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Applying Multi-Packet Reception with DTN in Vehicular Ad-hoc Networks

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APPLYING MULTI-PACKET RECEPTION WITH DTN IN VEHICULAR AD-HOC NETWORKS

BY

FENG GU

BACHELOR OF ENGINEERING

THESIS

Submitted in Partial Fulfillment of the
Requirements for the Degree of

Master of Science

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The University of New Mexico
Albuquerque, New Mexico

December, 2010

DEDICATION

To my family and friends

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ABSTRACT OF THESIS

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M.S., Computer Engineering, University of New Mexico, 2010

Abstract

In the past decades, wireless network technologies have been widely applied to numerous different scenarios, in which *Vehicular ad-hoc network* (VANET) is one application that provides inter-vehicle communication services by using self-organized routing schemes. VANET usually fits in *Delay Tolerant Network* (DTN) in which nodes are partially connected and existing path may not available between partial nodes due to limited distance for wireless transmissions. To achieve successful packets delivery in DTN, routing protocols have been proposed by using the mechanism of store and forward as well as propagating multiple copies of original packets in the network. With the mobility of nodes in DTN, the original packet or its copies may reach its final destination directly or after several relays. Among these routing protocols, Epidemic Routing is an important prototype. However, in the MAC layer, like most of wireless networks, DTN

suffers collisions among simultaneously multiple transmissions due to interferences of wireless signals. Recently, with mature of modern technologies such as CDMA or MIMO in the physical layer, *Multi-Packet Reception* (MPR) can be achieved in the MAC layer, to enable nodes receiving multiple packets simultaneously without collisions. In order to implement MPR in the MAC layer, scheduling schemes are generally required. In this thesis, our own scheduling scheme, *Group Based Scheme* (GBS), is introduced to coordinate sending and receiving activities in the MAC layer with MPR capability. A real VANET is evaluated by applying Epidemic Routing in DTN routing layer and by using different MPR capabilities in the MAC layer. This VANET is built from the mobility trace of taxis in Shanghai, China. The results of simulations demonstrate different impacts of using MPR on performances in VANET and prove that by using MPR in VANET, it outperforms the network without MPR capability, especially when the transmission range of wireless network is long which amounts to having high density of nodes in the network.

Table of Contents

List of Figures

List of Tables

List of Abbreviations and Acronyms

3G	Third Generation
3GPP	3rd Generation Partnership Project
CDMA	Code division multiple access
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CTS	Clear to Send
DAER	Distance-Aware Epidemic Routing
DIFS	Distributed Inter-Frame Space
DOA	Direction of arrival
DTNRG	Delay Tolerant Networking Research Group
FDMA	Frequency division multiple access
FIR	Finite impulse response
GIS	Geographic Information System
GPRS	General packet radio service
IEEE	Institute of Electrical and Electronics Engineers
IRTF	Internet Research Task Force
ITS	Intelligent Transportation Systems
ITU	International Telecommunication Union
MAC	Medium access control
MIMO	Multiple-Input and Multiple-Output
OFDM	Orthogonal frequency-division multiplexing
PN	Pseudo-noise

PROPHET	Probabilistic ROuting Protocol using History of Encounters and Transitivity
QoS	Quality of service
RAPID	Resource allocation protocol for intentional DTN
RFC	Request for Comments
RTS	Request to Send
SDMA	Space/ Spatial Division Multiple Access
SUVnet	Shanghai urban vehicular network
TDMA	Time division multiple access
UMTS	Universal Mobile Telephone System
WAVE	Wireless access in vehicular environments
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless local area network

Chapter 1

Introduction

1.1 Introduction

In recent two decades, wireless networks have achieved tremendously rapid developments and a variety of wireless networks are emerged in both the research works and the real applications. The wireless networks are roughly divided into infrastructure-based networks and ad hoc networks, while in the latter each node participates into packet forwarding under self-organized routing methods. Furthermore, if nodes in wireless ad hoc networks are mobile, this kind of networks is called *mobile ad hoc network* (MANET). In MANET, one of the most common issues is about the routing protocols which consider the ways to forward packets from the source to the destination. In the process of studying MANET, a special kind of MANET, which is called *delay tolerant network* (DTN), attracted researchers' attentions by its particular characteristics and usages. For example, most of *Vehicular ad-hoc Network* (VANET) belongs to DTN. In DTN, usually it may not have existent path between two nodes due to lack of wireless transmission range. In a point of view on the network level, the entire DTN is partially connected which is different from traditional MANET. Because of partially connectivity in DTN, traditional MANET routing protocols are not working well for DTN. A novel routing protocol called Epidemic Routing [1] was proposed to solve the problem and provided the methods to delivery packets successfully. After that, several improved routing protocols have been created based on Epidemic Routing. The common concepts used in all of these protocols are store and forward as well as spreading out multiple copies of original packets into the networks. However, most of existent works about DTN focus on the routing protocols, while little study is about cross-layer design. While most of DTN is based on wireless networks, it still suffers from collisions caused by interference of wireless signals. For traditional wireless technology, simultaneously transmissions in one area may cause collisions happened on the receive side and all the receivers are unable to receive correctly. This can severely affect the throughput of the network especially for the place where traffic and node density are heavy. To solve the problem, *multi-packet reception* (MPR) is usually implemented in the MAC layer. MPR is a technique which allows multiple packets can be received correctly at the same time. Therefore, it enhances the capability of nodes for receiving multiple packets simultaneously. Generally, by properly using MPR, the performance of the wireless networks is able to be improved. In order to implement MPR in the MAC layer, code division multiple access or antenna arrays is often used in the Physical layer to support MPR.

In this thesis, we implement MPR at the MAC layer to investigate the performances of DTN using Epidemic Routing protocol. The DTN model used in our work is a real VANET in which the mobility traces are collected from the GPS data of 4000 taxis in Shanghai, China. We focus on the performances of DTN by changing the number of allowed simultaneously received packets, which is defined as MPR capability. From the results of our simulations, by properly increasing MPR capability, the performances of DTN are improved especially when the wireless transmission range increases, equivalent to the situation with higher node density.

1.2 Background and Related works

A large number of works are concentrating on DTN routing. Epidemic Routing [1] was the first and also the most important method for successful packets delivery in DTN. Consequently many improved routing methods were proposed, and nearly all of them are inherited from Epidemic Routing [3] [4] [5]. However, these works only considered the routing in DTN layer and lacked the study of effects from other layers like MAC layer. While most of DTN belongs to wireless network, it is inevitably influenced by the factors from MAC layer such as collisions.

On the other hand, several MPR models and protocols have been studied in [7] [8], while other works were about the performance of the network using MPR [9] [10] [11]. The general improvements of using MPR were evaluated in [9]. However most of existing works are based on traditional ad hoc networks and WLAN [28], and little work is about DTN. In our previous work, several mobility models and a packet-oriented routing protocol related to Shanghai taxi GPS data trace were introduced in [12] [13] [14] [38] [40] [41]. In [39], we investigated the impact of performances by using MPR in DTN, which is the blueprint of this thesis.

1.3 Problem Statement

This thesis will evaluate the performances of a real VANET by using Epidemic Routing protocol in the routing layer with MPR capability in the MAC layer. To implement MPR in the VANET, a scheduling scheme is designed to manipulate the packet sending and receiving in the MAC layer.

1.4 Thesis Outlines

The thesis is organized as follows: Chapter 2 introduces the concept of vehicular ad-hoc networks and explains the motivation of our designs from the analysis of the mobility model of VANET. In Chapter 3, the DTN is presented and the corresponding routing methods are analyzed. We describe the MPR in Chapter 4, where two methods of achieving MPR are discussed in details. In Chapter 5, we present our routing-MAC cross-layer design and a group base scheduling scheme. In Chapter 6, the mobility trace of VANET is introduced. After that the setup of our simulation environment, the result of simulations as well as analysis of the results are described. Finally, we conclude our work and look ahead for the future works in Chapter 7.

The preliminary results of this thesis have been published as “Impact of Using Multi-Packet Reception on Performance in Delay Tolerant Networks” in proceedings of Vehicular Technology Conference, May, 2010 [39].

Chapter 2

Vehicular ad-hoc networks

2.1 Introduction of Vehicular ad-hoc networks

Vehicular ad-hoc Network (VANET) is a form of Mobile ad-hoc network, in which vehicles communicate with each other and with nearby fixed roadside equipments [15]. Recently, the research of VANET has attracted significant interest from both academia and industrial communities. This is due to the large amounts of design and implementation considerations in inter-vehicle communication applications and the growing of existent studies in MANET in the past decade. The main goal of VANET is to provide real-time traffic and related information for drivers and passengers, e.g., collision warning, construction alarms and etc., which can be used to facilitate path selection for the trip.

To achieve communications among vehicles, customized tracking and transceiver devices are installed in the vehicles, and each vehicle such equipped with these devices becomes a node enabled to send, receive and relay messages through wireless communications in the VANET network.

In the earlier design phase, several different wireless technologies were considered to be implemented in VANET, e.g., traditional IEEE 802.11, GPRS and UMTS [16]. By the reason of strong adaptability and successful implementation in WLAN, IEEE 802.11 technology family stands out to be most applicable in VANET. Specifically, one amendment of the IEEE 802.11 protocol suite, namely IEEE 802.11p, has been tailored to facilitate the *wireless access in vehicular environments* (WAVE) [17]. It supports Intelligent Transportation Systems (ITS) applications which include data exchange between high-speed vehicles and between the vehicles and the roadside infrastructures in the licensed ITS band of 5.9 GHz (5.85-5.925 GHz) and rely on the OFDM modulation scheme. Furthermore, the IEEE 802.11e standard can also be used in VANET to improve the quality of service (QoS) in the communications between vehicles [16].

Meanwhile, as the theoretical research on VANET advances various field implementations are also being tested and evaluated in many countries. For example, the "FleetNet-Internet on the Road" [18], is a project supported by German government and industries to develop and promote a vehicular communication system based on decentralized multi-hop ad hoc radio networks.

2.2 Mobility pattern of VANET

Even though VANET belongs to the range of MANET and derives numerous traits from the latter, however, there are notably different properties and characteristics of VANET that makes it unique and worth special consideration when it comes to its design and implementation.

Firstly, unlike in MANET, nodes in VANET may move out of effective distance to communicate with others due to the constraint of limited wireless transmission range. Thus, unlike in traditional MANETs, the paths between some nodes may not exist at that time. Secondly, as nodes are vehicles which have fast moving speed, the duration of two nodes located within the transmission range of each other may lasts for only a short period. Finally, since in the proposed VANET model, it is assumed that the mobility of vehicles is moving in most municipal streets in the city, the trace of nodes is constrained into lines in the 2-dimension space. This is different from the fully random moving model of nodes in free space used in many MANETs.

2.3 Analysis and Design

For the first character of VANET, it is very similar to the DTN, in which nodes are partially connected and it may have no existing path between two nodes. As many works have proposed a range of efficient routing protocols in DTN, it is straight forward to adapt the routing methods from DTN to VANET. For the second character of VANET, according to DTN routing protocols introduced later in Chapter 3, nodes may exchange packets when they move into the same transmission range. However, due to the fast speed of nodes, the duration of gathering time may be short in VANET, it is reasonable to use efficient transmission schemes in which simultaneously transmission is a proper choice. For the last character of VANET, since the moving trace of each node is constrained in lines, it is possible for a portion of nodes to gather together locally. This situation may exist in some real cases like several vehicles moving closely along the same road in same direction, some vehicles waiting at traffic lights at an intersection and several vehicles waiting at a public spot like hotel, shopping mall or bus station. However, if nodes gather together and exchange relevant packets simultaneously between each others, due to the interference of wireless signals, simultaneous transmissions may lead to collisions that cause failure of packet receiving. To solve this problem, MPR is one of candidate methods. In networks with MPR capability, multiple packets from different sources are able to be received simultaneously without collisions. Therefore, it is interesting to investigate the impact of using MPR on network performances in VANETs.

In summary, it is proper to bring DTN routing methods into VANET and it is also interesting to evaluate the impact of using MPR in VANET. Hence, the next chapter is for the discussions about DTN and the Chapter 4 further introduces the concepts of MPR.

