Studies on Distributed Cooperative Diversity for V2V Communications

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A thesis submitted for the degree of

Doctor of Philosophy in Engineering

September 2016

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Abstract

In recent years, intelligent transportation system (ITS) is well known as an effective way to provide road safety and comfortable driving. In vehicular communications, the current standards can be applied for safety related message exchange but in the future world, other new applications like autonomous controlled vehicles require more reliability and capacity with small delay. Moreover, multi-hop data delivery for emergency situations on road is not explicitly supported. Vehicular communications have some attractive characteristics such as constrained mobility along a predetermined road and predictability of vehicle's position, etc. However, network topology changes frequently and very fast due to vehicle mobility. As a result, inter-vehicle connectivity can be impacted significantly. Moreover, the line-of-sight signal components are often blocked by obstacles as buildings at intersections or trucks on highway. Consequently, signal attenuation is large. Therefore, multi-hop data delivery in vehicle-to-vehicle communications with high reliability and small delay should be investigated.

In wireless communications, cooperative communications are widely known as a technique allowing single-antenna nodes to reap the benefits of the conventional MIMO systems. By using distributed intermediate nodes, cooperative communications can obtain the same diversity gain benefits as conventional MIMO systems without requiring multiple antennas on the same node, which is also known as distributed cooperative diversity technique. In the cooperative diversity, space-time block code (STBC) is often applied because the diversity gain can be obtained without channel state information (CSI) at the transmitter. In addition, this encoding scheme can achieve both full

diversity order and full data transmission rate with simple decoding algorithm at the receiver. However, in multi-hop relay communications, it is difficult to establish the path route from the source node to the destination node with selecting the efficient cooperative relays. The existing routing protocols in MANETs are not suitable for most applications in multi-hop vehicular communications due to the distinctive characteristics of V2V communications. This is because in these routing protocols, one or multiple routes from a source node to a particular destination node should be discovered before transmitting data packet. Consequently, these protocols are not suitable for the scenarios with more than one destination node. Furthermore, problems of redundant broadcast messages and the broadcast storm can make the design of routing protocols further complicated.

However, in order to achieve high reliability for wireless multi-hop communications, the efficient cooperative relays must be selected to forward the packet in each hop. Distributed STBC encoding should be also applied to obtain higher cooperative diversity gain. In addition, the number of transmitted packet and the power consumption in network must be reduced while still maintaining the performance improvement of system, which can reduce the mutual interference in the shared radio channel. Therefore, in order to meet the requirements, transmission methods are proposed in this thesis as follows.

In proposal 1, a method of cooperative diversity transmission is proposed to reduce the power consumption normalized by one data packet transmission power consumption with keeping the performance improvement for wireless multi-hop ad-hoc networks. The normalized power consumption is reduced by limiting the number of transmitting relay nodes in each hop and the number of repetition of the same data packet transmission at each node, which in turn makes the reduction of the number of transmitted packets in network. As a result, this can also lead to the reduction of interferences and better efficiency frequency utilization in network. More specifically, a relay selection procedure is proposed to select the two relays with high contribution according to the transmission direction in each hop by installing a new timer at each node and using control packets. The timer is also used to assign the STBC encoding pattern to the two selected relays in order to obtain higher cooperative diversity gain.

In proposal 2, a cooperative diversity transmission method for wireless multi-hop relay V2V communications is proposed to disseminate emergency messages in the emergency situations. In this method, we consider to exploit the attractive characteristics of the constrained mobility and predictability in vehicular communications. In order to obtain higher cooperative diversity gain, a group of distributed vehicle stations which have high contribution according to the transmission direction is selected to forward the same data packet simultaneously to the further vehicle stations. This relay selection algorithm is based-on position, speed and movement direction, combining with the digital road map equipped on the vehicles. The STBC encoding is also used at the selected group of distributed vehicle relays. Moreover, in order to manage the transmission of whole network in each hop, a master vehicle station is selected by installing another new timer at each vehicle station and using control packets in each hop.

From the simulation results, we can confirm that the proposed methods can reduce the power consumption normalized by one data packet transmission power consumption and the redundant broadcast packets significantly with keeping the improvement of packet loss probability by limiting the number of repetition of packet transmission at each node and selecting the only distributed relays with high contribution according to the transmission direction. As a result, these methods can achieve high reliability and partly meet the requirements of ITS system in the future.

Acknowledgements

This thesis is a summary of my doctoral study at the University of Electro-Communications (UEC), Tokyo, Japan. I am grateful to a large number of people who have helped me to accomplish my work.

First, I would like to express my sincere gratitude to Prof. Takeo Fujii who is my supervisor. With his depth and wide knowledge and his enthusiasm, I have already received a lot of help under his supervision. He has been always listening to, discussing and giving helpful and insightful comments to make my research better. I have also learned so much from him, not only academic skills but being a nice supervisor to students. I feel lucky for being a student of him.

In addition, I am very much obliged to my thesis committee: Prof. Yasushi Yamao, Prof. Eiji Oki, Prof. Koji Ishibashi, Prof. Motoharu Matsuura. I would like to thank them for their insightful and helpful comments and questions, which make my thesis more comprehensive.

I would also like to thank all members of AWCC, and the other Vietnamese and Japanese friends in UEC for their kindly help, which make my stay in Japan so memorable. I am also grateful to Vietnamese Government for the financial support during my studying in Japan.

Last but not least, I am indebted to my family for their unconditional love and supports. Especially, I would like to thank my wife, Van Ha, for her love, understanding and sharing with me about all aspects of life, and our children, Hoang Bach and Bao Chau, for bringing much joy to our family. I also want to thank my parents and siblings for their silent supports and always believing in me. With their huge love, I know that they always hope all best wishes come to me.

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ACRONYMS

Acronyms

4G	The 4-th Generation cellular system
ACK	Acknowledgment packet
ACs	Access Categories
AF	Amplify-and-Forward
AIFS	Arbitration Inter-Frame Space
AIFSN	Arbitration Inter-Frame Space Number
AODV	Ad-hoc On-demand Distance Vector
ATPN	Average number of transmitted packets
CBR	Confirm to Become Relay
CSI	Channel State Information
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CTBS	Clear to Broadcast SYNT
CW	Contention Window
BER	Bit Error Rate
DCF	Distributed Coordination Function
DF	Decode-and-Forward
DSRC	Dedicated Short-Range Communications
EDCA	Enhanced Distributed Channel Access

ACRONYMS

FCC	Federal Communications Commission
FFT	Fast Fourier Transform
GPS	Global Positioning System
ITS	Intelligent Transportation System
ISM	Industrial, Scientific and Medical
ISI	Inter-Symbol Interference
ICI	Inter-Carrier Interference
LAN	Local Area Network
LDC	Linear Dispersion Codes
LoS	Line-of-Sight
LTE	Long-Term Evolution
MAC	Medium Access Control
MANET	Mobile Ad-hoc Network
MIMO	Multiple-Input Multiple-Output
MHVB	Multi-Hop Vehicular Broadcast
MVS	Master Relay Vehicle Staion
PCF	Point Coordination Function
PDR	Packet Delivery Rate
PHY	Physical Layer
QoS	Quality of Service
OFDM	Orthogonal Frequency-Division Multiplexing
OVS	Ordinary Vehicle Station
RREP	Route Reply Packet

RREQ Route Request Packet

RSU Road Side Unit

RTBS Request to Broadcast SYNT

RVS Relay Vehicle Station

SIFS Short Inter-Frame Space

SISO Single-Input Single-Output

SNR Signal to Noise Ratio

STBC Space-Time Block Coding

SYNT Synchronize and Trigger the Transmitting timing

TVS Transmit Vehicle Station

V2I Vehicle-to-Infrastructure

V2R Vehicle-to-Roadside

V2V Vehicle-to-Vehicle

VS Vehicle Station

VANET Vehicular Ad-hoc Network

WAVE Wireless Access in Vehicular Environment

WiMAX Worldwide Interoperability for Microwave Access

WLAN Wireless Local Area Network

ACRONYMS

Chapter 1

Introduction

In this chapter, an introduction for the research on distributed cooperative diversity for multi-hop Vehicle-to-Vehicle (V2V) communications is presented. This chapter is organized as follows. First, background and motivation of the studies is provided in Section 1.1. Next, contributions and objectives of this thesis are described in Section 1.2. Scope of the study are then shown in Section 1.3. Finally, organization of the thesis with the description of each chapter is given in Section 1.4.

1.1 Background and Motivation of the Study

In recent years, intelligent transportation system (ITS) is well known as an effective way in order to provide road safety, comfortable driving with infotainment applications, and distribution of updated information about the roads, etc. In addition, other goals of ITS are to reduce traffic congestion, waiting times, and fuel consumptions [1]. In Japan, ITS is considered as a foundation for solving the fundamental challenges facing society such as aging population, global warming, sustainable energy supply, and safety against natural and manmade disasters [2]. With a comprehensive plan and various phases of development and deployment of ITS, fully automated driving systems are expected to be implemented and commercialized in 2020s in Japan [3]. In order to support the ITS systems, wireless communications and vehicular ad-hoc network (VANET) technologies have been

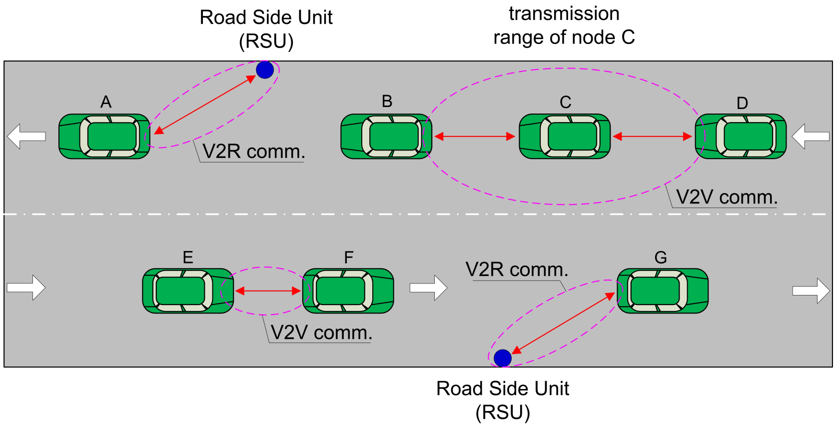

Figure 1.1: Vehicle-to-Vehicle (V2V) and Vehicle-to-Roadside (V2R) communications.

considered as an important part to improve the performance of vehicular communications and achieve the above goals. VANETs are defined as a subclass of mobile ad-hoc networks (MANETs) which use moving vehicles as mobile nodes, and created from the concept of setting up a network of vehicles for a specific situation without using any central base station or any controller.

