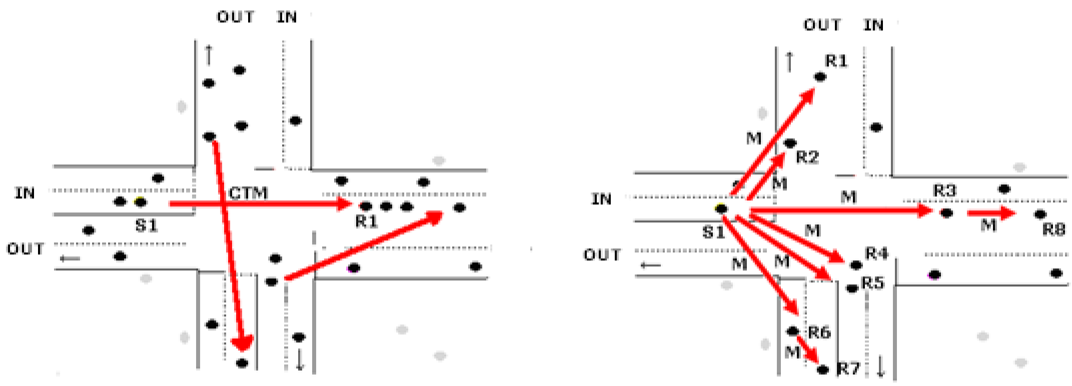
Scenario II: 1164m*905m Nottingham (UK) City Centre – This scenario (Fig. 5.3) shows a centre region of Nottingham city surrounded by many high buildings. In reality, the traffic density of the area varies in day time and night time. So, the simulation tests contain the number of CMCN nodes ranging from 101 to 1010. The maximum speed of movement is set as 30 mile/h. I-Routes are set as green routes in Fig. 5.3b, known as the bus lanes in the real map.



a) Satellite Map b) Nottingham Bus-stop Map

Fig. 5. 3 Scenario II: 1164m*905m Nottingham (UK) City Centre

In this scenario, both cases of Fig. 5.4 are involved. In particular, if the destination node is not specified in the CTM message, communications are evaluated in one-to-many fashion. Considering Fig. 5.4b as an example an originator (S1) broadcasts a unique CTM either WB or SB to the network and the message gets to all available recipients (R1~R8). Again, only one packet is transmitted in the network at a time. Compared with Scenario I, this one has more congested traffic flows with lower speed.



a) One-to-one mode b) One-to-multiple mode

Fig. 5. 4 The communication methods

5.2.2.2 Mobility pattern

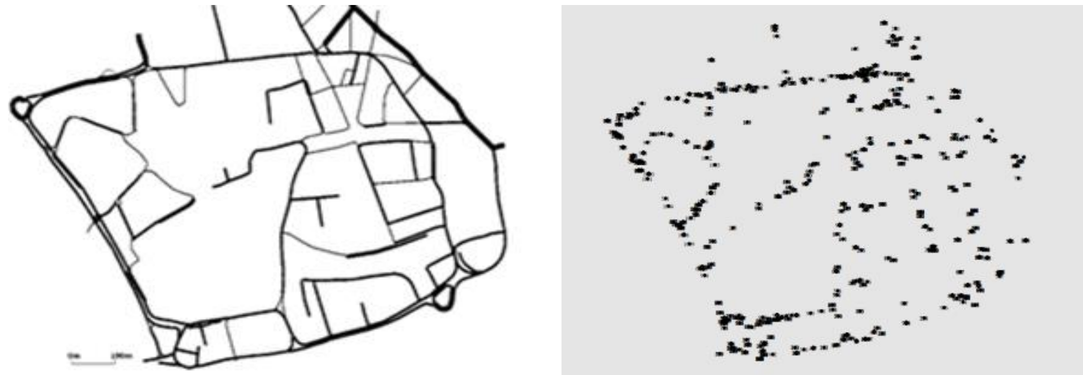
Nowadays, many different methods are available to generate mobility models for particular research aims. The relevant knowledge and simulators have been reviewed in Section 2.5.3. J. Harri (et al.) propose elaborate simulator surveys and taxonomy in [166] by giving a framework of realistic vehicular mobility models in conjunction with microscopic and macroscopic descriptions. They categorize vehicular mobility models as synthetic models, survey-based models, trace-based models and traffic simulator-based models. They further separate mobility models, according to the correlations of traffic simulators and networking simulators, into isolated mobility patterns, embedded mobility patterns and federated mobility patterns. According to the descriptions in [166], all traffic simulator-based models are realistic mobility models. Meanwhile, as shown in Fig 5.1, this work considers additional mobility data generated by SimDev and SUMO traffic simulators. The following parts will introduce three types of models; the first two are used in this thesis whilst the last has been adopted in previous papers.

Java-based SimDev model – The simulator written in Java created for the Trafimatics [165] project led by BT Research in the UK. It imports and interprets Meridian 2 NTF data of Nottingham city, featuring the streets, intersections based on British National Grid Coordinate system (Fig. 5.5a).

a) SimDev Mobility Map b) NS2 Nam Map

Fig. 5. 5 Scenario I: SimDev Mobility Model and NS2 Nam

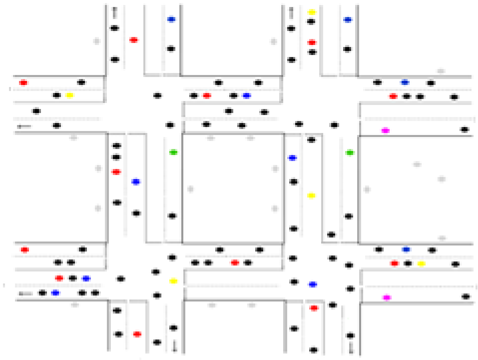
Simulation of Urban Mobility (SUMO) model – The mobility of vehicles generated by SUMO simulator based on the real Nottingham (UK) city centre map (Fig. 5.6a). It contains different categories of streets, acceleration and deceleration of movements, non-random distributions of vehicles and so on.



a) SUMO Mobility Map b) NS2 Nam Map

Fig. 5. 6 Scenario II: SUMO Mobility Model and NS2 Nam

User-defined mobility model – In previous published papers [111] and [167], an user-defined mobility model (Fig. 5.7) is used. It is organized by straight-lines only and few amount of intersections. The motion paths of nodes are along with the direction of roads, e.g. west-east way.



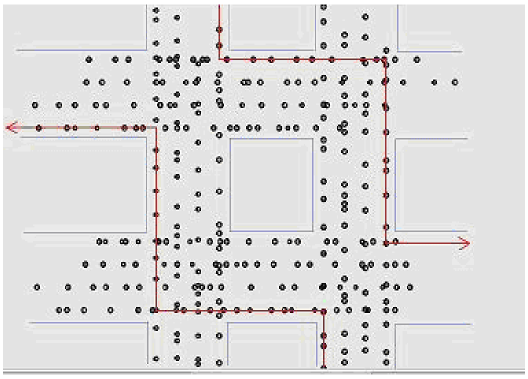


Fig. 5. 7 #-Shaped Mobility Model and NS2 Nam

5.2.3 Implementation details

5.2.3.1 Simulation tool – NS2

At present, there are many available network simulators for use as presented in Section 2.5.2. Due to the advantages shown below, NS2.35 was chosen for this project.

- Easy-configurability and fast simulation – Based on extensive tests, it is easy to get started with the NS2. The simulator supports the C++ and OTcl languages [145]. The C++ programming language provides efficient processes to deal with a large number of data and overheads while OTcl, as a type of script language, is responsible for controlling the configurations of various parameters, such as network components, topologies and events scheduling etc.
- Good visualization – NS2 supports programming and producing visible outputs (NAM) via a component animator. The feature helps researchers to conveniently view the status of simulation programs.
- Default elements – NS2 provides reliable default building blocks [145] allowing researchers to simulate operations and functions of corresponding layer protocols and applications from the stack of CMCN system in conjunction with traffic simulators.
- Versatility – One of most important part of using NS2 is to investigate the behaviour of different protocols. It is easy to replace or augment existing protocols

and introduce new ones.

- Open source simulator –NS2, a discrete event and packet level simulator developed at UC Berkeley, is free and open source simulator which means that sharing simulation results and techniques is easy and transparent. It is widely selected for MANET networks research and the validity of published results is widely accepted.

In the open source NS2, different modules with default parameters are provided for simple simulation designs and tests. However, to achieve our own research goals, this project provides a major effort which are much more pertinence and practicable (see in Fig. 5.1) – i.e. importing Nottingham maps, mobility data, network parameters to NS2; integrating and writing message delivery algorithms (e.g. PTMDA) for the simulation system; and also tracking and export raw data for analysis and evaluations.

5.2.3.2 System parameters

Parameters in Table 5.1 are chosen variables values leading to the simulation results, such as scenario details, transmission configurations (e.g. channel, propagation, message format and type etc.), mobility characteristics (e.g. traffic simulator and nodes' velocity etc.), topology settings (e.g. network density) and evaluation parts (e.g. comparable protocols and confidence interval).

Table 5. 1 Simulation parameter configuration

Simulation Parameter	Scenario I	Scenario II
Network Simulator	NS2-2.35	NS2-2.35
Scenario Area (m*m)	700 * 700	1164 * 905
Channel	WirelessChannel	WirelessChannel
Propagation	TwoRayGround	TwoRayGround
Network Interface	WirelessPhy	WirelessPhyExt
Channel Bandwidth (Mbps)	6	6
Mac Type	IEEE 802.11b	IEEE 802.11p
IFQ Length	50	50
Protocol	PTMDA, AODV	PTMDA, AODV, Prob-Flooding
Network Density	65	101,244,540,1010
Node Type	Mobile/Semi-mobile	Mobile/Semi-mobile/Static
Message Format	CTM	CTM

Message Type	WB/SB	WB/SB
Message Size (bytes)	512	128 , 256 , 512 , 1024
Transmission range (meter)	150	150
Number of messages	[1 - 10]	1/each observation
Broadcast Rate (per node)	1	1
Number of observations	50	50
Simulation time (second)	1500	1500
Mobility Simulator	SimDev & C++	SUMO
Maximum Veolicity (mile/h)	40	30
Communication mode	C2C	C2C & C2I
Confidence Interval	0.95	0.95
The ratio of infrastrutures (%)	0	0, 0.3,0.5,0.8,1

In this thesis, simulations and evaluations mainly focus on the effect of network density, message size, the number of messages and the ratio of gateway infrastructures to all CMCN nodes.

- **Network density (density)**: this is the number of network nodes, including mobile, semi-mobile and static nodes in the CMCN system. In Scenario I, the total number of network nodes is 65, solely consisting of mobile nodes. In Scenario II, the total number of network nodes, consisting of mobile nodes, semi-mobile nodes and static nodes, is 101, 244, 540 and 1010. The number of static nodes is fixed to 51 corresponding to the Bus Stop map of Nottingham city centre (Fig. 5.3b). Especially, a network with less than 200 nodes is defined as a sparse network; 244 for moderate medium network, 540 for medium network and finally, the 1010-node network is regarded as a dense network.
- **Message size (msgsize)**: this is another direct factor that affects the duration and the reliability of transmissions. For C2C communication, the speed of vehicles and the distance between cars are likely to determine the maximum message size for a successful sending and receiving process. Theoretically, if cars continue to move uniformly, the size of message could be larger than that transmitted between cars with increasing speed and distance. The effect of message size may be more significant to C2I applications. Usually, each node has a limit time slot passing an infrastructure with a certain speed. When the time is overdue, the conversation

between cars and the infrastructure ends. Thus, the worst packet loss happens when the mobility is too fast to support a transmission and the size of message exceeds a limit.

- **The number of messages**: this is a parameter defined for a pair of senders and receivers. In order to exclude complex impact factors and concentrate on the effect of broadcasting protocols, all experiments are formulated so that each source broadcasts a single packet instead of multiple injections per second. Simultaneously, the number of broadcasts from different sender-receiver pairs increases from 1 to 10 in this thesis. Theoretically, more transmissions over the network at a certain time increase possibilities of transmission congestions and low delivery ratio. Hence, the choice of parameters in this research is a result of the assessment of the effect of packet numbers and result of a judgment of the capability of broadcasting protocols to control and handle broadcast storms.
- **The ratio of gateway infrastructures to all CMCN nodes (talkratio)**: this is a parameter that helps investigate the effect of infrastructure in CMCN network communications. It helps to compare and evaluate communication performance in fully C2C approaches and C2I solutions. Observations provide a basis to discover most economic and optimum number of infrastructures used for communications. Note that 'infrastructure' in this case means a static node with both ad hoc and gateway functions that it delivers messages via direct radio links or wires. There are total 51 bus stops involved in Scenario II and the occupancy rate of gateway infrastructure nodes could be 0%, 30%, 50%, 80% and 100%.

5.2.3.3 Layer configurations

CMCN architecture (Fig. 3.5) contains five layers such as the PHY layer, the MAC layer, the network layer, the transport layer and application layer. By using NS-2.35, these layers are configured with the following parameters.

PHY layer – this layer is configured with specification values of IEEE 802.11p. It simulates at 5.9 GHz band of operating frequency which consists of one control channel

(CCH) and six service channels (SCHs) as WAVE spectrum [163]. It adopts OFDM modulation system with a C2C safety data transmission rate of 6 Mbps [160] for 10MHz bandwidth vehicle safety communications. These default parameters are shown in Table 5.2.

Table 5. 2 IEEE 802.11p PHY default parameters

WirelessPhyExt Para.	Configurations	Comments
CSThresh_	-85dBm	Wireless interface sensitivity (sensitivity defined in the standard)
freq_	5.9e+9GHz	Transmission frequency
noise_floor_	-99 dBm	Noise floor (for 10MHz bandwidth)
PowerMonitorThresh_	-102dBm	Power monitor sensitivity
HeaderDuration_	40µs	PLCP Header duration
SINR_PreambleCapture_	4dB	SINR for Preamble Capture
SINR_DataCapture_	10dB	SINR for Data Capture

MAC layer – In NS2.35, a channel coordination function (ECDA) is used to support priority messages and quality of service (QoS). Table 5.3 shows default values of Contention Window (CW) which gives a random backoff time and critical parameters for calculating the Arbitrary Inter-Frame Space (AIFS) which presents a minimal channel sensing time for wireless devices.

Table 5. 3 IEEE 802.11p MAC default parameters

Mac/802_11Ext Para.	Configurations	Mac/802_11Ext Para.	Configurations
CWMin_	15	ShortRetryLimit_	7
CWMax	1023	LongRetryLimit_	4
SlotTime_	13 µs	HeaderDuration_	40 µs
SIFS_	32 µs	SymbolDuration_	8 µs

Higher layers – CMCN Traffic Messages (CTM) are generated at the layer following a particular format (Table 4.1). The data type could be both warning-based and sharing-based messages via the difference of size and priority; this work mostly focuses on the effect of message size. As a result, these messages are passed to the lower layers and broadcast via IEEE 802.11p using PTMDA.

5.2.4 Evaluation details

5.2.4.1 Observed broadcasting-based protocols

According to the literature review in Chapter 2, broadcasting approaches are most suitable for MANET-based network communications. Many categories have been proposed in the field (Fig. 2.10), including blind flooding, probability-based broadcasting, area-based broadcasting mechanism and neighbour-knowledge based Flooding approaches.

In the experimental evaluations, the proposed Probabilistic Traffic Message Delivery Algorithm (PTMDA) compares with representative broadcasting-based protocols – Probabilistic Flooding [126] and Ad Hoc On-Demand Distance Vector Routing (AODV) [107].

Probabilistic Flooding – The protocol addresses broadcast storms, which may seriously cause poor communication performance. It uses pre-set probability ($P \in [0,1]$) to control and limit a certain number of rebroadcasts. When a node receives a packet for the first time, it randomly generates a probability value. If the probability is less than the threshold value of (P), then it forwards the message to neighbour nodes; otherwise, the packet is dropped. According to this principle, if the threshold is set low, the invoked broadcasts could be well controlled and this is best-suited for communications in dense networks. In this research, the comparing probabilities of probabilistic flooding are chosen as 0.25, 0.5, 0.75 and 1. Notice that a threshold of 1 means the blind Flooding.

In fully C2C environments, with the increase of network density and message size, PTMDA compares with probabilistic flooding. This thesis considers the following three performance indicators to investigate how effective PTMDA proves for the CMCN applications:

- The efficiency of transmissions;
- The reachability of message transmissions;
- The elimination of invoked broadcasts.

Ad Hoc On-Demand Distance Vector Routing (AODV) – The overall aim of AODV (Section 2.4.1.2) is to search for one or multiple proper routes for a certain pair of senders and receivers. The protocol could be summarized as route discovery and routing phase via three specific activities, such as request with RREQ packets, response with RREP packets and error detection with RRER packets. Although there are different issues considered in the routing phase, the effect of route discovery, as a preliminary action, greatly impacts on the transmission efficiency and reachability. The broadcasting phase of AODV addresses a problem of broadcast storms by a rebroadcasting mechanism to guarantee high reliability of transmissions. The comparison between PTMDA and AODV indicates how effectively PTMDA operates for C2C applications in the CMCN system, reflecting on the following two aspects:

- The efficiency of message delivery;
- The stability of transmissions.

Probabilistic Traffic Message Delivery Algorithm (PTMDA) – This is a new broadcasting protocol specially designed for the CMCN architecture. The overall aim of PTMDA is to best utilize the cooperation of CMCN nodes to generate and manage the exchanges of messages with a high quality of communication performance. It is designed based on conventional broadcasting mechanisms, in conjunction with novel ideas of various probabilistic forwarding mechanisms. On the one hand, these schemes are anticipated to address the problem of broadcast storms in C2C broadcasting, i.e. low reachability or high rate of collision and so on; on the other hand, they help to exploit and maximize the collaborations of CMCN nodes in C2I assistance networks. These are summarized as:

- The most economical and practical situation of the CMCN system;
- The efficiency of message delivery;
- The reliability of data transmission.

5.2.4.2 Performance metrics

The measurements of this project focus on communication performance metrics with respect to efficiency and reliability of communications, such as End-to-End Delay (E2ED), End-to-End Reachability (E2ERCH), Network Reachability (NRCH), Packet Drop (PktD) and Invoked Broadcast (IB).

1) End-to-End Delay (E2ED)

This metric evaluates the mean duration of an initial traffic message from an originator to a certain receiver. The delay covers direct or indirect delivery time for point-to-point performance.

Ideally, an end-to-end delay equals transmission time from a source node to the receiver; however there are more considerations by current wireless communication technologies. As discussed earlier with regard to WAVE standards (Section 2.3.3.3), a real end-to-end delay contains such time slots, plus the delays caused by message size, transmission rate, characteristics of Enhanced Distributed Channel Access (EDCA) and so on. Although this is a consideration related to E2ED, messages delivered observed here are safety packets and message sizes are significantly considered.

Moreover, when the stations are installed and configured by the same hardware and they broadcast the same size of payload under the same scenarios, then a message could reach all covered neighbours (not the destination) at the same time and these nodes may forward the message simultaneously. Probably, a serious packet collision occurs at a busy channel. To overcome the problem above, PTMDA computes a waiting delay. Here, a maximum of 10 CTMs are broadcast over the network by different source and destination pairs.

According to above considerations, the average End-to-End delay ($\overline{T_{E2ED}}$) between a pair of source and destination nodes is computed by Equation 5.1.

$$
\begin{aligned}
&T_{CN} = T_R - T_S \\
&T_{E2ED} = T_{MAC} + T_{WD} + T_{CN} \qquad (5.1) \\
&\overline{T_{E2ED}} = \frac{\sum_{i=1}^{n} T_{E2ED}}{N_{MSG}}
\end{aligned}
$$

Where:

- T_S : is the time when the message is originally broadcast to the network at PHY layer.
- T_R : is the time that a destination node receives it at PHY layer.
- T_{CN} : is the time slot spending on the channel from S to fixed R. It reflects how effective the broadcasting protocols are.
- T_{MAC} : is the overall interval for a message generated from the higher layer of SCH to the lower MAC CCH. This time varies depending on MAC specifications, such as parameters of enhanced distributed channel access (EDCA), and the message size, the transmission rate over the network and so on. In simulations, this is regarded to be the same in all devices.
- T_{WD} : is the waiting delay generated by PTMDA probabilistic priority schemes to reduce the conflicts of simultaneous broadcasting in urban city scenario.
- N_{MSG} : is the number of messages broadcast in the network at the same time, from 1 to 10 for this research.
- i : indicates the number of first time receipts, from the 1 to n (n $\leq$ N_{MSG}).

2) Network End-to-End Delay (NE2ED)

This measurement covers end-to-end delay from an originator to the last destination over the CMCN network. The rule of correspondence between an originator and many receivers implies that the last destination is unpredictable and is different from the pre-set destination. In the CTM, the section of destination's MAC address is recorded as -1. The calculation method for a Network End-to-End Delay (T_{NE2ED}) is shown as Equation 5.2.

$$T_{CH}' = T_R' - T_S$$
$$T_{NE2ED} = T_{MAC} + T_{WD} + T_{CH}' \quad (5.2)$$

Where:

- T_S : is the time when the message is originally broadcast to the network.
- T_R' : is the time that the last node receives the message.
- T_{CH}' : is the individual time interval that the message is broadcast from a sender to the last receiver.

3) End-to-End Reachability (E2ERch)

This metric evaluates the mean percentage of successful message delivery from an originator to its determined destination node. As the number of communication pairs increases, the E2ERch is measured as the number of intended recipients successfully receiving its CTM against the number of original broadcast CTMs from the corresponding sources. The result shows the reliability of transmissions by protocols which, on this point, focus on broadcasting schemes that help improve the success of one-to-one transmissions. In this project, $\overline{R_{E2ERch}}$ is computed as shown in Equation 5.3.

$$\overline{R_{E2ERch}} = \frac{\sum_{i=1}^{n} N_{RECV}}{N_{MSG}} \times 100\% \quad (5.3)$$

Where:

- N_{RECV} : is the number of successful received messages.

- N_{MSG}: is the number of messages broadcast in the network at the same time. It sets from 1 to 10.
- i : indicates the number of actual receivers, from the 1 to n (n N_{MSG}).

4) Network Reachability (NRch)

This metric evaluates the ratio of nodes preliminarily receiving CTM versus the total number of nodes over the CMCN network. Unlike E2ERch, this metric evaluates one-to-many communications and there are not any appointed receivers. The mathematical definition is shown as Equation 5.4.

$$R_{NRch} = \frac{N_{RECV}'}{N_{TOTAL}} \times 100\% \tag{5.4}$$

Where:

- N_{RECV}': is the number of nodes first receiving a CTM including the same source and broadcast ID.
- N_{TOTAL} : is the total number of network nodes, also known as network density.

5) Invoked Broadcasts (IB)

This measurement focuses on the total number of invoked broadcasts during the simulation time. If there is a case that the message transmission shows a large value of NE2ED and meanwhile, the value of NRch displays very low, then a possible reason is that the network suffers heavy redundant broadcasts. To prove the assumption, the results of IB are very helpful. This metric is evaluated based on trace files only. As once the file is obtained from the simulation, the number of IB is easy to be counted. By setting different threshold values in PTMDA operations, the level of invoked broadcasts is observed as well.

6) Packet Drops (PktD)

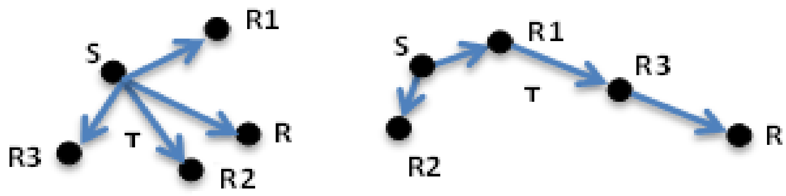
As analyzed in [168], the possible reasons of packet drops could be categorized in two groups. One is related to the signal strength. For example, the reason PND indicates that if the power reception is low enough (e.g. < CSThreshold) then the packet drops. On the other hand, the signal strength is high enough, but the channel cannot be properly used because of simultaneous transmissions or it is busy with transmitting and so on. The metric PktD here focuses on the second part. Therefore, high packet drops imply that the packets are frequently forwarded at the same time. This metric also supports investigating whether the long packet size causes serious drops because it may occupy wireless channels with a long delay.

5.3 Experimental Analysis: C2C Environment

C2C communications have a dominant role in the CMCN and vehicles actively detect and distribute what is seen and heard through wireless direct links. By comparing with well-known probabilistic Flooding, communication performance between CMCN nodes using PTMDA algorithm are observed and evaluated in terms of the effect of network density and message size. In order to enhance the cogency of experimental results, the experiments here set the following preconditions:

- **Uniform hardware and software configurations** – All CMCN nodes, i.e. normal mobile nodes, I-Route mobile nodes and static nodes, have same hardware and software configurations so that they are of similar communication capability.
- **Fully ad hoc static nodes**– This is a kind of nodes without any gateway functions and existing in C2C environments. That is to say, all static nodes are only linked via wireless radios as long as they are both in communication range.

- **Identical topology** – To ensure fairness, simulation tests are processed based on same topologies for each group of comparisons. For example, Fig. 5.8a and Fig. 5.8b display two possible cases of C2C applications. Comparing these two topological environments, the NE2ED of a case in Fig. 5.8a is much smaller than that in Fig. 5.8b (T<3T) but the NRch of both examples are the same. If two broadcast protocols act on different topological scenarios as follows, the result does not show the fact of comparisons.



a) One-hop operation   b) Multi-hop operation

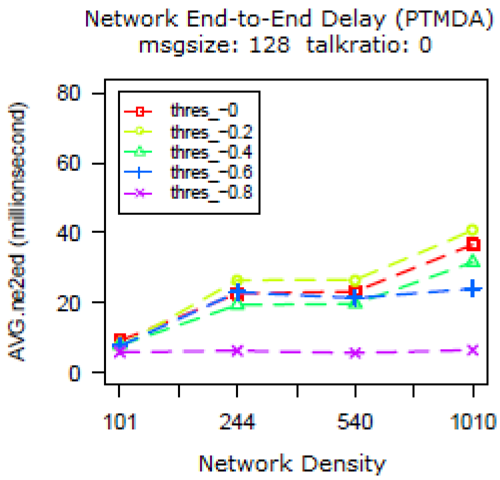
Fig. 5. 8 Two examples of network topologies

5.3.1 The effect of network density

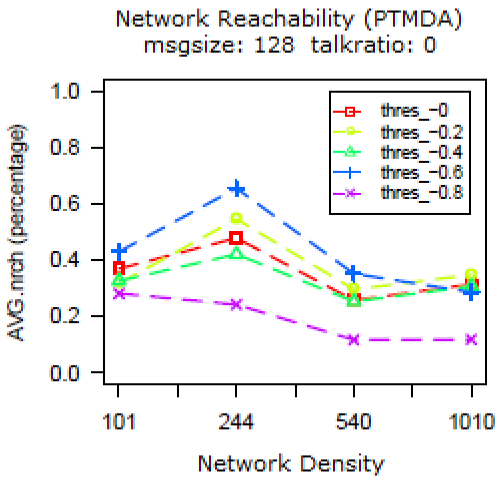
As in CMCN, communications between vehicles are achieved using multi-hop forwarding which means the message is delivered in car-to-car manner without any centralized controls. In the condition, network density may impact transmission connectivity. In theory, a dense network is likely to keep higher number of connections than a sparse network so C2C communications via broadcasting methods can be assumed to cover wider area with smooth delivery. On the other hand, according to literature and previous observations, broadcasting methods are easy to produce broadcast storms because of redundant transmissions and simultaneous forwarding. The problem is especially seen in dense networks. Indeed, whether the problem impact on data disseminations between CMCN nodes depends on the use of broadcasting mechanism. PTMDA, proposed for CMCN model, makes efforts to address the problem by adopting probabilistic priority schemes in which the invoked broadcasts are limited by a threshold value and these broadcasts have different forwarding time by Equation 4.1. As discussed in Chapter 4, the threshold value should reflect an optimal status of message delivery in

CMCN and this actually requires extensive tests according to different urban traffic scenarios. Generally, a threshold value of 0 (thres_=0) provides nodes more opportunities to broadcast the message but it may lead to a large number of redundant broadcasts. Whereas, thres_=0.8 can avoid such problem but it may risk lowering the reachability. For example, if a transmission occurs in an area without I-Routes, buses, or bus stops, according to the feature of PTMDA, the packet may experience long delay or even be dropped.