Chapter 3

Delay Tolerant Networks

3.1 Concept of DTN

Delay tolerant network (DTN) is a kind of network that suffers long delay between end systems or lacks continuous network connectivity. It covers a wide range of different networking scenarios, like deep space communications, terrestrial networks, military ad hoc networks, sensor monitor networks and etc. In general, the DTN philosophy is to use storage capacity, a variety of protocol techniques, replication and parallel forwarding and many other manners to overcome communication disruptions. In the network without reliable real-time, end-to-end communications, store-and-forward methods are important mechanisms for achieving operational success [19].

Since DTN is conductive to a broad range of application scenarios, notable efforts have been invested on building the general architecture for it [20]. The Delay Tolerant Networking Research Group (DTNRG), a research group chartered as part of the Internet Research Task Force (IRTF), proposed several RFCs and Internet Drafts concerning about DTN architecture and protocols [21].

However, these works are based on the generic DTN prototype. Since different kinds of DTN have their own special properties, it is reasonable to discuss their own characteristics respectively. More specific and germane to the discussion here, this work is based on the evaluations of DTN belonging to MANET. In the following part, without confusions, the word DTN will refer to this mobile ad-hoc delay tolerant networks.

3.2 Routing Protocols

Routing is an important topic in DTN due to the property of partial connectivity which makes it difficult to consistently deliver packets in the network. To successfully communicate along intermittently connected path between participating nodes in DTN, seven novel routing methods are discussed here, in which basic principles are all *store and forward*, only different in implementation details.

3.2.1 Epidemic Routing

The *Epidemic Routing* [1] is one of the efficient schemes to deliver messages between nodes in the DTN. The Epidemic algorithm is original used as a method to replicate and backup data in database maintenance [2]. However, Amin Vahdat et al [1] introduced this algorithm into the area of partially connected ad hoc networks. After proper modifications, the Epidemic algorithm is adapted to the partially connected network scenarios and is able to successfully deliver packets in DTN environments.

In Epidemic Routing protocol, each host stores the messages originated from its own as well as the messages received from other hosts as a relay. To improve the performance, messages stored in a node are digested into a hash table in order to achieve rapid search operation which has a high execution frequency in the algorithm. Specifically, when two nodes, e.g., node A and B, try to discover each other, node B will send a Hello message to node A like a beacon message. After that, node A transmits its summary vector SV_a to node B, where SV_a refers to the indexes of the messages stored in the buffer of node A. Next, by using the SV_a, node B enumerates the messages stored in node A but not in node B as a *request*. Then node B transmits the *request* back to node A for what messages it need. Finally, node A sends all the requested messages to node B. The Figure 3-1 illustrates the procedure in detail.

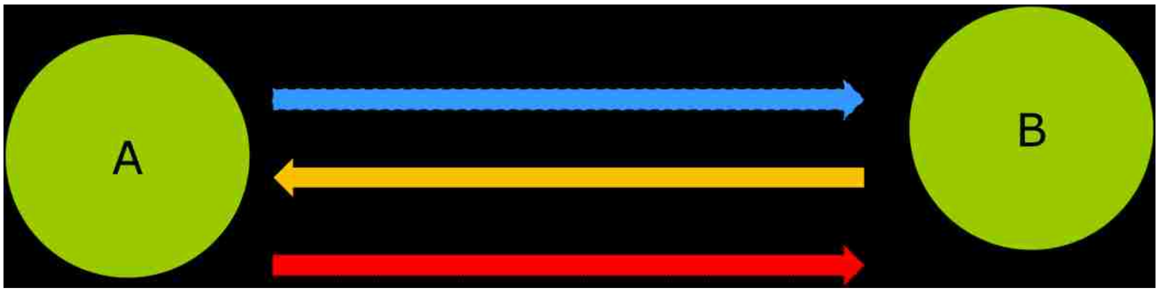


Figure 3-1 Epidemic Routing algorithm

In such a way, packets are propagated in the network in a flooding style. According to the result from [1], if the time for delivery is long enough, all of packets will arrive at their final destinations eventually. Although Epidemic Routing is able to achieve successful delivery in DTN, due to its flooding property, it generates too many copies of original packets and costs large amount of resources like buffer, bandwidth, etc.

However, Epidemic Routing still acts as a guiding prototype for designing new routing methods in DTN, since nearly all of the revised DTN routing methods apply the similar concept as the Epidemic Routing.

3.2.2 Spray and Wait Routing

The *spray and wait* routing [3] is based on Epidemic Routing but it strives to reduce the time of broadcasting packets to other nodes which significantly mitigates the flooding problem in the Epidemic Routing while still maintains the delivery ratio in an acceptable level. The spray and wait routing consists two phases, namely spray phase and wait phase. In the spray phase, several copies, say *L* copies of the original message are propagated to other nodes from the source node. Therefore, the message has L copies distributed to the different L nodes in the entire network after the spray phase. Later in the wait phase, each of the L nodes will carry the copy of the message and wait to forward it to its final destination directly if the node is adjacent to the final destination node in the movement by chance. Essentially, spray and wait routing is a combination of the Epidemic Routing and the simple direct transmission. It initially spreads messages using flooding mechanism like Epidemic Routing until certain number copies of the original messages are pumped into the network, then it stops flooding and lets each node carrying the copy do direct transmission to achieve final delivery. In such a way, the spray and wait algorithm overcomes the shortcomings of Epidemic Routing by only a slightly tradeoff on delivery ratio and packet delay. One thing should be mentioned is that, in the scenario of heavy traffic and small buffer size, the Spray and Wait may outperform Epidemic Routing since frequent buffer overflowing may occur in the latter and causes packet dropping in the relay nodes.

3.2.3 PROPHET Routing

To address the problem of heavy traffic load incurred by using Epidemic Routing in networks where storage resources are scarce, a novel routing protocol, *Probabilistic ROuting Protocol using History of Encounters and Transitivity* (PROPHET), is proposed by Anders Lindgren et al. [4]. Here the PROPHET protocol, which is also evolved from Epidemic Routing but unlike Spray and Wait, will route messages to nodes which have a higher probability to be adjacent to the final destination node. The assumption of this protocol is that from the practical experience, the mobility of nodes in the real world is not fully randomly distributed, but likely in a predictable fashion based on repeated routing patterns. In this way, if a node visited a location several times before, it tends to visit the same location in the future, such that the mobility of a node in future can be predicted in some way by observing its mobility in the history.

For the details of PROPHET, at each node A, a probabilistic metric called delivery predictability P(A, B), is established for each other known destination node B. This metric shows how likely it can deliver messages to the destination B successfully. When two nodes meet together, like in Epidemic Routing, they exchange the summary vectors and they also exchange the probabilistic information in order to update their probabilistic metrics respectively. After this step, a node only requires the messages which satisfy both the following conditions from another node: 1) no existing copy of this message is stored in the node, which is the same as in Epidemic Routing; 2) the delivery predictability of the destination of this message is higher, which ensures that a message only can be routed from node with low delivery predictability to node with high delivery predictability measured by the destination of this message.

When node A meet node B, it update the value of delivery predictability P(A, B) by $\mathrm{P}_{(\mathrm{A,B})} = \mathrm{P}_{(\mathrm{A,B})\mathrm{old}} + \left(1 - \mathrm{P}_{(\mathrm{A,B})\mathrm{old}}\right) \times \mathrm{P}_{\mathrm{init}}$, where $\mathrm{P}_{\mathrm{init}} \in [0,1]$is an initialization value. As the time past, the delivery predictability should be reduced periodically by $\mathrm{P}_{(\mathrm{A,B})} = \mathrm{P}_{(\mathrm{A,B})\mathrm{old}} \times \gamma^{\mathrm{k}}$. Another important operation is that when two nodes meet, they exchange the delivery predictability metrics as mentioned above, so each node is able to calculate the delivery predictability value by this information using the equation: $\mathrm{P}_{(\mathrm{A,C})} =$

$P_{(A,C)old} + (1 - P_{(A,C)old}) \times P_{(A,B)} \times P_{(B,C)} \times \beta$. From this point, it shows that the delivery predictability has a transitive property, which propagates in the whole network. This mechanism is similar to using distance vectors to propagate routing information in traditional networks.

From the result of [4], PROPHET is able to perform better and uses less network resource comparing to Epidemic Routing if the nodes have partially predictable mobility pattern.

3.2.4 RAPID Routing

All of routing protocols introduced above only have an incidental effect on the performance metrics, but for *resource allocation protocol for intentional DTN* (RAPID) [5], it has intentional effect on the performance metrics by explicitly considering the effect of replication on the routing metric as well as resource constraints. The main idea of RAPID is using the concept of a utility function, which presents the contribution of a packet to one performance metric. The principle of replicating a packet is to make the highest increase in utility function for that node and it can be considered as solving local optimization for a certain metric at each node. Therefore RAPID is like a resource allocation problem. Except for the replicating principle, all other steps of RAPID are very similar to the Epidemic Routing.

3.2.5 MaxProp Routing

The *MaxProp* protocol [6] emphasizes in what sequence the packets are exchanged during the period of nodes meeting together as well as how nodes manage their buffers. For packets exchanging, it ranks the packet by both the hop counts of the packet and the likelihood of delivery which is a similar concept like in PROPHET routing introduced in the previous part. When two nodes encounter, packets will be exchanged in a certain sequence based on the ranks of packets. For buffer management, it drops packets if particular conditions are satisfied in order to utilize the limited buffer resource while still keeping overall delivery rate unchanged.

3.2.6 Distance-Aware Epidemic Routing

In [40] another novel DTN routing protocol, *Distance-Aware Epidemic Routing* (DAER), is proposed. Like MaxProp protocol, it considers three metrics, namely the order of packets to be forwarded, the number of duplications generated and the buffer replacement policy. However, the decisions for all of these problems are based on the geographical distance information between related nodes. The principles behind the mechanisms are that firstly, a packet should stay on nodes moving forward to its destination or it should be dropped to release the limited resource; secondly, when a packet is approaching its destination, more copies are generated in order to increase the chance for successful delivery.

3.2.7 Summary

In general, the basic idea for most of existent DTN routings is store and forward and to enhance the probability of successful delivery. Meanwhile the mechanism of using multiple copies of original packets is adopted by most protocols. The difference is in what conditions and how many copies should be used. Epidemic Routing uses maximum copies, spray and wait uses limited copies, while in other protocols the number of copies may depends on probability or certain conditions and regulations.

Chapter 4

Multi-Packet Reception

4.1 Introduction of MPR

Multi Packet Reception (MPR) is an advanced technology that allows multiple packets to be simultaneously received without collisions in wireless communication. It is an enhancement for the traditional wireless networks, in which only one packet can be received at one time due to collisions induced by simultaneously transmissions.

4.1.1 Collisions in Wireless Communications

In traditional wireless networks, due to the interference of radio signals on same or adjacent frequencies, simultaneously transmissions in the same or closely adjacent wireless channel will cause collisions, rendering transmission unsuccessful. Known as the multiple access problem, this issue can be coped with by approaches which can be largely divided into three categories, namely channel partitioning, random access and taking-turns.

Cellular network is a common application example of channel partitioning protocols. In cellular network, an area is divided into regular shaped cells, which can be hexagonal, square, circular or other shapes and the total bandwidth of the channel is divided into several non-overlapping frequency channels. Each of these divided channels will cover one unit cell and for each cell, the adjacent cells are assigned with different frequency channels. In this way, the distance between cells using same frequency channel is made as far away as possible to mitigate the interferences. Figure 4-1 shows an example of cells in cellular network.