In vehicular communications, a vehicle can communicate with another vehicle directly, called Vehicle-to-Vehicle (V2V) communications, or a vehicle can communicate to an infrastructure such as a Road Side Unit (RSU), known as Vehicle-to-Roadside (V2R) or Vehicle-to-Infrastructure (V2I) communications. A typical scenario with V2V communications and V2I communications is shown in Fig. 1.1. While V2I communications provides better service in sparse networks and long distance communications, V2V communications enables direct transmission among vehicles for short and medium distances and at locations where RSUs are not available [4]. However, deployment of wireless infrastructures in V2I communications is unprecedented challenges such as financial cost, geographical scale, and the number of users to be supported. Therefore, we concentrate on studies on V2V communications in this thesis.

In V2V communications, VANETs have some attractive characteristics as follows. First, the movement of vehicles is limited in road trajectory. As a result, if the information of road maps, speed, and movement direction are available then the future position of vehicles in network can be predicted. In addition, since the vehicle nodes can provide continuous power to communication devices by themselves, transmission power in VANETs is not a significant constraint as in the conventional ad-hoc or sensor networks. Finally, the vehicle nodes have usually higher computational capability because of the no limitation of device size. However, along with the useful characteristics, VANETs have to cope with several challenges [5]. First, the network topology changes frequently and very fast due to high vehicle mobility and different movement direction of each vehicle. As a result, inter-vehicle connectivity can be impacted significantly from a network perspective in comparison with low-velocity mobile communication systems. In addition, the harsh communication environment is also one of the most difficult challenges in VANETs. Highly dynamic topology and obstacles such as buildings and trees at intersections or trucks on highways, which cause shadowing, multipath, and fading effects, are causes of frequent network partitioning and intermittent connectivity [6]. The line-of-sight (LoS) component of the signal is often blocked by the obstacles. Consequently, signal attenuation is large.

In order to achieve the goals of ITS systems, vehicular communications have to meet the requirements of standards, routing protocols, applications and automatic driving systems. The original IEEE 802.11 standard no longer works well in vehicular communication environments. The IEEE 802.11p protocol cannot well meet the requirements of the efficiency, performance, and throughput for a potential large number of vehicle nodes [7][8][9]. Furthermore, in order to reduce the potential driving risk and enhance road safety as the number of vehicles is rapidly increasing, the V2V communications and V2R communications are able to meet requirements of the ITS by providing various applications. Vehicular networking applications can be classified into active road safety applications, traffic efficiency and management applications, and infotainment applications [10]. The current VANET applications and standards can be applied for safety-related message exchange but in the future world, other new applications for autonomous controlled vehicles require more reliability and capacity with small delay. Therefore, advanced techniques should be investigated to meet requirements of ITS systems in the future.

1. INTRODUCTION

The existing routing protocols in MANETs [11][12][13] are not suitable for most application scenarios in multi-hop vehicular communications due to the distinctive characteristics of VANETs. This is because one or multiple paths from a source node to a particular destination node should be discovered before transmitting data packet. Therefore, these protocols are not suitable for the scenario with more than one destination node. Furthermore, problems of redundant broadcast messages and the broadcast storm [14][15] can make the design of routing protocols further complicated. As a result, a design of effective and efficient routing protocol in VANETs is still a critical challenge and requirement for vehicular communications with high mobility of vehicle nodes and highly dynamic topology.

Due to the shadowing and multipath fading effects of wireless environments, in order to increase the reliability and capacity without additional bandwidth or transmission power, Multiple-Input Multiple-Output (MIMO) technology, which uses multiple antennas at both transmitter and receiver, is widely known as an effective and efficient approach in wireless communications in comparison with that of a Single-Input Single-Output (SISO) system [16]. The main advantages of a conventional MIMO system have been widely acknowledged such as diversity gain, spatial multiplexing gain, and array gain. However, a wireless mobile node may not be equipped with multiple antennas because of size and hardware limitations. In order to overcome these problems, cooperative communications are widely known as a technique allowing single-antenna nodes to reap the benefits of the conventional MIMO systems [17][18]. This technique is also known as user cooperation diversity or distributed cooperative diversity technique. By using distributed intermediate nodes, cooperative communications can obtain the same diversity gain benefits as conventional MIMO systems without requiring multiple antennas on the same node. Therefore, this technique is also able to achieve significant improvements in the reliability and the outage probability.

In the cooperative communications, space time block code (STBC) encoding schemes are often applied in order to obtain the higher cooperative diversity gain without channel state information (CSI) which is referred as channel properties of a communication link at the transmitting node [19]. In addition, these STBC encoding schemes can achieve both full diversity order and full data transmission rate with simple decoding algorithm at the receiving node. In this system, relay nodes simultaneously transmit the signals encoded by one of the STBC encoding patterns in a cooperative manner. At the receiving node, because the STBC encoded signals with different encoding patterns from the different distributed relay nodes are received, the cooperative diversity gain can be obtained by decoding STBC as shown in [19]. However, the user cooperative diversity schemes in multi-hop communications have a problem that is difficult to establish the path routes from the source node to the destination node with the the efficient cooperative relay. In wireless multi-hop ad-hoc networks, there are two main broad categories of routing protocols, proactive and reactive protocols, used to establish the path routes from the source node to the destination node before transmitting data packets. Proactive schemes posed a negligible delay since route information is generally kept in the routing tables and is periodically updated. However, in these schemes, the overhead of the control packets is large. In addition, it is difficult to establish the efficient routes when network topology is large and frequently changed. On the other hand, reactive protocols search for the path routes from the source node to the destination node in an on-demand manner. Therefore, these protocols are suitable for the network topology which is frequently changed. However, the delay of this type of routing protocols is large since the routing information is not stored at each node [20].

To overcome this problem, [21] has proposed a scheme called STBC distributed ARQ. In this scheme, the source node first broadcast the data packet to the destination node without finding the path routes in advance. Then, if the destination node does not receive the data packet correctly from the source node, the data packet is simultaneously retransmitted by the source node and the surrounding nodes which have already received the error-free data packet. A control packet is broadcasted from the source node to trigger the transmission timing for the surrounding nodes. As a result, this method can achieve significant improvement of performance with a small average number of hops. However, drawback of this scheme is that the number of transmitted packets in network increases significantly. This is because the data packet is transmitted toward all direction, which is cause of the redundant broadcast packets which do not highly contribute to the communication direction from the source node to the destination node. This can lead to increasing in the average power consumption and collision in network. In addition, this scheme cannot select the best relay nodes with high contribution according to the transmission direction. Therefore, an effective and efficient transmission scheme for multi-hop communications should be investigated.

In order to achieve high reliability for wireless multi-hop communications, the efficient cooperative relays must be selected to forward the packet in each hop. Distributed STBC encoding should be also applied to obtain higher cooperative diversity gain. In addition, the number of transmitted packet and the power consumption in network must be reduced while still maintaining the performance improvement of system, which can reduce the mutual interference in the shared radio channel. Therefore, in order to meet the requirements, transmission methods are proposed in this thesis as follows.

In proposal 1, a method of cooperative diversity transmission is proposed to reduce the power consumption normalized by one data packet transmission power consumption with keeping the performance improvement for wireless multi-hop ad-hoc networks. The normalized power consumption is reduced by limiting the number of transmitting relay nodes in each hop and the number of repetition of the same data packet transmission at each node, which in turn makes the reduction of the number of transmitted packets in network. As a result, this can also lead to the reduction of interferences and better efficiency frequency utilization in network. More specifically, after limiting the number of potential relay nodes based-on the predictable future location of distributed relay nodes, a relay selection procedure is proposed to select the two relays with high contribution according to the transmission direction in each hop by installing a new timer at each node and using control packets. This timer is also used to assign the STBC encoding pattern to the two selected relays in order to obtain higher cooperative diversity gain. The convolutional code is also employed to obtain coding gain and higher performance improvement. The performance of the proposed method is evaluated through computer simulations. From the simulation results, we can confirm that the normalized power consumption is reduced significantly while still maintaining the improvement of performance. This proposed method is described in detail in Chapter 4.

In proposal 2, a cooperative diversity transmission method for multi-hop V2V communications is proposed to disseminate emergency messages in the emergency situations. In this method, we consider to exploit the attractive characteristics of the constrained mobility and predictability in vehicular communications. Thanks to the digital road maps and the exchange of routine messages in current ITS systems, the information of position, speed, and movement direction of vehicles are available. In order to obtain higher cooperative diversity gain, a group of distributed vehicle stations which have high contribution according to the transmission direction is selected to forward the same data packet simultaneously to the further vehicle stations (VSs). This relay selection algorithm is based-on position, speed and movement direction, combining with the digital road map equipped on the vehicles. The STBC encoding is also used at the selected group of distributed vehicle relays. Moreover, in order to manage the transmission of whole network in each hop, a master vehicle station (MVS) is selected by installing another new timer at each VS and using control packets. In this method, we focus on the emergency messages in multi-hop V2V communications. The emergency information is provided to the behind vehicles on the same way in the emergency situations such as traffic congestion, traffic accidents, and road hazards to avoid chain collisions on highway for ITS systems. In the proposed method, a vehicle station which can first detect the emergency situations broadcasts the warning messages to the behind vehicle stations on the same way. By communicating between vehicles, it can be predicted possible collision and automatically speed down or alert drivers. The proposed method can also be used in applications for emergency vehicles (e.g., ambulances and fire trucks) to disseminate alarm messages to the other vehicles in the forward direction by simply changing the conditions of position, speed and direction of movement to select intermediate vehicle stations in each hop. The performance of the this method is evaluated by computer simulations. From the simulation results, we can confirm that the proposed method can achieve reliability improvement and reducing the redundant broadcast packets with keeping the significant improvement of packet loss probability by limiting the number of repetition of packet transmission at each node and selecting the only distributed relay vehicle stations stations with high contribution according to the transmission direction. This proposed method is described in detail in Chapter 5.