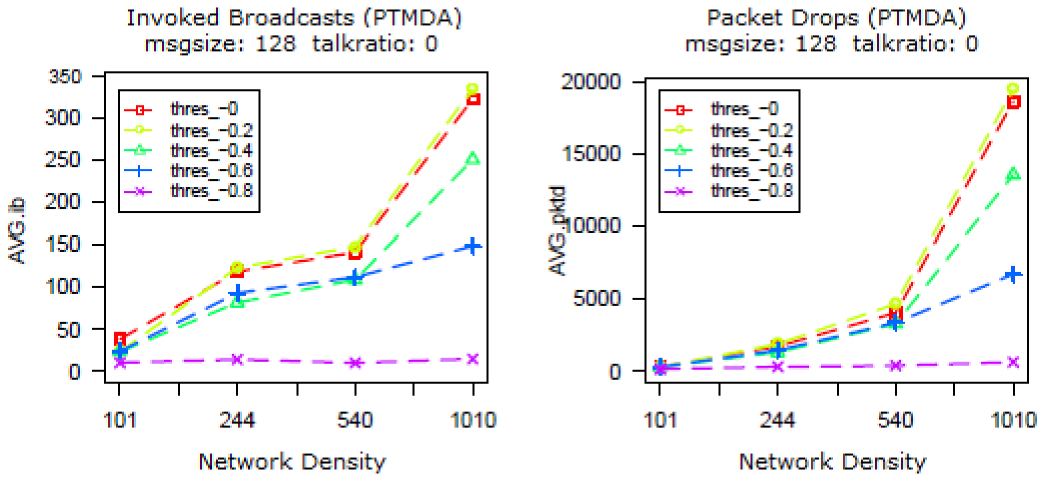
According to Fig. 5.9, while network density increases, the overall end-to-end delays (NE2ED) using PTMDA (Fig. 5.9a) present an increasing trend but a special case occurs between a moderate medium network (244 nodes) and a medium network (540 nodes) that those almost reach at zero growth or slightly decrease. Fig. 5.9b illustrates that the reachability (NRch) of messages firstly increases from a sparse network to a moderate network, but it drops until the number of network nodes increases to be 540 and then rises slightly (thres_=0, 0.2 and 0.4) or stays stable (thres_=0.6). At the same time, the invoked broadcasts (IB) have a similar shape of curves (Fig. 5.9c) as NE2ED and packet drops (PktD) rise in all threshold cases (Fig 5.9d). In both IB and PktD lines, a sharp upward trend is seen since the network density is up to 540. Note that the impacts of density are not significant for PTMDA with a threshold value 0.8 and it presents fairly smaller delays, lower reachability, less invoked broadcasts and very fewer packet drops in all density networks.



a) network end-to-end delay



b) newtork reachability



c) invoked broadcasts d) packet drops

Fig. 5. 9 The effect of network density in PTMDA with different threshold values[1]

On the basis of graphical analysis, the results tell that network density does impact network connectivity so that when the number of nodes increases from 101 to 244, the reachability of messages becomes higher and at the same time while the drops are not significant. However, an abnormal situation is found in the segment that the number of network nodes increases from 244 to 540. In this part, the NRchs are anticipated to go up owing to the doubled amount of network nodes; instead, they drop sharply, i.e. Fig. 5.9b. Two possible reasons can account for this result. One is that serious packet collisions or congestions occur during the communications; or the physical layout of the network such as node distributions is not suitable for the observations here.

[1] This group of figures just shows an example where the message size is 128 bytes and the talking static ratio is 0% (fully C2C). Figures are shown in *Appendix A-1*.

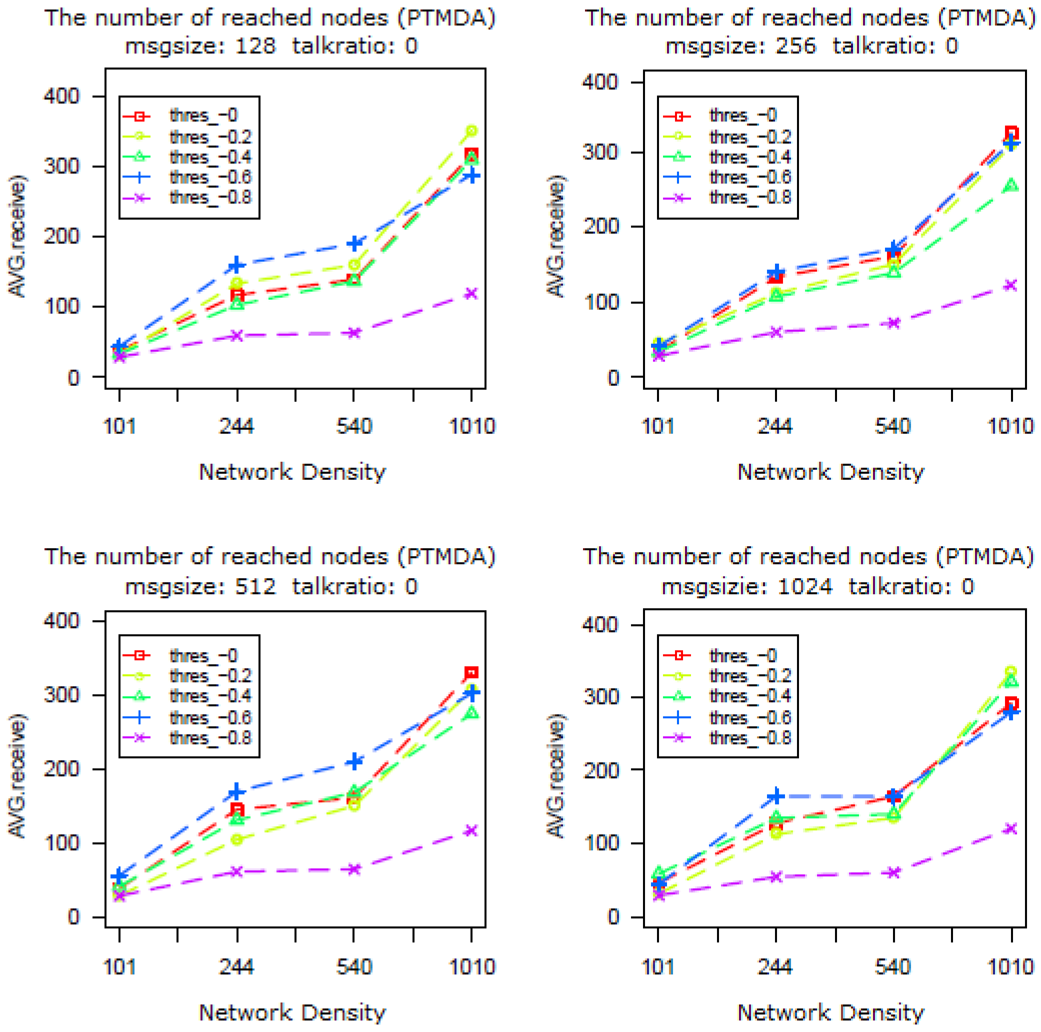


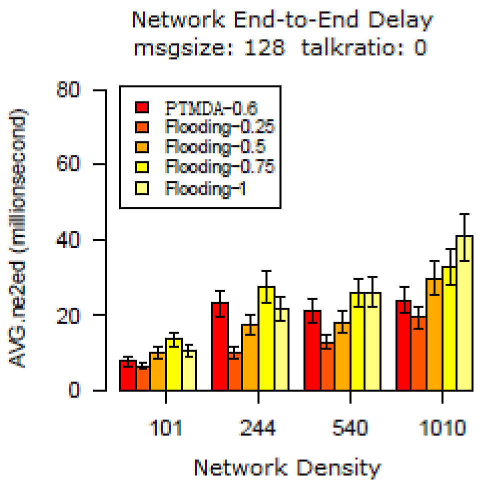
Fig. 5. 10 The comparisons of message receptions in C2C networks

If a decreased value of NRch corresponds to a high level of invoked broadcasts or packet drops, then packet collisions probably occur. Focusing on all threshold values of PTMDA in Fig. 5.9b, c and d, the NRchs are on average 50% (244-node) and 30% (540-node); IBs are about 105 (244-node) and 125 (540-node), occupying 43% and 23% or so over the network. Also, the number of packet drops is not significantly different from that in a moderate medium network. The curves show that PTMDA does not suffer abnormal shocks by increasing network density. Moreover, Equation 5.4 shows that the NRch is expressed as the number of receiving nodes against the total number of network nodes. While the denominator factor becomes larger, the NRch is displayed as an increment only when the amount of receiving nodes significantly increases and, at the same time, the increment speed is similar to that of density growth. Seen in Fig. 5.10, the average number of nodes receiving the message actually increases with the growth of network density. However, the increasing level, particularly in the medium network, is not significant. Hence, a conclusion can be given that the reduction of NRch is not caused by serious packet collisions or congestions. As a result, the physical environment, such as uneven distribution of nodes and lane layouts etc., causes the graphic trend.

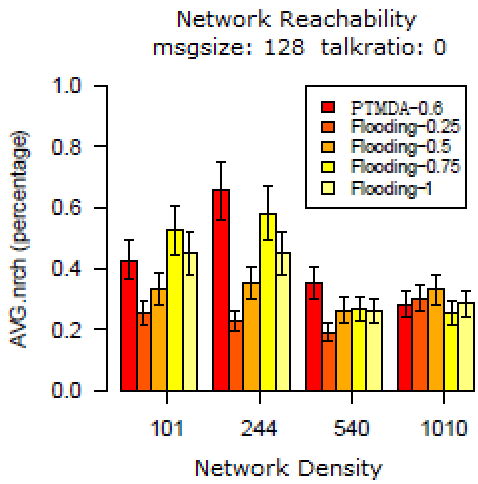
The above evaluations are based on a macro-analysis basis which concentrates on the overall performance of all threshold values of PTMDA. Next, micro-analysis makes efforts to determine an optimum threshold value of PTMDA for C2C communications in target urban traffic scenarios. In theory, a higher NRch with smaller NE2ED and less IB, under the same conditions, presents as a better performance between protocols. In Fig. 5.9b, PTMDA with a threshold value of 0.6 shows positive results in terms of NRchs in most cases. In Appendix A-1b, when the message size is fixed, the NRchs by PTMDA (thres_=0.6) retains higher values while the number of network nodes increases. The highest value is shown in 244-node networks, approximately 65% (128-byte), 58% (256-byte), 70% (512-byte) and 66% (1024-byte). At the same time, the NE2EDs (22ms, 24ms, 58ms, 99ms separately), IBs (about 80 for all message sizes) and PktDs (less than 2500 for all message sizes) using PTMDA with such threshold value have lower values compared to others. In this case, PTMDA (thres_=0.6) is regarded as an optimum case fort the probabilistic priority scheme so that simultaneous forwarding and redundant broadcasts are well balanced. With respect to the optimum threshold value of PTMDA, the communication performance is compared to probabilistic Flooding (Fig. 5.11) to further identify the effectiveness of PTMDA in the CMCN system.

Seen in Fig. 5.11b, when network density increases from 244 to 540, the trend of NRch by all probabilistic Flooding declines. The phenomenon reconfirms that the reduction of NRchs is caused by physical environment rather than broadcasting storms. When the message size is 128 bytes, PTMDA in moderate medium and medium networks performs better, showing as higher NRchs (approx. 10% more) and smaller NE2EDs (approx. 8 ms less) than the best case of probabilistic Flooding. Particularly, in 244-node networks with 1024-byte message transmissions (Appendix A-2b), the difference of NRch becomes the largest, i.e. 70% by PTMDA, 50% by blind Flooding, 45% by 0.75-prob Flooding, 35% by 0.5-prob Flooding and 5% by 0.25-prob Flooding while relatively smaller NE2ED, IB and PktD are given by PTMDA (thres_=0.6). Obviously, probabilistic Flooding with a probability of 0.75 and blind flooding always provide greater values for NE2EDs, IBs and PktDs than other protocols when the network density and message size increase in the network.

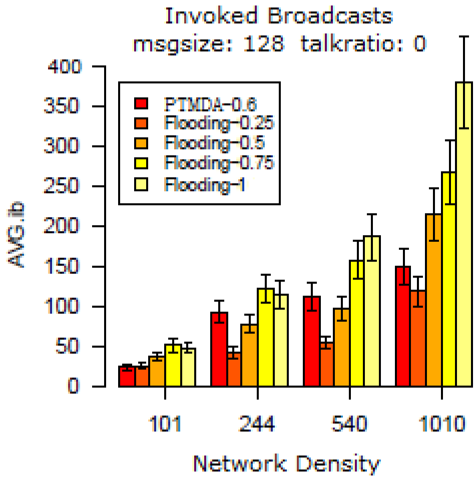
According to the above analysis, PTMDA with the threshold value 0.6 exhibits good performance in C2C communications leading to relatively efficient and wide-coverage data disseminations. However, PTMDA is not suitable for all density of network. For example, Flooding with a probability 0.25 outperforms others in the dense network, having fewer NE2EDs, IBs and PktDs than those of PTMDA when they have very similar reachability results.



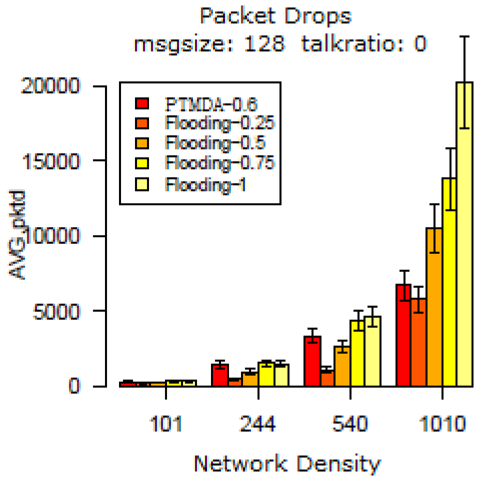
a) network end-to-end delay



b) network reachability



c) invoked broadcasts



d) packet drops

Fig. 5. 11 The effect of network density in PTMDA and Probabilistic-Flooding[2]

5.3.2 The effect of message size

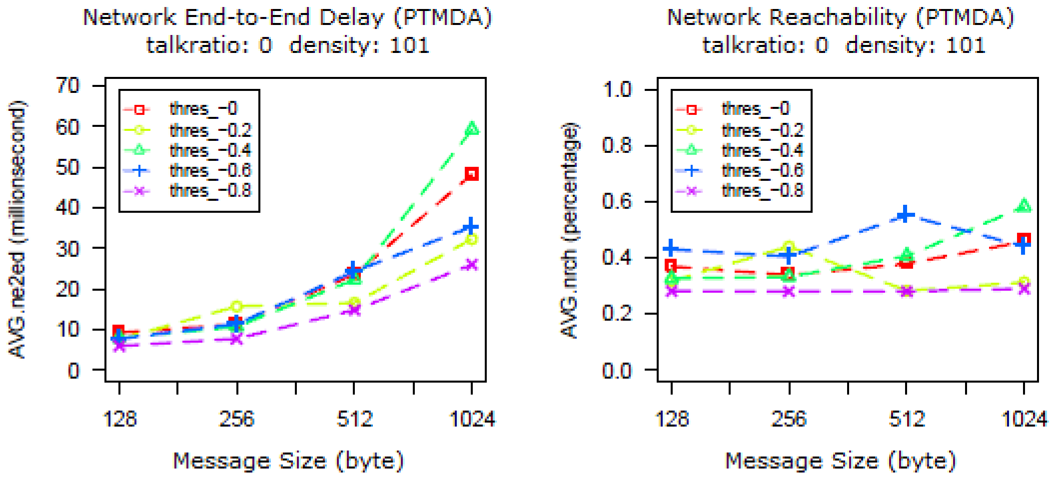
The investigation of the effect of data volume in C2C communications is essential and vital because the demands of increased traffic information become ever higher. In terms of CMCN message types, usually, a warning-based (WB) message with simple and urgent information needs to be delivered quickly so that the size of message cannot be too large; whereas a sharing-base (SB) message emphasizes the richness of contents and the involved data can be of greater size. According to WAVE specifications [163], the maximum packet size transmitted in C2C communications is set to be 1400 bytes based on the WAVE MAC and PHY specifications. Experiments in this research investigate the effect of message sizes, ranging from 128 bytes to 1024 bytes so that the proper size of C2C WB and SB can be deduced. Theoretically, a large message size transmitted in the network is likely to cause packet congestion, resulting in raising NE2ED, decreasing NRch and growing PktD.

Appendix A-3 shows the NE2ED, NRch, IB and PktD provided by PTMDA with different threshold probabilistic values in cases of different sizes of message transmissions, maintaining the network density as fixed. In this part, following figures

[2] This group of figures just shows an example where the message size is 128 bytes and the talking static ratio is 0% (fully C2C). Figures with other message sizes are shown in *Appendix A-2*.

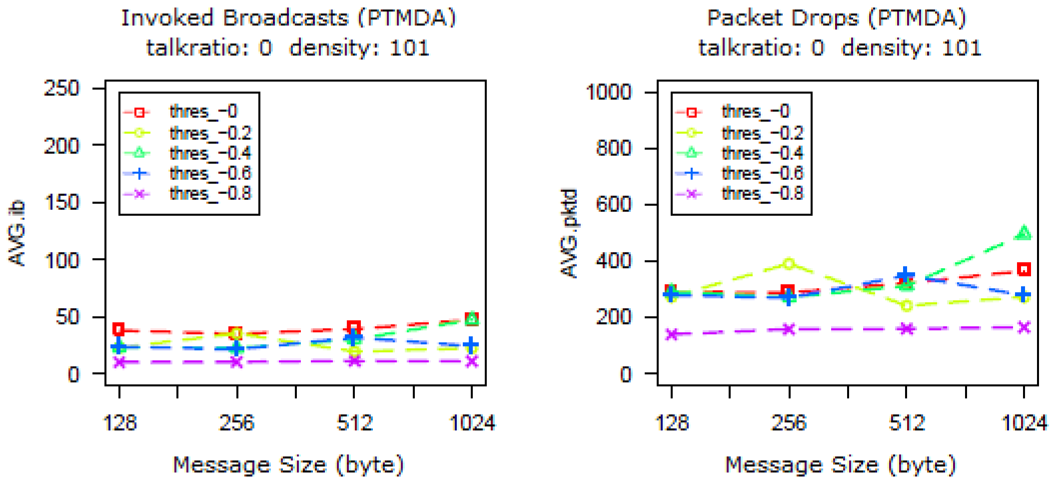
are focused on. Generally, the trend of NE2EDs in all networks (Fig. 5.12a) goes up when message size increases from 128 bytes to 1024 bytes. A rapid increase starts from 256-byte transmissions. On the other hand, the increase of message size does not significantly influence network communications in terms of NRch, IB and PktD, although there are slight changes at different threshold values of PTMDA. Therefore, NE2ED is regarded as the primary basis to determine the optimal size of WB and SB messages.

The results indicate that a proposed CMCN network could support large sizes of message transmission, e.g. 1024 bytes. Note that the difference of average delays between 128-byte transmissions and 1024-byte transmissions varies depending upon the network density; it is approx. 52 ms (101-node), 81 ms (244-node), 98 ms (540-node) and 110 (1010 node). Additionally, the difference of NE2ED between 128-byte and 256-byte messages is much smaller: no more than 13 ms. According to [169], the allowable latency of emergency events based on WAVE specifications is about 100 ms. In such basis, a maximum tolerated size of WB messages can be 512 bytes by using PTMDA (no more than 100 ms) and SB messages can have 1024 bytes for contents.



a) network end-to-end delay

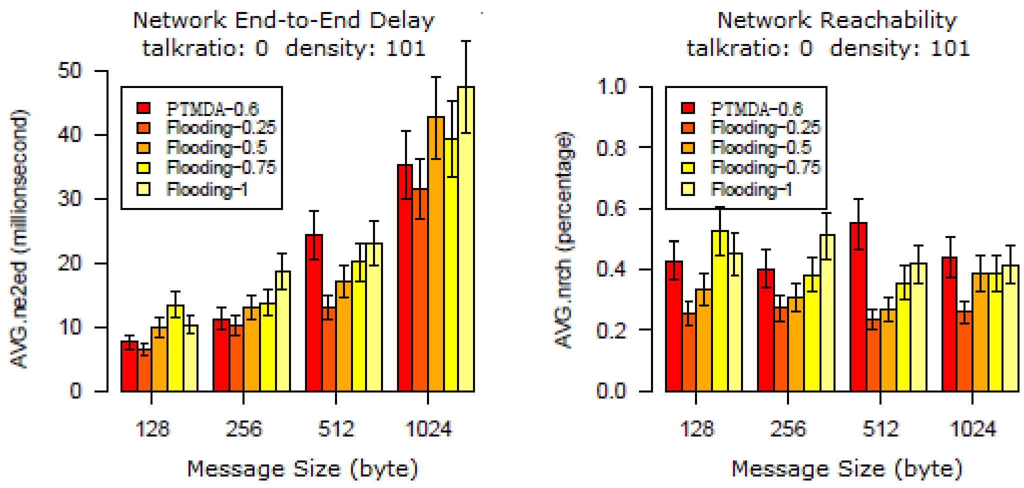
b) newtork reachability



c) invokde broadcasts d) packet drops

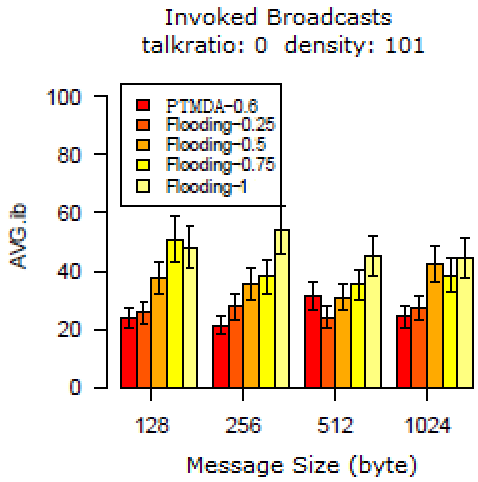
Fig. 5. 12 The effect of message size in PTMDA with different threshold values[3]

Balancing all metrics, the optimum threshold value 0.6 also performs better than others under different message sizes. Generally, it outperforms when the message size is 512 bytes, regardless of network density. The following section compares the optimum case of PTMDA with probabilistic flooding in various densities of fully C2C communication networks (Appendix A-4) to further investigate the effect of message size. The following graphs are taken from Appendix A-4 as the example figures (Fig. 5.13).

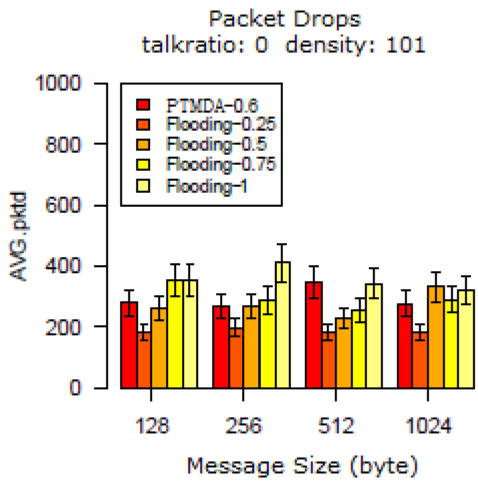


a) network end-to-end delay b) network reachability

[3] This group of figures just shows an example where the number of nodes is 101 and the talking static ratio is 0% (fully C2C). Figures with other densities are shown in *Appendix A-3*.



c) invoked broadcasts



d) packet drops

Fig. 5. 13 The effect of message size in PTMDA (0.6) and probabilistic Flooding[4]

The trends of NE2ED, NRch, IB and PktD using probabilistic Flooding are similar to those under PTMDA, and thus a macro-conclusion can be drawn that the protocols with proper probability value or threshold values permit a large size of message based on the current data rate and configurations of CMCN network layers. Note that increasing message size impacts less on PTMDA operations than that of probabilistic Flooding, except for sizes up to 512 bytes. An example in Fig. 5.13b shows that when 512 bytes of messages are transmitted over the network, the NRch under PTMDA is nearly 18% higher than Flooding with a probability value of 1 which is regarded as the best case in terms of broadcasting coverage, while the NE2ED and PktD by PTMDA are similar (Fig. 5.13a, c, d). Obviously, the number of invoked broadcasts by PTMDA is reduced nearly by half compared with blind Flooding. Likewise, PTMDA provides relatively high NRch and low values of NE2ED, IB and PktD in the moderate medium and medium networks in comparison with probabilistic Flooding (Appendix A-4). Nevertheless, an exceptional case is found in the dense network where the effect of message size are more positive for probabilistic Flooding with the probability value 0.25, as evinced by equal NRch, smaller NE2ED, less IB and PktD.

[4] This group of figures just shows an example where the number of nodes is 101 and the talking static ratio is 0% (fully C2C). Figures with other densities are shown in *Appendix A-4*.

5.3.3 Result summary

In a C2C communication environment, PTMDA with the threshold value 0.6 presents better performance balancing all metric results. Positively, PTMDA provides relatively efficient and reliable message delivery showing as high NRchs, small NE2EDs, controlled IBs and PktDs at the same time. Compared with probabilistic Flooding, PTMDA-0.6 outperforms Flooding in most cases of network communications when considering realistic network density and message size. With respect to network density, an abnormal situation is noticed in a medium network where the NRchs for all protocols are sharply reduced. After investigating, it can be concluded that the physical environment causes negative influences. In Scenario II, a real city environment is considered, including street shapes, vehicle mobility patterns and so on. PTMDA with an optimal threshold value 0.6 is shown to be able to support message sizes ranging from 128 bytes to 1024 bytes. Also, PTMDA performs better than probabilistic Flooding at larger sizes of message transmissions (e.g. 512 and 1024 bytes) as less NE2ED, higher or equal NRch, less invoked broadcasts and less PktD are observed.

From the results, a doubt that dense networks provide better transmission connections than sparse networks has been proved as a kernel of truth; however, at the same time, it is prone to have broadcast storms in dense networks with negative effects to performance. For the latter, PTMDA with a threshold value of 0.6 in C2C communications performs well in considering the reduction of redundant broadcasts and simultaneous forwarding using probabilistic priority schemes in comparison with probabilistic Flooding. However, it is noted that the values of reachability in such C2C environments are still not satisfactory with a maximum 70% (244-node network) and a minimum of 25% achieved (1010-node network). Besides, the delay of transmissions is high at 1024-byte transmission in the dense network, at around 100 ms. Indeed, in current fully C2C communications, the features of CMCN architecture and the cooperation of all nodes are not completely exploited. Consequently, a special type of nodes in CMCN - gateway static nodes – is considered. These may contribute to improvements in reachability by enabling their gateway functions and are strongly linked to I-Routes which are designed to increase the efficiency of transmissions.

The following experiments emphasize C2I communications to investigate optimum communication performance achieved by PTMDA with the aid of a number of gateway static nodes.

5.4 Experimental Analysis: C2I Environment

In the city centre scenario (Fig. 5.3), the infrastructure is composed of bus stops, of which the layout is based on the real transport map of Nottingham city (Fig. 5.3b). The total number of bus stops is set to be 51. Among CMCN nodes, the static nodes are differentiated from the other two types by their gateway function. So, bus stops in CMCN are not only traditional ad hoc nodes for wireless connections with other mobile nodes but also gateways which allow wired links with other types of networks. In this thesis, communications via gateways are termed ‘static talking’. In this way, mobile nodes can access the Internet through bus stops, and enable the traffic centre to obtain timely information via them.

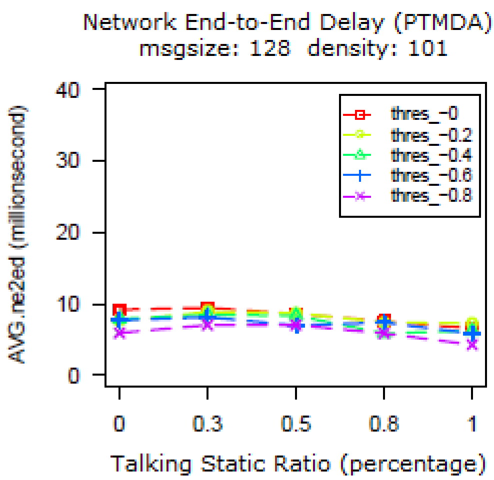
On the basis of the analysis in Section 5.3, the strengths of PTMDA are expected to be further enhanced by adding the aid of infrastructure nodes. Two points are relevant in the section: the effect of infrastructure nodes and the effect of I-Routes. In the following analysis, the gateway nodes are also called talking static nodes and the talking static ratio is defined as the number of gateway bus stops over the total number of bus stops.