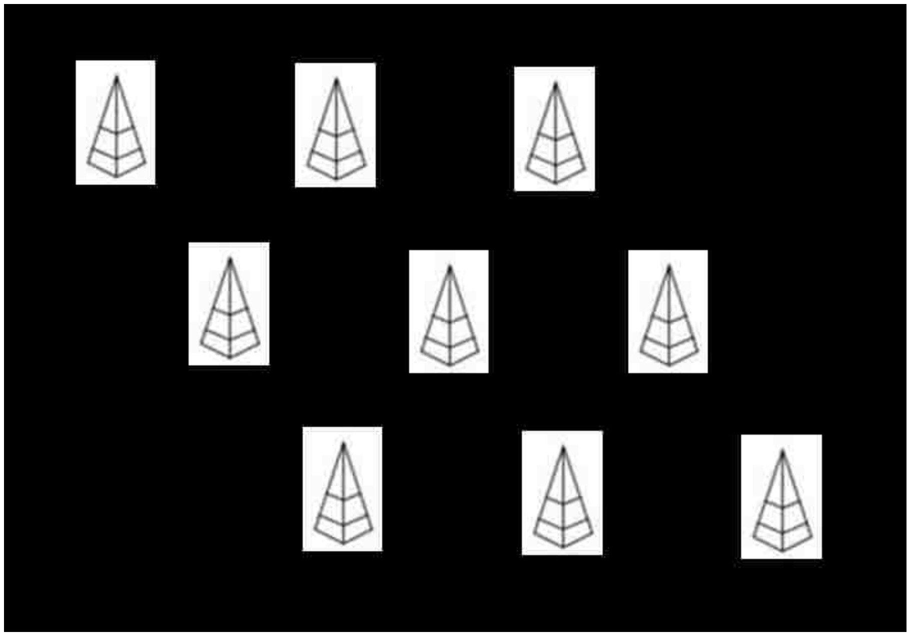


Figure 4-1 Cellular networks

However the cellular network has some disadvantages and one of them is that a node only can have one limited narrow bandwidth at a time even it is the only node in the cell. By this reason, a node is unable to talk to multiple nodes simultaneously.

Unlike in cellular network, WLAN uses random access protocol to achieve multiple accesses. In WLAN, it uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), a kind of random access protocol, in medium access control (MAC) layer to provide the ability of multiple accesses. The main idea in CSMA/CA is to reduce the probability of collisions as far as possible since the cost of retransmission in wireless channel is high and the fact that traditional wireless nodes are unable to detect collisions during transmitting which makes the impact of collision worse. The scheme of CSMA/CA is introduced below:

1. At the beginning, if the station senses the channel is idle, it transmits the frame after a short period time which is called Distributed Inter-Frame Space (DIFS).

2. Otherwise, the station randomly chooses a back off value and counts down this value after it detects that the channel is idle. The counter is frozen when the channel is sensed busy.

3. When the counter becomes zero, the station transmits the entire frame and then waits for an acknowledgement from the receiver.

4. If the acknowledgement is received successfully, the transmitting station will know the frame is correctly received. If the station has another frame to send, it goes to step 2. If the acknowledgement is not received, the transmitting station will retransmit this frame by reentering the step 2 with a larger random back off value.

In WLAN, the problem of hidden terminals may present itself. To cope with the potential collisions from hidden terminals, the mechanism of Request to Send (RTS) and Clear to Send (CTS) is defined, whose details are discussed in [27].

In the CSMA/CA, the intense use of back off methods leads mostly idle wireless channel and waste of network resource, so more efficient mechanisms are considered to be implemented.

4.1.2 Motivation for using MPR

In both the cellular network and the WLAN, the bandwidth of wireless channel is not fully used. To improve the efficiency of the channel, the approaches to achieve simultaneously multiple packet receptions are studied. Two methods are most commonly used in real environments now, one is using CDMA, and another is using MIMO system.

4.2 Methods to achieve MPR

4.2.1 CDMA

In communication area, to allow multiple transmitters to send messages simultaneously over the same channel is called multiplexing. Traditionally, *time division multiple access* (TDMA), in which access is divided by time, and *frequency division multiple access* (FDMA), in which access is divided by frequency are used to solve the multiplexing problem in wireless communication. However, *Code division multiple access* (CDMA) is a channel access method used by various radio communication technologies [27]. It utilizes spread spectrum technology and special coding scheme to allow multiple users to access a single channel simultaneously.

Specifically, at the sender side of CDMA, a locally generated pseudorandom code called chipping code runs at a much higher rate than the data to be transmitted. The modulation procedure is simply by multiplying the data for transmission with the chipping code by Kronecker product [22]. In addition, each user uses a different code to modulate their signal and the code assignment is very important in the CDMA system. The Figure 4-2 shows how spread spectrum signal is generated.

Figure 4-2 CDMA modulation scenario

At receiver side, the separation of the signals is made by correlating the signal with its local generated code. If the signal matches the receiver’s code, the system will consider the signal to be destined for this receiver and can extract the original transmitted messages; if the desired receiver's code fails to match the signal, the system will consider this signal is not for this receiver and ignore it. So the system will have a desirable performance if the signal of a certain user has good separation from other users, which also implies that the code for each user should be well separated since the code is related to signal in the modulation and demodulation operations. The Figure 4-3 shows how spread spectrum signal is demodulated. The details of modulation and demodulation will be discussed in the follow section.

Figure 4-3 CDMA demodulation scenario

4.2.2 Modulation and Demodulation in CDMA

In detail, CDMA may use two kinds of coding schemes: synchronous (orthogonal codes) and asynchronous (pseudorandom codes).

Synchronous CDMA exploits mathematical properties of orthogonality between vectors representing the data strings. For example, string 1 -1 1 1 is represented by the vector (1, -1, 1, 1). Vectors can be multiplied by taking their dot product, which sums the products of their respective components. For example, if u = (a, b) and v = (c, d), the dot product u v = ac + bd. If the dot product is zero, the two vectors are said to be orthogonal to each other. In synchronous CDMA, each user uses a chipping code orthogonal to any others' chipping codes. An example of four mutually orthogonal chipping codes is shown in the Figure 4-4. Orthogonal codes have a cross-correlation equaling to zero so they do not interfere with each other.

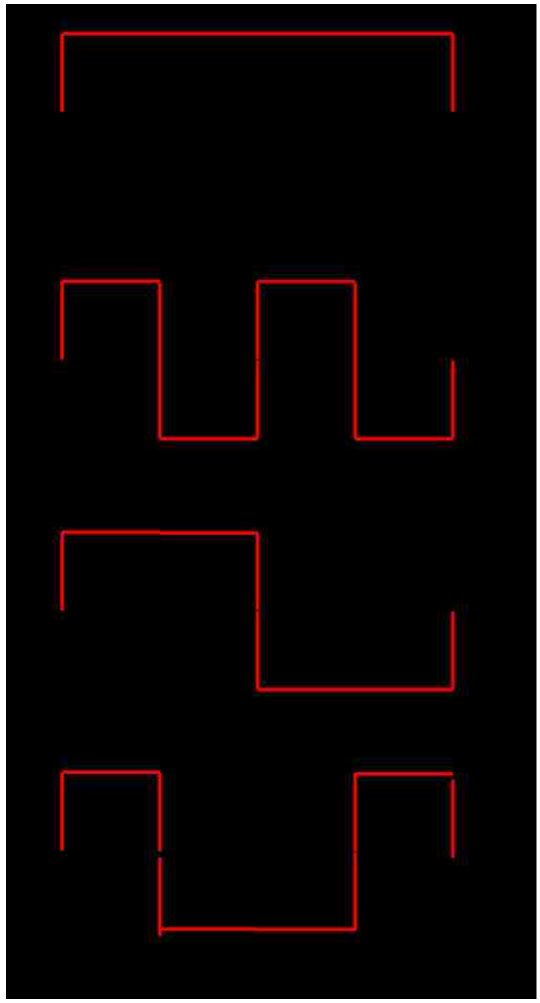


Figure 4-4 Four mutually orthogonal chipping codes

After each user is associated with a different chipping code, the binary data for transmission is encoded by mapping the bit of 1 to a positive symbol 1 and the bit of 0 to a negative symbol -1. Then the encoded symbols are modulated by the chipping code to generate the signals transmitted into the wireless channel. The modulation process could be expressed as Kronecker product of encoded symbols and the chipping code. For example, if the chipping code is (1, 1, 1, -1) and the encoded symbols are (-1, 1), then the modulated signals are $(-1, 1) \otimes (1, 1, 1, -1) = (-1, -1, -1, 1, 1, 1, 1, -1)$, where $\otimes$ presents the Kronecker product.

In the entire network, each sender transmits its own modulated signals into wireless channels. Due to the interference, two signals may add to each other if they are in phase or they may subtract each other if they are out of phase. In digital views, it can be modeled as the addition operation of the modulated symbols, bit by bit.

However, because of orthogonality, at the receiver side, the system still can demodulate the received signals by using the same chipping code as the corresponding sender and finally decoded it to original data.

To demonstrate the successful communication in interfering cases, a simple example is illustrated. For simplicity, in this example, chipping codes only have 4 bits for each user.

If *sender 1* has code (1, 1, 1, –1) and data (0, 1), and *sender 2* has code (1, -1, 1, 1) and data (1, 1), and both senders transmit simultaneously, then table 4-1 describes the steps at the senders and table 4-2 describes the steps at the receivers.

	Sender 1	Sender 2
chipping code	(1, 1, 1, –1)	(1, -1, 1, 1)
original binary data	(0, 1)	(1, 1)
encoded symbols	(-1, 1)	(1, 1)
modulated signal	(-1, -1, -1, 1, 1, 1, 1, -1)	(1, -1, 1, 1, 1, -1, 1, 1)
Overlapped signal in channel	(-1, -1, -1, 1, 1, 1, 1, -1) + (1, -1, 1, 1, 1, -1, 1, 1) =(0, -2, 0, 2, 2, 0, 2, 0)	

Table 4-1 Steps at Senders

	Receiver 1	Receiver 2
chipping code	(1, 1, 1, –1)	(1, -1, 1, 1)
received signal	(0, -2, 0, 2, 2, 0, 2, 0)	
demodulated symbols	((0, -2, 0, 2), (2, 0, 2, 0)) · (1, 1, 1, -1) = (-4, 4)	((0, -2, 0, 2), (2, 0, 2, 0)) · (1, -1, 1, 1) = (4, 4)
decoded data[1]	(0, 1)	(1, 1)

1. In demodulated symbols, a positive symbol is for bit 1 and a negative symbol is for bit 0

Table 4-2 Steps at Receives

In the case if the sender does not transmit anything, at the corresponding receiver side, it will demodulated the signal into all zero, which means the cross correlation is equal to zero and the sender did not transmit any data. The table 4-3 describes the case of *sender 1* transmitting the same thing as in the last example but *sender 2* keeping silent.

	Receiver 1	Receiver 2
chipping code	(1, 1, 1, –1)	(1, -1, 1, 1)
received signal	(-1, -1, -1, 1, 1, 1, 1, -1)	
demodulated symbols	((-1, -1, -1, 1), (1, 1, 1, -1)) · (1, 1, 1, -1) = (-4, 4)	((-1, -1, -1, 1), (1, 1, 1, -1)) · (1, -1, 1, 1) = (0, 0)
decoded data	(0, 1)	None

Table 4-3 Steps at Receives with a single Sender

In synchronous CDMA, all the users need to be coordinated to transmit their symbols at the same time, so the signal could arrive at the receive side at the same time. However, to synchronize all transmitters is difficult to implement in real world unless all the signals originate from the same transmitter like the base-to-mobile links, so asynchronous CDMA system is developed to cope with this problem. Specifically the asynchronous CDMA uses "pseudo-random" or "pseudo-noise" (PN) sequences as its chipping codes, which based on the theory that it is not mathematically possible to create signature sequences that are orthogonal for arbitrarily random starting points. A PN code is a binary sequence that appears random but can be reproduced in a deterministic manner by intended receivers. The functions of the PN codes in asynchronous CDMA are as same as the orthogonal chipping codes in synchronous CDMA and since these PN codes are statistically uncorrelated, the sum of a large number of PN codes results in multiple access interference approximately like a Gaussian noise process.

On the other hand, at the receiver side, signals encoded by the specified PN code have a strong gain, while signals with other PN code or the same code but a different timing offset appear as wideband noise. Thus, unlike synchronous CDMA, in which receivers can reject arbitrarily strong signals, the asynchronous CDMA can only reject partially unwanted signals. If unwanted signals are strong enough, the desired signal will be overwhelmed, so in asynchronous CDMA, the power control mechanism is necessary.