1.2 Contributions and Objectives

This dissertation proposes cooperative transmission methods exploiting distributed cooperative diversity for wireless multi-hop vehicular communications. The main contributions and objectives of this thesis lie in the following aspects:

- In proposal 1, a relay selection procedure is proposed to select distributed relay nodes with high contribution according to the transmission direction from the source node to the destination node.
- A new timer which is set according to the information of relative location between potential relay nodes and the destination node is installed at each node to select the two best distributed relay nodes in each hop.
- In addition, this timer is also used to assign STBC encoding pattern to the two distributed relay nodes in order to obtain higher cooperative diversity gain in each hop.
- In proposal 2, a design of cooperative transmission method for multi-hop vehicular communications is proposed to disseminate emergency messages in emergency situations on highway.
- In order to exploit the attractive characteristics in vehicular communications, a relay selection algorithm based-on position, speed and direction of movement, combining with the digital map equipped on the vehicles is proposed to select a group of distributed vehicle relay stations with high contribution according to the transmission direction.
- A master vehicle station which manages transmission of whole network, triggering and synchronizing transmission timing of vehicle relay stations is selected in each hop by using another new timer which is set according to the information of relative location between the potential master vehicle stations in the next hop and the current master vehicle station.

- In order to obtain cooperative diversity gain in vehicular communications, distributed STBC encoding is also used at the selected vehicle relay stations.
- In the proposed methods, high reliability can be achieved without complicated routing algorithms.
- The analysis of signal model and transmission time of the proposed methods is also provided.
- By selecting the only distributed relay nodes with high contribution according to the transmission direction and limiting the number of repetition of the same message transmission at each node, the proposed methods can reduce the normalized power consumption and redundant broadcast messages considerably with keeping the significant improvement of performance.

1.3 Scope

In order to meet requirements of vehicular communications in the ITS systems, a wide range of activities and challenges are involved [2], which include the challenges of standards, PHY and MAC techniques, routing protocols, applications, requirements of reliability and delay in automatic driving systems, big data, security problems, timing and frequency synchronizations, etc. In this thesis, we consider the solutions related to PHY and MAC layers, and routing in order to obtain high reliability and reduce redundant broadcast packets for multi-hop relay communications. More specifically, multi-hop broadcast transmission, and on-demand and location based routing schemes are considered. In order to obtain both full diversity gain and full transmission rate, we apply the simple STBC encoding with two transmit antennas and one receive antenna [19]. Therefore, if there are more than two distributed relay nodes transmit the signals, one of the two STBC encoding patterns is selected and assigned to the distributed relay nodes. The other STBC encoding with three-branch or four-branch transmit antennas can be also implemented in a distributed manner. However, in order to obtain the same diversity order, the STBC encoding schemes with additional antennas should be reducing the coding rate. Furthermore, this can lead to increasing in the operation complexity but the performance improvement is negligible. In addition, the power balance of each transmit antenna is not constant thus the diversity gain can be decreased [21]. In order to achieve high reliability over frequency-selective channels, orthogonal frequency-division multiplexing (OFDM) technique is combined with STBC encoding. The guard interval of OFDM has tolerance to not only the influence of the delay spread but also the transmitting timing offset among distributed relay nodes [22]. Although timing and frequency synchronizations for distributed STBC systems is a challenging task in highly dynamic communication environment, some papers have proposed the solution to solve these problems [23][24][25]. Therefore, it is assumed that the perfect synchronizations can be obtain by using OFDM technique and a control packet which is used to trigger and synchronize transmitting timing of distributed relay nodes.

1.4 Organization of the Thesis

This thesis summarizes our research works on distributed cooperative transmission methods for wireless multi-hop vehicular communications. This thesis consists of six chapters as follows.

Chapter 1 This chapter introduces the research background and motivation, contributions and objectives, and scope of the studies.

Chapter 2 This chapter presents the overview of vehicular Communications. First, the information about characteristics, challenges and requirements of ITS communications is given. Next, propagation model in vehicular communications is described. Physical layer (PHY) and medium access control (MAC) specifications of the IEEE 802.11p standard are then presented. In addition, the overview of routing protocols in VANETs is also given in this chapter. Finally, frequency band allocations and DSRC technique in Japan and the other places are provided.

Chapter 3 This chapter presents the background of distributed cooperative diversity in wireless cooperative communications. First, the characteristics, advantages and limitations of the well-known MIMO technology are described. Next, cooperative communications is presented as an effective and efficient approach to overcome drawbacks of the conventional MIMO systems. Alamouti's STBC scheme and distributed cooperative transmission technologies are also presented in this chapter. Finally, OFDM cooperative diversity such as coding gain, diversity gain in wireless multi-hop relay networks is given.

Chapter 4 A cooperative diversity transmission method for STBC-OFDM wireless multi-hop relay networks is presented in this chapter. First, the introduction of the proposed method is provided. System model and the analysis of signal model are then described. Next, transmission procedure and relay selection algorithm are provided to select the two distributed relay nodes with high contribution according to the transmission direction from the source node to the destination node. Finally, performance evaluation through computer simulations and summary are presented.

Chapter 5 This chapter presents a cooperative diversity transmission method to disseminate emergency messages in the emergency situations for wireless multi-hop relay vehicular communications. First, the introduction of the proposed method is provided. System model and the analysis of signal model are then described. Next, the proposed method is described in detail. The analysis of transmission time of the proposed method is also provided. Finally, performance evaluation through computer simulations and summary are presented.

Chapter 6 This chapter summarizes the studies on distributed cooperative transmission methods for wireless multi-hop vehicular communications of the thesis and explores the future works.

Chapter 2

Vehicular Communications

2.1 Introduction

In recent years, in order to achieve safe, comfortable, and efficient road transportation for ITS systems, a solution that has attracted researchers' attention is the use of wireless communications and VANET technology. Wireless communications and VANETs are considered as an important part to improve the performance and archive these goals. VANET is defined as a subclass of mobile ad-hoc networks (MANETs) which use moving vehicles as mobile nodes, and created from the concept of setting up a network of vehicles for a specific situation without using any central base station or any controller. In VANETs, a vehicle can communicate with another vehicle directly, called Vehicle-to-Vehicle (V2V) communications, or a vehicle can communicate to an infrastructure such as a Road Side Unit (RSU), known as Vehicle-to-Roadside (V2R) or Vehicle-to-Infrastructure (V2I) communications. Figure 1.1 shows a typical VANET scenario for V2V communications and V2I communications.

While V2I communications provides better service in sparse networks and long distance communication, V2V communications enables direct communication among vehicles for short and medium distances and at locations where RSUs are not available [4]. However, deployment of wireless infrastructures in V2I communications is unprecedented challenges such as financial cost, geographical scale, and the number of users to be supported. Therefore, we concentrate on V2V communications in this thesis due to flexibility and low cost.

The remainder of this chapter is organized as follows. An overview of characteristics, challenges and requirements of V2V communications are presented in Section 2.2. Next, propagation model in vehicular communications is given in Section 2.3. The IEEE 802.11p standard and routing protocols for ITS communications are then described in Sections 2.5, 2.6, respectively. Finally, Section 2.7 summarizes this chapter.

2.2 Characteristics, Challenges and Requirements of ITS Communications

As mentioned above, VANET is a self-organizing network for ITS systems in order to provide communications among vehicles and between vehicles and roadside station, in which vehicles are considered as mobile nodes in MANETs. Therefore, VANETs are a special case of MANETs. However, VANETs have their own distinctive characteristics. In comparison with other communication networks, VANETs have to cope with several challenging features as follows,

- **Highly dynamic topology**: Since vehicle nodes have high relative velocities, which can be about 50 [km/h] in urban and more than 100 [km/h] on highways, and can also move at different directions, vehicle nodes can quickly join or leave the network in a very short time. Consequently, network topology changes frequently and fast.

- **Frequently disconnected network**: Due to the highly dynamic topology, the link between two vehicles can be impacted significantly and is intermittent connectivity. In addition, the line-of-sight (LoS) component of the signal in inter-vehicle connectivity is often blocked by obstacles as buildings at intersections or trucks on highway. Consequently, the signal attenuation and packet loss rate due to the obstacles are large [6].

- **Communication environment**: In VANETs, there are two main kinds of communication environments including highway and city. In highway environments, it is assumed that the propagation model is free-space, however the signal can be affected by interference from the reflection of surrounding wall panels and trucks. In city environments, inter-vehicle connectivity can be impacted significantly by obstacles such as buildings and trees which cause shadowing, multipath, and fading effects.

However, VANETs have some attractive characteristics as follows,

- **Constrained mobility and predictability**: The movement of vehicles is limited in road topology. As a result, if the information of road maps, speed, and direction are available then the future position of vehicles in network can be predicted.
- **Unlimited battery power and storage**: Since the vehicle nodes can provide continuous power to communication devices by themselves, transmission power in VANETs is not a significant constraint as in the conventional ad-hoc or sensor networks. In addition, the vehicle nodes have usually higher computational capability because of the no limitation of device size.