5.4.1 The effect of infrastructure-node

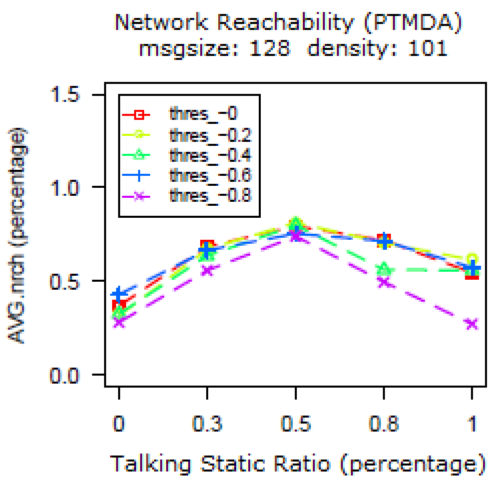
Appendix A-5 shows the complete results of the comparisons performed with different threshold values of PTMDA in C2I communication environments. A static ratio of 0 means full C2C communications and all CMCN nodes operating in ad hoc manner only. While the gateway functions are active in the network, the talking static ratio increases from 30% to 100%. Again, figures Fig. 5.14 here are characteristic examples taken from Appendix A-5.

Generally, NE2EDs of communications are reduced as talking static nodes are introduced to the network (Appendix A-5a). These changes become obvious when the network density and the message size increase. The maximum difference between C2C and C2I communications is up to 40 ms in a case where the amount of network nodes is 244 and the message size is 1024 bytes (Appendix A-5b). In contrast, the NRchs of all cases from fully C2C to C2I communications are shown to increase (Fig. 5.14b).

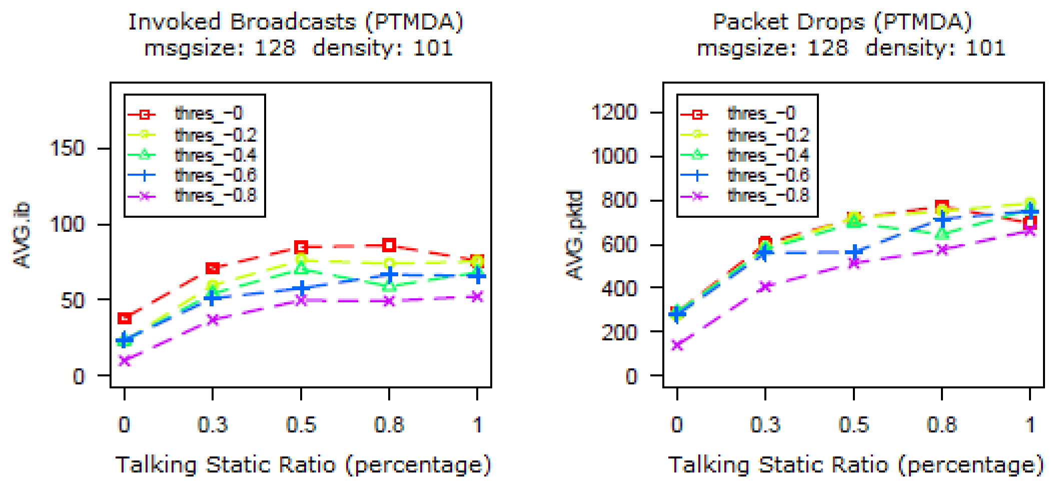
As an example, the figures below (Fig. 5.14) show the network density to be 101 and message size set to 128. An interesting condition is obviously shown in this case (Fig. 5.14b) so that NRchs emerge as almost fundamental symmetrical curves. The peak point is at 0.5 where 50% of bus stops start their gateway functions. On the left side of this demarcation point, the cooperation of all CMCN nodes is improved by PTMDA, as evinced by the reducing NE2EDs and increasing NRchs. The maximum NRch (80%) based on all threshold values is observed in the network with 50% talking static ratio, increasing up to 40% more than the values in a fully C2C environment in average. Particularly, PTMDA with a threshold value of 0.8 in the C2C environment gives the poorest NRchs in C2C communications with a nearly fourfold increase. On the other hand, a sharp downtrend is seen for NRchs when there are more than 50% talking static nodes in the network. This situation is possibly due to packet collisions and to verify this, the PktD metric is employed.



a) network end-to-end delay



b) network reachability



c) invoked broadcasts d) packet drops

Fig. 5. 14 The effect of Infrastructure-node in PTMDA with different threshold values[5]

In Fig. 5.14d, after a peak point 0.5 in the talking static ratio, packet drops keep increasing, up to 800 while all bus stops start their gateway functions. A question is asked about where these drops are coming from. One possibility lies in the increase of IBs and the other is probably due to the position of bus stops. As seen in Fig. 5.14c, invoked broadcasts by almost PTMDA threshold values start remaining stable when the talking static ratio reaches 0.5. Hence, the first assumption related to increasing IB can be rejected. The following figure provides clues to the answer. In this example, a large number of redundant broadcasts are produced between bus stops (red dots) because they are too close to each other. Therefore, the position of bus stops with gateway function is a contributing factor to broadcast storms. Also, in the case below (Fig. 5.15), nodes in the area are mostly a fixed number of static nodes (red) and a few mobile nodes (black). Based on PTMDA algorithm, forwarding only occurs at nodes that match with the value of the threshold set. Suppose the network gathers very few mobile nodes. If all nodes are impacted by broadcast storms, then it is likely to miss receiving packet. That is to say, a certain number of possible nodes have been already excluded from the queue of forwarding operation

[5] This group of figures just shows an example where the number of nodes is 101 and the talking static ratio is 0% (fully C2C). Figures with other densities are shown in *Appendix A-5*.

because of broadcast storms and finally, communication links are probably disconnected.

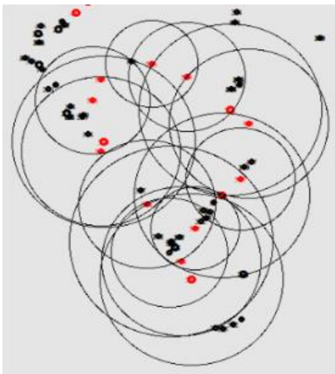


Fig. 5. 15 An example case of negative impacts in CMCN
due to the layout of bus stops

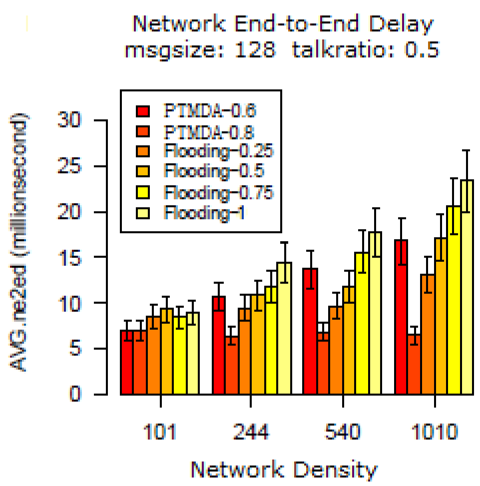
As shown in Appendix A-5b, when network density increases, the symmetrical curves of NRchs become flat under PTMDA with a threshold value less than 0.8. On this point, the occupancy of infrastructure nodes which are generated based on the real bus stop map needs to be considered. Originally, the higher occupancy rate of these nodes may contribute in an obvious manner, vice versa. For example, 51 bus stops take 50% in a 101-node network but only 5% in a 1010-node network. Thus, the collisions caused by bus stops should be more serious in the former case. Intuitively, 1010-node network has more mobile nodes within or beyond the area that bus stops are positioned, and as a result, there are more conforming nodes injected to the network to prolong the transmissions and improve the NRch metric.

For the observed probabilistic protocols, the increase of NRch is from a best case approximately 52% (Appendix-2b, prob-0.75, msgsize=128, density=101) to 77% (Fig. 5.16b, prob-0.75, msgsize=128, density=101). Also, the best case of PTMDA with the threshold value of 0.6 shows even greater increase at this point from 42% (Appendix-2b, msgsize=128, density=101) to 78% (Fig. 5.16b, msgsize=128, density=101) overall. In particular, PTMDA with a threshold of 0.8 increases more than 50% in the same case. It is a certainty that the NRchs values are enhanced to a large degree owing to the imports of gateway nodes, in conjunction with reduced NE2EDs, increasing IBs (Fig. 5.14c) and PktDs (Fig. 5.14d).

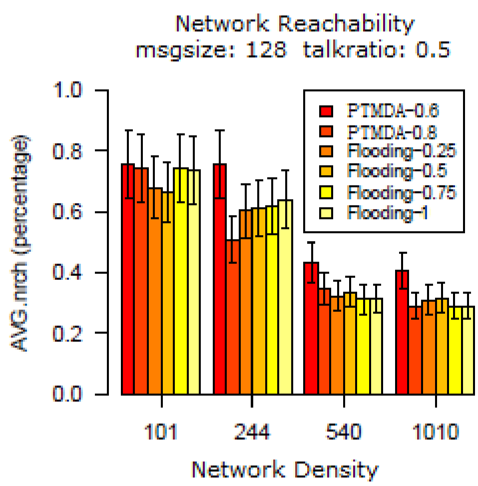
Regardless of the physical impact factors, an optimum condition of C2I communications by the PTMDA protocols is when the gateway nodes are set as 50% of bus stops, i.e. 25 out of 51 in this particular urban area. In this case, the appropriate threshold value of PTMDA is still 0.6 which provides relatively high NRchs while other metrics are observed to be sufficiently good. Note that a most special case in C2I communications is PTMDA with a threshold value of 0.8. This threshold actually sets a high standard for CMCN nodes so that a very small group of nodes is able to meet the requirements in these scenarios. The best demonstration is found in Fig. 5.14b in that it gives a good NRch at 0.5-C2I scenario (70% or so) as well as good values of other metrics. Although the performance by PTMDA with thres_= 0.8 show poorer results in other C2I scenarios, especially NRch, it is still regarded to be of potential value for particular situations, such as cases where there are mostly buses in the network or substantial mobility on I-Routes.

5.4.2 The effect of I-Routes

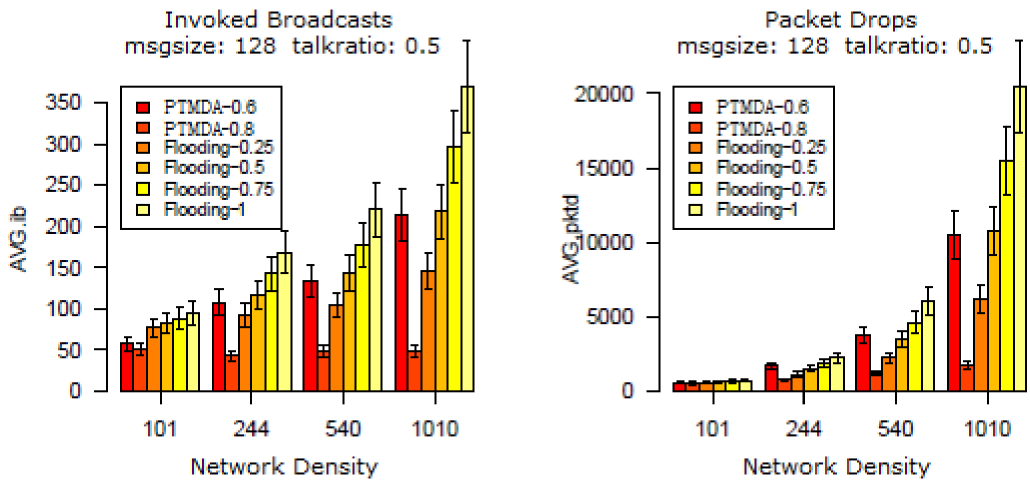
I-Routes are designed in the CMCN system to improve the transmission efficiency through the collaborations of network nodes. The basic idea is that nodes on I-Routes have higher priority than on ordinary roads. In target scenarios, these routes are pre-configured as bus lanes. Actually, they could be identified and shared by buses via C2C communication approaches. Appendix A-6 displays all comparisons between PTMDA (thres_=0.6, 0.8) and probabilistic Flooding (prob=0.25, 0.5, 0.75, 1).



a) network end-to-end delay



b) network reachability



c) invoked broadcasts d) packet drops

Fig. 5. 16 The effect of I-Routes in PTMDA and probabilistic Flooding in 50%-C2I[6]

As message sizes do not show significant differences in the overall trend, the evaluation focuses on an example when the message size is 128 (Fig. 5.16). On the basis of the NRchs under testing protocols, the relation of I-Routes and transmission efficiency is mainly evaluated via the value of NE2ED. PTMDA (thres_=0.6) shows the highest NRch values than other protocols but the NE2EDs results are only average in above example figures. PTMDA (thres_=0.6) does not reveal an increased efficiency with I-Routes. On the contrary, PTMDA with thres_ of 0.8 is more conclusive in proving the positive effect of I-Routes according to experimental outcomes.

In Fig. 5.16a, the NE2EDs of PTMDA with the threshold value of 0.8 remains the lowest (approx. 7 ms) while the NRch value is almost the same as that of probabilistic Flooding. As all protocols are operated in the same physical environments with the same propagation model for transmissions, same mobility patterns of nodes, same broadcasting sources, and same percentage of infrastructure nodes available (50%), therefore, the probable difference of NE2ED under similar NRch results is the utilization of I-Routes which actually is a key feature of PTMDA. The fundamental idea is that nodes on I-Route are forced to forward the message faster than other nodes because these routes are next to

[6] This group of figures just shows an example where message size is 128 and the talking static ratio is 50%. Figures with other densities are shown in *Appendix A-6*.

gateway nodes. While the reachability results are closer, PTMDA (thres_= 0.8) displays consistent smaller values of NE2ED from 7 ms to 25 ms than that of the best case in Flooding (Flooding-0.25) from 8 ms to 50 ms varying by different message sizes. Obviously, the inclusion of I-Routes in PTMDA is a promising idea to improve the efficiency of transmissions.

5.4.3 Result summary

To summarize, PTMDA performs better in a 50%-C2I environment where CMCN nodes cooperate with each other. The main contributions here are the integration of gateway static nodes and the inclusion of I-Routes.

C2I approaches are recommended to support C2C communications as long as the number of gateway static nodes is tweaked for target scenarios. From a financial point of view, the fewer infrastructure nodes used in the network, the less the expenses spent on construction, maintenance and repair. On the other hand, the laboratory results show that the optimum utilization of gateway infrastructure nodes is based on a boundary value. Within their boundary limit, PTMDA addresses the problem of broadcast storms well. On the other hand, PTMDA provides high priority to CMCN gateway nodes and this, at the same time, causes redundant broadcasts when they are too close to each other, as Fig. in 5.15. In this thesis, 50% is shown as a suitable boundary. However, this could be different when the scenario parameters are changed.

Another prospect explored in the thesis is the inclusion of I-Routes. As they are shaped as bus lanes and linked to bus stops, collaborative communications between mobile nodes, semi-mobile nodes and static nodes can be achieved. In fact, the effect of I-Routes has been investigated in experiments by comparing it with an advanced broadcasting protocol which intends to solve the problem of broadcast storms. Because PTMDA defines the forwarding on I-Routes to be of top priority, messages are given a great possibility of arriving first at gateway bus stops. This helps to explain why PTMDA provides faster transmissions than probabilistic Flooding when the reachability is same.

5.5 Experimental Analysis: Point-to-Point Delivery

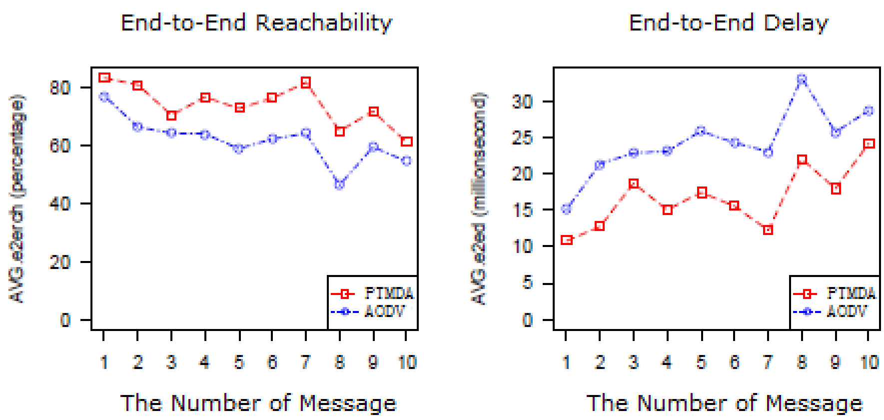
One of the targets for broadcasting protocols is to implement route discovery in reactive routing protocols. Motivated to study the potential of efficient and reliable route discovery in C2C communications by PTMDA, an optimum case of PTMDA (thres_=0.6) is compared with Ad Hoc On-Demand Distance Vector Routing (AODV) [107], which is a well-known broadcast-based protocol for C2C communications of MANETs. As mentioned in the literature review of Chapter 2, AODV consists of route discovery and route management. In the preliminary route discovery phase, AODV operates broadcasting methods maintaining reliability of transmissions via schemes of link repair and broadcasting retries. On this point, AODV may tolerate larger broadcasting delays to obtain good reliability results. AODV is greatly affected by broadcast storm and if simultaneous transmissions occur in the network, there is substantial increase in packet loss. Furthermore, even if AODV is still popular in MANETs, the mechanism may not adapt for dense networks or large packet sizes. In view of above points, three questions need to be resolved:

- Whether PTMDA overcomes AODV by providing higher reliability and smaller delays of end-to-end communications;
- Whether PTMDA addresses broadcast storms even when increased number of messages are forwarded over the network;
- Whether PTMDA provides better mechanism to adapt for different density of networks and different sizes of messages.

In theory, the NRch metric can reflect transmission reliability because wider coverage of messages usually creates high rates of successful delivery to a certain node. However, it does not prove the reliability of end-to-end delivery. A case shown in Fig. 5.8a illustrates that a high NRch does not always imply a wide coverage of message delivery. Therefore, this section considers End-to-End Reachability (E2ERch) and End-to-End Delay (E2ED) focusing on point-to-point C2C communications to address the previous questions on PTMDA and AODV performance.

5.5.1 Analysis based on Scenario I

This section concentrates on a very sparse network with only 65 mobile vehicles (Fig. 5.2). In the experiments, transmission data is set to be 512 bytes. The independent variable is the number of messages, ranging from 1 to 10. With the increasing amount of messages, average E2EDs and E2ERchs reflect the effectiveness of PTMDA in tackling broadcast storms and transmission efficiency.



a) end-to-end reachability b) end-to-end delay

Fig. 5. 17 The effect of message amount in PTMDA and AODV in Scenario I

According to Fig. 5.17a, both E2ERchs decline with the increasing number of messages broadcasting at the same time. Compared with the AODV, the E2ERch under PTMDA stays at a higher level, approximately between 62% and 81%, even though the number of messages rises. By Equation 5.3, E2ERch depends on the number of received messages and the number of messages in the network. Increasing the number of simultaneous message deliveries risks packet collisions in the network. This is a major reason causing the reduction of the amount of received messages. AODV utilizes a certain number of rebroadcasts in route discovery and route maintenance strategies to keep high E2ERch but it pays the price in longer delays of transmissions (Fig. 5.17b). In contrast, PTMDA with probabilistic priority schemes outperforms AODV with regard to E2ERch and also exhibits E2ED that at 10 ms less time. In terms of high delivery ratio and acceptable E2ED, PTMDA is not suitable for route discovery.

Indeed, according to Equation 5.1, E2ED is organized by the time in MAC layer and the time slots between source and receiver. Here, it is assumed that all devices are the same in terms of hardware configuration and broadcasting capability. Therefore, the simulation E2ED actually means the channel time of S-R transmission, namely T_{CN} and T_{WD}. In PTMDA, the channel time reflects the environment conditions such as noise, collisions and so on and waiting delay is related to the mobility patterns of nodes, the configurations of I-Routes etc. However, in AODV, the channel time includes broadcasting time of route delivery plus the time spent on the routing phase. The differences between the two may cause discrepancies. Nevertheless, this part, as mentioned before, focuses on the E2ERch metric rather than E2ED.The next section will investigate the effect of protocols in both E2ERch and E2ED.

5.5.2 Analysis based on Scenario II

As mentioned in Section 5.5.1, the E2ED by AODV contains a delay which presents more than those in the broadcasting part. Therefore, the most remarkable change of outcomes in this section is that communication performance is evaluated between broadcasting phase of AODV and PTMDA. Again, the independent variable is message amount and dependent variables are E2ED and E2ERch.

According to Equation 5.1 and Equation 5.3, the E2ED and E2ERch are evaluated by the sum of values against the number of messages. Analysis of the experimental results needs to consider both metrics at the same time. For example, even though the sum of E2ED by each protocol is small, it cannot prove that the protocol has efficient broadcasting mechanism and the conclusion depends on the corresponding E2ERch. If this metric is very low which means that the communication experiences largely packet loss, then the small value of E2ED just means that the number of counting E2ED is much less than the real number of messages in the network. Alternately, when E2ERch is high and E2ED is small then communications are likely to be concluded confidently. The following observations are reflected the effect of network density and the effect of message size respectively. Complete results for the following evaluations can be found in Appendix A-7 and the following parts only use example figures (Fig. 5.18 and Fig. 5.19) for analysis.

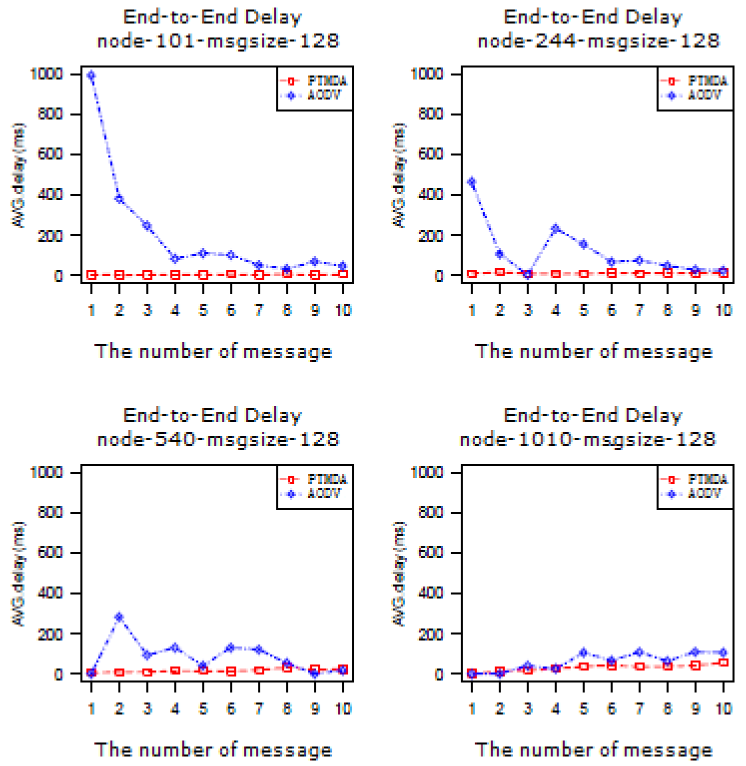
1) The effect of network density

Focusing on a case with 128 bytes of message size, the trend of E2ED (Fig. 5.18b) by PTMDA between 1 and 10 network transmissions does not show significant changes while the network density increases. However, the average E2ED of AODV reduces in a sparse network (101-node) and the reduction speed is more significant than that in a dense network (1010-node). Particularly, the trends of delays are very similar as the mean E2EDs by PTMDA in the dense network. This phenomenon is evident in the case of all message sizes (rows of Appendix A-7a).

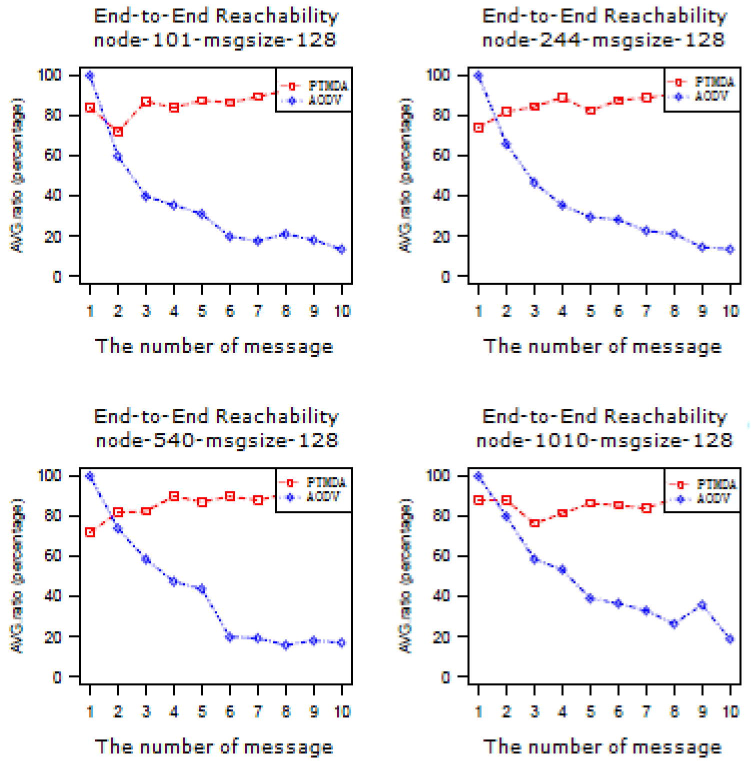
The curve of E2ERch (Fig. 5.18b) provided by PTMDA is more stable and is set higher than that by AODV, which goes down with the increase of message amount based on all density of networks. It is noticed that the end-to-end reachability under AODV is approximately 20% higher than that of PTMDA when there is only one message transmitted. Although the delivery ratio is high for AODV broadcasting methods, it results in high delay due to a certain number of retries; the difference is nearly 1000 ms when comparing the two protocols. After that, the trend of reachability under AODV becomes a downtrend and the minimal value is seen when 10 messages are transmitted. At the same point, the average E2ERch of PTMDA is set 80% higher.

It is interesting that when the number of network nodes and the number of simultaneous broadcasting packet increase, the E2ERch of transmissions under PTMDA presents as slight increments and the general curve is over 80% (Fig. 5.18b-node-1010). This phenomenon does not show up for the AODV mechanism. The findings indicate that PTMDA tackles the broadcast storms well and the multi-hop function contributes in effective manner.