4.2.3 MIMO System

In radio, *Multiple-Input and Multiple-Output* (MIMO) system uses multiple antennas at both the transmitter and the receiver to improve the performance of communications. MIMO technology is able to offer significant increases in data throughput without additional bandwidth or transmit power. It is an important part of many wireless communication standards such as IEEE 802.11n, 3GPP and WiMAX. In MIMO, it usually utilizes the technology of antenna array.

By using antenna array, the MIMO systems are able to achieve *Space/ Spatial Division Multiple Access* (SDMA) base on the principle of spatial multiplexing. In spatial multiplexing, high rate signals are divided into multiple low rate streams and each of these streams is transmitted by different transmit antennas in the same frequency band. The receiver is able to distinguish these steams if they have sufficiently different spatial signatures at the receiver side. In such a way, it can be used for simultaneous transmission to multiple receivers, which is called SDMA. In addition, in MIMO system, the maximum number of spatial streams transmitted in the channel is limited by the number of antennas at the transmitter or receiver. The details of principle and implementation are introduced in [23] [24] [25]. Figure 4-5 describes the channel model of MIMO system.

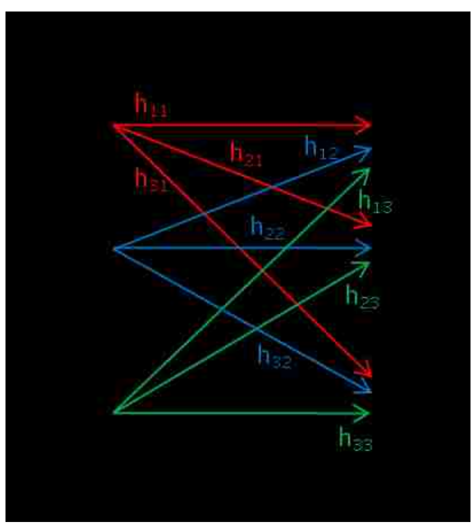


Figure 4-5 MIMO channels

4.3 Existent Implementations of MPR

The concept of using CDMA in cellular network was proposed as early as in the late 1980s and the milestone standard of CDMA, *IS-95A*, was completed in 1993. Since then commercial CDMA networks began to be deployed through the world. In 1998, the standard *CDMA2000* was submitted to International Telecommunication Union (ITU) and chosen as part of Third Generation (3G) solutions. Nearly at the same time, Universal Mobile Telephone System (UMTS) also provided a solution for 3G mobile system but using different CDMA technologies like *WCDMA*. Now CDMA is the foundation for 3G services and two dominant *IMT-2000* standards, *CDMA2000* and *WCDMA* are widely used based on CDMA technologies. According to the statistics from the *CDMA Development Group*, there are more than 350 *CDMA2000* networks deployments and more than 540 million subscribers worldwide in the first quarter of 2010 [26].

In United States, most of wireless communications service providers have services based on CDMA technologies. Table 4-4 shows the technologies used in main U.S. cell phone operators.

Operator	Voice Technology	Data Technology
AT&T Mobility	GSM, UMTS, HSDPA	GPRS, EDGE, UMTS, HSPA
Sprint Nextel	CDMA, iDEN, UMTS	CDMA2000, EV-DO, WiMAX
T-Mobile USA	GSM, UMTS, GAN	GPRS, EDGE, UMTS, HSPA
Verizon Wireless	CDMA, UMTS	CDMA2000, EV-DO,

Table 4-4 Technologies used by main U.S. cell phone companies

In contrast to the popular utilizations of CDMA in cellular networks, using MPR in WLAN is still in a few research papers. In [28] [29], P. Zheng and Y. Zhang et al introduced their own MAC protocol and physical layer design to implement MPR in WLAN. This novel MAC protocol is based on basic IEEE802.11 MAC protocols, in which they modified the collision avoidance schemes in the original protocols and added several new schemes as well as new parameters to enhance the MAC layer with MPR capability. The main change to improve the efficiency is concerning with the back off time, which is a key factor affecting channel utilization. According to their simulation results, the throughput has a great increase comparing to the traditional IEEE802.11 if the amount of stations in the WLAN is proper.

4.4 Scheduling

In WLAN the channel is accessed by nodes randomly, however in order to optimize one or more performance objectives like throughput, delay or energy, the system needs to schedule the actions of each elements. The main issue scheduling dealing with is that how resource is shared between users in a network. In wireless networks, this resource is usually for the capacity of the channel. It can be the time slot in TDM, frequency in FDM, chipping code in CDM or other type's resources in wireless communication systems.

In MANET, due to the mesh topology, the routing, channel allocation, as well as mobility of nodes are complicated. To improve the performance in MANET and to fully use the channel capacity, the transmission scheduling is one of necessary components in the system. To explain the purpose of scheduling, a simple example is illustrated below. Figure 4-7 is a topology abstraction for a MANET and each node wants to transmit packets through links. By the reason of interferences between links, they may not transmit simultaneously. The scheduling scheme is to decide that which links should transmit at each instant of time, thus the performance metrics, like throughput and delay, can be optimized.

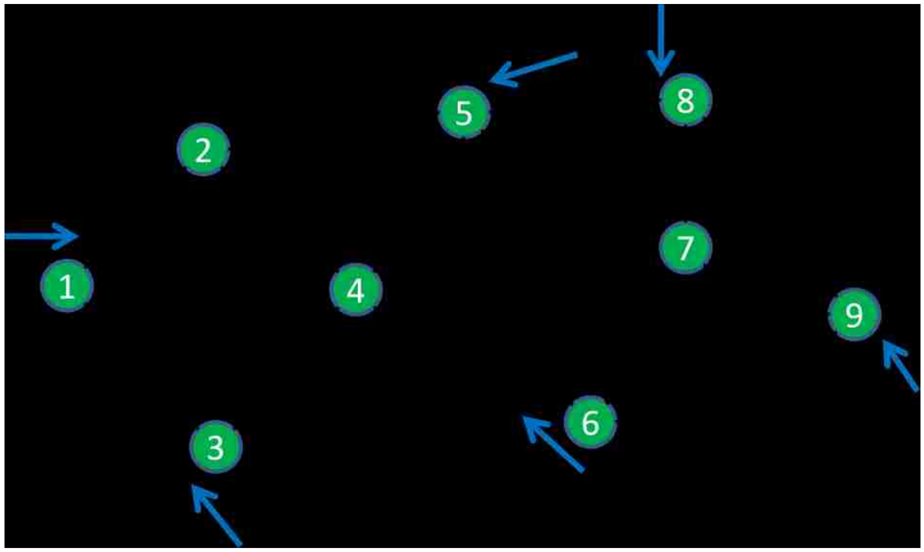


Figure 4-6 An example for scheduling in MANET

While the scheduling problems have been studied for decades, its application in MANET has also been an interesting topic over years. In the sense of using MPR in MANET, it may relate to the problem of scheduling with joint routing and scheduling with directional antennas. In [30], K. Jain et al. proposed a max-flow linear programming scheme for computing the bounds of the optimal throughput. In [31], A. Capone et al. presented a heuristic method to solve an integer linear program generated by max-flow formulation. J. J. Garcia-Luna-Aceves et al. [32] [33] proved the MPR could increase the capacity of random wireless networks by a logarithmic factor, while the throughput is also increased. X. Wang et al [34], proposed a centralized algorithm to jointly perform routing and scheduling. J. Crichigno et al. [35] provided a generalized scheme to compute the optimal throughput in wireless networks with MPR capability.

Chapter 5

Utilizing MPR Capability at MAC Layer for Application-Aware DTN at Routing Layer

5.1 Motivation

As mentioned in Chapter 4, using MPR can improve the performance in MANET. However, to our best knowledge, there is no works leading MPR in VANET in the perspective of using DTN concept. In addition, most studies of MPR are based on the theoretical analysis and the simulations in a simple network setting.

In our work, we introduce the MPR into a VANET, in which the trace data is extracted from real vehicle networks in Shanghai, China.

5.2 Routing-MAC Cross-Layer Architecture

According to discussion in previous chapters, for our SUVnet, in routing layer we use one DTN routing scheme and in MAC layer we use our own scheme to implement MPR. The technology used in physical layer can be either CDMA or MIMO system. In [43], MPR is achieved base on CDMA in MANET, while in [42], SDMA is applied to a VANET. The methods used in these two papers can also be adopted in our work. Thus we will not consider the detail implementation for the physical layer.

In Chapter 3, several kinds of DTN routing protocols are introduced, which either belong to Epidemic Routing or can be classified as variation of Epidemic Routing. Although Epidemic Routing suffers with flooding problem, it still serves as a benchmark for all kinds of routing schemes in partially connected MANETs. Epidemic Routing has been chosen as the routing protocol in our architecture.

For Epidemic Routing, each node periodically broadcasts Hello messages as its beacon messages to detect nodes located in its transmission range. When a node receives such a hello message, it will exchange its summary of stored packets with the sender. Consequently it will send out all the packets requested by the sender. In these steps, several packet transmissions, including both summary packet exchanging and data packet exchanging, are handled. In our model, all the packet transmissions are delivered to the MAC layer and then sent out by the scheme used in the MAC layer. Symmetrically, at receiver nodes, a packet arrived at the MAC layer will be delivered to the DTN routing layer.

Since the MPR is applied at the MAC layer, a node is able to receive multiple packets simultaneously. From the concept discussed in previous chapters, there is a limit for maximum concurrent receiving packets, such as the available chipping codes in CDMA or the number of available antennas in MIMO. We call this limit value as **MPR capability** and represent it as "***K***" in the rest part of the thesis. Thus at most K packets are able to be correctly received at the same time, otherwise all simultaneously transmitted packets are failed to be received due to collisions. From this definition, the situation of $K=1$ implies that the network degrades to a traditional network without the MPR capability.

While a node with the MPR capability can receive multiple packets simultaneously, only one packet is able to be sent out each time. This brings a problem that the capability of receiving is larger than the capability of transmitting at each node.

Since a major characteristic of Epidemic Routing is to store and forward, it requires a balance between sending and receiving. To deal with the problem, a new scheduling scheme --- *Group Based Scheme* (**GBS**) in the MAC layer is proposed.

5.3 GBS---a Scheduling Algorithm at the MAC layer

With GBS, nodes are divided into groups based on their node IDs for roughly equal distribution. The number of distributed groups is called as *group factor* and represented by ***M***. The policy of distribution is taking the remainders of node ID divided by group number *M*. We use the operator "*mod*" here as to calculate the remainder. Thus nodes with same remainders of M will be distributed into the same node group. In this way, all nodes are distributed into a set of groups: $\{\boldsymbol{NG_0, NG_1, \ldots, NG_{M-1}}\}$ where $\boldsymbol{NG_i}$ is the node group that node ID mod group factor *M* is equal to *i*. For example, if we divided nodes into four groups where M equals 4, node 24 is distributed to group NG_0 because the remainder is 0 when dividing 24 by 4. Similarly, node 398 belongs to group NG_2 as 398 *mod* 4 equals 2.

Next, the time is divided into time slots (**TS**). In our work each time slot is for one second and ***M*** slots compose to a time circulation (**TC**), in which the value of *M* here is as same as the value of the group factor defined above. Thus a time circulation can be expressed by $\boldsymbol{TC} = \{\boldsymbol{TS_0, TS_1, \ldots, TS_{M-1}}\}$ where $\boldsymbol{TS_j}$ is the $(j+1)^{th}$ time slot in a time circulation.

Then, we define two states for nodes sending state and receiving state. In the sending state, a node only can send out packets or stay in idle if there is no packet to send;

in the receiving state, a node only can receive packets or stay in idle. According to our *GBS* schemes, a node is either in its sending state or receiving state in each time slot.