In order to achieve the goals such as road safety, comfortable driving with entertainment applications, and distribution of updated information about the roads, etc., vehicular communications have to meet the main requirements and challenges as follows:

- **Standards**: Due to the distinctive characteristics of VANETs, the original IEEE 802.11 standard no longer works well in vehicular environments. The IEEE 802.11p protocol cannot well meet the requirements of the efficiency, performance, and throughput for a potential large number of vehicle nodes [7][8][9]. In order to overcome such scalability issues, therefore, advanced techniques should be investigated in research community.
- **Routing Protocols**: Although there are many kinds of routing protocols and algorithms as described in Section 2.5, a design of effective and efficient routing protocols is still a critical challenge and requirement for vehicular communications with high mobility of nodes and highly dynamic topology.
- **Applications**: In safety related applications, it is assumed that there are two main types of messages, periodic and emergency messages. While the

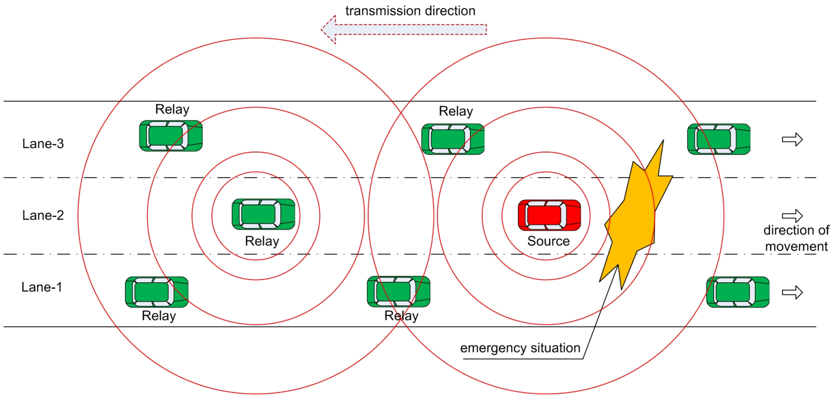

Figure 2.1: An example of emergency messages transmission in multi-hop wireless relay networks.

former contains the information of position, speed, direction of movement, and type of vehicle, etc., the later contains the information such as traffic accidents, traffic congestion, road hazards, etc. For the routine messages, maximum transmission interval is 100 [ms], allowable delay is less than 100 [ms], packet delivery rate (PDR) must be greater than 95%, communication range is from 50 to 250 [m] depending on particular applications [26][27]. By using the routine messages broadcasted periodically from vehicle stations in network, an vehicle can be aware of the other vehicles nearby, thus traffic collisions can be predicted. For the emergency messages, due to the importance of the emergency information, these messages should be disseminated immediately to a large area by the vehicle station which senses an emergency situation first in network, as a result, behind vehicles can avoid potential dangerous situations. Comparison between periodic and emergency messages in safety related applications is described in Table 2.1. Figure 2.1 shows an example of emergency messages transmission for emergency situations in wireless multi-hop relay networks.

- **Automatic driving systems**: In order to support automatic driving systems, advanced technologies and communications related to the global positioning system (GPS), the dynamic maps, the three-dimensional road data profile, ITS look-ahead information via vehicular communications have to achieve higher reliability and smaller delay in comparison with conventional systems [3].

Table 2.1: Comparison between periodic and emergency messages in safety related applications [26][27].

Types of messages	Emergency Messages	Periodic Messages
Packet delivery rate	95%	95%
Information	Accidents, road hazards, traffic congestion, etc.	Position, speed, movement direction, type of vehicles
Latency	Immediately	< 100 [ms]
Occur	Occasionally	Periodically
Transmission area	Large (500 - 1000 [m])	Trans. range (50 - 250 [m])
Transmission type	Multi-hop broadcast	Single hop broadcast

2.3 Propagation Model

In wireless networks, the radio propagation is strongly impacted by the communication environment. The level of influence varies depending on the object types, the link types, and the communication environment. In the vehicular communication environment, the most important objects that have an impact on the propagation are buildings, vehicles (e.g., personal vehicles, commercial vans, trucks, scooters, and public transportation vehicles), and different types of vegetation. Locations, and density of static objects as well as the velocity and density of vehicles significantly influence the signal propagation in these environment. The propagation mechanisms in vehicular communications are varying path loss across space and time, potentially Doppler effect, and frequency-selective fading caused by both the static and mobile objects, since both are sources of reflections, shadowing, and diffraction [6][28]. Therefore, a realistic channel model for simulations that can predict the propagation loss for wireless transmission is necessary for the efficient evaluation of applications before they are deployed in the real world. The Recommendation ITU-R P.1411-8 [29] provides methods for estimating path

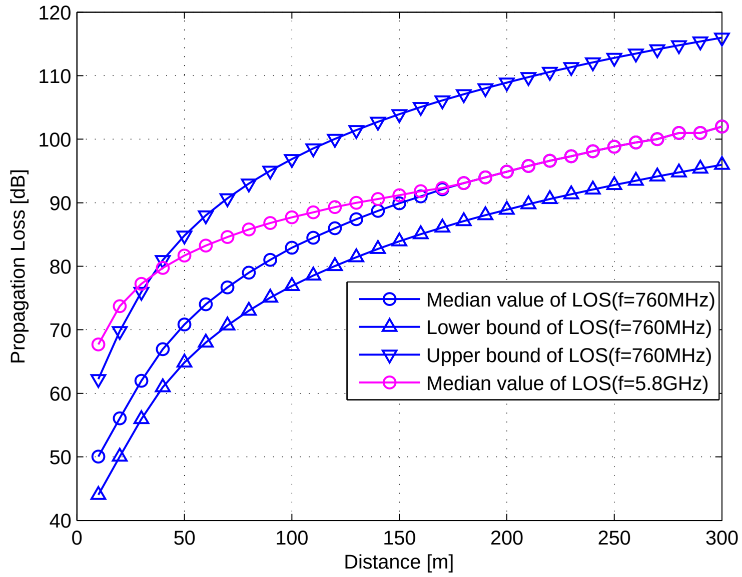

Figure 2.2: Propagation losses for LoS situations.

loss, delay spread, and angular spread on outdoor short-range propagation (operating range less than 1 km) over the frequency range 300 MHz to 100 GHz. This Recommendation is widely accepted and commonly used for vehicular channels [30]. In addition, the feasibility and accuracy of using the Recommendation is investigated and confirmed by authors in [31]. Therefore, the path loss models of line-of-sight (LoS) paths in [29] are used for vehicular communications in this thesis. In the ITU-R P.1411-8, basic transmission loss can be characterized by two slopes and a single breakpoint which propagation changes from one regime to the other as follows,

$$L_{LoS} = L_{bp} + \begin{cases} 10\alpha_1 \log_{10}(\dfrac{d}{R_{bp}}) & \text{for d} \leq R_{bp}, \quad (2.1a) \\ 10\alpha_2 \log_{10}(\dfrac{d}{R_{bp}}) & \text{for d} > R_{bp}, \quad (2.1b) \end{cases}$$

where d is the distance from transmit antenna to receive antenna in m, L_{bp} is a value for the reference path loss at the breakpoint $d = R_{bp}$. R_{bp} is the breakpoint distance in m. α_1 and α_2 are the path loss exponent for cases $d \leq R_{bp}$ and $d > R_{bp}$, respectively. In the ITU-R P.1411-8, the reference path loss L_{bp} at the breakpoint and the breakpoint distance R_{bp} are given by,

$$L_{bp} = \left| 20\log_{10}\left(\frac{\lambda^2}{8\pi h_t h_r}\right)\right|, \tag{2.2}$$

$$R_{bp} = \frac{4h_t h_r}{\lambda}, \tag{2.3}$$

where h_t and h_r are transmit antenna height and receive antenna height, respectively. λ is the length of the Radio Frequency (RF) carrier. In this Recommendation, for the lower bound of the path loss model, α_1 and α_2 values are set to be 2 and 4, respectively. For the upper bound, α_1 and α_2 values are set to be 2.5 and 4, respectively, and L_{bp} is added to 20 [dB]. For the median value of path loss model, which is used in this thesis, α_1 and α_2 values are the same as the lower bound and L_{bp} is added to 6 [dB]. The propagation losses over frequencies 760Mhz and 5.8Ghz, which are allocated for ITS in Japan, for LoS signals are shown in Fig. 2.2. In this figure, transmit and receive antennas are set to be the same height, $h_t = h_r = 1.5[m]$.

2.4 The IEEE 802.11p Standard

In order to facilitate the harsh vehicular communication environment and enable deployment of VANETs, IEEE has defined the IEEE 802.11p/1609.x protocol stack [32], as known as Wireless Access in Vehicular Environment (WAVE) standard for V2V and V2I communications. The IEEE 802.11p standard is not a standalone standard. The IEEE 802.11p is the amendment to the IEEE 802.11a standard [33] at lower layers, which are Medium Access Control (MAC) and Physical (PHY). Specification of MAC and PHY layers is described in Subsections 2.4.1 and 2.4.2, respectively.

2.4.1 Physical Layer Specification

As mentioned above, the PHY layer specification in the IEEE 802.11p is modified from the IEEE 802.11a standard. In order to make signal more robust against multiple path fading and Doppler shift due to movement, reducing inter-symbol interference (ISI) as well as inter-carrier interference (ICI), some parameters are changed in the 802.11p. In the 802.11a, One OFDM channel uses 52 subcarriers including 4 pilot subcarriers and 48 subcarriers are used to transmit data. The IEEE 802.11p uses the same number of subcarriers, but operates in a smaller bandwidth per channel, 10 MHz in comparison with 20 MHz in the 802.11a. As a result, all PHY parameters of the 802.11p in the time domain are double compared to that of the 802.11a. This also means that data transmission rates in the 802.11p are half of that in the 802.11a. The changes of PHY layer specification are listed in detail in Table 2.2.

Table 2.2: Comparison of PHY specifications between IEEE 802.11a and IEEE 802.11p.

Parameters	IEEE 802.11p	IEEE 802.11a	Changes
Channel bandwidth	10MHz	20MHz	Half
Data rates (Mbps)	3, 4.5, 6, 9, 12, 18, 24, 27	6, 9, 12, 18, 24, 36, 48, 54	Half Half
Modulation	BPSK, QPSK, 16QAM, 64QAM	BPSK, QPSK, 16QAM, 64QAM	No No
Code rate	1/2, 2/3, 3/4	1/2, 2/3, 3/4	No
Number of subcarriers	52	52	No
Guard time	0.16μs	0.8μs	Double
FFT period	6.4μs	3.2μs	Double
Header duration	8μs	4μs	Double
Preamble duration	32μs	16μs	Double
Subcarrier spacing	0.15625MHz	0.3125MHz	Half

2.4.2 Medium Access Control Layer Specification

Medium Access Control (MAC) method of the IEEE 802.11p standard operates based-on the enhanced distributed channel access (EDCA), which is an enhanced version of the basic distributed coordination function (DCF) from the IEEE 802.11 standard [33] and based-on the IEEE 802.11e standard [34] designed for contention-based prioritized quality of service (QoS) support. EDCA uses the