Consequently, with the increment of network density, PTMDA at a threshold value of 0.6 performs with much better broadcasting capability than AODV with respect to both E2ED and E2ERch.



a) The effect of network density for end-to-end delay



b) The effect of network density for end-to-end reachability

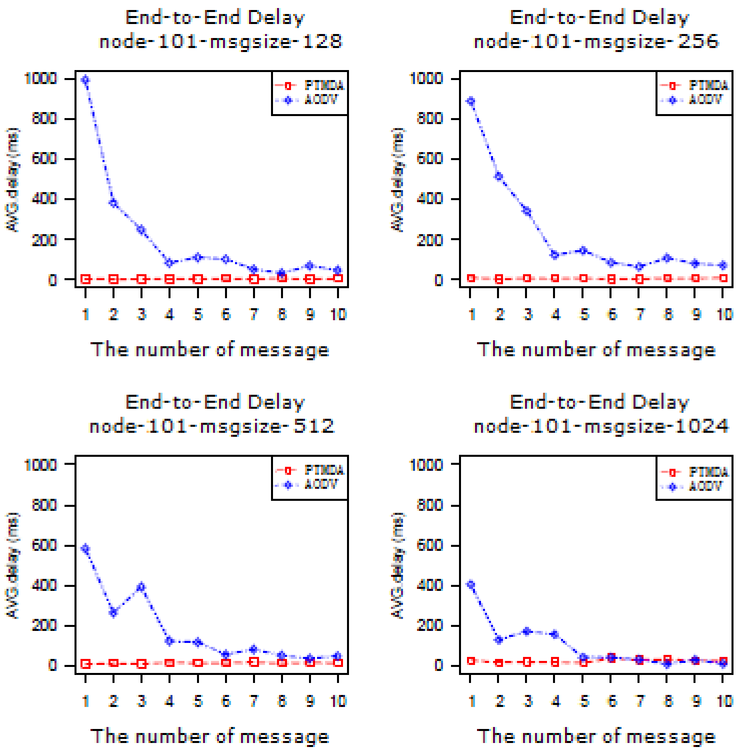
Fig. 5. 18 The effect of network density in PTMDA and AODV based on Scenario II [7]

[7]This group of figures are taken from *Appendix A-7: Efficiency and reliability in PTMDA and AODV based on Scenario II End-to-End communications (Fig. 5.18 - Vertical: the effect of network density)*

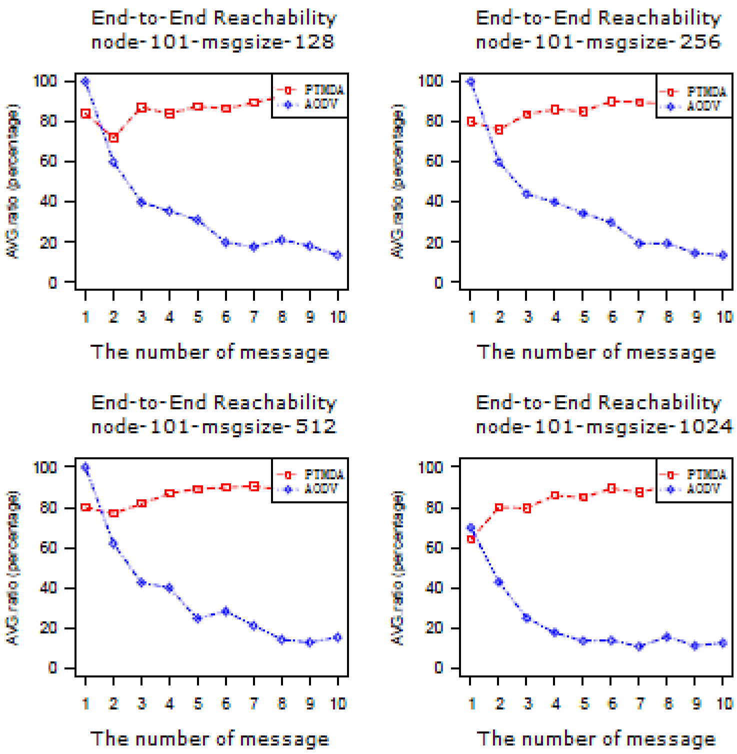
2) The effect of message size

Fig. 5.19 below focuses on example figures of Appendix A-7 lying lengthwise and considers a case when the network density is 101. For PTMDA, the changes are not obvious on the whole except for communications in medium and dense networks. The growth of message size results in increasing delay from 1-message transmission to 10-message transmissions. However, in such networks, AODV presents very small delays with all packet sizes and even smaller several milliseconds than that of PTMDA. It is found that while the message size rises, the downtrends of AODV in Fig. 5.19a become stable. An obvious change is displayed in the single-transmission case. For E2ERch (Fig. 5.19b), PTMDA provides stable results from 1 to 10 broadcasts over the network and the trends stay higher than those by AODV since the number of messages is 2. Nevertheless, the increase of message size leads to slight reduction from an average of 90% to 80% or so. Also, a similar action occurs in the trend of AODV with the maximum being around 100% is reduced to 80%. The findings based on experimental analysis [14] shows that larger packet size causes lower successful packet receptions in high-speed C2C communications. Current experiments reconfirm this.

Based on analyses in the effect of network density and message size here, two conclusions may be deduced. For the individual protocol, as network density increases, PTMDA outperforms AODV. It provides relatively smaller E2ED coupled with higher E2ERch accompanying the increase of simultaneous transmissions. In general, the stability of communication performance in diverse network conditions by PTMDA is better than that by AODV. On the other hand, the effect of message size causes the reduction of E2ERch for PTMDA, from 82% to 61% as well as AODV, from 100% to 70, in a 128-byte and 1024-byte transmission networks respectively (Fig. 5.19b). As can be seen, AODV suffers from serious transmission collisions when the message amount increases while PTMDA has better strategies to control and manage the problem.



a) The effect of message size for end-to-end delay



b) The effect of message size for end-to-end reachability

Fig. 5. 19 The effect of message size in PTMDA and AODV based on Scenario II [8]

[8] This group of figures are taken from *Appendix A-7: Efficiency and reliability in PTMDA and AODV based on Scenario II End-to-End communications (Fig. 5.19 - Horizontal: the effect of message size)*

5.5.3 Result summary

This section concentrates on point-to-point evaluations based on the characteristic scenarios. The aim is to evaluate the impact of message amount, network density and message size on fixed communication pairs and investigate the capability of PTMDA for route discovery as well as evaluate the improvements of PTMDA broadcasting mechanism in comparison to AODV.

Experimental outcomes and analysis resolve the questions set in Section 5.5. The outcomes of PTMDA are much better than the broadcasting mechanism of AODV in the aspects of E2ED and E2ERch. Firstly, AODV is a popular broadcasting-based routing protocol but the simple broadcasting methods used in route discovery cannot handle the problem of broadcast storms. Therefore, with the increase of message amount, E2ERchs are characterized by a downtrend. In addition, PTMDA with a threshold value of 0.6 provides priority forwarding to nodes matching requirements so that a certain number of redundant broadcasts are effectively prevented. This is a main reason why the E2ERch of PTMDA remains at a high level while the number of simultaneous broadcasts increases.

PTMDA performs well in terms of network reachability and end-to-end reachability, in conjunction with acceptable NE2EDs and E2EDs, although it results in cases that there are 1010 nodes or the message size is up to 1024 bytes may present a certain of predict bias. As far as the capability of route discovery is concerned, PTMDA can be properly utilized in reactive routing protocols based on the proposed CMCN architecture.

5.6 Summary

This section aims to provide an experimental proof of concept for PTMDA which highlights its advantages to the efficiency and reliability of communications in urban traffic C2X environments.

Experiments are performed with different protocol parameters depending on the area of focus. As shown in [126][127], probabilistic Flooding performs well in to addressing the problem of broadcast storms and results in improvements of communication performance. The effect of PTMDA broadcasting mechanism is evaluated and the communication performance is compared to that of probabilistic Flooding with respect to diverse network density and message size. The metrics used are NE2ED, NRch, IB and PktD.

On the other hand, AODV is a broadcasting-based routing protocol widely used in the MANET domain. It includes ACK-based broadcasting schemes and routing management to guarantee a high successful delivery ratio of transmissions. Thus, comparing broadcasting mechanism of PTMDA to that of AODV helps to exploit whether PTMDA is suitable for route discovery of reactive routing protocols with the effect of message amount, message size and network density.

5.6.1 Efficiency of message delivery

The metrics NE2ED and E2ED are mainly used to support efficiency evaluations. According to the analysis of fully C2C communications (Section 5.3), PTMDA (thres_=0.6) provides generally smaller NE2EDs and higher NRchs than most of probabilistic Flooding regardless of increased network density and message size. When infrastructure is introduced to the CMCN network, the NE2EDs are reduced and NRchs rise until the optimum amount of infrastructure nodes is exploited. In a 50%-C2I environment, PTMDA (thres_=0.8) which limits invoked broadcasts in a large degree provides similar reachability results and significantly smaller NE2EDs in comparison to probabilistic Flooding. For the result, the inclusion of I-Routes becomes a vital factor.

In addition, PTMDA performs much better in terms of E2ED and E2ERch in both scenarios considered compared with AODV. With the increase of message amount, PTMDA provides smaller E2EDs and higher E2ERchs than AODV, especially in 65-node, 101-node as well as 244-node networks.

5.6.2 Reliability of message delivery

PTMDA performs well in achieving message delivery towards an acceptable section of the network. In particular, the optimum performance is found in moderate-medium (244 nodes) networks. The metrics NRch and NE2ERch evaluate reliability of C2X communications. According to comparisons in Section 5.3, PTMDA with a threshold value of 0.6 leads to higher NRchs than probabilistic Flooding.

In point-to-point transmissions, PTMDA performs well by achieving more stable traffic message delivery in target urban traffic scenarios, taking all factors into considerations. E2ERch increases the reachability of message between originators to pre-set destinations. In such a case, E2ERchs under PTMDA are higher than those by AODV in both scenarios considered. It is found that AODV performs better in terms of packet delivery ratio when the number of messages is very small (single message only), but then the E2ED results are still relatively high. However, PTMDA keeps fairly high levels on E2ERch, up to an average of 75%, even when there are up to ten message transmissions.

Consequently, PTMDA is considered as a well-suited broadcasting protocol to be utilized in the CMCN system. The broadcasting algorithm provides the greatest degree of controls for the risk of broadcast storms by implementing I-Route scheme, Farthest Node First Send (FNFS) scheme, Direction-based Priority (DP) scheme and High-Speed Priority (SP) scheme, plus a waiting delay that helps to differentiate the time of broadcasting behaviors.

Additionally, a set of experiments is conducted to investigate the effect of C2I communications in a selected city centre area. By comparing the performance of PTMDA with different threshold values in C2X communication systems, the optimum infrastructure scenario is determined. According to the results shown in Section 5.4, good communication performance by PTMDA is found in a network with 50% gateway static nodes. Based on the specified amount and layout of bus stops, the effectiveness of infrastructure nodes is mostly observed in sparse networks because the occupancy of bus stops in this density network is larger (50%) than other density networks, such as 20% (244-node), 9% (540-node) and 5% (1010-node).

Chapter 6

Conclusions and Future Work

6.1 Review of Research Motivation

Recent development in wireless communication technologies directs traffic management and control towards widespread deployment of ITS systems in which self-organized operations are favoured. Urban traffic requires not only fair road sharing for vehicles, but also an information-exchange environment for traffic conditions identification and control generation. To achieve this goal, C2C communication becomes a promising prospect since it allows efficient, economical, large capacity local transmissions via on-board units of vehicles.

A C2C communications system, consisting of a large number of roaming participants, can operate in a spontaneous and intelligent manner, which results in robust and high quality communications performance. This research proposes a novel dynamic, flexible and non-infrastructure based architecture, which uses MANET technologies and exploits collaboration between transportation tools, such as cars, buses and public facilities, to improve the efficiency and reliability of data disseminations. Consequently, the establishment of a Collaborative MANET-based Communication Network (CMCN) architecture is proposed and empirically evaluated through using a simulation model incorporating an instance of a Nottingham (UK) city traffic scenario and also using 802.11p-based C2C communications.

Motivated to overcome frequently changed topologies and disconnected routes in such networks and to foster better collaboration between traffic participants, this thesis proposes a new broadcasting protocol named the Probabilistic Traffic Message Delivery Algorithm (PTMDA); therein provisions are made to support C2X applications with the definition of a high transmission priority location strip called the I-Route. Due to the shared transmission medium and limited transmission bandwidth, traditional broadcasting operations in such a system are likely to be challenged by broadcast storms in the form of packet collisions, transmission congestion packet loss and so on. To avoid such eventualities, PTMDA adopts probabilistic priority schemes to eliminate a certain number of redundant rebroadcasts and suppress unnecessary forwarding at the same time.

6.2 Review of Contributions

The major contributions presented in this thesis, as well as a review of experimental findings are summarized below.

6.2.1 CMCN: network layers

The CMCN architecture is specifically built to investigate the viability of C2C communications for ITS applications in urban traffic scenarios. Such system is well-structured by NS2 simulation technology so that messages are successfully generated and delivered during the network according to 5-layer model (Section 3.3.2), namely, in ascending order, the IEEE 802.11 PHY layer, the IEEE 802.11p MAC/LLC layer, the Network layer, the Transport layer and the Application layer. The assessment of the work at each layer can be subject to trace files (see Fig. 5.1: blue part) provided by NS2.

At the highest layer, there is a unique message format designed for CMCN Traffic Messages (CTM), consisting of a broadcasting header and warning-based (WB) or sharing-based (SB) data. WB messages focus on fast and reliable delivery within local areas while SB messages are meant to be informative and widely spread. The MAC and PHY configurations in the proposed CMCN system follow the WAVE standard [163].

6.2.2 CMCN: classification of nodes

In order to rationally utilize the nature of traffic participants for providing better communication performance, this thesis specifies three categories of nodes depending on their mobility characteristics. By using NS2 technology, the visualization of nodes can be presented via NAM animator (Fig. 5.5b).

The first group is composed of fully mobile nodes, which have a critical role in the network, namely achieving anywhere and anytime event detection, generation and broadcast. An instance of this group is a 'car'. Due to the unpredictable movement locus, uneven distribution and variable destination intentions, these nodes are difficult to track without infrastructure aid. Essentially, communications between them perform well in day time (e.g. rush hours) via multi-hop transmissions. However, when the number of cars is reduced, in particular scenarios, the connectivity of the CMCN network becomes poor.

To address this problem, a second group of CMCN nodes, namely semi-mobile nodes, is considered. For these, in reality, behaviour can be controlled and predicted to a degree. For instance, consider that buses, a particular example of semi-mobile nodes, are invoked by the Bus Control Centre through fixed schedules and regular operations; they also generally move on their priority lanes in city scenarios. This group of nodes helps to diversify transmission possibilities so that the reliability of message delivery is enhanced. Furthermore, this type of nodes can be exploited in tandem with the third group mentioned below, resulting in significant improvements in efficiency and reachability, as shown in experiments of Section 5.4.

The third category is defined as static nodes, such as bus stops. Bus stops are, in infrastructure rich regions, connected by wire or even wirelessly. In the CMCN network, wireless connections are assumed to be present, by default, between nodes. They allow, when necessary, to act as gateway and provide an outlet to other networks, or even the Internet. Overall, if the number of cars in a region is too low to independently complete a WB transmission for incoming cars, a broadcast could be further propagated via buses and even bus stops.

These concepts, indeed, are exploited by the adaptable Probabilistic Traffic Message Delivery Algorithm (PTMDA).

6.2.3 PTMDA: non-ACK broadcasting

PTMDA adopts non-acknowledgement broadcasting by which, message delivery occurs without pre-connection. Such mechanism aims to offset following weak points of ACK-based broadcasts. Usually, acknowledgement packets in broadcasting methods are used to guarantee the reliability of transmissions. However, this is not an efficient way to deliver WB messages for two main reasons. Firstly, transmission of ACK packets is normally separated from real data transmissions so that there are special control and management mechanisms to deal with them. In this case, the complexity of broadcasting and the bandwidth overheads per node increase. Further, acknowledge-based exchanges require responses from receivers, which intuitively lead to increased transmission delays.

Only one format of messages is used in the algorithm, called CMCN Traffic Message (CTM). It contains broadcast specifications and timely traffic data, which make the protocol straightforward in terms of message controls. Senders broadcast data packets regardless of the surrounding environment and neighbour information available. Receivers, in turn, pay more attention to forwarding rather than interacting with senders. Consequently, the total end-to-end delay improves upon its ACK-based counterpart – in particular, compared with AODV, the end-to-end delay of PTMDA is significantly less (Fig. 5.18a).

6.2.4 PTMDA: the inclusion of I-Routes

A high transmission priority location strip called the I-Route (e.g. Fig. 5.2b, Fig. 5.3b) is defined based on the bus lanes and is utilized to enhance the efficiency of message transmissions while features of buses and bus stops are fully exploited in the network. The I-Route scheme (Section 4.4) provides transmission timing probability calculations according to node type (Equation 4.2) and position (Equation 4.3).

Experiments in Section 5.4.2 demonstrate that the inclusion of I-Routes enhance transmission efficiency somewhat when all CMCN nodes are fully used. When infrastructure is considered the benefits become even more pronounced and the transmission delays are effectively reduced and reachability improves significantly.

Compared to probabilistic Flooding the I-Route method can offer a better alternative in terms of overhead, delay and reachability provided the transmission timing parameters are chosen with care; this thesis offers empirically good value for a typical urban scenario.

6.2.5 PTMDA: elimination of redundant rebroadcasts

PTMDA includes transmission probability considerations (Section 4.4.3) aiming to eliminate redundant rebroadcasts. The central idea of probability scheme is that a probability value is computed based on the role of node and its mobility pattern, and that value is then compared to a present probability threshold. Only if the computed probability is greater than the threshold value, will a broadcast be invoked after their waiting delay.

According to the experimental data (Fig. 5.11c, Fig. 5.13c), by using a particular threshold in PTMDA, the invoked broadcasts are significantly less than those of probabilistic Flooding in all cases. The thesis empirically evaluates different threshold values and compares their efficacy in the target scenarios (e.g. Fig. 5.9). A "good" value range for thresholds is identified in Section 5.3 and is suggested as an appropriate starting point in similar urban environments. For particular threshold values, which however cannot be known a-priori, PTMDA can provide outstanding controlled number of invoked broadcasts and packet drops in an optimum C2I environment (Section 5.4).

6.2.6 PTMDA: asynchronous forwarding

Beyond redundant broadcasts, another major reason causing packet loss is simultaneous forwarding. To address the problem, PTMDA implements an idea of waiting delay for a node permitted to forward received messages. In another words, a node with a higher probability forwards the message earlier than others. An obvious benefit is to prevent broadcasts at the same time by more neighbouring nodes in the case of no interactions.

It is shown that since PTMDA differentiates bases the forwarding time on a probability value obtained at the receiver, simultaneous broadcasting behaviours are effectively avoided, shown as low packet drops (e.g. Fig. 5.11d). The other contribution of this strategy is to improve reliability of transmissions that consists of the successful delivery ratio and the proportion of reachable messages. The former is evaluated by a metric of end-to-end reachability (Section 5.2.4.2), which is obviously shown that PTMDA gives higher percentages and more stable results than those of AODV (e.g. Fig. 5.18b), even though the number of messages, the network density and the message size increase. On the other hand, the latter is defined in this thesis as network reachability which is shown that PTMDA with a threshold value of 0.6 gives the best reachability results and also higher than different probabilities of probabilistic Flooding in the observed scenario (e.g. Fig. 5.11b).

6.2.7 Metropolitan mobility model study

This thesis considers two metropolitan mobility models based on the layout of the city of Nottingham in the UK. The first scenario (Scenario I) is generated by a custom-written simulator, which imports the map based on British National Grid Coordinate system data. The other one (Scenario II) derives its map and traffic from traffic simulations using the well-known SUMO traffic simulator.

For our purposes, Scenario I (Fig. 5.2) is a 700m*700m area of the Nottingham region including only 65 vehicles. This area is sparse and uncongested so that disconnections happen frequently. In this case, probabilistic Flooding is not properly compared by PTMDA in aspects of network end-to-end delay, network reachability, invoked broadcasts and packet drops. However, the end-to-end communication is evaluated by comparing with AODV, which adopts the rebroadcast mechanism to maintain reliability of messages. In this scenario, PTMDA is obviously shown as an efficient and reliable broadcasting protocol which is well-suited for the CMCN network.

Scenario II (Fig. 5.3) is a 1164m*905m sized area of the Nottingham city centre, which contains dense and congested traffic. In such settings, the network may experience a large number of broadcast problems. The area contains complicated interactions in the physical area so that the effect of network density and message size are of interest to be investigated in experiments. There is, further, evaluation of the effect of infrastructure, the inclusion of I-Routes, and the effect of number of simultaneous broadcasts. In this scenario, PTMDA with a threshold value of 0.6 outperforms probabilistic Flooding and AODV protocols, showing efficiency of transmissions, reduction of simultaneous broadcasts, high reachability of messages and stability and reliability of end-to-end transmissions.

6.3 Conclusions

Overall, the research aims to construct a new MANET network (CMCN) architecture, which provides C2C communications for ITS, has been achieved. The simulation runs showed that the new system delivers traffic information and control messages faster than other similar algorithms. The aim has been achieved through applying advanced simulation techniques to the research. Every single objective and sub-objective as listed in Section 1.3 has been investigated and its viability proved via theoretical analysis and experiment evaluations, including the design of CMCN architecture, the design of PTMDA algorithm and the assessment of network performance.

The framework simulation model, concerning the nature of the traffic participants, has been structured as a 5-layer model in the NS2 simulator. Each layer has been configured to adapt for modern inter-vehicle communication requirements. Focusing on city traffic scenarios, the system components have been specified as three types, which were subsequently successfully incorporated in the NS2 simulation model according to their mobility status and routes. In particularly, a set of pre-set routes (I-Route) was distributed in the CMCN system to provide CMCN mobile nodes priority-forwarding strategies. These were implemented by the newly designed broadcasting protocol (PTMDA). The algorithm supports efficient and reliable message delivery, which was observed and the results supported by experiments.

6.4 Directions of Future Work

The work conducted in this thesis indicates that exchanges of information among CMCN nodes can be relatively efficient and reliable by implementing PTMDA schemes when targeting urban scenarios. Although the potential gap between reality and simulation needs to be further investigated, the CMCN system can be seen as a promising architecture for C2X applications. Its first advantage is that as a network structure, consisting of mostly mobile nodes, it operates in a self-organized, dynamic and economically viable manner. Moreover, as the wireless mobile communication technology seems to be uniformly adopted by vehicle manufacturers, it can be reasonably assumed that cars in the near future will be equipped with the essential in-car devices needed for the system to function.

This thesis investigates the communication performance of CMCN system, in which the collaboration of three types of nodes is highlighted. Particularly, bus stops are given gateway functions to help for the increase of reachability and provide accesses to the Internet. Further the idea of a floating gateway node may be exploited in future works. Based on the current knowledge, 'buses' could be the best deployment as floating gateways. It is well-known that buses move with structured paths and schedules and are afforded by companies or government and equipped with high quality of in-car devices. They are able to store messages and carry them to the area that fixed infrastructures cover. The direct benefit of the method is to utilize existing technologies to maintain the security of message transmissions and also help to improve communication quality and quantity. Therefore, the utilization of floating gateway node is a potential idea added to the CMCN network.

As mentioned previously, PTMDA operates in an efficient broadcasting manner so that each vehicle needs not rebroadcast the message. While this method brings satisfactory transmission results in most cases, however, the reliability of message delivery in particular scenarios is not adequate such as in the case of a sparse network.

The direction of future developments for PTMDA ought to focus on two aspects. One is to import a concept of store-carry-forward scheme into CMCN bus-nodes and non-gateway static nodes. The basic idea is when a critical message available cannot reach acceptable coverage of nodes in a sparse network, and then a bus will store it. Buses, with structured movements and schedules, could bring the message to a denser part of the network and then forward it - this method should improve transmission reachability to a certain degree. Additionally, PTMDA could be evaluated for use in a routing protocol, such as AODV or DYMO, for route discovery; there is evidence that it provides acceptable efficiency and reliability, compared to conventional broadcasting mechanisms.

In urban traffic scenarios, the I-Routes, node type, directions of motion and distance between communications pairs are significant impact factors for message deliveries, however, the effect of speed-based priority is not obvious. This is because city scenarios, compared with highway areas, are more congested and traffic regulations restrict the speed of vehicles significantly. Hence, future work could examine a developed CMCN architecture on highway settings, in which the classifications of nodes and I-Routes definitions are re-structured.

The definition and experimental evaluation of the CMCN system using the dedicated PTMDA algorithm prove that it is a suitable architecture for C2X applications. However, the CMCN architecture is not just suitable for ITS applications, but may also be employed in other areas of activity, i.e. the management of nature reserves, scenic areas, historical sites and tourist attractions. In such a network, travellers and tourist vehicles would be able to obtain relevant information, such as routes, time and weather information, through message exchanges with other participating vehicles and fixed information stop points. These are exciting potential uses for the infrastructure presented above and an interesting case-study for future research efforts.

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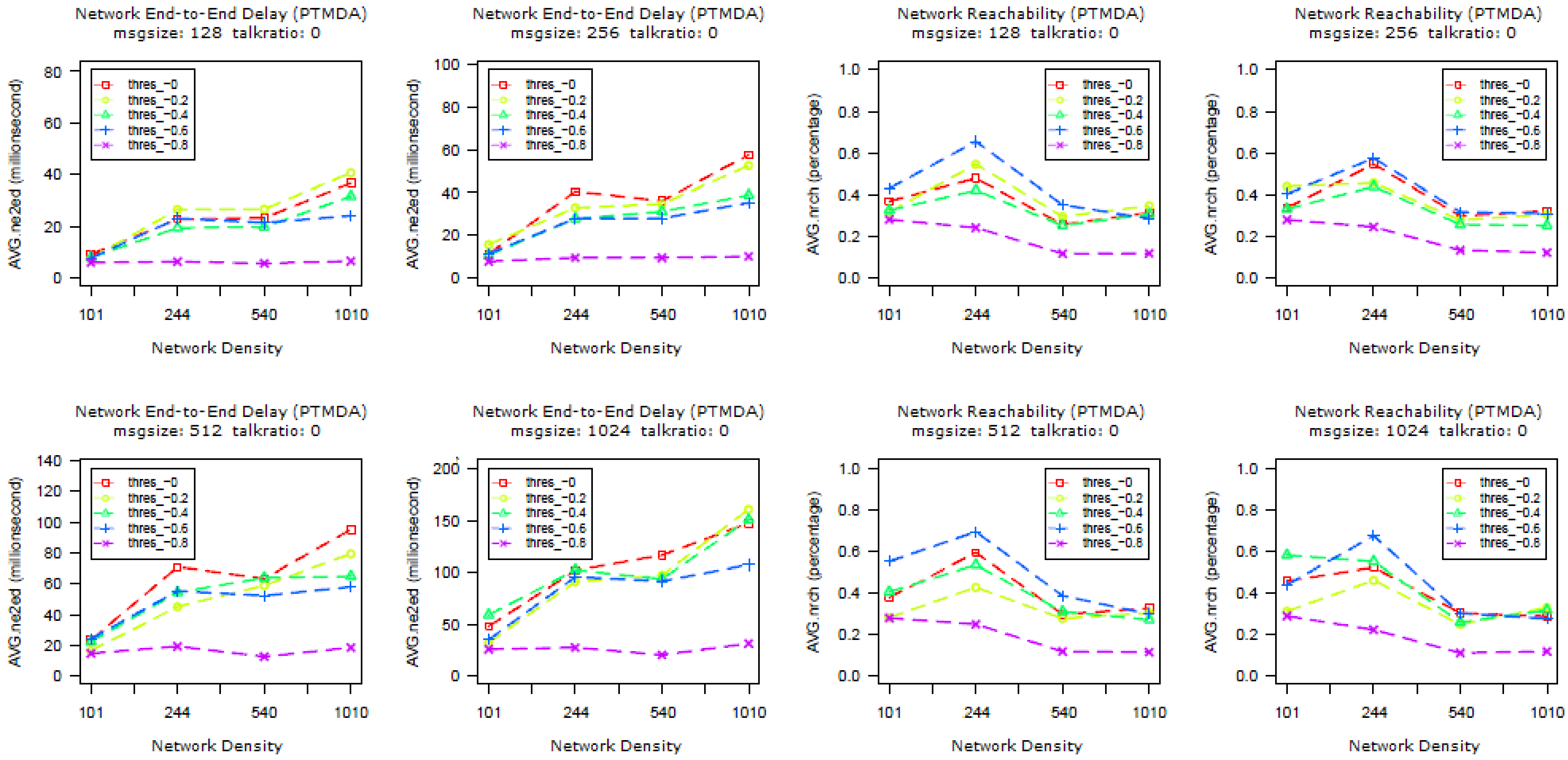
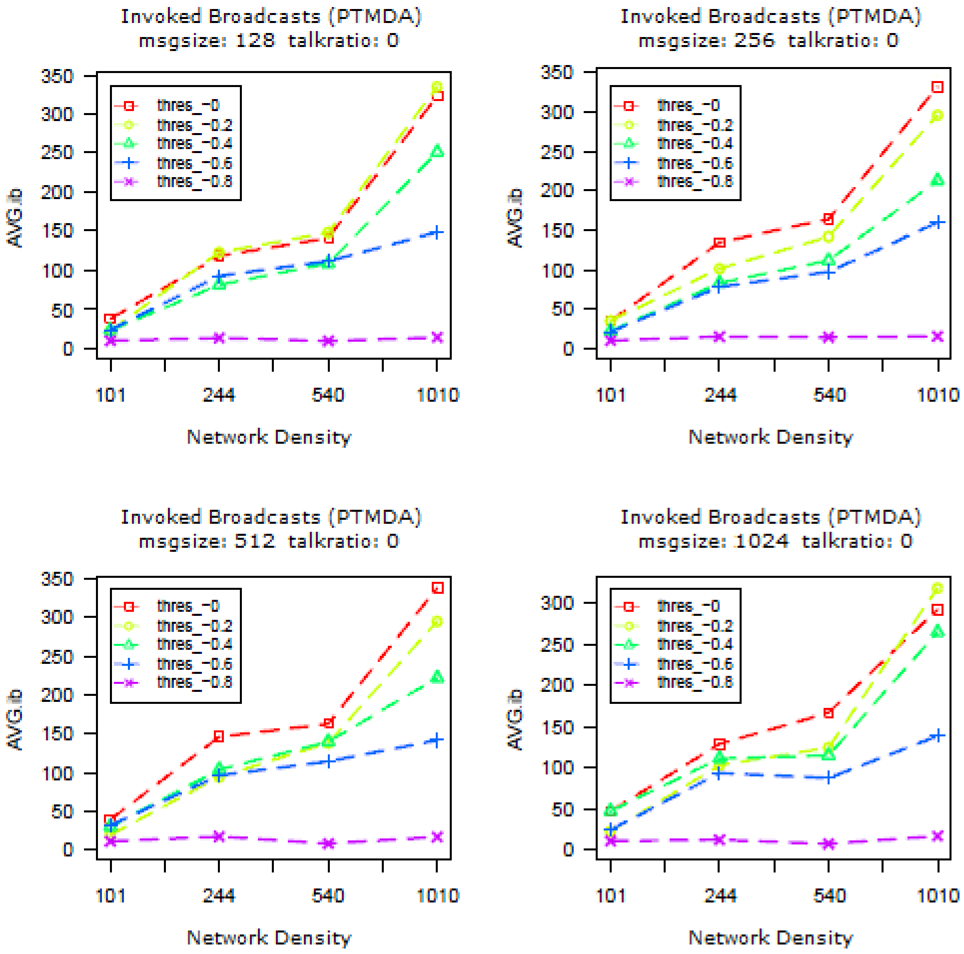
Appendix A-1 Effect of network density for PTMDA with different threshold values (Fig. 5.9)