We present a packet by its source node, destination node and generating time. Therefore P_{uvt} is a packet from node *u* to node *v* with generating time *t* at the source node. Particularly, if the packet is a Hello message, we assign its *v* equaling to *-1* since the destination of a Hello message is a broadcast address.

```
At node i, belonging to NGi, with group factor M
  During time slot j, TSj
   if (j equals i)
     then
                    Node i stay in its receiving state
   else
       Node i stay in its sending state
       while (deque packet Puvt)
         if (v equals -1 or (v mod M) == j ))
           then
             send out Puvt
           else
             keep idle
```

Figure 5-1 Schedule of sending and receiving in GBS

Figure 5-1 shows the schedule algorithm of nodes belonging to NG_i at the time slot TS_j. Thus, if TS_j equals to TS_i, according to our schemes and MPR capability limitation, a node belongs to NG_i may receive no more than ***K*** packets simultaneously from other nodes belonging to NG_j ($j \neq i$) at this time slot. In addition, note that in one *TC*, any node group has only one *TS* for receiving state and M-1 *TS* for sending state. For example, in time slot TS_2, nodes belonging to node group NG_2 are staying in receiving state, while nodes belonging to other node groups (NG_0, NG_1, NG_3,…, NG_{M-1}) are staying sending state. To verify the balance of packet amount between sending and receiving, we can use a simple calculation to demonstrate. For an arbitrary node group NG_i, in each time circulation, the total number of packets received is at most $\min(\boldsymbol{K}, (M-1)) \times node\_num \times packet\_rate$ at the only receiving state time slot TS_i, in which *node_num* is the number of nodes in one group and *packet_rate* is for the number of packets can be sent out in one time slot. The amount of packets sent out by the same node group in one time circulation is computed as $node\_num \times packet\_rate \times (M-1)$. Thus, if the MPR capability $\boldsymbol{K}$ is larger than $(M-1)$, these two values will be the same.

A limitation in this scheme is that nodes belonging to the same node groups are unable to communicate with each other, since they are always stay in the sending or receiving state. To alleviate this problem, we use two group factors $\boldsymbol{M_1}$ and $\boldsymbol{M_2}$, usually two relatively prime numbers, instead only one group factor M. The rules for distributing nodes are still based on "*mod*" operation. Since there are two group factors now, two sets of nodes are generated as set $\boldsymbol{A}$ $\{NG_0, NG_1, \ldots, NG_{M1-1}\}$ and set $\boldsymbol{B}$ $\{NG_0', NG_1', \ldots, NG_{M2-1}'\}$. Note that every node belongs to one element in set A as well as one element in set B. Then set B is concatenated at the end of set A to compose a large set with $\boldsymbol{M_1}+\boldsymbol{M_2}$ elements denoted as $\{NG_0, NG_1, \ldots, NG_{M1-1}, NG_{0+M1}, NG_{1+M1}, \ldots, NG_{M2-1+M1}\}$ (the sequence numbers for the last M2 elements can be computed by the sum of the original sequence numbers in set B and the offset M1). In a similar manner, a time circulation is consisted by $\boldsymbol{M_1}+\boldsymbol{M_2}$ time slots, so $TC=\{TS_0, TS_1, \ldots, TS_{M1+M2-1}\}$. Like the original scheme, nodes in NG_i are in their receiving state only in time slot TS_i. Therefore a node has two time slots in receiving state in each time circulation since it belongs to two node groups. By using this improved scheme, the ratio of nodes which are unable to communicate with each other is reduced from 1/*M* to 1/*M'*, where *M'* is the least common multiple of M_1 and M_2. If M_1 and M_2 are relatively prime, *M'* will equal to the product of M_1 and M_2. Therefore, the probability of two nodes without being able to communicate with each other will substantially reduced. Even it happens they will still be able to exchange packets indirectly by any other nodes.

For example, we choose 4 and 3 as two group factors. Thus, all nodes are distributed into 7 node groups by the remainders of dividing 4 and 3 respectively. The set of node groups is represent by {NG_0, NG_1, …, NG_6}, where NG_0 to NG_3 is corresponding to the remainder of dividing 4 and NG_4 to NG_6 corresponds to the remainder of dividing 3. Under this configuration, a node with node ID of 398 belongs to NG_2 since the remainder of 398 dividing 4 is 2 and also belongs to NG_6 because the remainder is 2 when 398 dividing by 3. Base on this improved scheme, only nodes having the same remainder when dividing by 4 and also the same remainder when dividing by 3 are unable to communicate with each other. The probability that a node meets a non-contactable node is 1/12, comparing to 1/4 if only one group factor 4 is used. Table 5-1 shows the detail scheduling for this example.

TS / NG	1	2	3	4	5	6	7
NG0 (node id mod 4= 0)	***R***	***S***	***S***	***S***			
NG1 (node id mod 4= 1)	***S***	***R***	***S***	***S***			
NG2 (node id mod 4= 2)	***S***	***S***	***R***	***S***			
NG3 (node id mod 4= 3)	***S***	***S***	***S***	***R***			
NG4 (node id mod 3= 0)					***R***	***S***	***S***
NG5 (node id mod 3= 1)					***S***	***R***	***S***
NG6 (node id mod 3= 2)					***S***	***S***	***R***

R = receiving, S = sending

Table 5-1 Detail of scheduling

Chapter 6

Performance study

6.1 The GPS Trace of Taxis in Shanghai

In general, data extracted from real life setting can provide more accurate and reliable information than those statistically generated data. Our work is based on the real GPS data collected from about 4000 taxis in Shanghai, China.

In Shanghai, over 4000 taxis are equipped with GPS devices by which it can report their location in real time. To enhance the reliability, we collected data several times from the August, 2006 to May, 2007. In general, the duration of data collecting each time is about 48 hours. During the data collecting, each active taxi reported its longitude and latitude coordinates, timestamp, taxi ID etc. The average interval between sampling time is 61 to 129 seconds. We mapped these data onto the digital map of Shanghai to obtain their traces and constructed a virtual VANET, which is named as *Shanghai urban vehicular network* (SUVnet). In this work, we only consider the downtown area of the city, which is called “inner-loop area”. This area covers about 102 km^2 and there are 5,743 roads located in it. Although taxis travel inside and outside of this area, there are always around 1000 taxis which are located within this area. Figure 6-1 is a visualization of the area and each dot in the map represents a taxi. Figure 6-2 shows the density which is the number of taxis in a circular surrounding area with 500 m radius.

Figure 6-1 Visualization of VANET
(Surrounded area depicts the simulation area, each dot represents a taxi.)

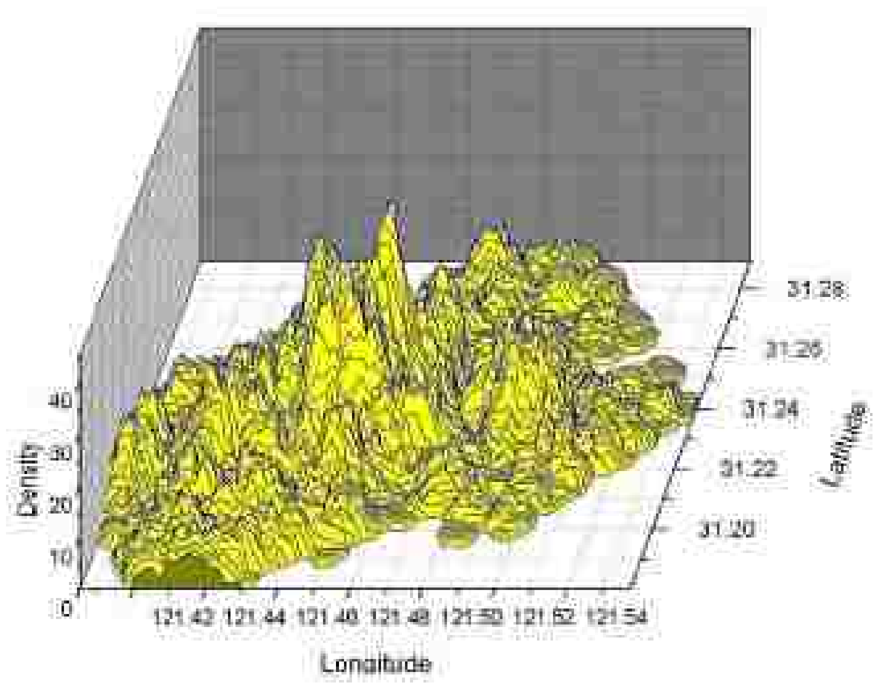


Figure 6-2 Vehicle density at 2006-11-23 10:30
(Density represents the number of taxis in surrounding 500m area.)

6.2 From GPS Traces to Mobility Pattern

Since the sampling is not continuous, the traces of taxis are incomplete and imprecise. In order to reconstruct the exactly moving trace of taxis, three procedures are manipulated to process the collected data [38]. Firstly, the GPS data is mapping to the map by their longitude and latitude coordinates. Secondly, a route between two consecutive data samples is determined. The methods of map mapping and route determination are introduced soon. Thirdly, more points are interpolated along this route to achieve the mobility pattern with precision of every second for each taxi.

Some researches use probabilistic [36] or fuzzy logic [37] to process map-matching and route determination of GPS data. However they are not suitable for either GPS data with a long interval or a complicated network topology of urban-area roads. In this work, the *Geographic Information System* (GIS) is used to describe the road system, in which two types of legends, point and polyline, are defined. Nodes present several geographical points along a link and link is concatenated by polylines which are defined by nodes. For link L_i, there are K_i nodes (k_1, k_2, … , k_{Ki}) and K_{i-1} lines ($e(k_1, k_2)$, $e(k_2, k_3)$, … ,$e(k_{Ki-1}, k_{Ki})$). Road consists several connected links and each link has an attribute value assigned as the road name. We present the GPS data by a four-tuple *D (Sid, T, Ψ, Ω)*, in which *Sid* is the unique ID of the taxi, *T* is the timestamp, *Ψ* is the location expressed by longitude and latitude coordinates and *Ω* is its direction of headway, which means the angle clockwise from the north direction to the moving direction. To do map-matching, we filter out the links whose distance to the taxi is larger than 40 m or whose directional difference with the direction of headway of the taxi is larger than 45°. Then a link with minimum distance to the taxi is chosen. However, if the distances to several links are similar, the link having the same road name as the last matched link will have a higher probability to be chosen.

After the map-matching, the next step is to determine the route between any two consecutive sample data. It is assumed that the taxi will stay on the same road unless it meets an intersection. The rules to determine the action on intersection are that if the next intersection along the current road is nearer to the next sample point, it will go straight; otherwise it turns to another road which leads to a nearer intersection from the next sample point. Finally, using the time interval and the length of route between two consecutive sampling, we are able to interpolate every intermediate point.

With contrast to the recorded real trace of taxis, the result of applying the above method to the GPS data provides more than 95% accuracy for map-matching [38]. Figure 6-3 demonstrated the map-matching, route determination and interpolation from a set of 25 consecutive GPS sampling. The number stands for its origin location and the dotted line represents its trace.

Figure 6-3 Map-matching and interpolation

6.3 Simulation Environment

We have developed our own discrete event-driven simulator to evaluate the performance and have selected the trace of 400 vehicles and run the simulation for 7200 seconds (2 hours). The time of trace we chose is from 8:00 am to 10:00 am, since it is during the rush hours of a day and the traffic is pretty heavy during this period in Shanghai.

In the DTN routing layer, Epidemic Routing protocol is used. Each node generates one packet every 600 for total 1800-second period which includes start time point and end time point at the initial stage. As the result, total 1600 original packets are generated for the entire network. This period is considered as warm up phase, since nodes are still generating packets. Therefore, we start the measurements from 1800 seconds. The Hello messages are broadcasting every 3 seconds from each node.

In the MAC layer, our improved *GBS* is implemented with two group factors 4 and 3. The size of one time slot is 1 second and the rate of packet transmission is 10 packets per time slot i.e. 10 packets per second. To investigate the influence of using different group factor, a reference group with one group factor 2 is implemented.

To investigate performances in different group factors and heavy traffic load, scenarios with single group factor 2 and two group factors 2 and 3 are evaluated as comparisons. Furthermore, a setup with total 2800 original packets is also implemented.

6.4 Metrics

In wireless networks, the transmission range of a node is an important factor for network performance. Thus in our simulation, two different transmission ranges are investigated: a short transmission range --- 250 m and a long transmission range --- 500 m. Since the main purpose of the simulation is to study the impact of using MPR in VANET, the MPR capability is another major factor we need to investigate. Therefore, for each transmission range, different MPR capabilities are examined.