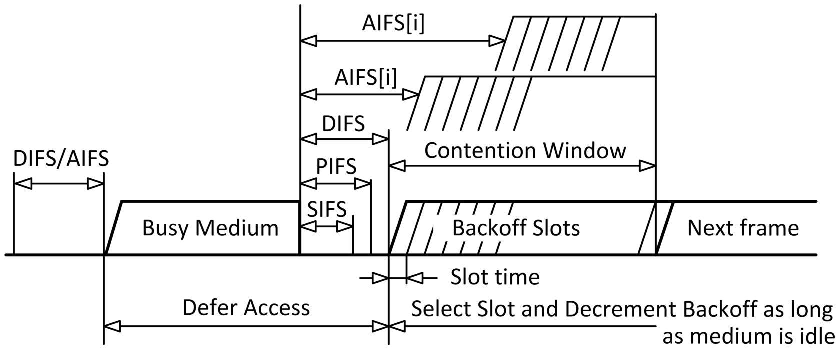

Figure 2.3: DCF access procedure in 802.11p and some IFS relationships [33].

carrier sense multiple access with collision avoidance (CSMA/CA) method as shown in Fig. 2.3, where nodes listen to the wireless channel before sending. If channel is idle for an arbitration inter-frame space (AIFS), a new value is defined for different access categories (ACs) in EDCA, the node starts transmitting immediately. If the channel is sensed busy or becomes busy during the AIFS, the note must delay its transmission and perform a backoff procedure. The backoff procedure is designed to avoid a collision between the nodes that are waiting for transmission after the channel becomes idle. The backoff procedure operates as follows. First, the node initializes a timer as given by,

$$T_{backoff} = n_{backoff} \times aSlottime, \tag{2.4}$$

where $n_{backoff}$ is an integer which is selected from a uniform distribution [0, CW] with the contention window CW, and $aSlottime$ is the unit slot time derived from the PHY layer. At the next step, the timer starts to count down when the channel is sensed as idle. During the decrement process, if any transmission is sensed or the channel becomes busy. The timer will suspend until the channel becomes free again. Finally, when the timer reaches to zero, the node transmit its frame immediately. For every attempt to transmit a specific packet, the size of the contention window (CW) will be doubled from its initial value (CW_{min}) until a maximum value (CW_{max}) is reached. After the packet is transmitted or when the packet is discarded because the maximum number of channel access attempts was reached, the the contention window will be reset to CW_{min}. In 802.11p standard, prioritization of transmission is implemented by using four queues corresponding with four different priority levels in each node. These queues have different value AIFS and different backoff parameters, which can be considered as an extension of the backoff procedure in DCF as shown in Fig. 2.3. In the figure, SIFS is the original short interframe space. DIFS and PIFS are DCF interframe space and point coordination function (PCF) interframe space, respectively. The duration AIFS[AC] is derived by the following equation,

$$AIFS[AC] = AIFSN[AC] \times aSlottime + SIFS, \tag{2.5}$$

where AIFSN[AC] is arbitration inter-frame space number, which is set to determine the length of an AIFS interval corresponding to each AC. Different ACs are allocated with different AIFSNs and different values of CW_{min} and CW_{max}. The AC with a smaller AIFS has higher priority to access the channel. Default parameters setting in 802.11p for the EDCA mechanism are shown in Table 2.3, where value DIFS = $58\mu s$ is the shortest AIFS possible value corresponding to the highest priority in IEEE 802.11p standard.

Table 2.3: Comparison of MAC specifications between IEEE 802.11a and IEEE 802.11p.

Parameters	IEEE 802.11p	IEEE 802.11a
Slot time	$13\mu s$	$9\mu s$
SIFS	$32\mu s$	$16\mu s$
DIFS	$58\mu s$	$34\mu s$
CW_{min}	3	15
CW_{max}	1023	1023

2.5 Routing Protocols in VANETs

Routing is one of key issues in multi-hop VANETs. Therefore, this section presents a brief overview of routing protocols in VANETs. In order to guarantee reliable, continuous and seamless communications in V2V and V2R communications, routing is a challenging task since the characteristics of the network are high mobility and time-varying density of nodes, frequent disconnections, highly partitioned and dynamic topology as mentioned above. The performance of routing protocols also depends on the external factors such as road shapes, traffic conditions, environmental factors and obstacles (e.g., buildings, trees, and trucks). The existing routing protocols in MANETs [11][12][13] no longer work well for most application scenarios in VANETs due to the characteristics of VANETs. In addition, the broadcast storm [15] can make the design of routing protocols further complicated. However, VANETs have some attractive features over MANETs. The vehicle stations in VANETs are usually equipped with the higher capability of transmission power and storage than those in MANETs. The stations have also higher computational and sensing capabilities in comparison with the nodes in MANETs. Furthermore, the movement of stations in a particular VANET can be predicted if the current velocity, direction, and road trajectory are available [35]. The routing protocols can be roughly classified into the following categories: unicast, broadcast, multicast/geocast and hierarchical as shown in Fig. 2.4. The main features of the routing protocols are described in detail in [36].

The unicast schemes distribute information from a source node to only one destination node [37]. The classification and characterization of existing unicast routing protocols are presented in [38].

Dissemination of messages from a source station to a group of vehicle stations in VANETs is the objective of multicast. Geocast is a variation of multicast transmission in which special messages are disseminated to a specific group of vehicle stations in designated areas by using location services. The classification and features of the geocast routing protocols can be found in [38][39][40].

Delivery of messages from a source station to many unspecified destination stations is the primary objective of broadcast transmission scheme. One of the drawbacks of broadcast is known as the broadcast storm problem, causing serious packet collision and packet loss that reduce communication reliability [15]. However, various approaches are proposed to mitigate broadcast storm problem as described in [41]. Therefore, in the safety-related applications, the broadcast routing is the most frequently used to disseminate the packet to all the other vehicles located near by the sender [36].

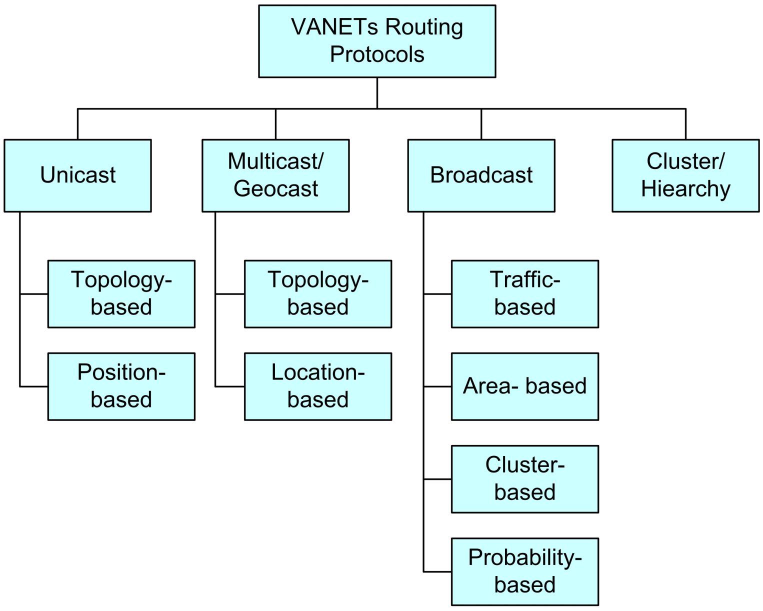

Figure 2.4: Routing protocols in VANETs.

Routing strategies can be divided into tow main broad categories, proactive and reactive routing protocols. Proactive schemes posed a negligible delay since route information is generally kept in the routing tables and is periodically updated. However, the overhead for the control packet becomes large and it is difficult to establish the appropriate route when network topology is large and often changed. On the other hand, reactive protocols search for the route from the source node to the destination node in an on-demand manner. Therefore, the protocols are suitable for the situation in which the topology is often changed. However, the delay of this type of routing protocols is large since the routing information is not stored at each node [20].

From the Fig. 2.4, routing protocols in VANETs are further classified into topology based, position/location/area based, traffic based, cluster based, and probability based. Topology based routing protocols select the path from the source node to the destination node by using the information about the network topology and the communication links [12][13]. Therefore, the routing protocols is not suitable in the context of VANETs due to high mobility factor, which is the cause of the frequent network partitioning and route disconnection demanding update of the topology information. In cluster based routing schemes, a group of stations are identified to be part of a cluster [42][43]. In each cluster, a special station is designated to operate as gateway node or cluster-head which is responsible for routing, relaying of inter-cluster transmission, scheduling of intra-cluster transmission and channel assignment for member stations. The member stations do not participate in routing process. Communication within each cluster is made by using direct transmission. In this scheme, when the complexity and mobility of the network increases, the selection of cluster-head and the management of clusters become a challenging task. Traffic based routing protocols use the local traffic density or local one-hop neighbor topology to make routing decisions [44]. These protocols can deal with different situations of traffic conditions during certain hours of the day. However, these methods can introduce high overhead and high end-to-end delay. In order to reduce collision and rebroadcasting, probability based routing schemes are simple to implement and do not create any overhead, however, have the risk of missing packets. As the name implies, position based protocols make routing decisions and forward a packet to intended destinations based-on geographic position of the vehicle stations [45][46][47]. In the protocols, establishment and maintenance of routes are not required but they require location services to determine the position of the nodes in network. Routing based-on position is an efficient transmission scheme in VANETs since it can achieve higher performance of packet delivery ratio than that of the other schemes in a highly mobile environment [36].