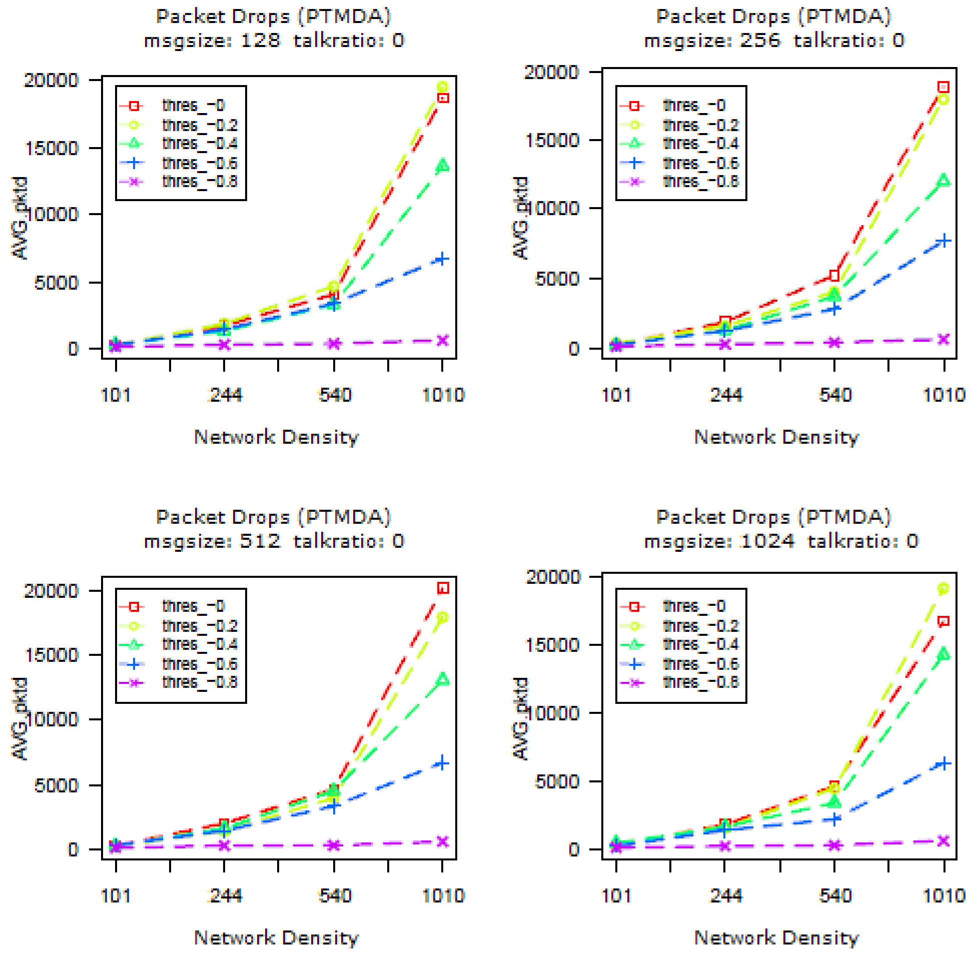


a) Network End-to-End Delay (NE2ED)

b) Network Reachability (NRch)

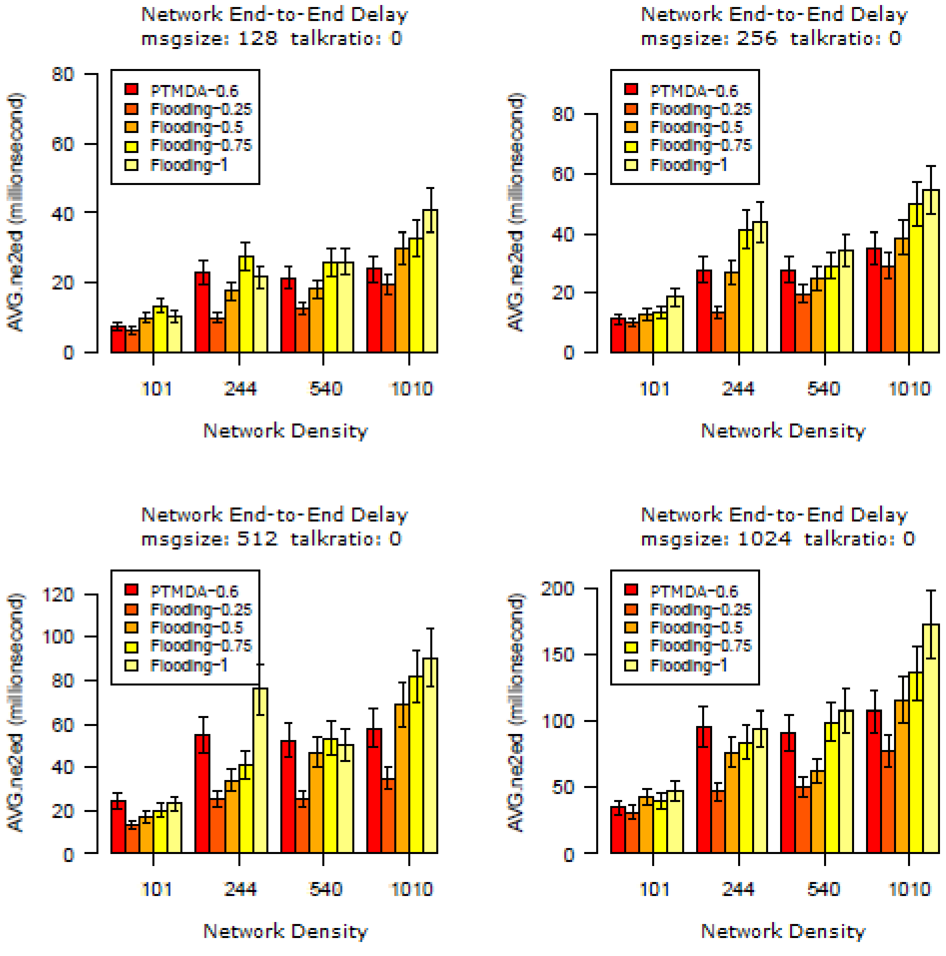


c) Invoked Broadcasts (IB)

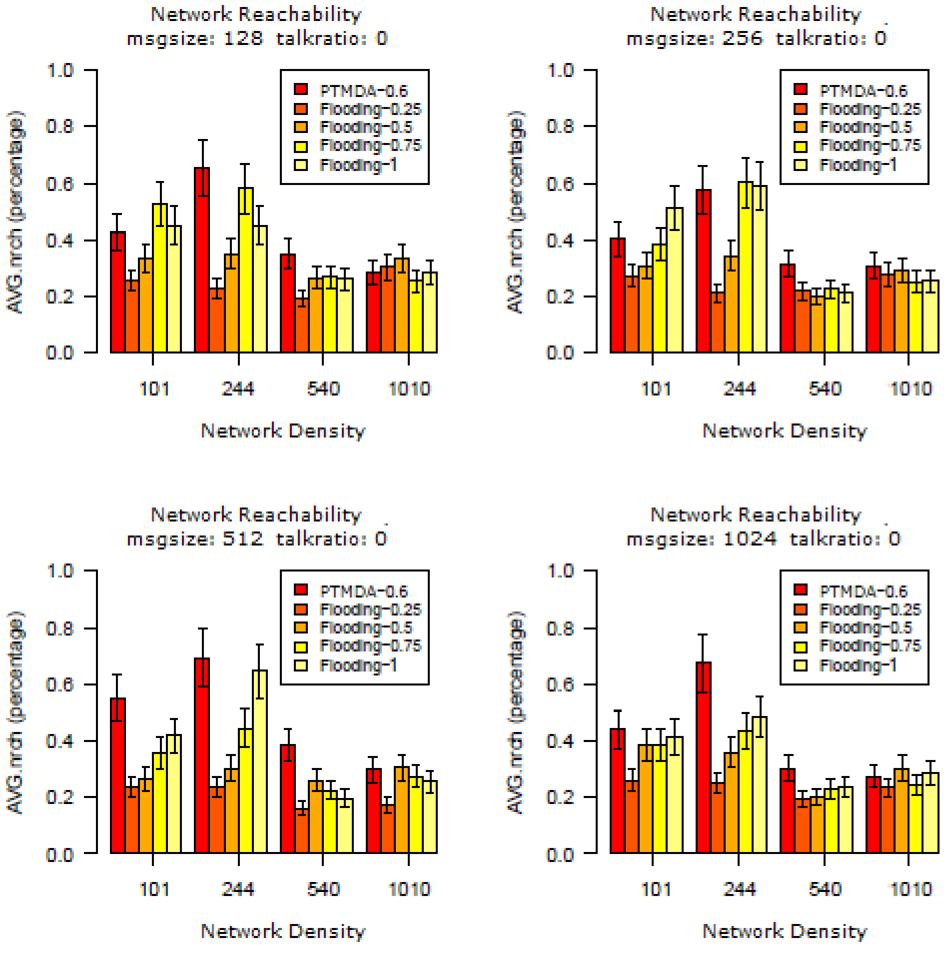


d) Packet Drops (PktD)

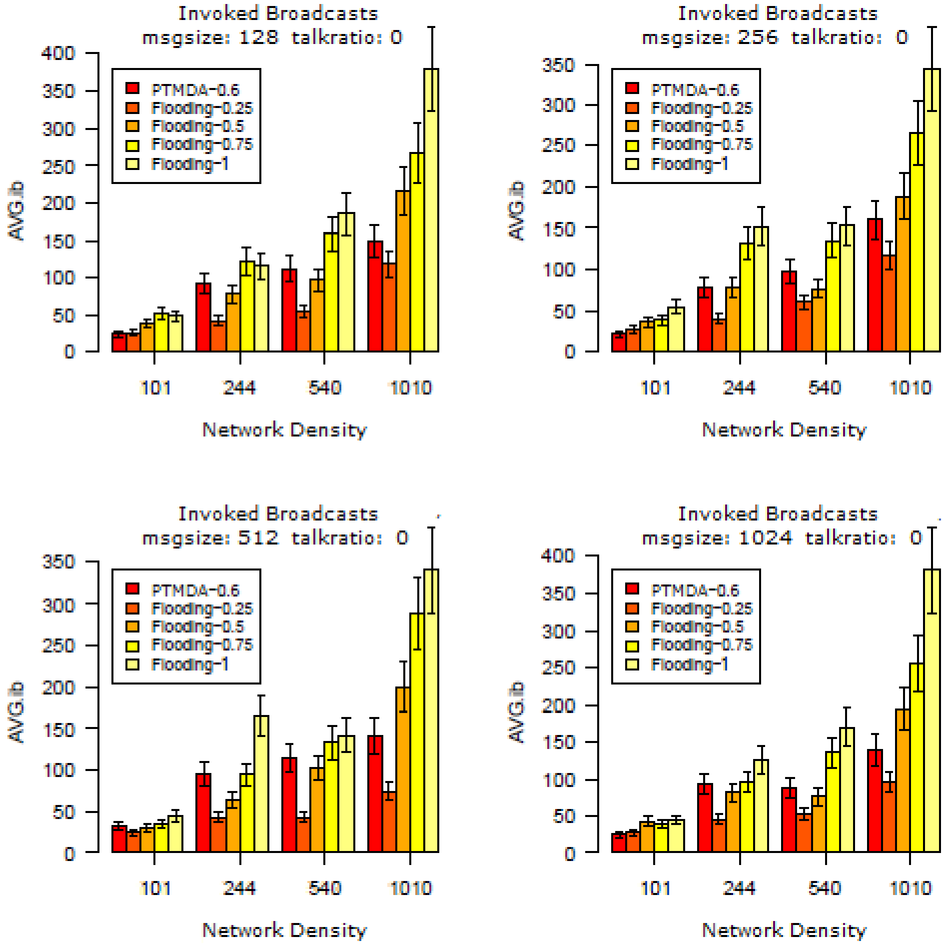
Appendix A-2 Effect of network density in PTMDA and Probabilistic-Flooding (Fig. 5.11)



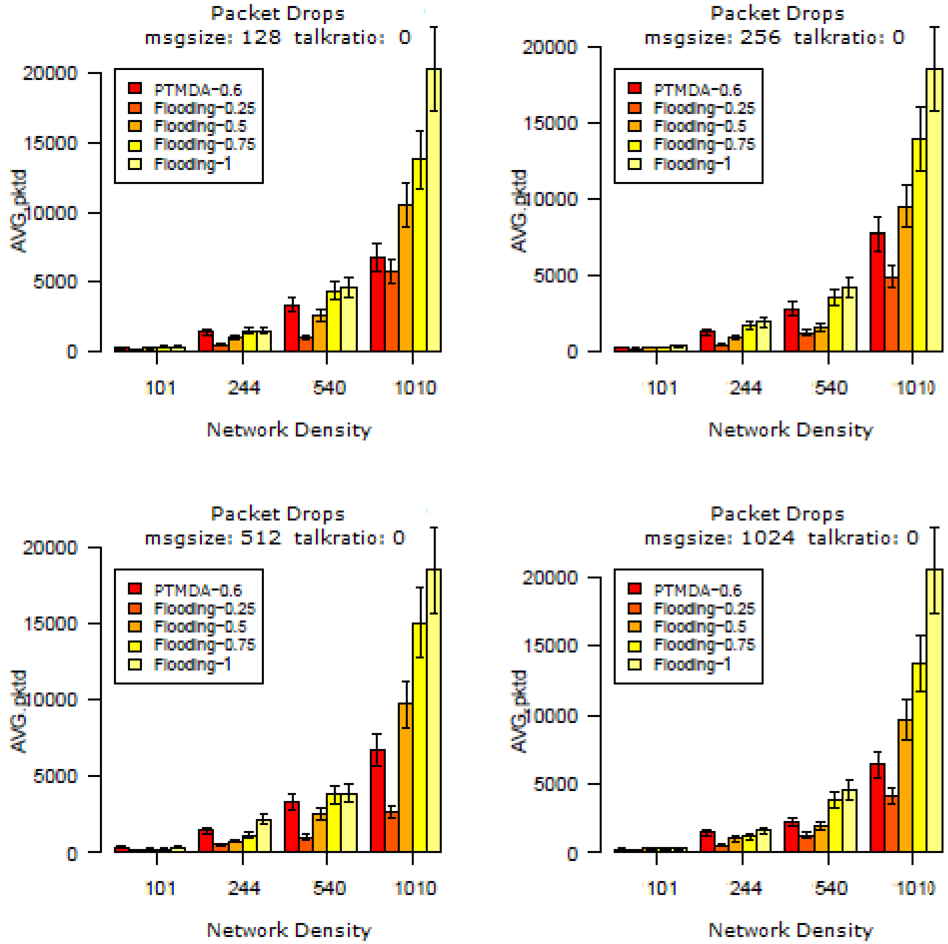
a) Network End-to-End Delay (NE2ED)



b) Network Reachability (NRch)

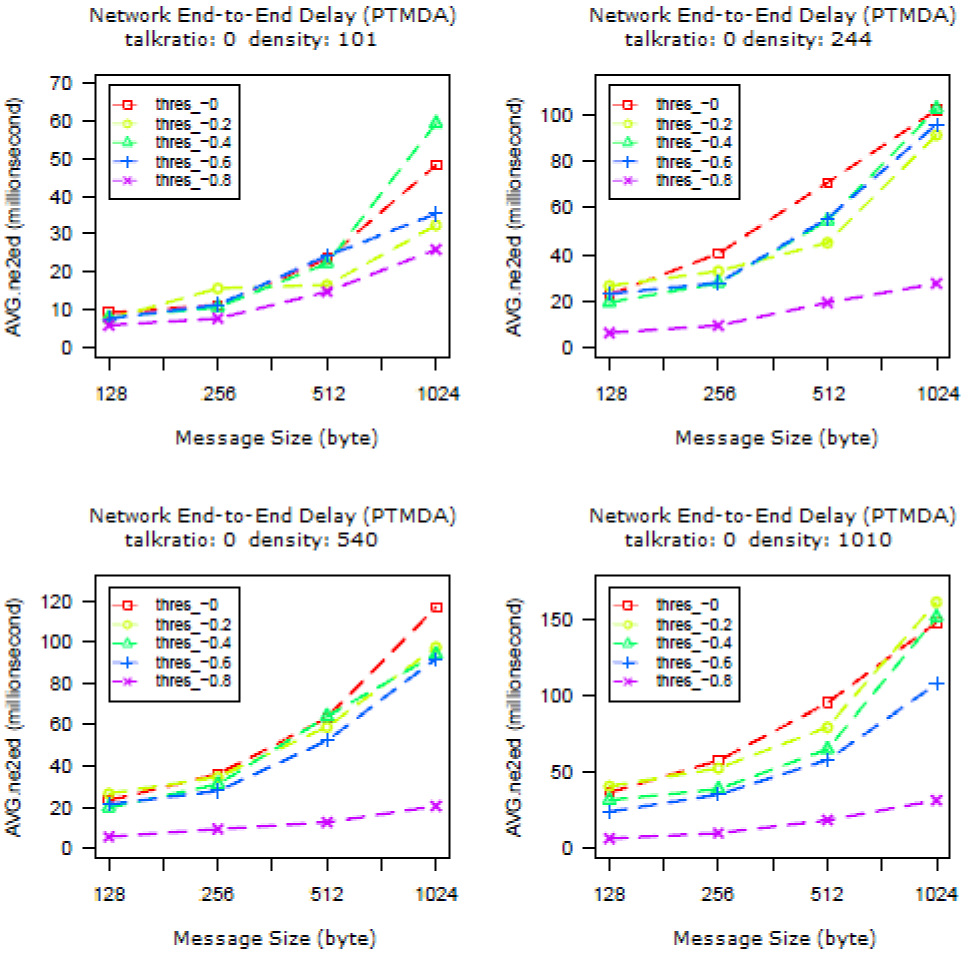


c) Invoked Broadcasts (IB)

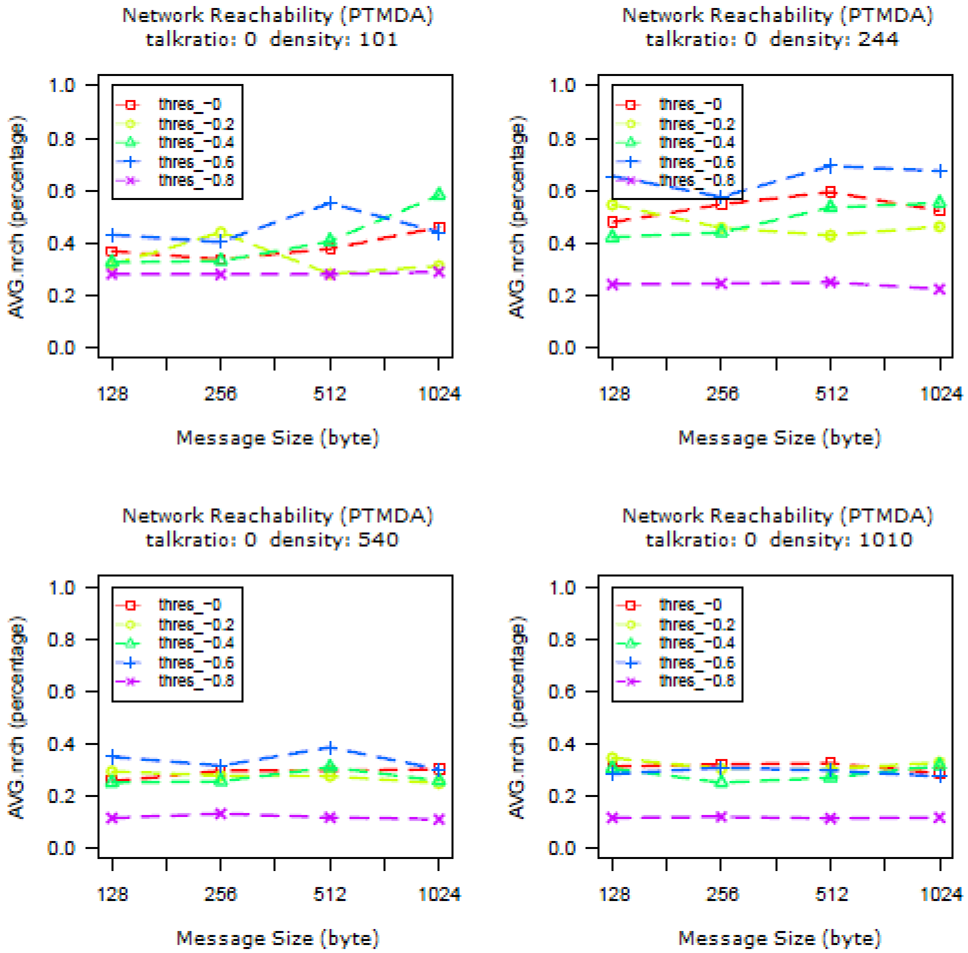


d) Packet Drops (PktD)

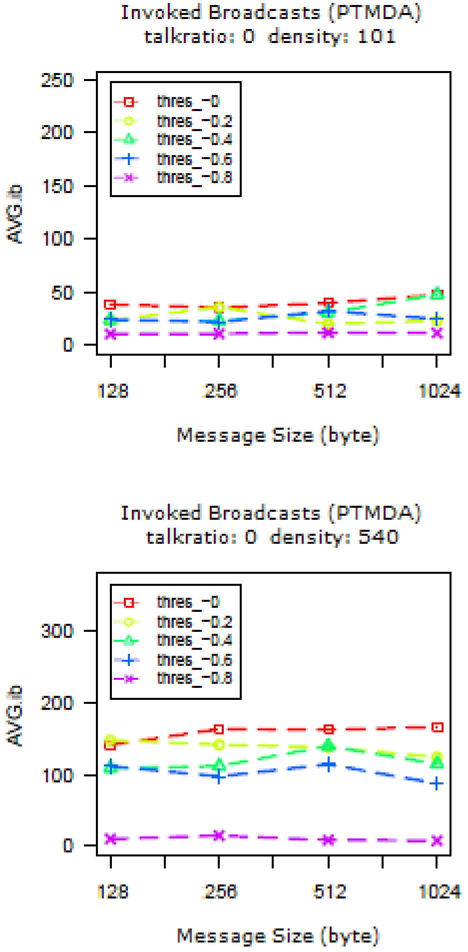
Appendix A-3 Effect of message size for PTMDA with different threshold values (Fig. 5.12)



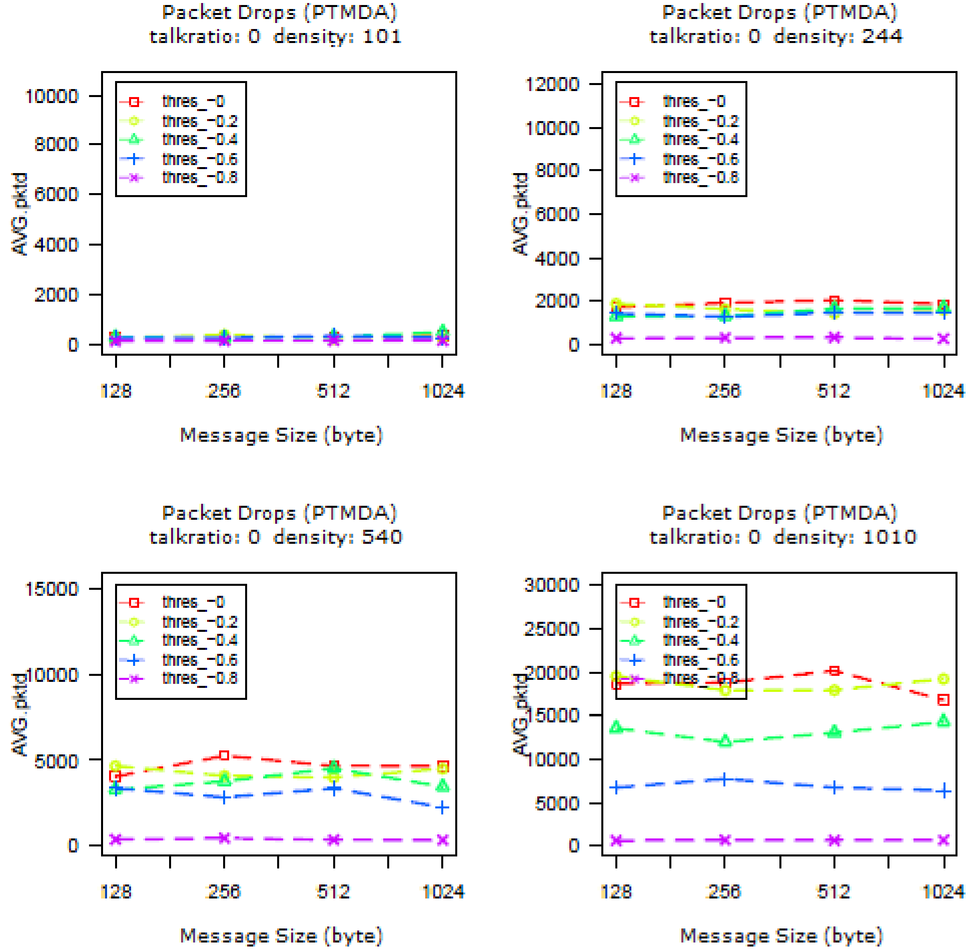
a) Network End-to-End Delay (NE2ED)



b) Network Reachability (NRch)