To verify that nodes are distributed as a DTN, the connectivity in each transmission range is evaluated. The criteria to determine connectivity is that at one instant time, any nodes which are able to communication with each other by direct transmission or intermediate relay nodes belong to the same set. Thus, at an instant time, it is possible to find a path between any nodes in the same set, while no path exists between nodes in different sets. The number of nodes in a set is called set size. Figure 6-4 and 6-5 show the average distribution of set size for two transmission ranges respectively. In the short transmission range, nodes are dispersed into sets with small size; in the long transmission range, although there is one big set in the network, other sets only have a few nodes. Therefore, the network under both transmission ranges belongs to DTN.

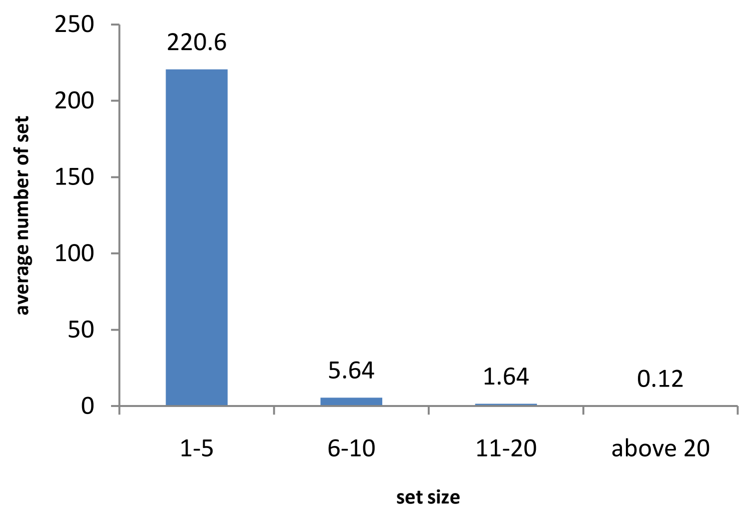


Figure 6-4 Set size distribution for short transmission range

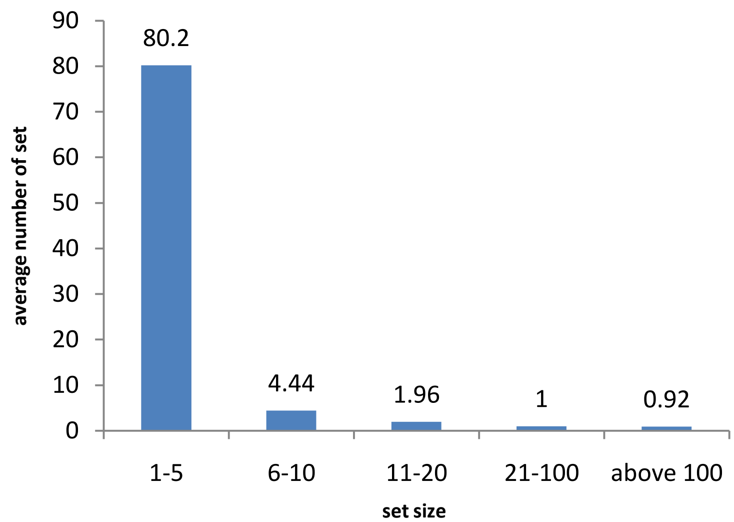


Figure 6-5 Set size distribution for long transmission range

In each scenario with different transmission ranges, for a node, the number of neighbor nodes located within its transmission range is different as well as the number of simultaneously sending neighbor nodes, since the latter is directly related to the former due to our *GBS* in MAC layer. Figure 6-6 shows the average number of neighbors and average simultaneously sending neighbors in the same transmission range at the same time. It is clearly to see the average number of simultaneously sending neighbors is less than 2 for the short transmission scenario, which implies that the probability to have collisions is low even without using MPR. Figure 6-7 and figure 6-8 describe the frequency distributions and Cumulative Distribution Function (CDF) of the average numbers of simultaneously sending neighbors of a node during 2 hours simulation time for both transmission ranges respectively. From the previous discussion, to successfully receive packets, the MPR capability should be equal or greater than the number of simultaneously sending nodes. Thus, it is reasonable to conclude that the performance under different MPR capability is also affected by these frequency distributions. On the one hand, if MPR capability is lower than the number of simultaneously sending nodes, the collisions will happen; on the other hand, if MPR capability is much larger than the number of simultaneously sending nodes, the benefit of using MPR is unable to reflect due to insufficient utilization of MPR capability.

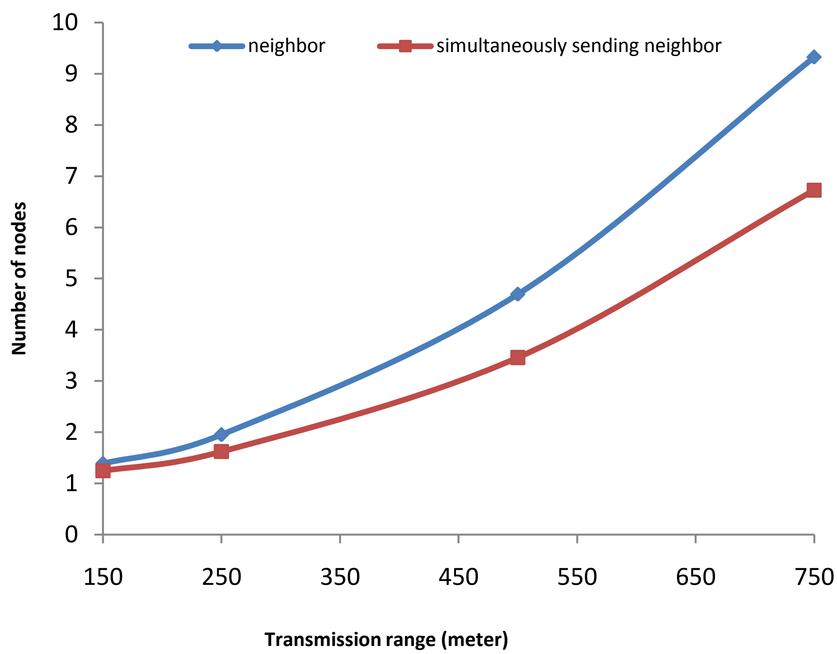


Figure 6-6 Number of average neighbors and simultaneously sending neighbor

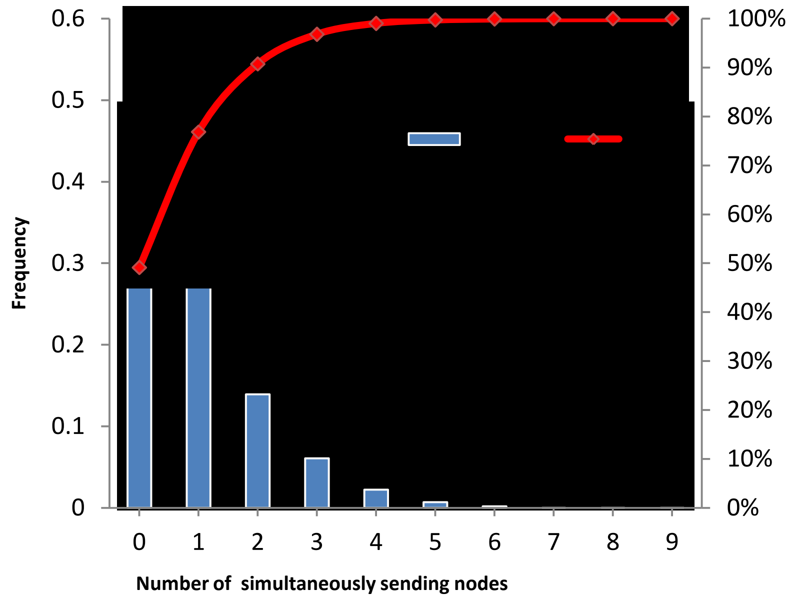


Figure 6-7 Frequency distribution and CDF of simultaneously sending neighbor for short transmission range

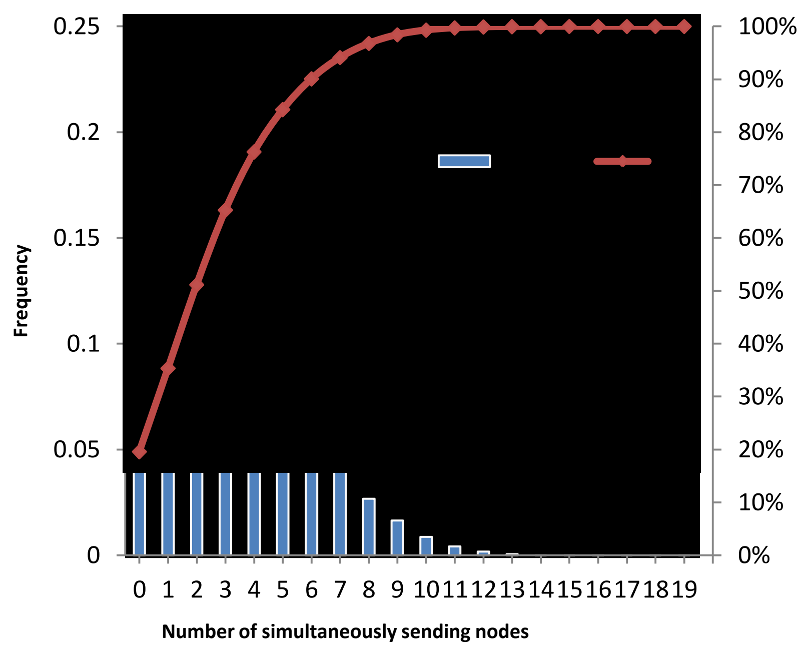


Figure 6-8 Frequency distribution and CDF of simultaneously sending neighbor for long transmission range

6.5 Performance Evaluations

As discussed in Chapter 3, the delivery ratio and the average latency are two important metrics for DTN. Therefore, we use these two metrics to evaluate the performance under different transmission ranges and MPR capability.

Delivery Ratio

The delivery ratio in DTN usually is defined as the fraction of the original packets received at their final destinations. It is an important metrics to study the robustness and efficiency of a routing protocol in DTN.

Figures 6-9 and 6-10 depict the delivery ratio under different MPR capability in short transmission range (250m) and long transmission range (500m), respectively. In both transmission ranges, the MPR capability ***K*** increases from 1 to 8, however the improvement in short transmission range is not substantial while the enhancement in long transmission range is significant. It can be explained by CDF curve in Figure 6-7, in which the frequency of having more than 1 simultaneously sending node in the short transmission scenario is about 0.25, thus the effect of using MPR is not notable. One typical example is that, in Figure 6-9, the curve of K=8 almost coincides with the curve of K=4, because the frequency of having 5 to 8 simultaneously sending nodes in the short transmission range scenario is nearly closed to zero. In contrast, more than 0.65 of frequency has above 1 simultaneously sending node for long transmission range scenario. Therefore, it provides the condition for using MPR to reduce collisions caused by simultaneously transmission and improving the performance eventually. Unlike in the short transmission range scenario, a remarkable gain of delivery ratio is still achieved by increasing MPR capability ***K*** from 4 to 8, since the frequency of having 5 to 8 simultaneously sending nodes is about 0.2.