2.6 Frequency Band Allocations and DSRC

The next generation of vehicular communications technology designed for safety and efficiency is commonly known as the dedicated short-range communications (DSRC) since it is dedicatedly designed to support short to medium range communications in VANETs. Spectrum allocation for DSRC applications in Europe, North American, and Japan is shown in Fig. 2.5. According to the Recommendation ITU-R M.1453-2, which is approved in 2005, an Industrial, Scientific and Medical (ISM) frequency band at 5.8GHz range (5725MHz - 5875MHz) is specified for DSRC applications [49]. The 5.8GHz frequency band is also allocated for DSRC operation in Japan and Europe. In Europe, future ITS applications, ITS

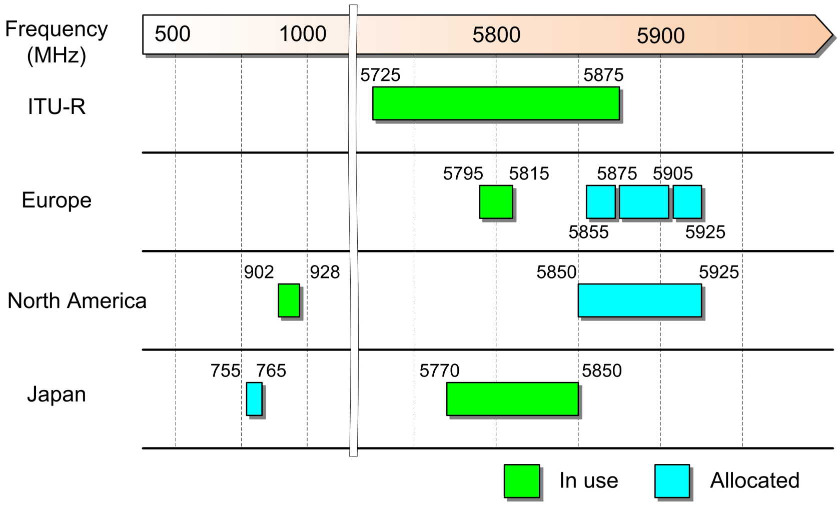

Figure 2.5: Frequency band allocated for DSRC applications in Europe, North American, and Japan [48].

road safety related applications, and ITS non-safety applications are considered to operate in frequency ranges (5905MHz - 5925MHz), (5875MHz - 5905MHz), and (5855MHz - 5875MHz), respectively [50]. In 1999, the Federal Communications Commission (FCC) of the United States allocated 75 MHz bandwidth in 5.9GHz band (5850MHz - 5925MHz) for DSRC operation to support high speed, low latency, and reliable WAVE for safety applications, traffic management applications, and infotainment applications [51]. This spectrum is divided into seven 10MHz channels (one control channel and six service channels) and one 5MHz guard band at the low end as described in Fig. 2.6. This is because most physical testing of DSRC shows that 10 MHz width to be the ideal candidate to deal with the delay and Doppler shift in the V2V and V2I communication environment [52]. The FCC has also designated the channels as a service channel or as a control channel. The two consecutive 10MHz service channels can be combined to create one 20MHz channel. The use of individual channels in detail can be found in the IEEE 1609.4 standard [53]. In the North America, the earlier standard for DSRC operates in the 900MHz band. This spectrum is mainly used for electronic toll collection systems. In Japan, in addition to the 5.8GHz band, the frequency band of 760MHz is currently allocated for ITS applications. The process of rearrangement of the 760MHz band is illustrated in Fig. 2.7. In the past, this

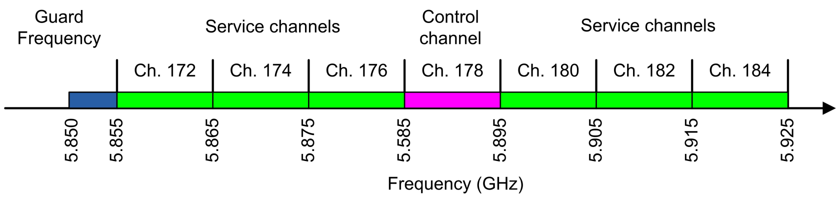

Figure 2.6: DSRC channels arrangement at 5.9GHz band [7].

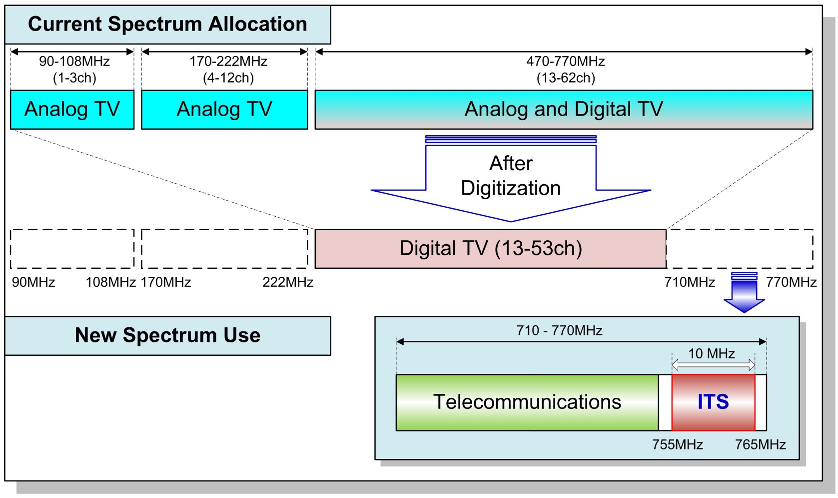

Figure 2.7: 700MHz frequency band arrangement for ITS services in Japan [58].

band was allocated for analogue television broadcast services. However, when the television broadcast services are completely digitized, the 760MHz band has become available and has started to be considered as a potential candidate for vehicular communication environment. In order to confirm the compatibility of the 760MHz band ITS land mobile stations, a series of tests and road experiments are carried out [54]. In addition, several studies also show that the extension of the service area or low propagation loss can be achieved by using the lower frequencies [55][56][57]. Therefore, this band has been officially allocated for ITS safety related applications since December 2011 [58].

2.7 Chapter Summary

ITS systems that contributes to enhancement of the transportation network are a necessary and natural trend in the future. This chapter provides the information about the distinctive characteristics, challenges and requirements of ITS communications. In addition, the overview of background techniques such as propagation model, the physical layer and medium access control layer specifications in the IEEE 802.11p standard, the routing categories, schemes and strategies in VANETs is also analyzed. Finally, the frequency band allocations and DSRC in Europe, North America, and Japan are described in this chapter. It is worth noting that the lower band (760MHz) with benefits of the extension of the service area or low propagation loss has been officially allocated for ITS communications in Japan.

Chapter 3

Distributed Cooperative Diversity

3.1 Introduction

Due to the shadowing and multipath fading effects of wireless environments, the direct link between a source node and a destination node is not always usable or enough quality. This is especially true in ad-hoc wireless network environments where the most of the nodes do not have line-of-sight (LoS) connections. In order to achieve high reliability and high spectrum efficiency, MIMO technology which uses multiple antennas at both transmitter and receiver is widely known as an effective and efficient approach. However, a wireless node may not be equipped with multiple antennas because of size and hardware limitations. Therefore, user cooperative communications which use the antenna of distributed relay nodes to create a distributed antenna array have been proposed to reap the benefits of the conventional MIMO systems. In the cooperative relay communications, STBC encoding is often applied since the higher cooperative diversity gain can be obtained without channel state information (CSI) which is referred as channel properties of a communication link at the transmitting node [19]. In addition, the STBC encoding scheme can achieve both full diversity order and full data transmission rate with simple decoding algorithm at the receiving node. In this system, relay nodes simultaneously transmit the signals encoded by one of the STBC encoding patterns in a cooperative manner. At the receiving node, because the STBC encoded signals with different encoding patterns from the different distributed relay nodes are received, the cooperative diversity gain can be obtained by decoding STBC as shown in [19]. In the remainder of this chapter, the basic characteristic of these background techniques is presented in more detail. First, the advantages and limitations of the conventional MIMO systems, and cooperative communications are described in Section 3.2. Next, in Section 3.3, STBC encoding scheme and distributed cooperative transmission technology are provided. The characteristic of OFDM scheme and coding in multi-hop wireless communications are then presented in Section 3.4. Finally, Section 3.5 summarizes this chapter.

3.2 Cooperative Communications

In the past few decades, a solution that has caught researcher's attention is the use of multiple antennas at both transmitter and receiver which is also known as MIMO system as shown in Fig. 3.1. One of the most important contribution of MIMO system lies in the ability to increase the reliability and capacity without additional bandwidth or transmission power in wireless communications in comparison with that of a Single-Input Single-Output (SISO) system [16]. This is because MIMO systems have the three main advantages such as diversity gain, spatial multiplexing gain, and array gain. Thanks to the benefits of using multiple antennas, MIMO technology has being exploited in many wireless communication standards such as IEEE 802.11 standard, IEEE 802.16 standard, and the 4-th generation (4G) and long-term evolution (LTE) cellular systems. The first advantage in MIMO systems is that high diversity gain can be achieved in order to mitigate channel fading effects in wireless communication. In multiple antennas systems, signals are transmitted and received by each pair of transmit and receive antennas. By using many pairs of transmit and receive antennas, the transmission of signals carrying the same information allows the receiver to obtain and combine multiple independently faded replicas of the data symbols. As a result, higher reliability can be achieved. Therefore, the maximum diversity gain (G_d) can be calculated as the number of independent channels in the multiple antennas systems as follows [59], $G_d = N_t \times N_r$, where N_t and N_r are the number

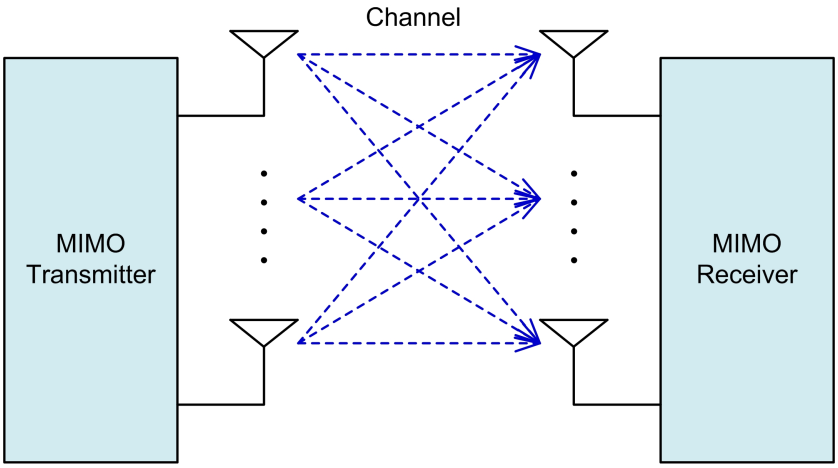

Figure 3.1: Multiple-Input Multiple-Output (MIMO) system model.

of transmit and receive antennas, respectively. The diversity gain indicates also the magnitude of the slope of the average probability of error with an increase in transmit power. In term of probability of error, the diversity gain is given by [60][61],

$$G_d = - \lim_{SNR \to \infty} \frac{\log(P_e(SNR))}{\log(SNR)}, \tag{3.1}$$

where P_e is the average probability of error at average signal-to-noise rate (SNR).