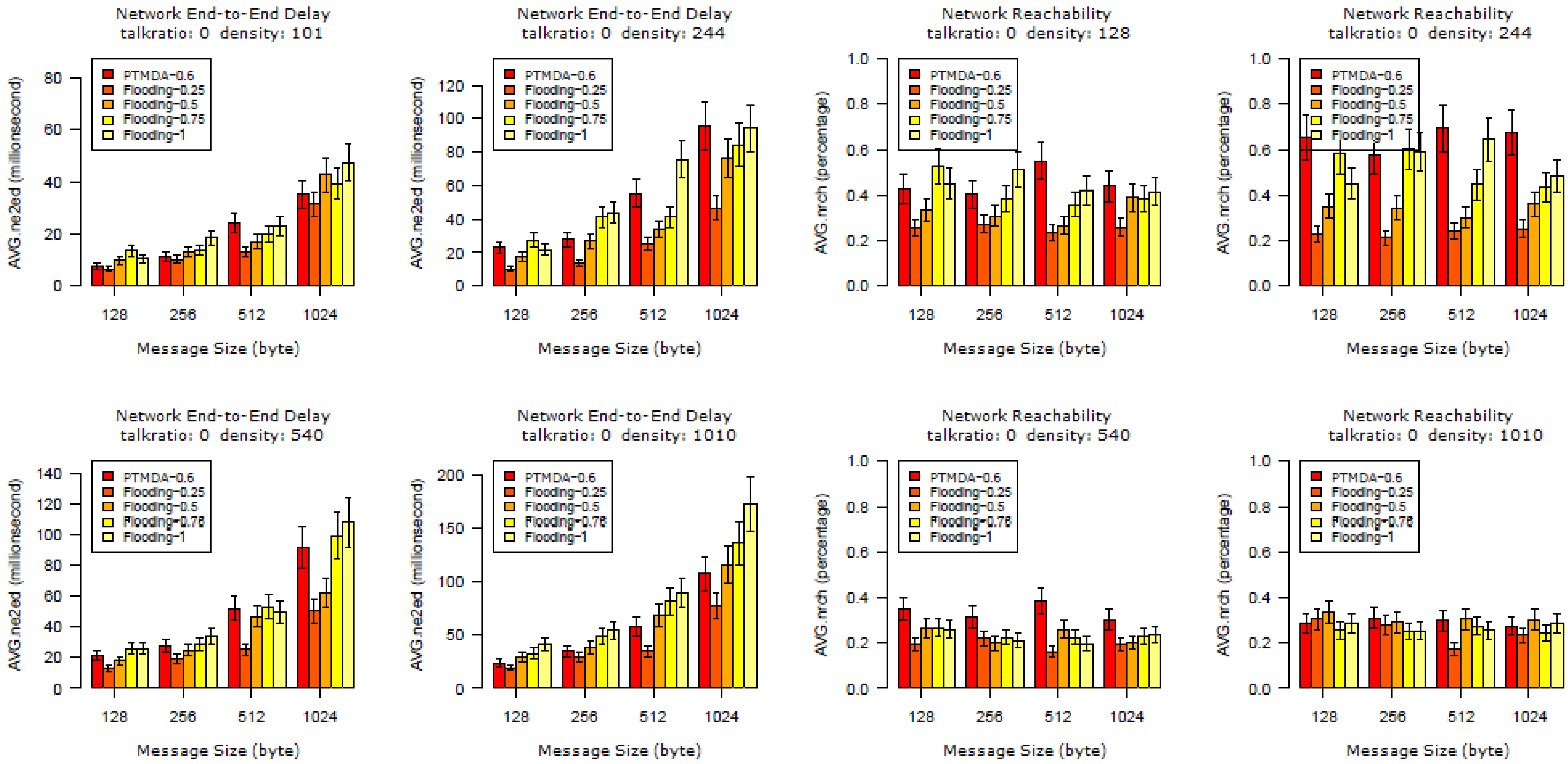


c) Invoked Broadcasts (IB)



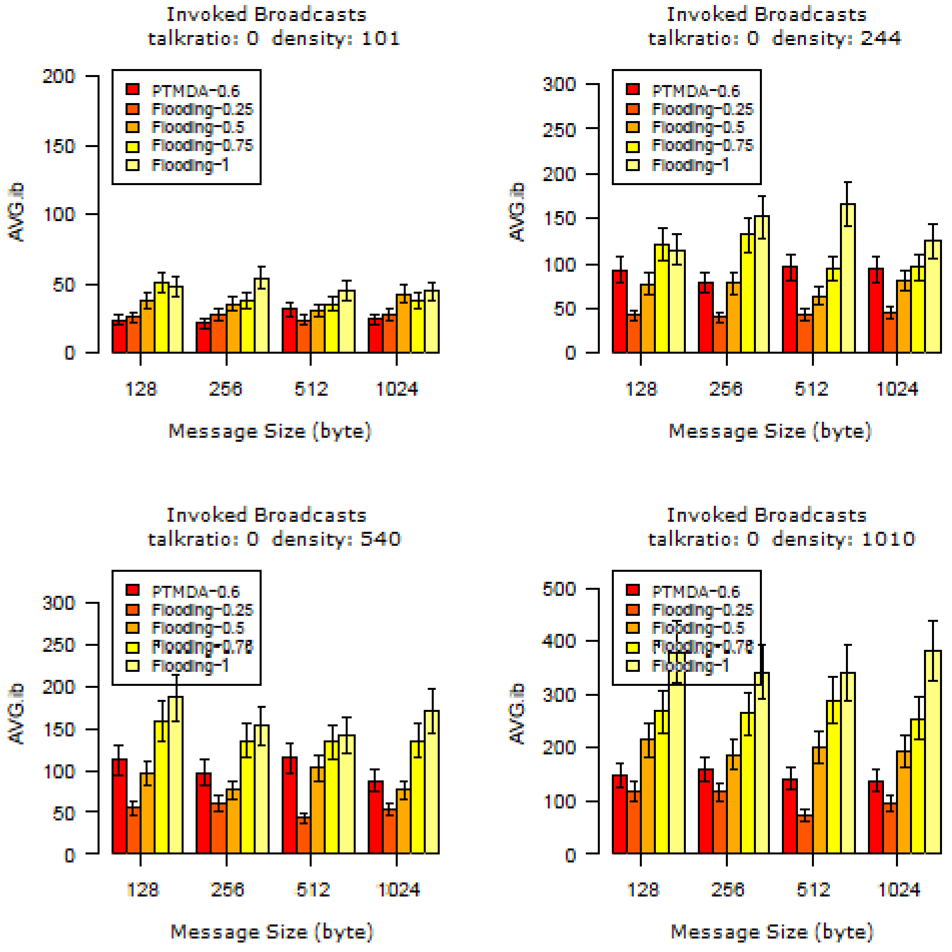
d) Packet Drops (PktD)

Appendix A-4 Effect of message size between PTMDA (0.6) and probabilistic Flooding (Fig. 5.13)

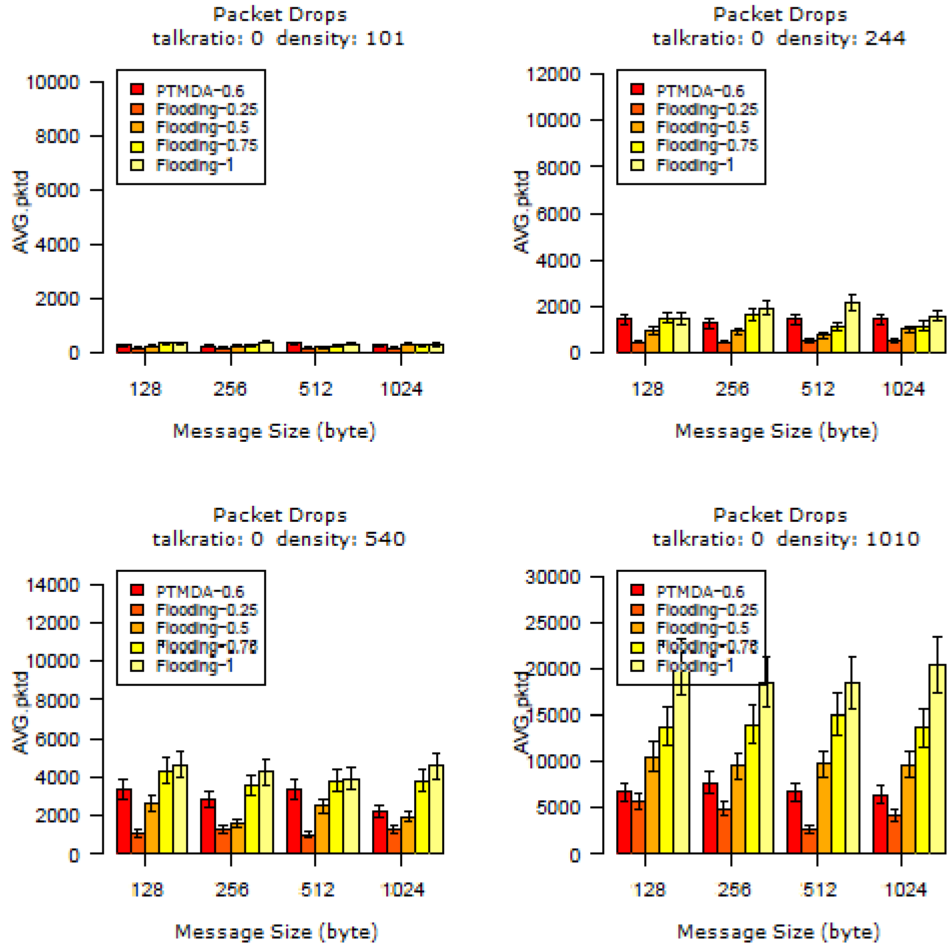


a) Network End-to-End Delay (NE2ED)

b) Network Reachability (NRch)

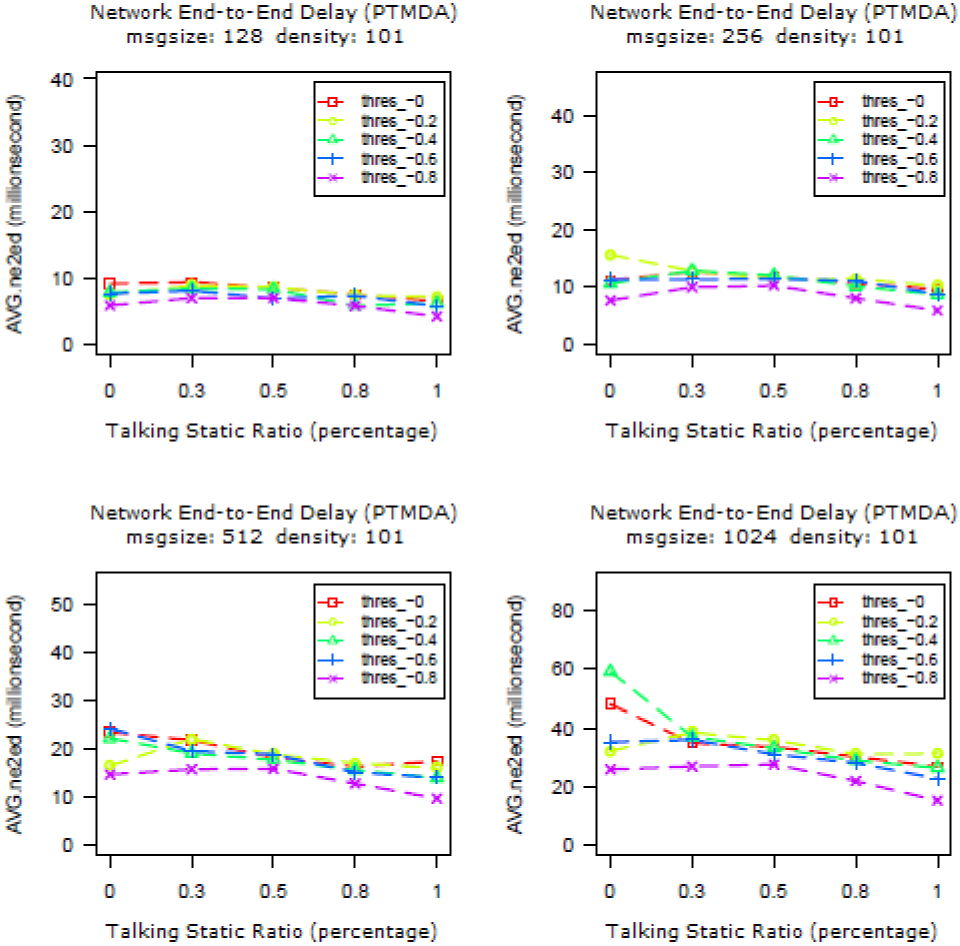


c) Invoked Broadcasts (IB)

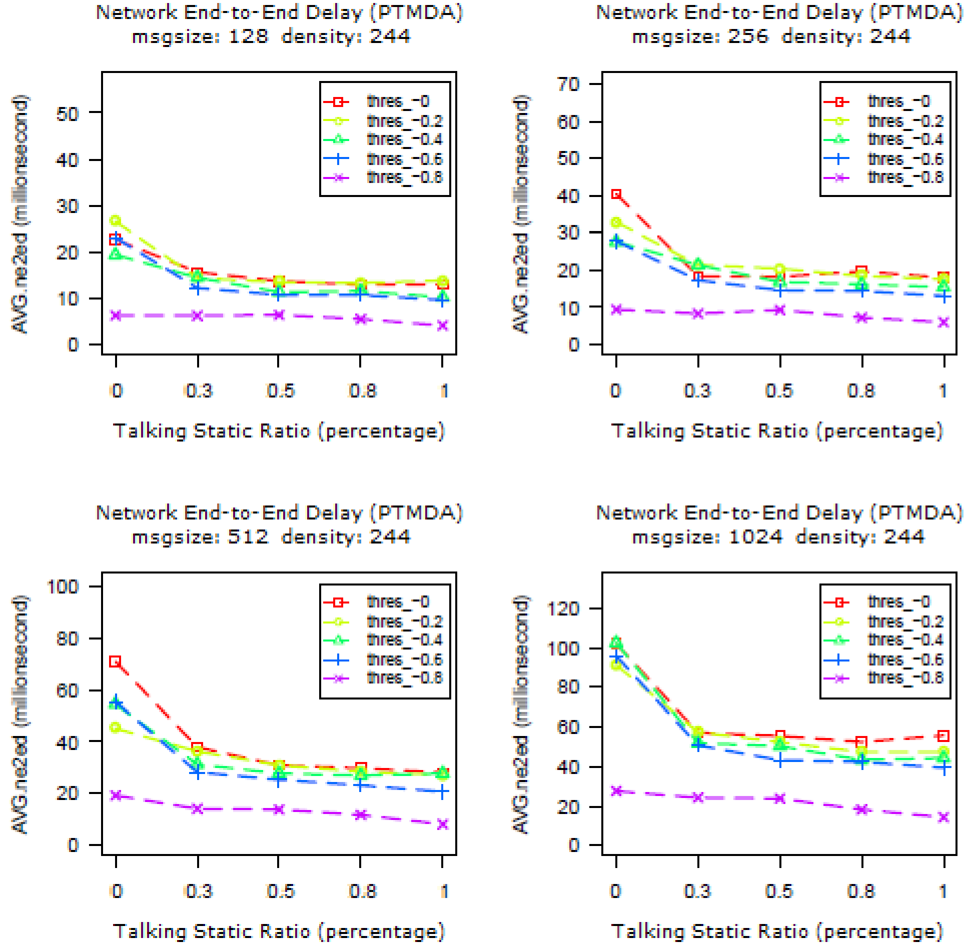


d) Packet Drops (PktD)

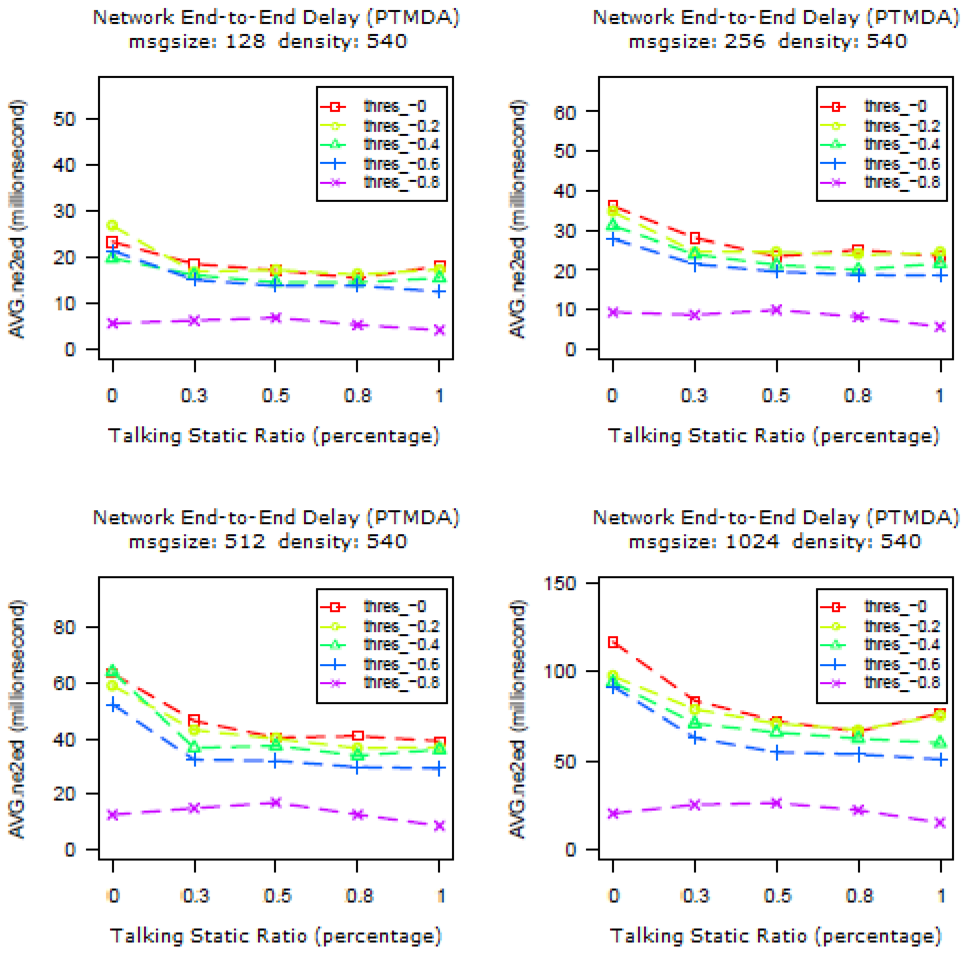
Appendix A-5 Effect of Infrastructure-node for PTMDA with different threshold values (Fig. 5.14)



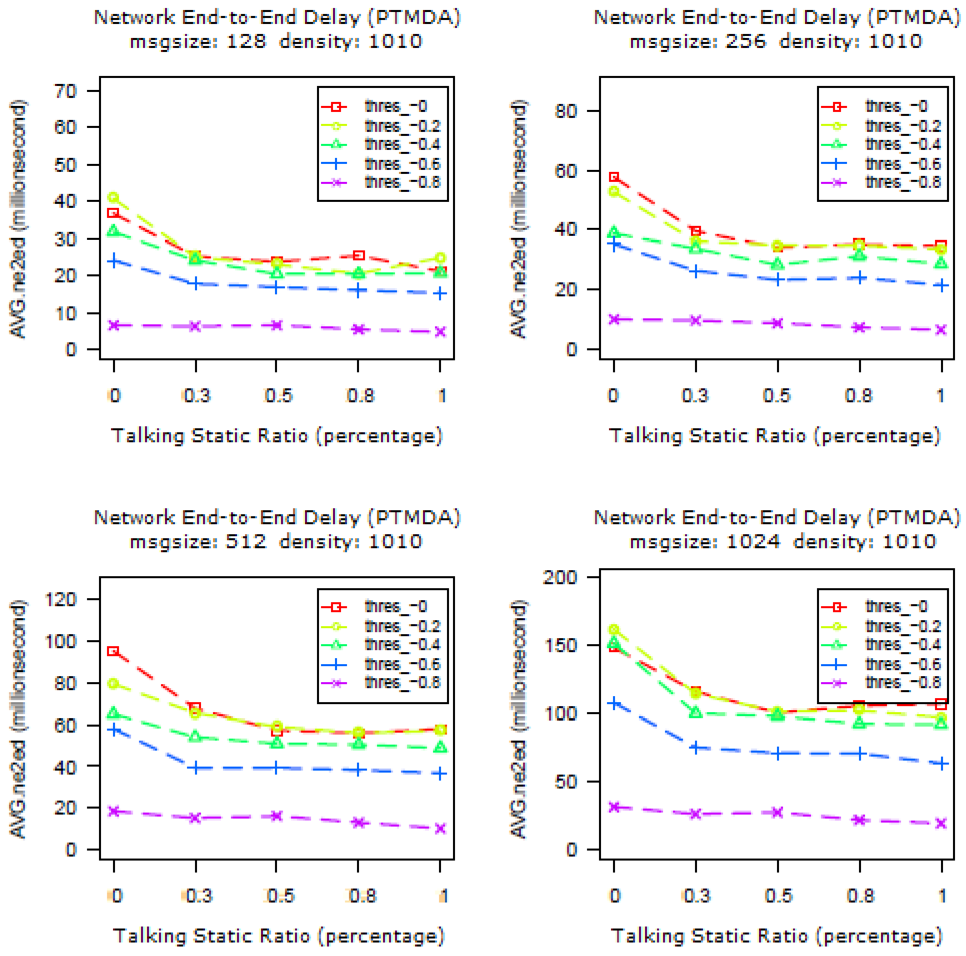
a) Network End-to-End Delay (sparse network)



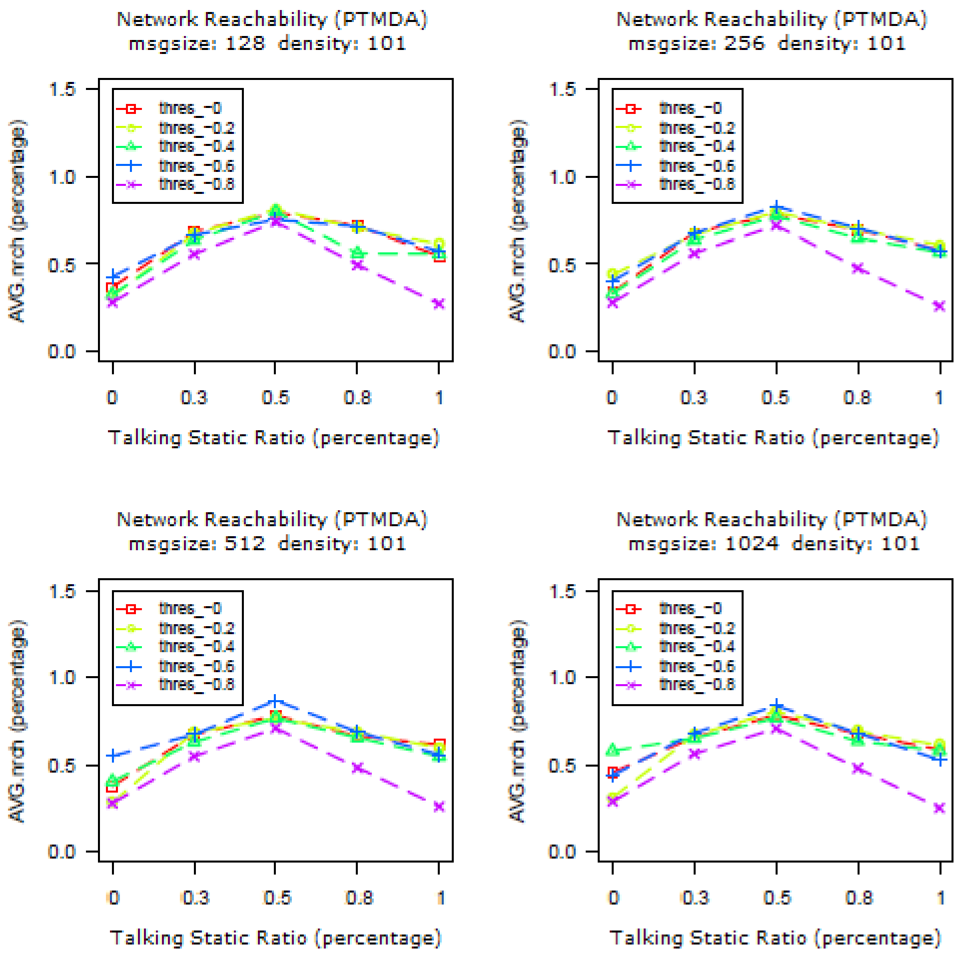
b) Network End-to-End Delay (moderate medium network)



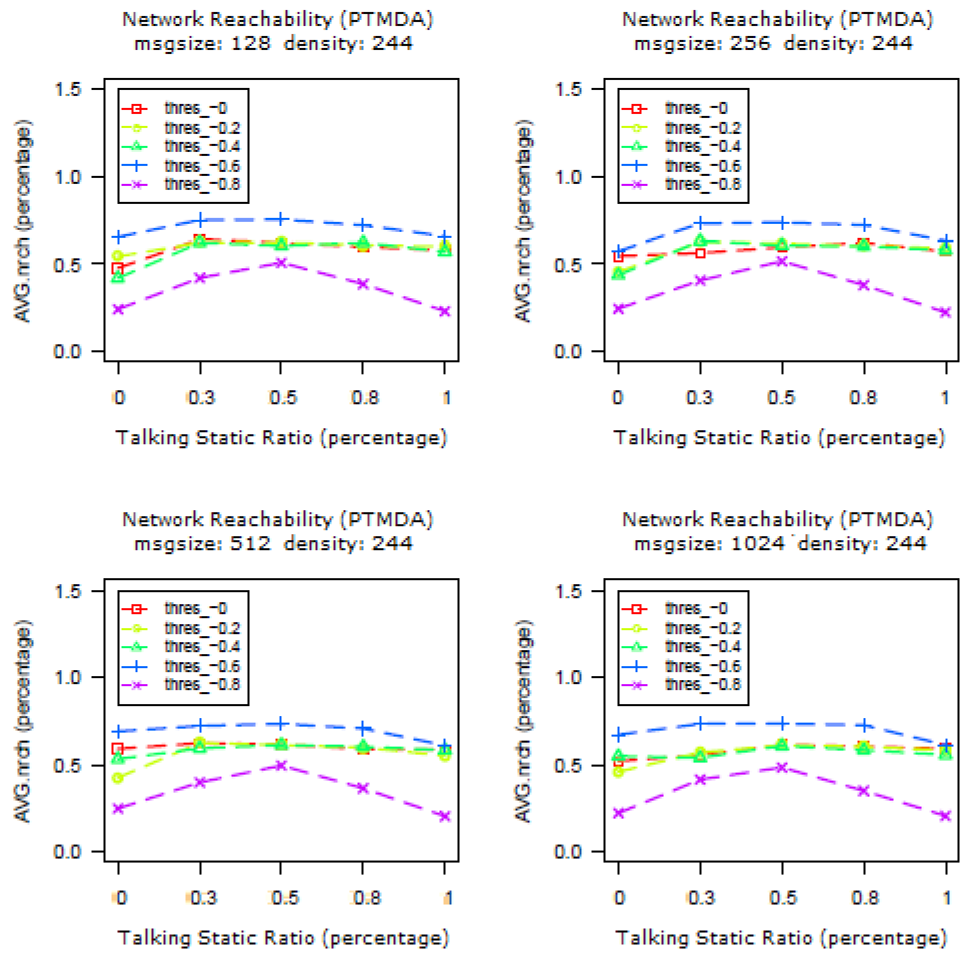
c) Network End-to-End Delay (medium network)



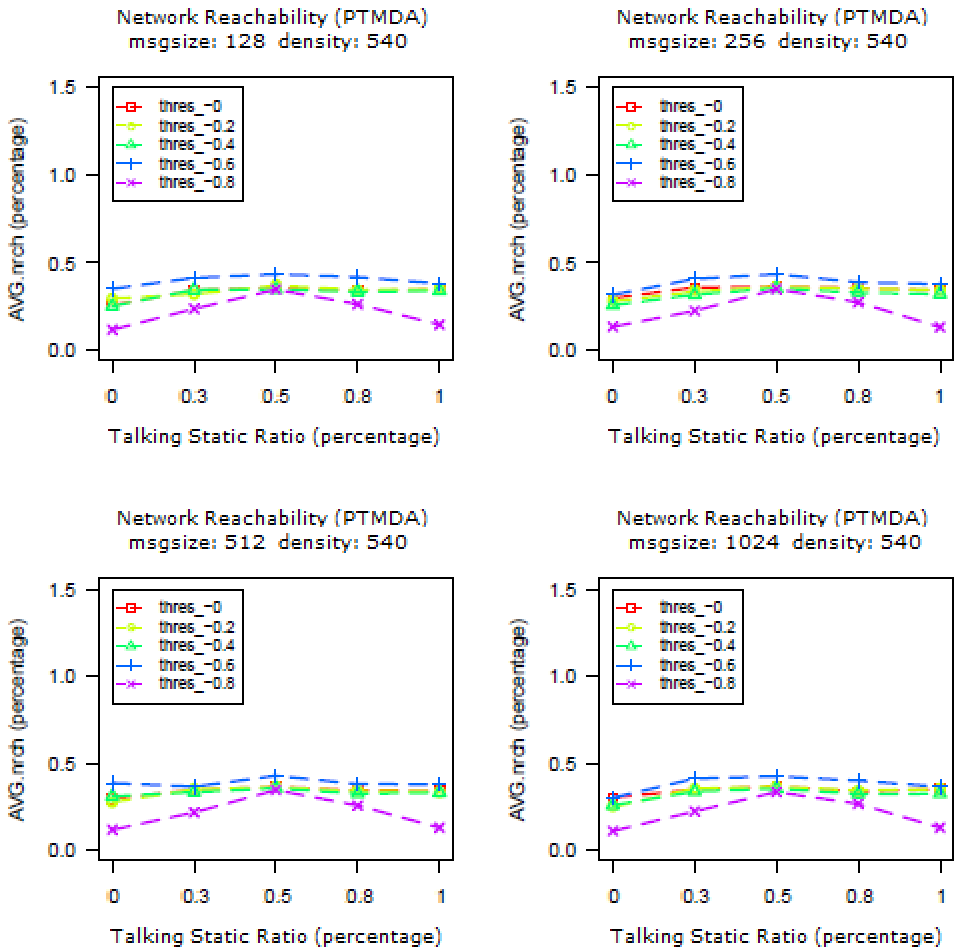
d) Network End-to-End Delay (dense network)