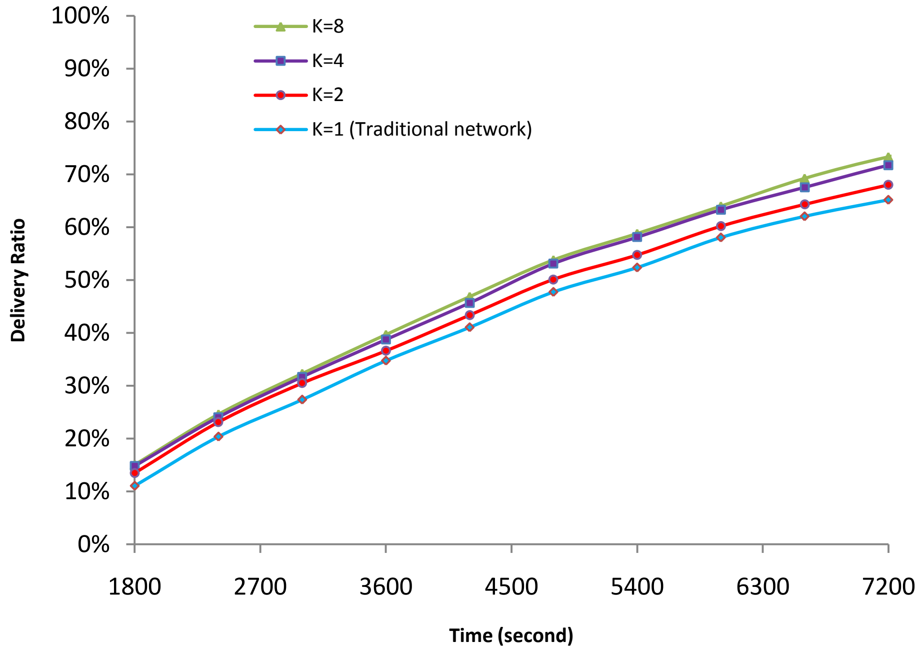


Figure 6-9 Delivery ratio: short transmission range

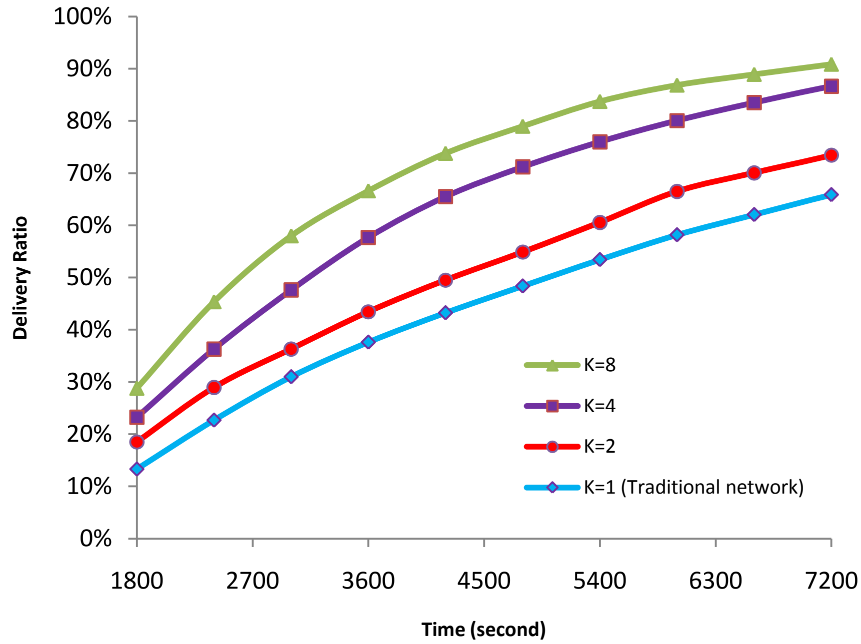


Figure 6-10 Delivery ratio: long transmission range

It is also interesting to compare the performance of using the same MPR capability in two scenarios. In wireless networks, a long transmission range can usually provide more opportunities for a node to communicate other nodes. However, in Figures 6-9 and 6-10, the curves of K=1 have no obvious difference. The reason is that severe collisions in communications prevent successful transmissions and restrain the benefit of using long transmission range. As the MPR capability increases, better performance is attained in long transmission range scenario, since by increasing the MPR capability collisions are diminished gradually, the inherent benefit of using long transmission range in DTN is emerging.

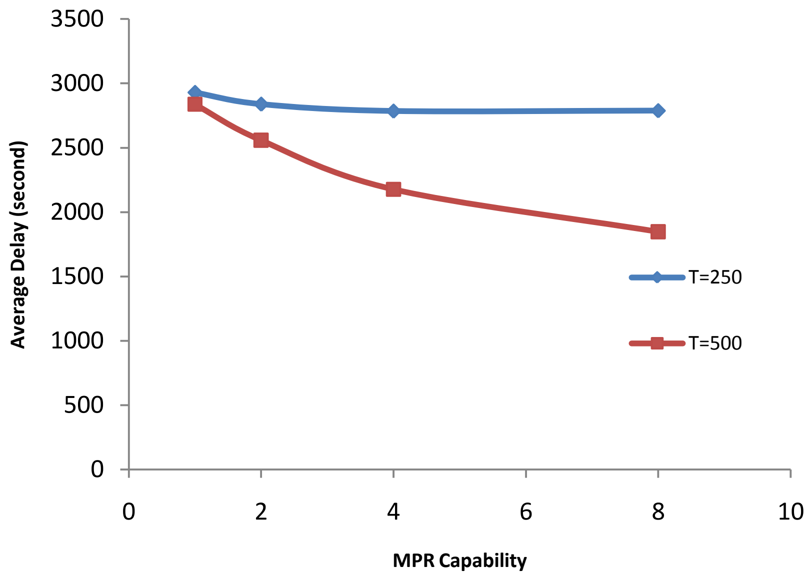
On the other hand, when the transmission range increases to 500 m, more nodes are located within the same transmission range allowing more simultaneous transmissions.

In such a condition, by using a large MPR capability, the number of collisions can be significantly reduced which increases the probability of correctly receiving packets and improves the performance for the entire networks. However, it is interesting to investigate more intense traffic in a short transmission range which still retains as a valid DTN.

Nevertheless, in all cases, the delivery ratio is increasing as time passed. Although, in the end of simulations, the delivery ratio does not reach 100%, if the simulation lasts for enough long time, it will approach 100%.

Average Delay

Average delay in DTN is defined as the average value of the delays for each successfully delivered packet. Figure 6-11 shows the result of average delay of the network in both transmission ranges. As the MPR capability growing large, the reduction of delay in the long transmission range scenario is much distinct than in the short transmission range scenario due to the different number of simultaneously sending nodes in these two scenarios as we discussed above for delivery ratio. We can also observe that the delay for long transmission range is explicitly lower than the average delay for the short transmission range except for the situation of K=1. The reason is also similar as we discussed previously that by increasing the MPR capability, collisions are reduced and better performance can be achieved in the long transmission range.



(T: Transmission Range)

Figure 6-11 Average delay

Number of Collisions

To verify the simulation outcome, number of collisions is counted in each scenario and average collision ratio is computed as the number of collisions per second. From Table 6-1, the collision is much severe in the long transmission. In the long transmission range, the average collision ratio reduced 80.04 when the MPR capability K increased from 1 to 8; while the corresponding reduction value for the short transmission range scenario is just 10.43. By using MPR, the effect of collision reduction for the long transmission range is much significant than for short transmission range.

	K=1	*K=2*	*K=4*	*K=8*
Short transmission range	10.46	4.25	0.81	0.03
Long transmission range	90.50	60.28	24.72	4.32

(K=1 is equivalent to traditional network)

Table 6-1 Average collision times per second

6.6 Influence of Group Factor Number

To investigate the effect of using different group factor in the MAC layer, the setups of the same configurations except for different group factors are evaluated. One setup uses one group factor 2 and another use two group factors 2 and 3. Figures 6-12 and 6-14 describe the delivery ratio of the short transmission range for each setup and Figures 6-13 and 6-15 describe the delivery ratio of the long transmission range. By analyzing these two setups, the same results of the performances can be concluded as in the case with two group factors 3 and 4. In addition, by comparing Figures 6-9 with 6-12, 6-14 and Figures 6-10 with 6-13, 6-15, using two group factors outperforms a little than just using one group factor 2. The reason may be that two group factors provide more opportunity for nodes to communicate with each other as discussed in Chapter 5. However, the improvement is not significant, since at an instant time, the number of simultaneously sending nodes and receiving nodes in the same area is uncertain. It is not trivial to describe the situations by using a fix group factor. Thus the group factor number may not be a crucial factor for the whole network performance.