In addition, by transmitting independent symbols with different information content, higher transmission rate can be obtained due to the increase in the available degrees of freedom for MIMO systems, which is well known as the spatial multiplexing gain. Therefore, a point-to-point MIMO system can offer a linear increase in capacity proportional to the number of transmit and receive antennas [62]. The tradeoff between the diversity gain and the spatial multiplexing gain in MIMO communication can be found in [63]. Finally, multiple antennas systems can obtain a array gain, which can lead to the increase in the average signal to noise ratio (SNR) at the receiver. The increase is proportional to the number of receive antennas. However, MIMO systems have increased computational complexity and require higher hardware cost than SISO systems. Furthermore, in order to reduce the effects of antennas space on MIMO channel capacity and to achieve the optimal spatial diversity gain, distance between antennas is set to be approximately a half of the wavelength at the selected operating frequency.

Therefore, it can be difficult to install multiple antennas in a mobile terminal due to the limitations of size and hardware.

In order to reap the benefits of the conventional MIMO systems in an ad-hoc wireless network and overcome the limitations, user cooperative communications has been proposed [17][18], which is well known as user cooperation diversity or distributed cooperation diversity. The basic structure of cooperative relay communications is shown in Fig. 3.2. In a cooperative relay system, the antenna of relay nodes can be shared to create a distributed antenna array, also known as a virtual MIMO system, where each relay node is a part of the virtual antenna array. The process of transmission can be divided into two phases. First, the source node broadcasts its signals to the surrounding nodes, which is including both the relay nodes and the destination node. The relay nodes then process the received signals from the source node and forward them to the destination node. There are two main cooperative strategies that the relay nodes can apply to process the received signals: non-regenerative and regenerative relaying. The former approach which is well known as amplify-and-forward (AF) relaying means that the relay nodes just operate as a repeater in which the received signals are amplified and re-broadcasted to the destination node, while the latter method is called the decode-and-forward (DF) relaying in which the received signals are first decoded, and then re-encoded and forwarded to the destination node [64]. We consider DF strategy in this thesis. This transmission approach has become a powerful technique and recently gained much attention in both academic and industrial research communities due to its ability to provide efficient solutions for challenges in wireless communications. In fact, cooperative communication by using distributed intermediate nodes can obtain the same diversity gain benefits as conventional MIMO systems without requiring multiple antennas on the same node. Therefore, this technique is able to achieve significant improvements in the reliability and the outage probability, decrease power consumption due to transmitting over shorter links, provide higher capacity, and increase throughput performance of system without additional bandwidth. In cooperative relay communications, the performance improvement can be achieved when the same information is carried in the independent channels between the relay nodes and the destination node. This is because when the number of independent channels

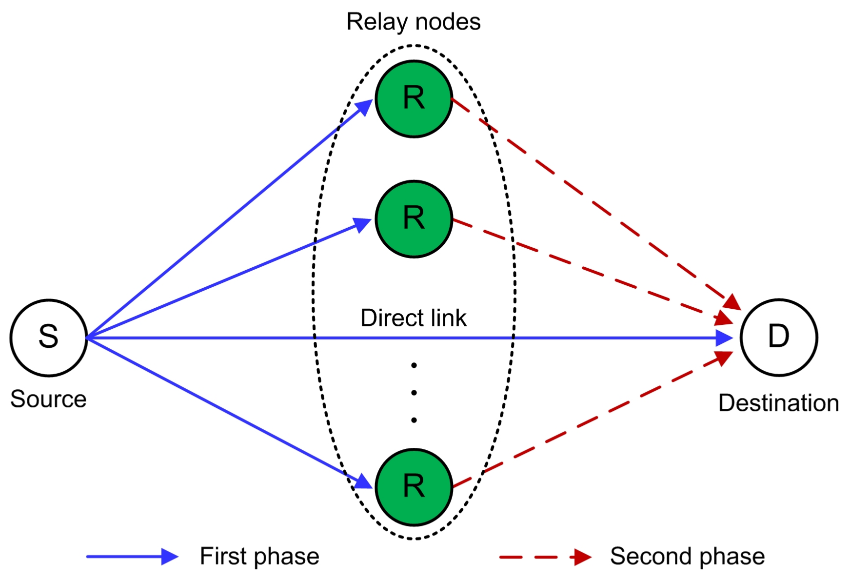

Figure 3.2: The basic structure of cooperative relay communications.

increases, the probability of all of the independent channels affected by deep fading will decrease [59][64]. It is assumed that each node in network has a single antenna as shown in Fig. 3.2. Therefore, in term of the number of independent channels, the maximum cooperative diversity gain (G_{cd}) at the second phase can be derived as $G_{cd} = N_r$, where N_r is the number of selected relay nodes to transmit the packet simultaneously to the destination node.

3.3 Distributed Cooperative Space Time Coding Schemes

Cooperative communications by using distributed space-time block codes (STBC) has recently been considered as an efficient technique that can provide considerable benefits in fading wireless environments. By processing the received signal distributedly at the different relay nodes to create a virtual antenna array, the cooperative diversity gain can be achieved as in the conventional STBC systems [65]. Therefore, Alamouti's STBC scheme is first described and then distributed cooperative transmission technology is provided in this section.

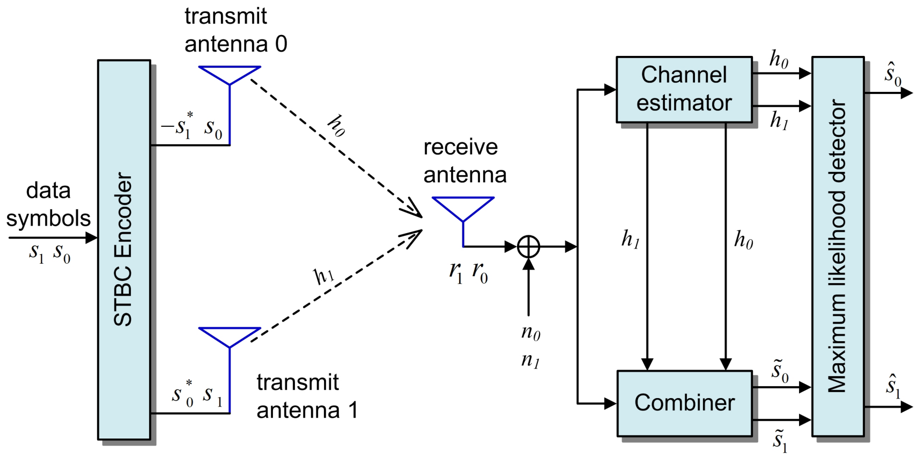

Figure 3.3: STBC transmit diversity scheme with two transmit antennas and one receive antenna [19].

3.3.1 Alamouti Space Time Block Coding

In the cooperative communications, Alamouti's STBC encoding scheme is often applied in order to obtain the higher cooperative diversity gain without channel state information (CSI) which is referred as channel properties of a communication link at the transmitting node [19]. In addition, Alamouti's scheme can achieve both full diversity order and full data transmission rate with simple decoding algorithm at the receiver. The original STBC transmit diversity scheme with two transmit antennas and one receive antenna is shown in Fig. 3.3. In the figure, the two consecutive data symbols s_0 and s_1 are encoded. Then, the encoded signals are transmitted simultaneously from the two antennas installed at the transmitter. r_0 and r_1 are the signals which are received at the first and second symbol transmission periods, respectively. h_0 and h_1 are the channel responses for the signal from the transmit antenna 0 and antenna 1. n_0 and n_1 are the noise components of the s_0 and s_1 symbols at the receiver, respectively. In the STBC encoding scheme, two consecutive data symbols are encoded as follows. First, it is assumed that the input signal for the j-th symbol is s_j, and the next symbol is s_{j+1}, where $j = 2a$ and a is the even number (a=0,2,4,6,...). The s_j and s_{j+1} symbols are encoded according to Table 3.1 and then simultaneously transmitted to the receiver. The rows of the table illustrate the number of transmit antennas

Table 3.1: Alamouti STBC Encoding Patterns.

data symbol (period)	symbol s_j (t)	symbol s_{j+1} $(t+T)$
branch 0	s_j	-s_{j+1}^*
branch 1	s_{j+1}	s_j^*

and the columns illustrate the number of symbol transmission periods. In the STBC model with two transmit antennas and one receive antenna, the encoded pattern of the branch 0 and branch 1 are assigned to the transmit antenna 0 and antenna 1, respectively as shown in Table 3.1, where * denotes complex conjugate operation. More specifically, during the first symbol transmission period (t), the transmitter sends the s_j symbol from the transmit antenna 0, the s_{j+1} symbol from the transmit antenna 0. During the next symbol transmission period $(t+T)$, the $-s_{j+1}^*$ and s_j^* symbols are simultaneously transmitted from the antenna 0 and the antenna 1, respectively.

Since assuming that fading is constant across the two consecutive symbol periods, the channel responses during the first and second symbol transmission periods are written as,

$$\begin{aligned} h_1(t) = h_1(t+T) = h_1 = \alpha_1 e^{j\theta_1} \\ h_2(t) = h_2(t+T) = h_2 = \alpha_2 e^{j\theta_2} \end{aligned} \tag{3.2}$$

where T is the symbol period, α and θ are the amplitude and phase factor for the channel gain. In the case with one receive antenna, the received signals can be represented in term of vector $\mathbf{r}$ as follows,

$$\mathbf{r} = \begin{bmatrix} r_j \\ r_{j+1} \end{bmatrix} = \begin{bmatrix} s_j & s_{j+1} \\ -s_{j+1}^* & s_j^* \end{bmatrix} \begin{bmatrix} h_j \\ h_{j+1} \end{bmatrix} + \begin{bmatrix} n_j \\ n_{j+1} \end{bmatrix}, \tag{3.3}$$

where r_j and r_{j+1} are the received signals at the two symbol transmission periods (t) and $(t+T)$, respectively. h_j and h_{j+1} are the channel responses from the transmit antenna 0 and antenna 1 to the receive antenna during the two consecutive symbols. n_j and n_{j+1} are the noise components. Therefore, equation 3.3 can be written in term of matrix as follows,

$$\mathbf{r} = \mathbf{Sh} + \mathbf{n}, \tag{3.4}$$

where **r, h,** and **n** are 2×1 matrices, **S** is a 2×2 matrix. The orthogonality of Alamouti STBC scheme can be verified by,

$$\mathbf{s}_1^H \mathbf{s}_2 = \begin{bmatrix} s_j^* & -s_{j+1} \end{bmatrix} \begin{bmatrix} s_{j+1} \\ s_j^* \end{bmatrix} = s_j^* s_{j+1} - s_j^* s_{j+1} = 0, \tag{3.5}$$

where $(.)^H$ denotes Hermitian conjugate, $\mathbf{s}_1$ and $\mathbf{s}_2$ are the first and second column vector of matrix **S**, respectively. Without loss of generality, after some elementary manipulations and conjugating the second row of 3.3, the received signals can be equivalently expressed as follows,

$$\begin{bmatrix} r_j \\ r_{j+1}^* \end{bmatrix} = \begin{bmatrix} h_j & h_{j+1} \\ h_{j+1}^* & -h_j^* \end{bmatrix} \begin{bmatrix} s_j \\ s_{j+1} \end{bmatrix} + \begin{bmatrix} n_j \\ n_{j+1}^* \end{bmatrix}. \tag{3.6}$$