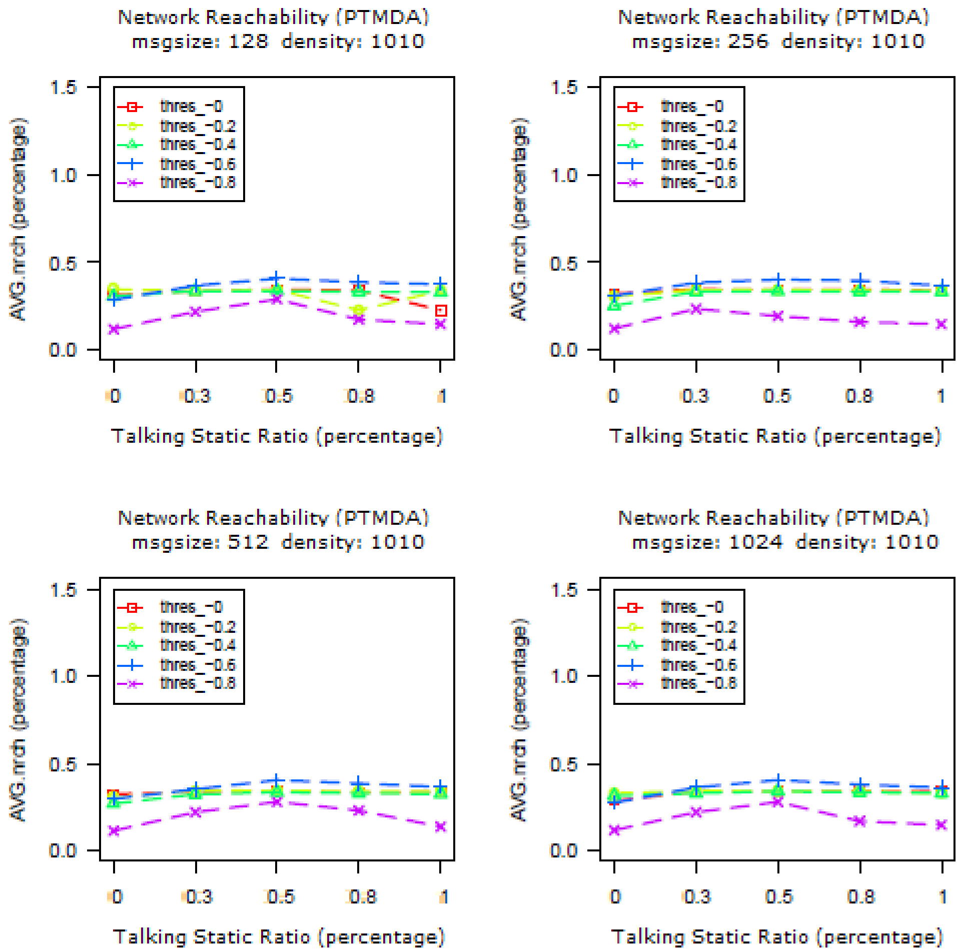
a) Network Reachability (sparse network)



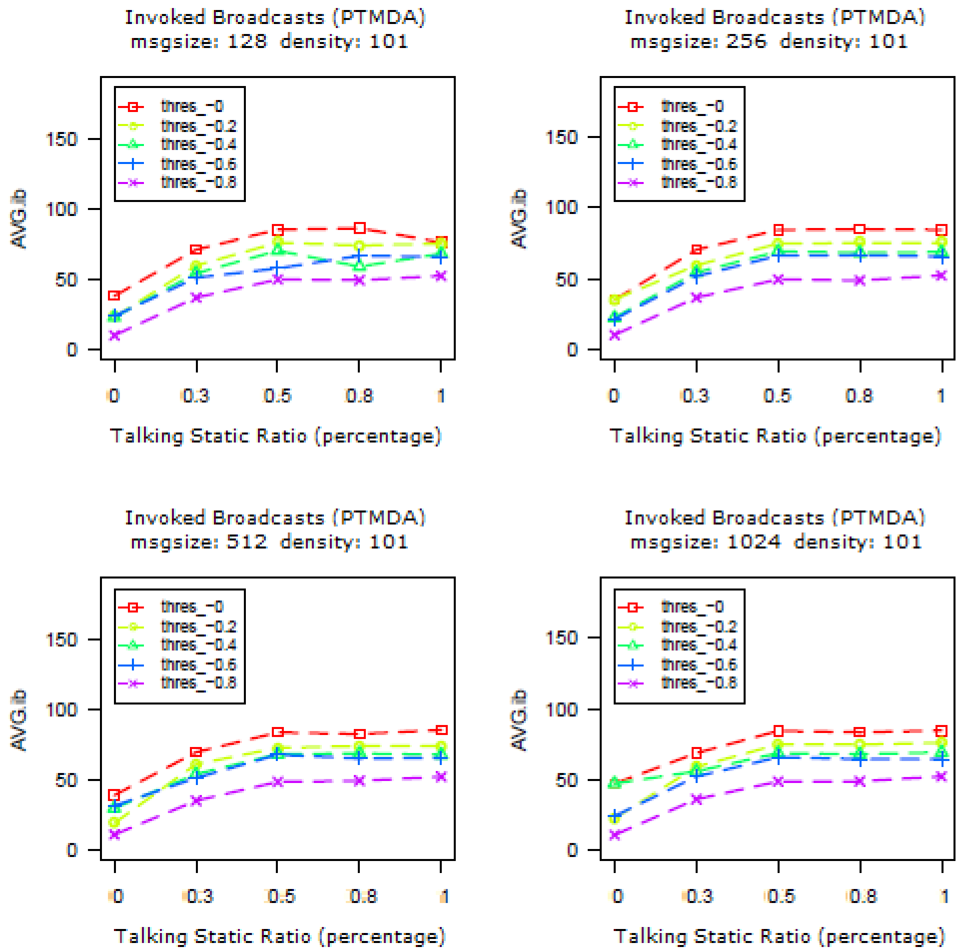
b) Network Reachability (moderate medium network)



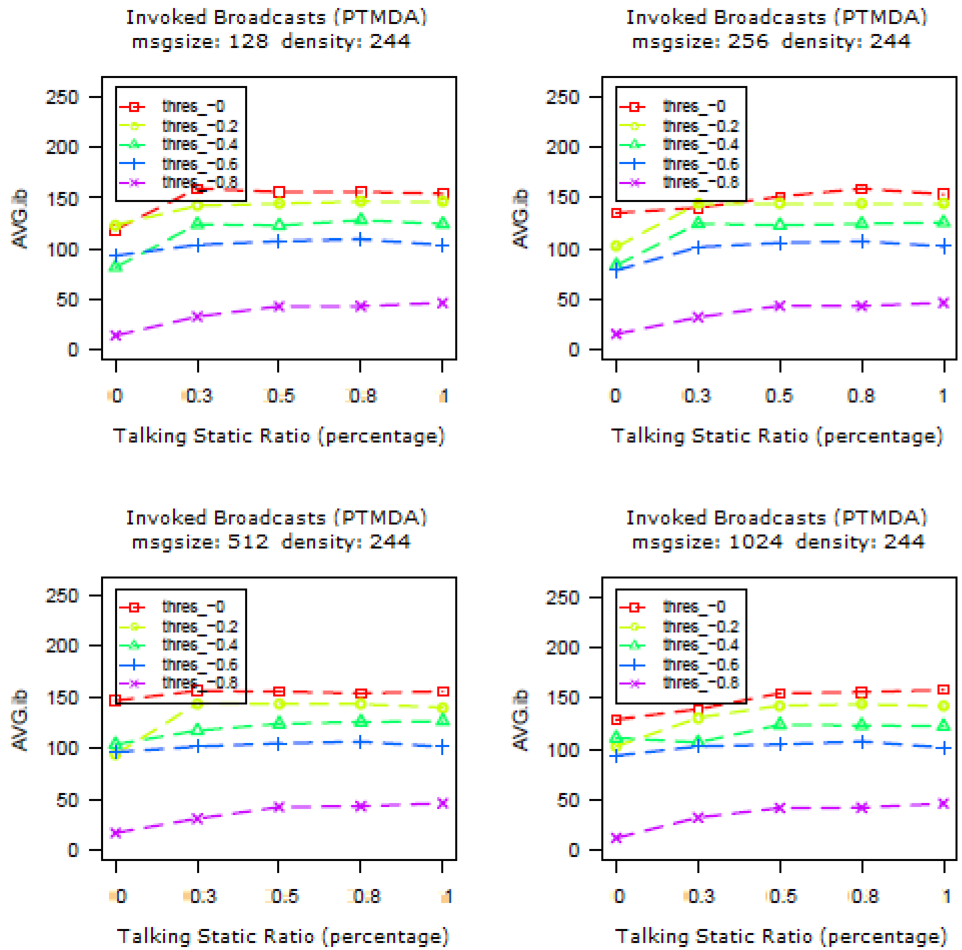
c) Network Reachability (medium network)



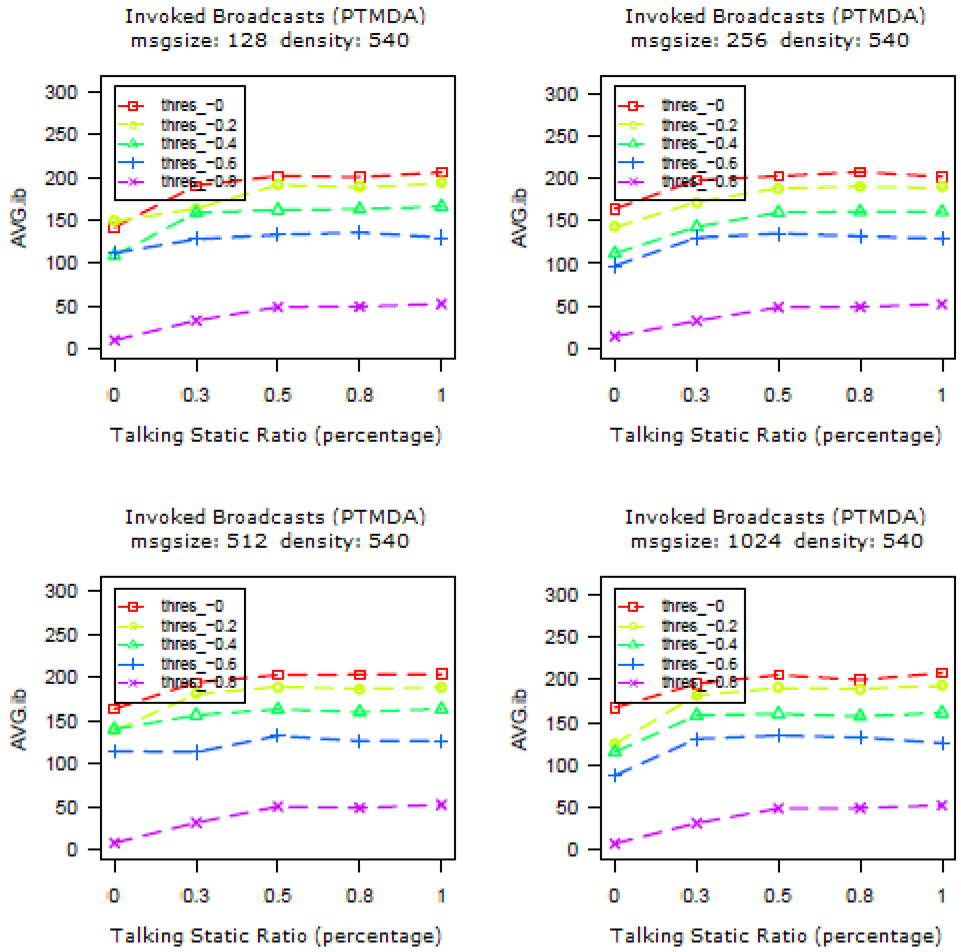
d) Network Reachability (dense network)



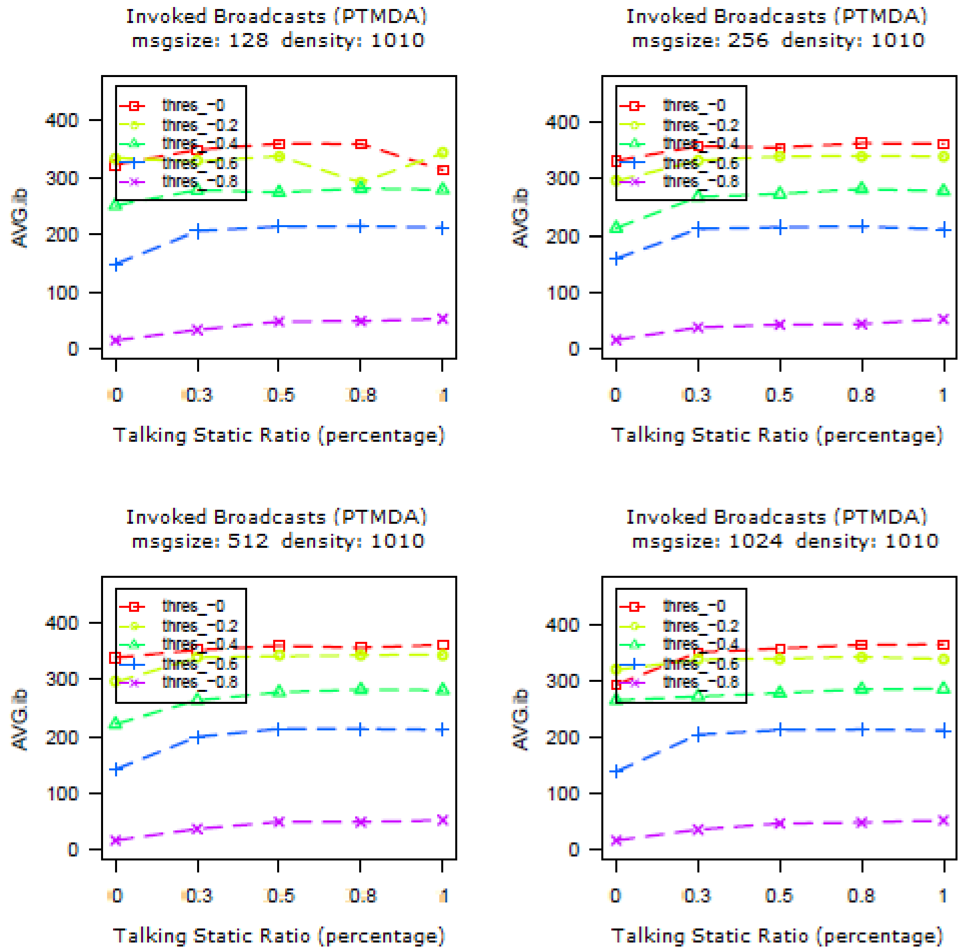
a) Invoked Broadcasts (sparse network)



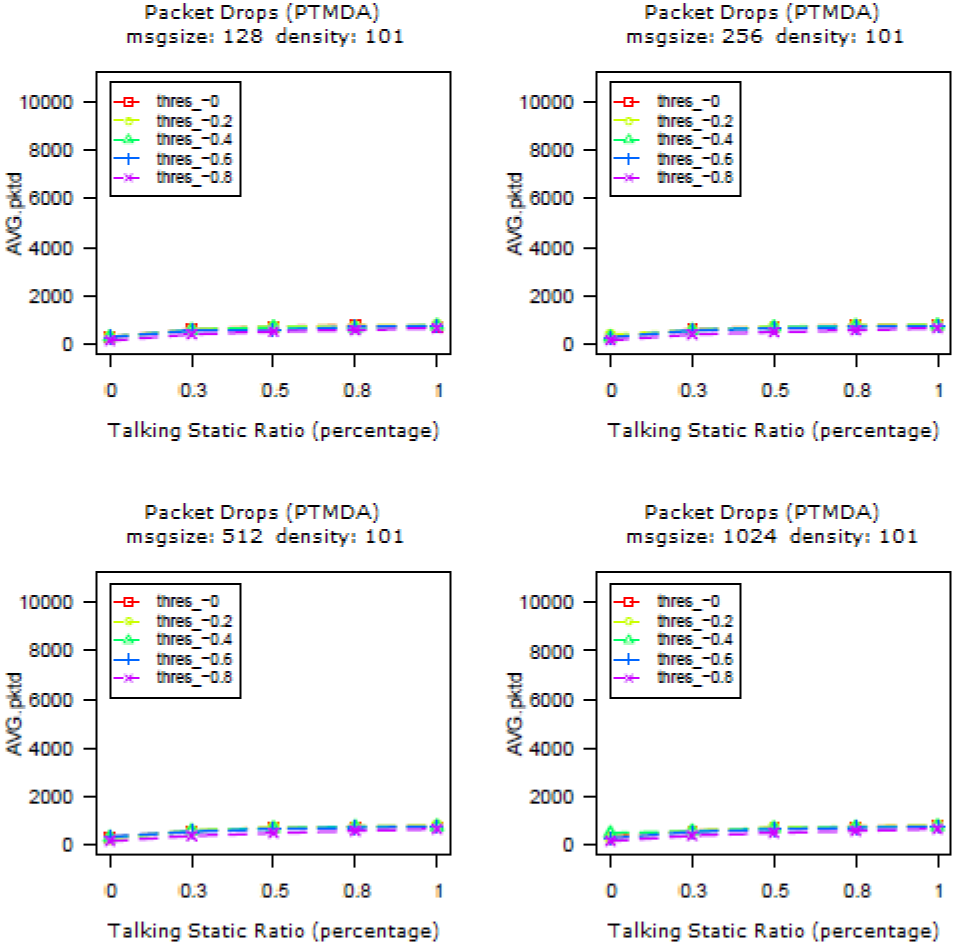
b) Invoked Broadcasts (moderate medium network)



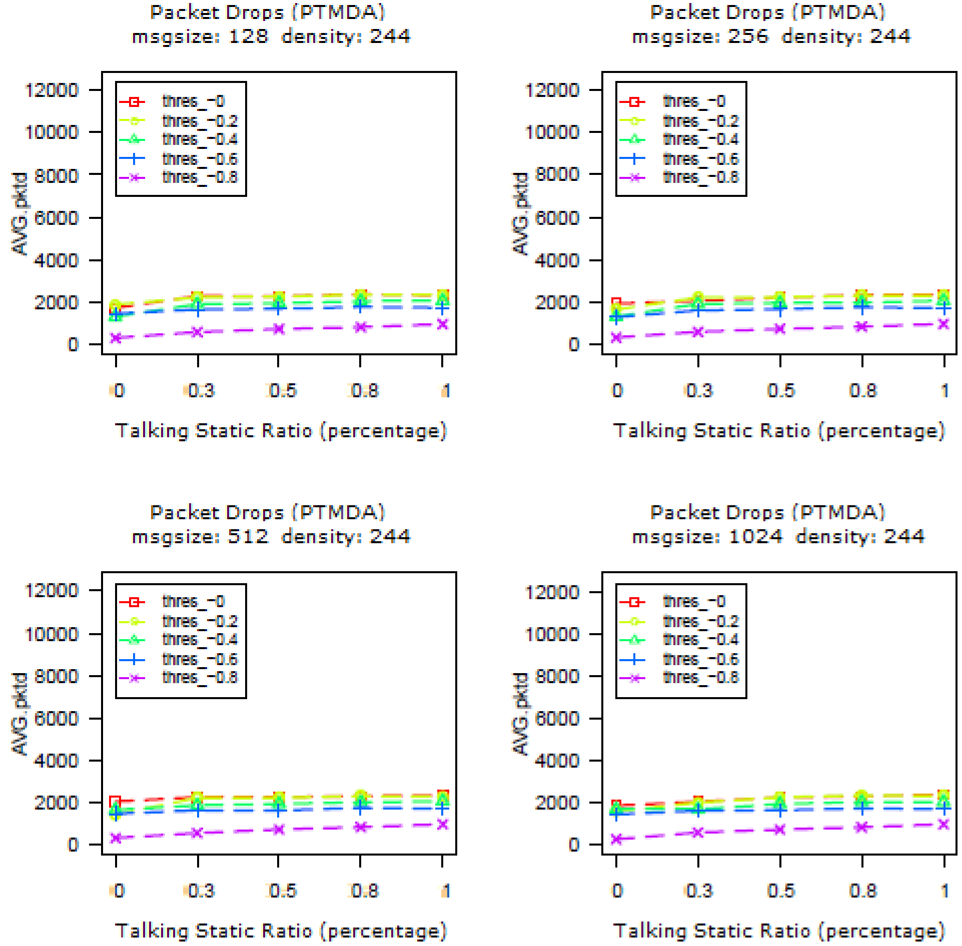
c) Invoked Broadcasts (medium network)



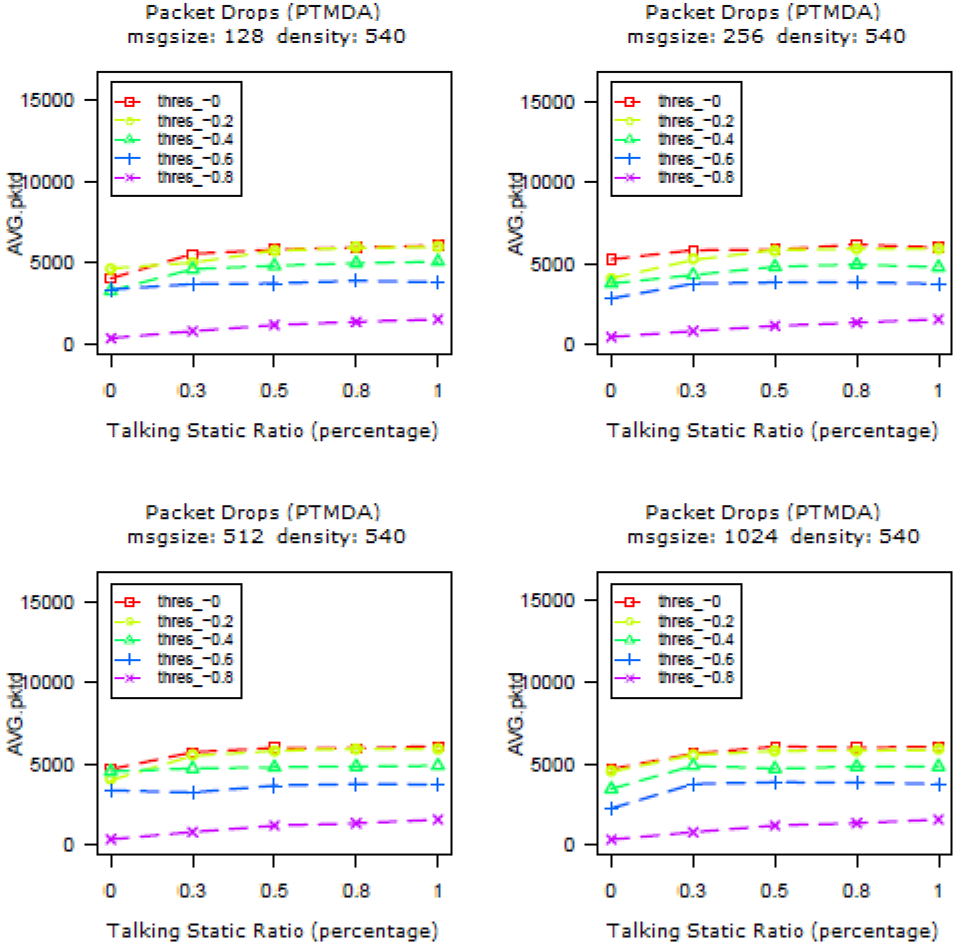
d) Invoked Broadcasts (dense network)



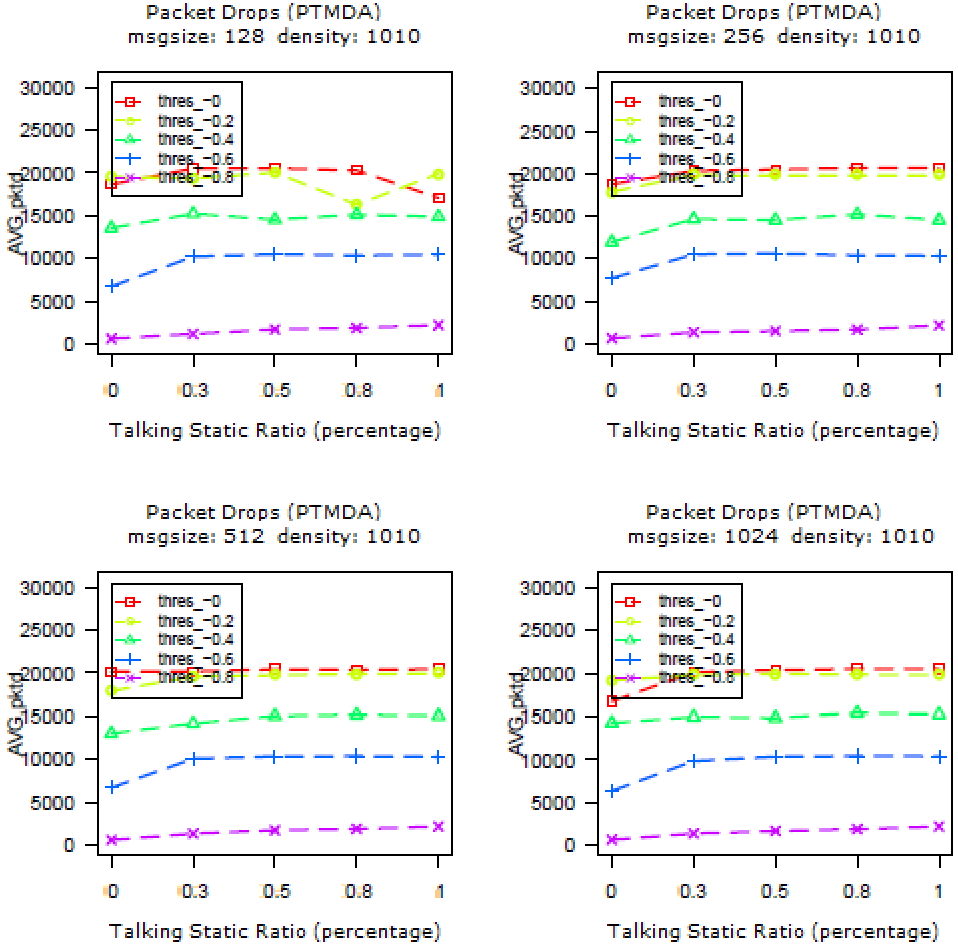
a) Packet Drops (sparse network)



b) Packet Drops (moderate medium network)