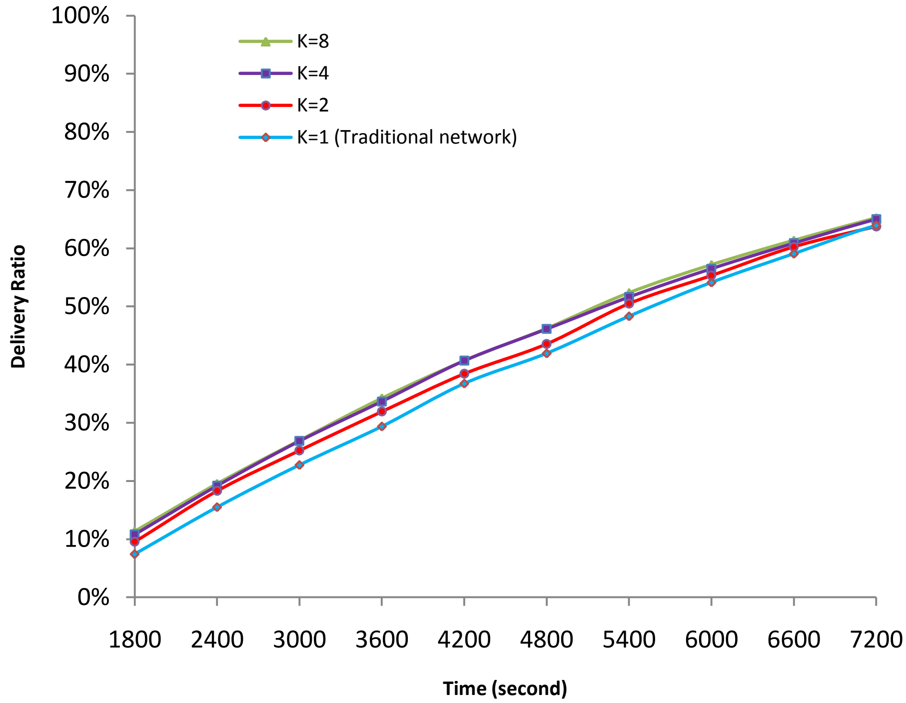


Figure 6-12 Delivery ratio: short transmission range with group factor=2

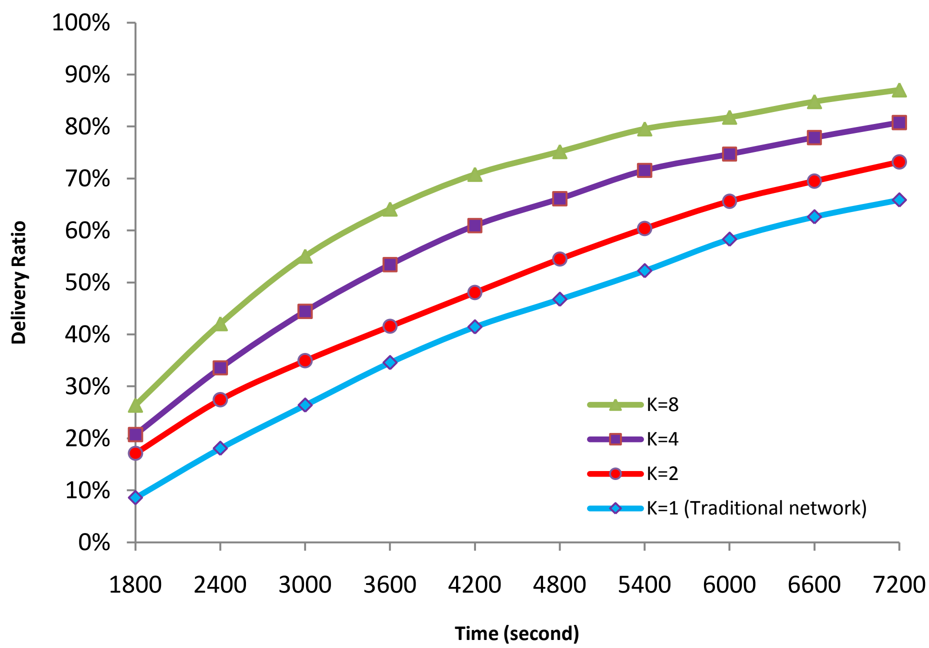


Figure 6-13 Delivery ratio: long transmission range with group factor=2

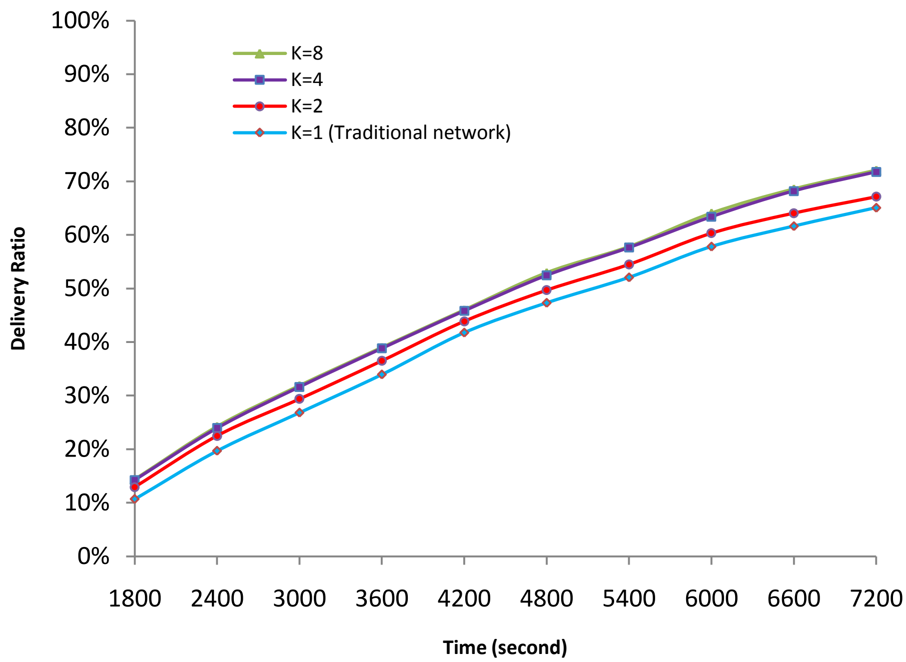


Figure 6-14 Delivery ratio: short transmission range with group factors=2 and 3

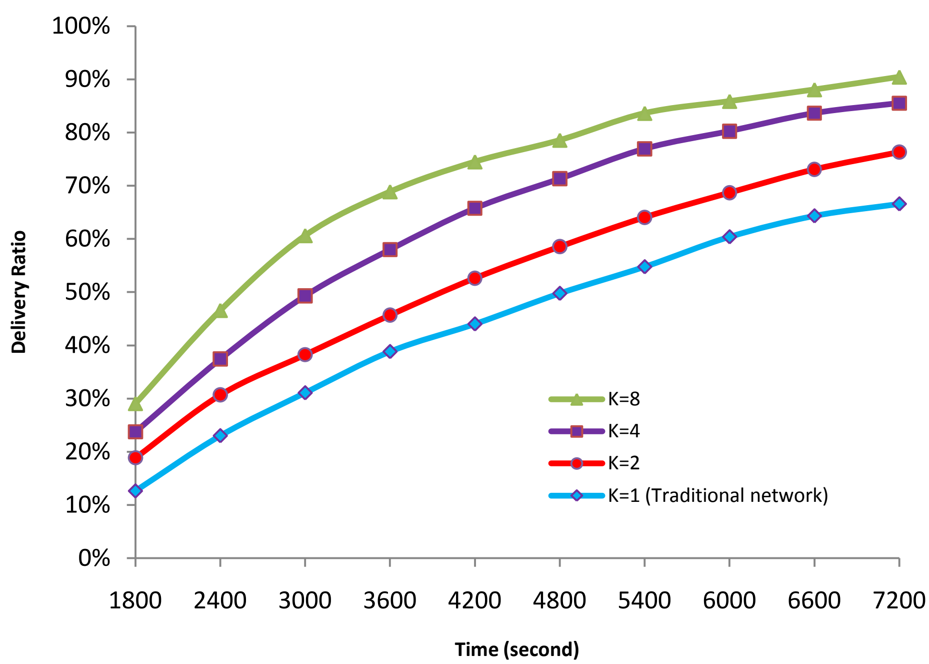


Figure 6-15 Delivery ratio: long transmission range with group factor=2 and 3

6.7 Heavy traffic load

In heavy traffic load case, each node generates one packet every 300 seconds during 1800- second initial stage and total 2800 original packets are generated for the entire network. In this setup, two group factors 3 and 4 are used. Figure 6-16 and 6-17 illustrate the delivery ratio for the short transmission range and the long transmission range respectively. By comparing the result to the scenario of light traffic load with 1600 original packets, the delivery ratio is degraded for all different MPR capability in both transmission ranges. It is because that it requires longer time to deliver additional packets in DTN, which was evaluated in [3]. However, the analyses for the impact of different MPR capability discussed in previous sections are still held for the heavy traffic load scenario.

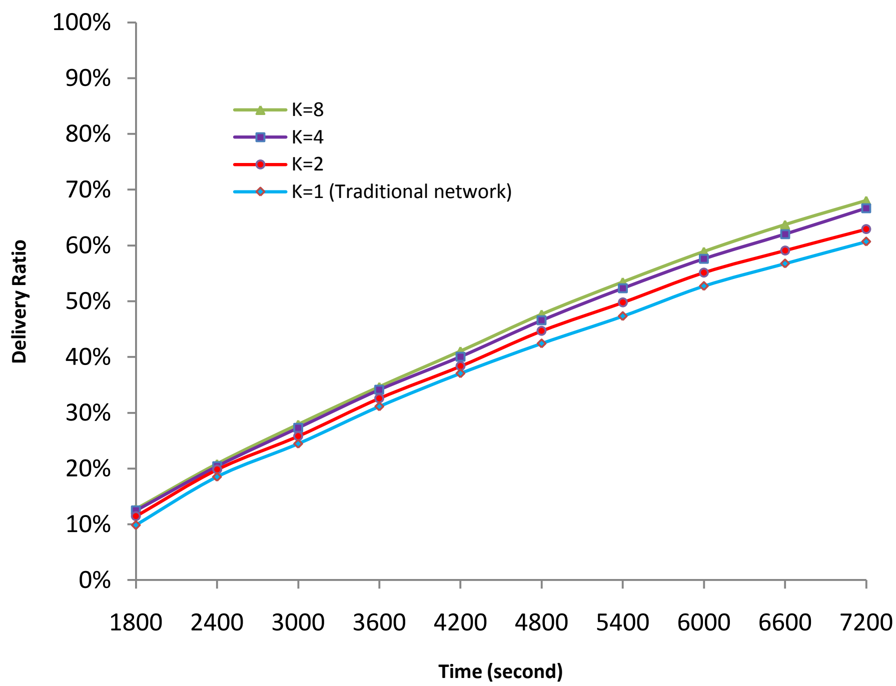


Figure 6-16 Delivery ratio: short transmission range with total 2800 original packets

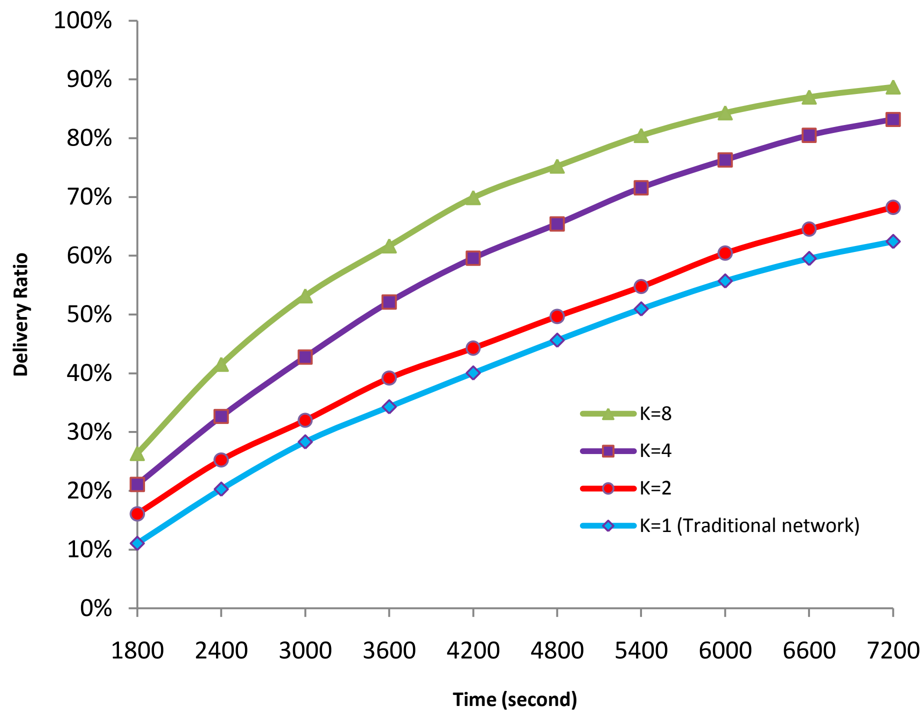


Figure 6-17 Delivery ratio: long transmission range with total 2800 original packets

Chapter 7

Conclusion and Future work

7.1 Conclusions

In this thesis, the performance of VANET using Epidemic Routing with MPR support at the MAC layer has been studied. We use the trace of GPS data collected by taxis in Shanghai, which provides a real environment to investigate the impact of using MPR in VANET. For scheduling in MPR, we propose a simple scheme, Group Base Scheme, to coordinate the transmission and receiving in the MAC layer. The simulation results indicate that by using MPR, the performance of VANET can be improved comparing to the conventional case without MPR support. When the transmission range increases or the communication traffic becomes heavy, by increasing MPR capability properly, the improvement for delivery ratio as well as the reduction of delivery latency can be substantial.

7.2 Future Works

As we discussed in Chapter 3, based on Epidemic Routing protocol, several improved protocols such as the spray and waiting, PROPHET and RAPID are proposed in order to solve the flooding problem of Epidemic Routing and have shown better performances. It is interesting to bring these novel DTN routing methods into the environment with underlying MPR support. However, from our analysis for MPR capability, to employ benefit of MPR needs large number of simultaneously sending nodes, otherwise improving MPR capability could not play its superiority. These improved routing methods reduce the time of exchanging packets significantly by their own ideas. Thus the total number of packet transmissions in the network is much less than in the network using Epidemic Routing, which will very likely cut down the chance of simultaneously sending. Therefore, although these routing protocols could perform better than Epidemic Routing, MPR may not suitable for them as no much gains attained by using MPR. Another interested topic is to develop two closely correlated schemes in DTN routing layer and in MAC layer respectively. From our discussions in Chapter 4 and analysis for our simulations in Chapter 6, it is clearly that MPR will improve the performance when the networks are full of simultaneously transmissions; we call it the *fitted condition to use MPR*. In other words, MPR may benefit the networks in all cases as long as the fitted condition to use MPR is satisfied. It works not only for DTN but also nearly for all kinds of networks. However, for all existent DTN routing methods, none of them initiatively builds an environment which is directly related to the fitted condition of using MPR. Thus, how to propose a novel DTN routing method that is closed related with MPR condition is an interesting and important issues. Fortunately, as we mentioned in Chapter 3, the principle of DTN routings is store and forward and usually multiple-copy schemes are used. Since multiple copies are spread out into networks, it may become feasible to coordinate with MPR in MAC layer directly. However, the details of implementation may still need further study as well as confront many challenges.

In general, design of scheduling methods to support MPR capability is always a subject, particularly under assumption of DTN routing. As discussed in Chapter 4, many scheduling problems are mathematically based on optimization but complex to implement. It is challenge to design an efficient and practical scheduling method to incorporate both the optimization issue and constrains from real circumstances.

Finally, multicast in DTN has been studied by researchers [44] [45]. Based on the property of wireless channels, any unicast transmission is propagated to all nodes in the transmission range, which can be utilized to multicast without much difficulty. Similarly, it will be interesting to investigate the impact of using MPR in multicast DTN.

In summary, DTNs and its application in VANET, together with MPR, have been intensively studied in recent years. Although many valuable outcomes have been proposed by researchers, there are still many unsolved problems, especially the correlation of DTN routing layer with other layers. Therefore, besides developing efficient routing protocols, the studies of the cross-layer in partially connected MANET systems may become a new interesting direction. On the other hand, MPR, a topic from years, will have more novel places to be utilized in the future as the fast development of wireless networks.

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