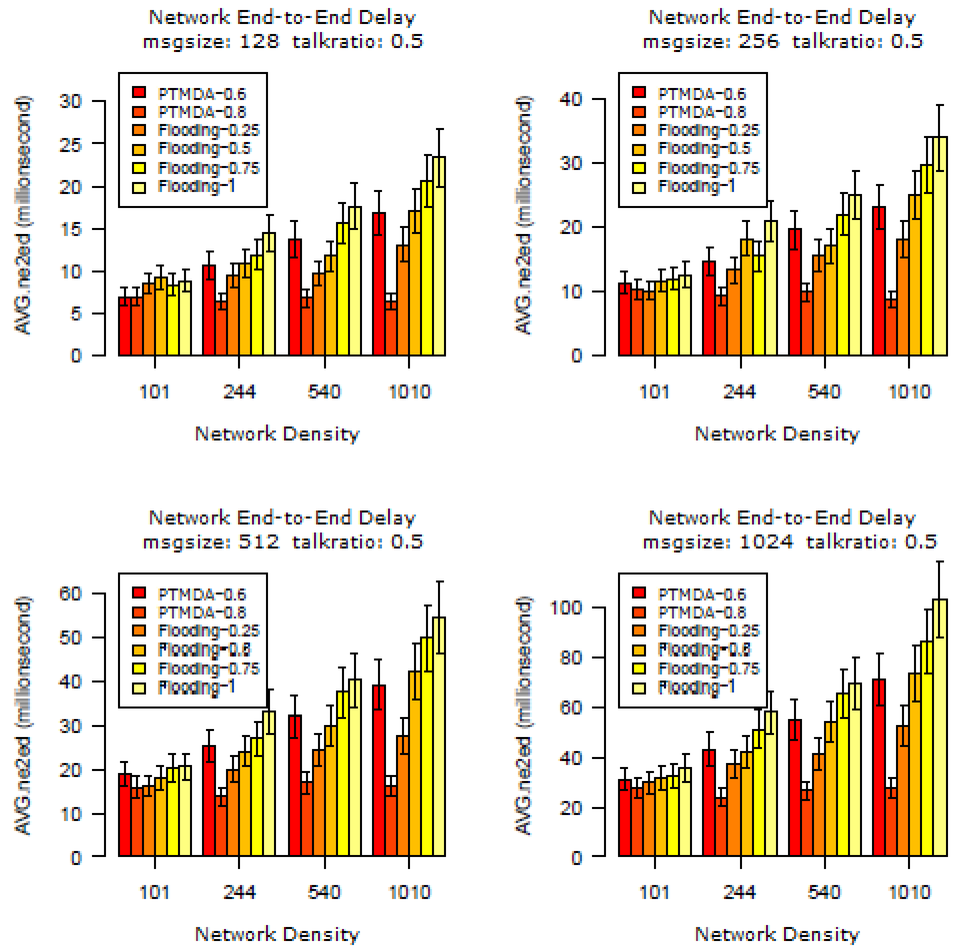


c) Packet Drops (medium network)

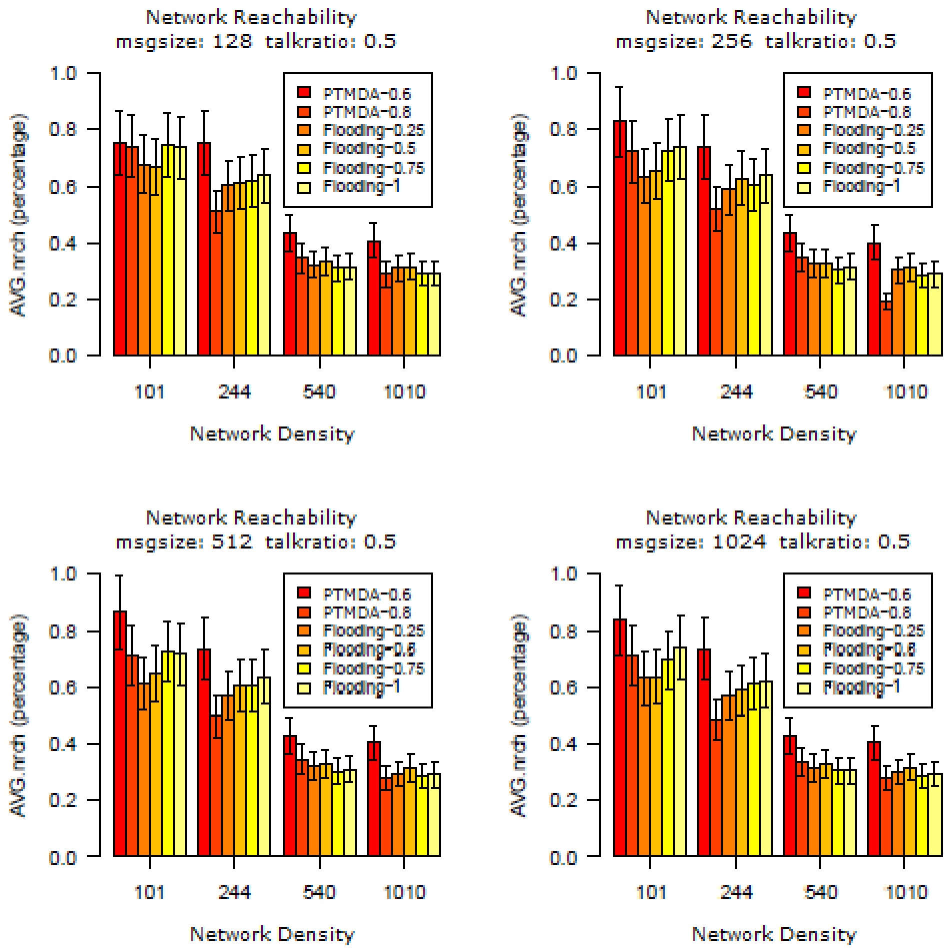


d) Packet Drops (dense network)

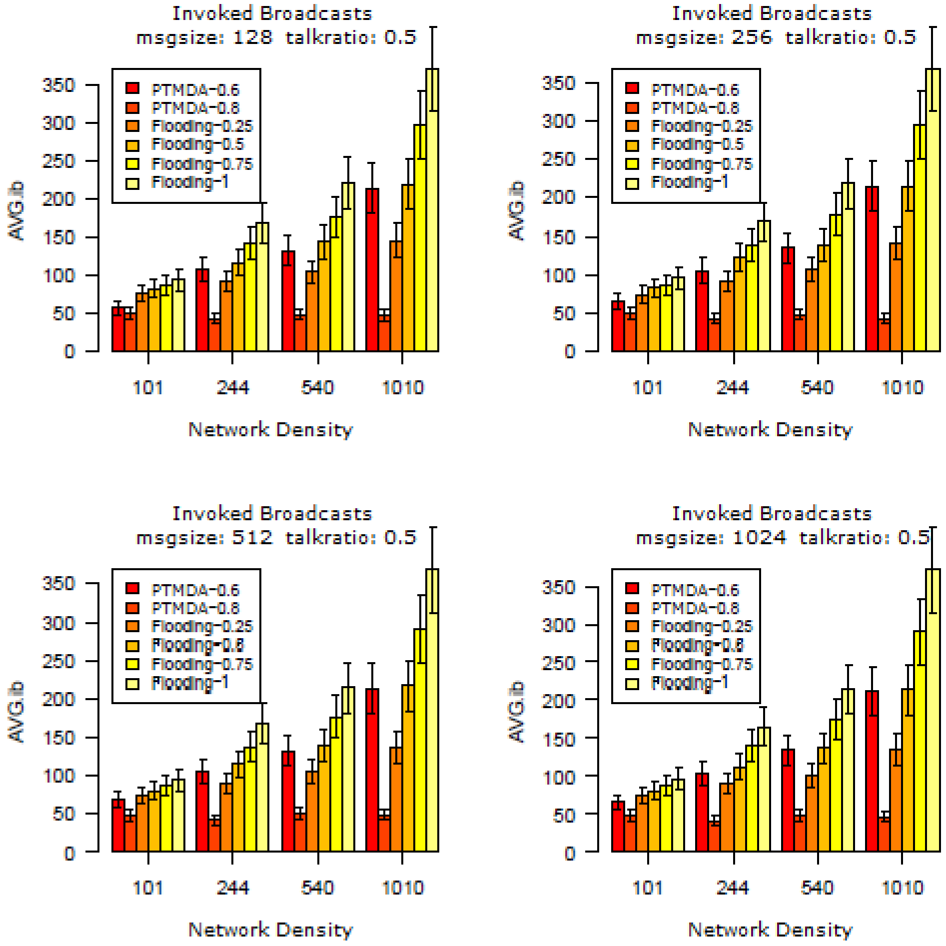
Appendix A-6 Effect of I-Routes between PTMDA and probabilistic Flooding in 50%-C2I (Fig. 5.16)



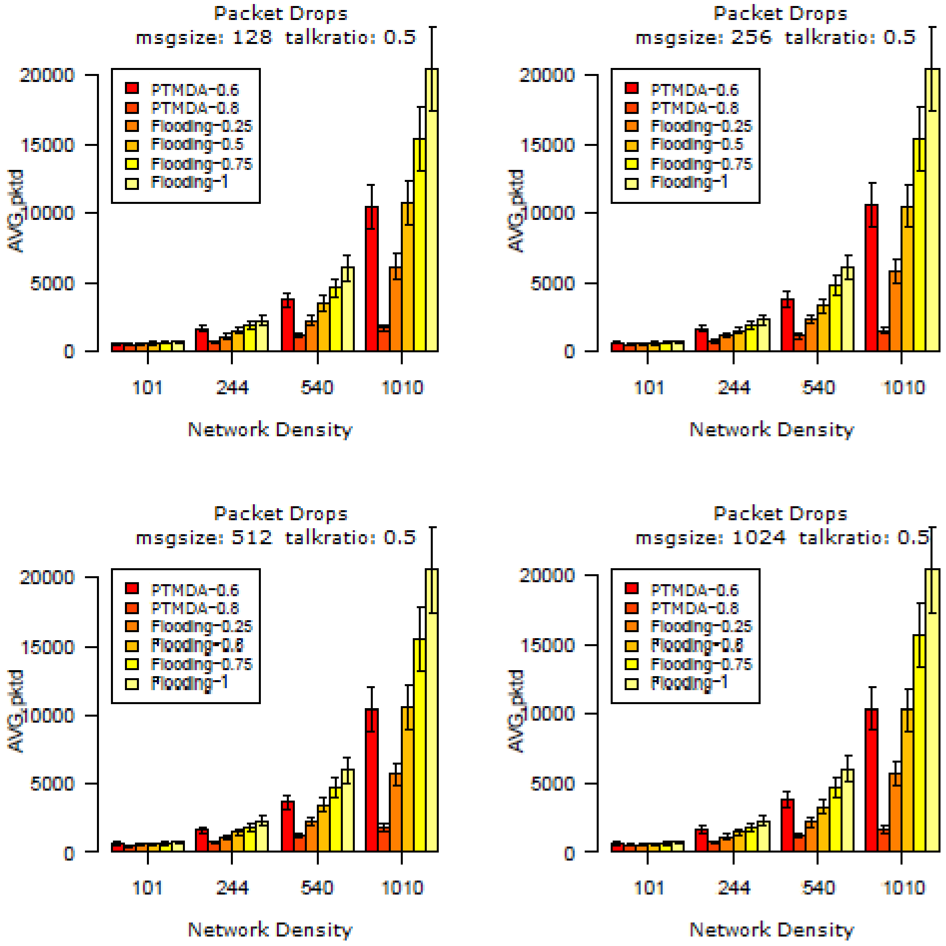
a) Network End-to-End Delay (NE2ED)



b) Network Reachability (NRch)

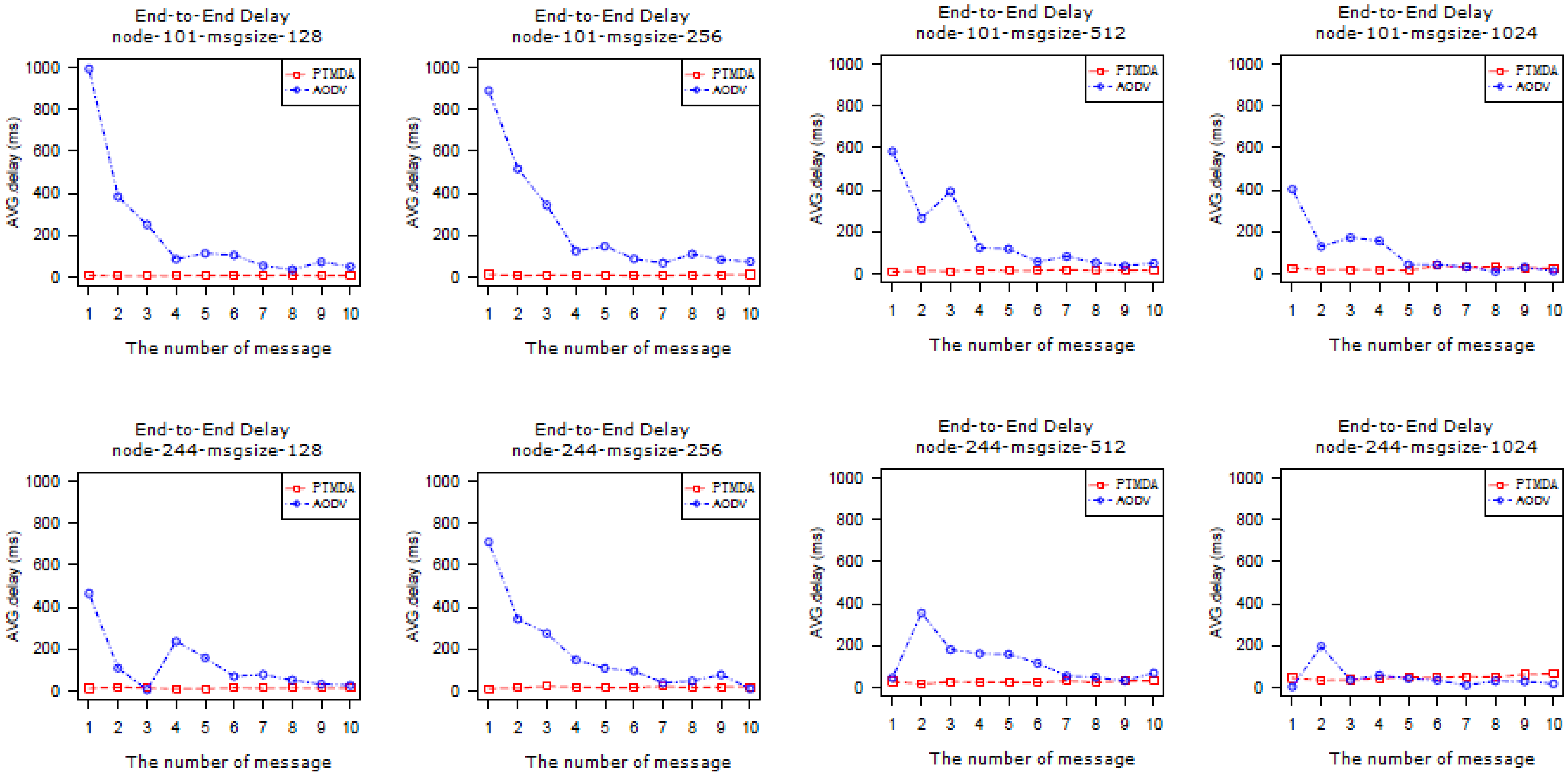


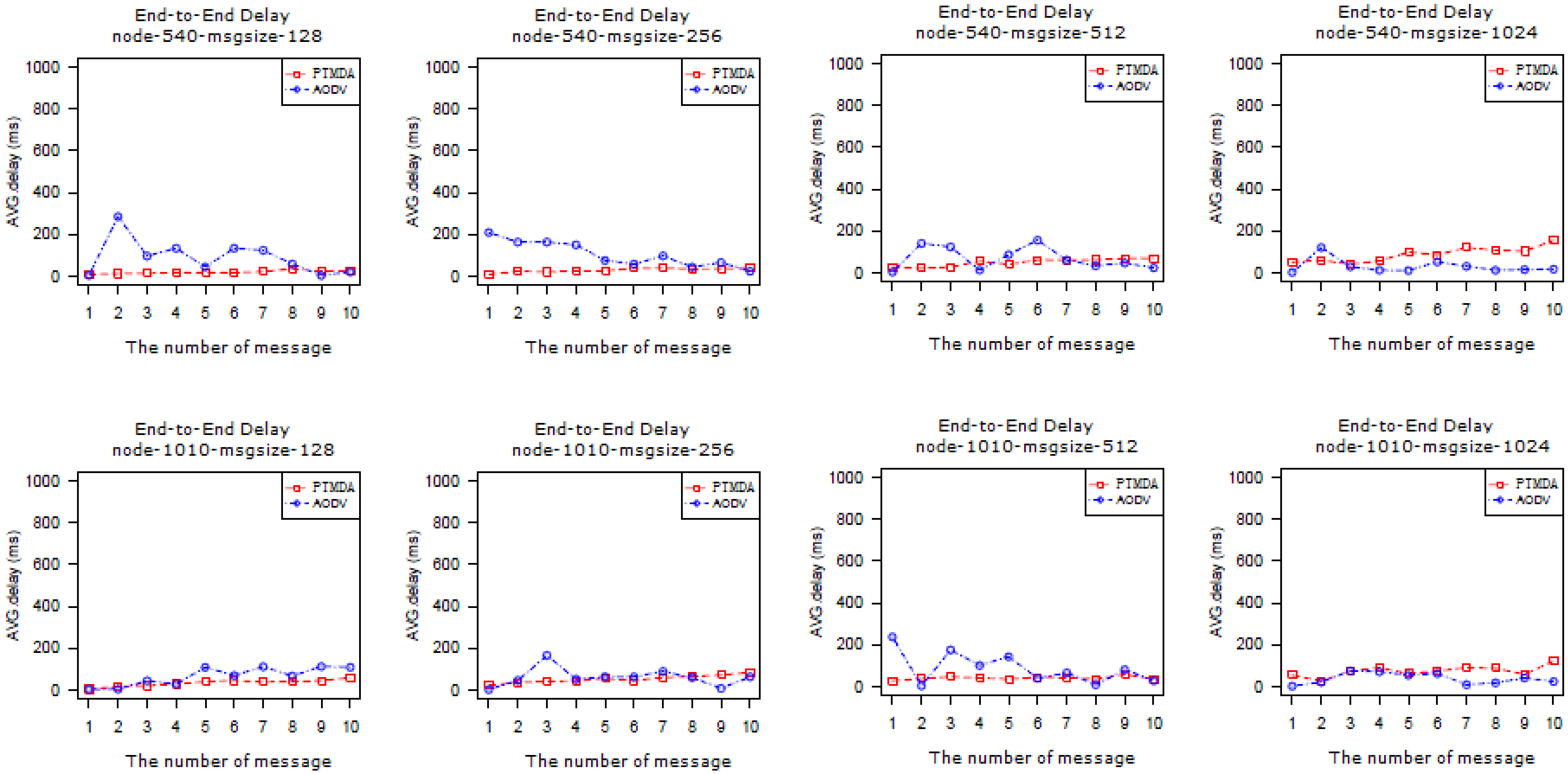
c) Invoked Broadcasts (IB)



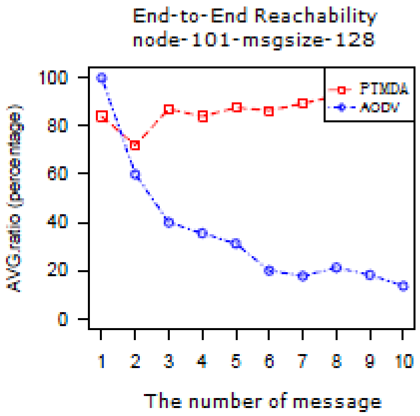
d) Packet Drops (PktD)

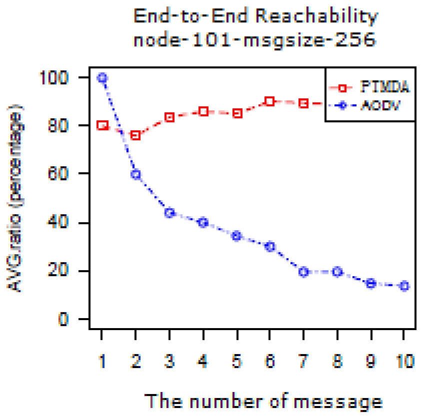
Appendix A-7 Efficiency and reliability in PTMDA and AODV based on Scenario II end-to-end communications (Fig. 5.18/Fig. 5.19-Horizontal: the effect of message size; Vertical: the effect of network density)

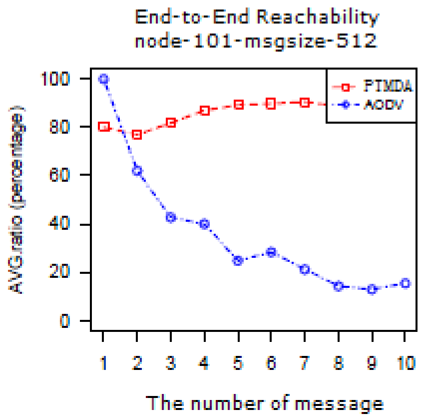


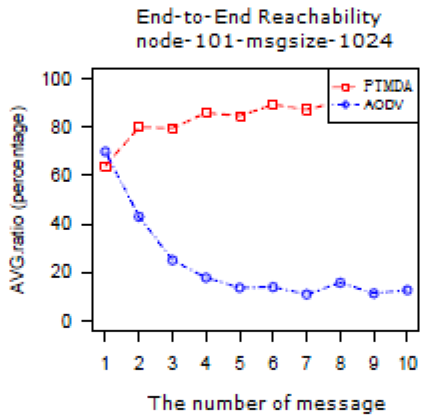


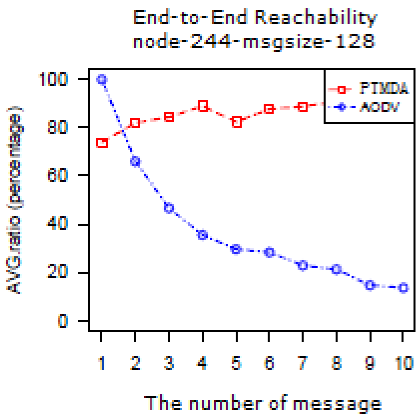
a) End-to-End Delay

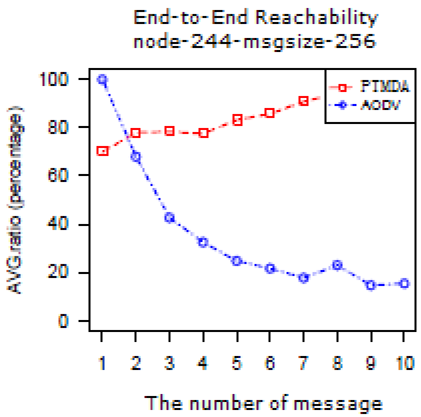

End-to-End Reachability
node-101-msgsize-128
PTMDA
AODV
AVG.ratio (percentage)
The number of message

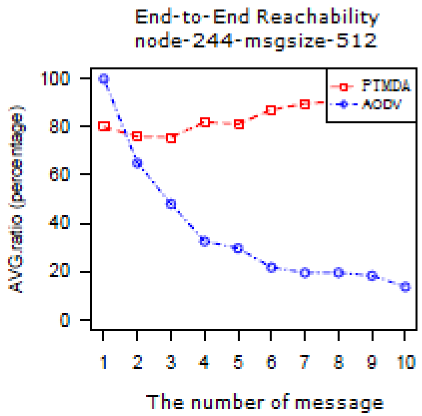

End-to-End Reachability
node-101-msgsize-256
PTMDA
AODV
AVG.ratio (percentage)
The number of message

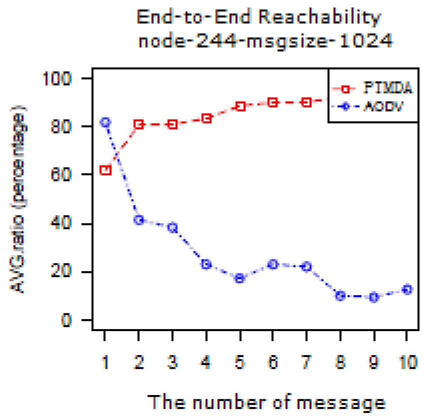

End-to-End Reachability
node-101-msgsize-512
PTMDA
AODV
AVG.ratio (percentage)
The number of message

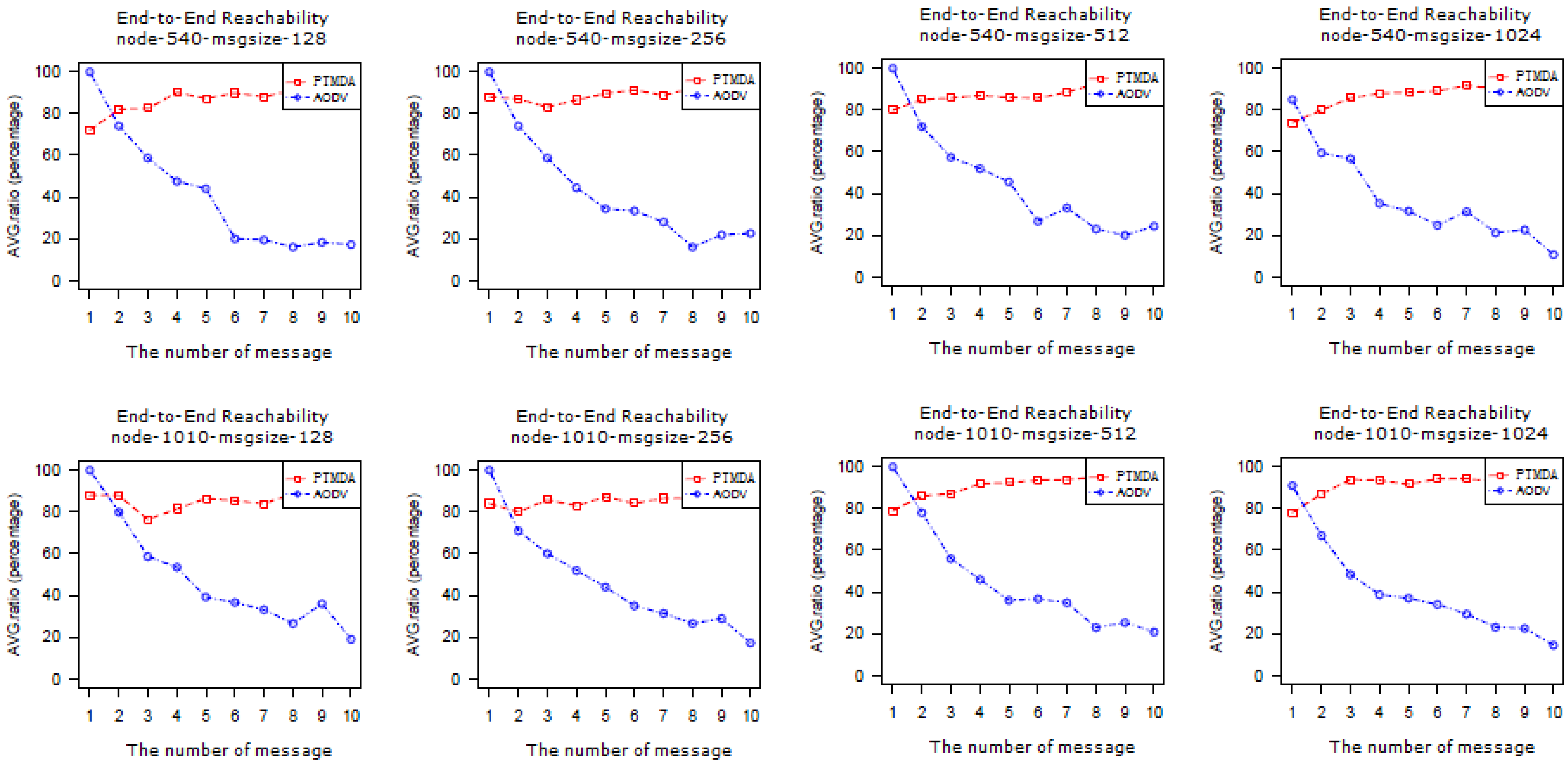

End-to-End Reachability
node-101-msgsize-1024
PTMDA
AODV
AVG.ratio (percentage)
The number of message


End-to-End Reachability
node-244-msgsize-128
PTMDA
AODV
AVG.ratio (percentage)
The number of message


End-to-End Reachability
node-244-msgsize-256
PTMDA
AODV
AVG.ratio (percentage)
The number of message


End-to-End Reachability
node-244-msgsize-512
PTMDA
AODV
AVG.ratio (percentage)
The number of message


End-to-End Reachability
node-244-msgsize-1024
PTMDA
AODV
AVG.ratio (percentage)
The number of message



b) End-to-End Reachability