It also can be represented in term of matrix form,

$$\tilde{\mathbf{r}} = \mathbf{H}\mathbf{s} + \tilde{\mathbf{n}}. \tag{3.7}$$

where $\tilde{\mathbf{r}}$, $\mathbf{s}$, and $\tilde{\mathbf{n}}$ are 2×1 matrices, $\mathbf{H}$ is a 2×2 matrix. At the receiver, it is assumed that the channel response is known exactly, the combined signals can be obtained by multiplying both sides of equation 3.7 by $\mathbf{H}^H$ as follows,

$$\tilde{\mathbf{s}} = \mathbf{H}^H \tilde{\mathbf{r}}. \tag{3.8}$$

Substituting 3.7 into 3.8, these combined signals can be written as follows,

$$\begin{aligned} \tilde{s}_j &= (|h_j|^2 + |h_{j+1}|^2) s_j + h_j^* \tilde{n}_j + h_{j+1} \tilde{n}_{j+1}^*, \\ \tilde{s}_{j+1} &= (|h_j|^2 + |h_{j+1}|^2) s_{j+1} + h_{j+1}^* \tilde{n}_1 - h_j \tilde{n}_{j+1}^*. \end{aligned} \tag{3.9}$$

As shown in Fig.3.3, these combined signals are then sent to the maximum likelihood detector to choose which symbol was actually transmitted from the transmitter by applying least squares (LS) detection,

$$\hat{s}_k = arg \min_{s_k \in S_M} |\tilde{s}_k - \alpha s_k|^2, \tag{3.10}$$

where $k \in \{j, j+1\}$, $\alpha = |h_j|^2 + |h_{j+1}|^2$, S_M is the set of M transmitted symbols which is known at both the transmitter and receiver, and $|.|$ denotes a magnitude operator. The performance of bit error rate (BER) of Alamouti's scheme is shown in Fig. 3.4. Thanks to the advantages such as simple decoding algorithm at the

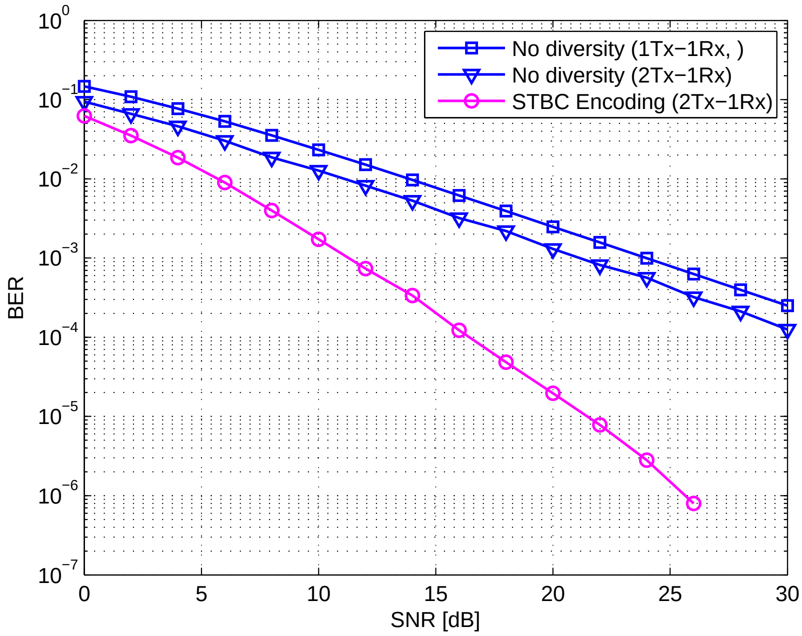

Figure 3.4: Comparisons of the BER performance between with and without using STBC encoding.

receiver, without CSI at the transmitter, achieving both full diversity order and full data transmission rate, Alamouti's scheme is widely used for applications in wireless communication systems like WiFi, WiMax, 3G, LTE and 4G.

Although, Alamouti's scheme is only designed for two transmit antennas, this scheme is a simple and important design of space-time code. The various schemes of space-time code are often designed based on this scheme. The analysis in [66] shows that the orthogonal STBC designs cannot achieve both full diversity gain and full transmission rate simultaneously when the number of antennas is greater than two. A general design of orthogonal space time block codes extended for more than two transmit antennas can be found in [66]. In this design, full diversity gain can be obtained however data transmission rate is less than unity. In order to overcome this limitation, the combination of a real orthogonal STBC generator matrix and its conjugate form is proposed in[67]. However, this scheme has more complex decoding process than Alamouti's scheme. Similarly, Linear Dispersion Codes (LDC) schemes which have the linear combination of the real part and the

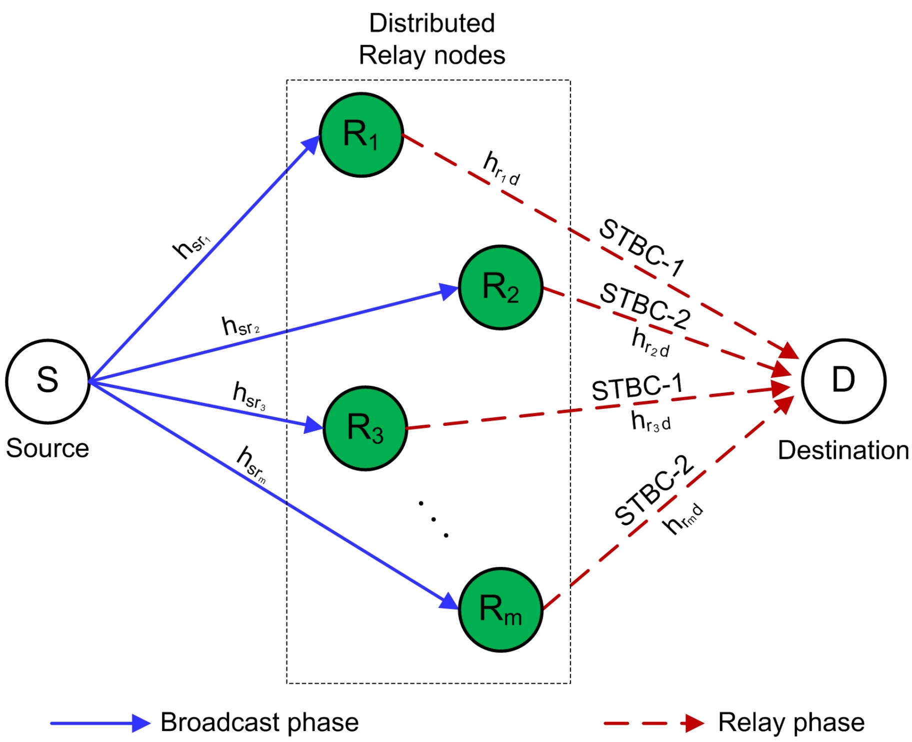

Figure 3.5: Distributed STBC for cooperative communications.

imaginary part of the symbols in order to maximize throughput in MIMO systems have high computational complexity detection methods [68][69][70]. Therefore, Alamouti's scheme is considered in this thesis.

3.3.2 Distributed Cooperative Transmission Technology

In order to obtain cooperative diversity in multi-hop ad-hoc wireless networks, the distributed intermediate nodes between the source node and the destination node are considered as antenna branches. One of the STBC encoding patterns as shown in Table 3.1 is assigned to relay nodes for the cooperative communications as described in Section 3.2 in a distributed manner, which is also well known as Distributed STBC scheme. In this scheme, it is assumed that all nodes in network are equipped with a single antenna or two half-duplex antennas. Similar to the point-to-point MIMO systems using the conventional STBC encoding, in which full transmit diversity gain can be obtained without the the availability of CSI at the transmitter, the Distributed STBC scheme in cooperative wireless communications allows also the relay nodes to achieve full cooperative diversity gain without the availability of CSI at the relay nodes. As a result, the capacity and reliability of system can be significantly improved.

In distributed cooperative diversity, transmission can be divided into the first and second phases, which are also called broadcast phase and relay phase, as represented in Fig. 3.5, where m is the number of relay nodes. In the broadcast phase, the source node broadcasts the data packet to the relay nodes as well as the destination node. In the second phase, the relay nodes detect the packet, if the error-free packet is received, the relay nodes encode the packet by using STBC encoding scheme and then forward to the destination node. If the signals from all relay nodes are transmitted at the same time then the transmission is called synchronous cooperative relay networks. Otherwise, it is known as asynchronous cooperative relay networks. The synchronous cooperative communication is considered in this thesis.

At the first transmission phase, the received signal of s_j symbol from the source node at the i-th relay node is given by,

$$r_{ji} = \sqrt{P_t T_s}\beta_{s,r_i} h_{s,r_i} s_j + n_{ji}, \tag{3.11}$$

where $(i = 1, 2, 3, ...m)$ and m is the number of relay nodes in network. P_t and T_s are the average transmission power used at both the source and relay nodes for every transmission and the period of a symbol, respectively. β_{sr_i} is the path loss gain between the source node to the i-th relay node, $\beta_{s,r_i} = \left(\frac{d_{s,d}}{d_{s,r_i}}\right)^{\alpha}$, where $d_{s,d}$ and d_{s,r_i} are the distance between the source node to the destination and the i-th relay node, α is the path loss exponent. h_{s,r_i} is the fading channel coefficient between the source node and the i-th relay node. n_{ji} is noise component of the s_j symbol.

In the relay phase, the received signals of the s_j and s_{j+1} symbols at the destination node are expressed as follows,

$$r_{ji} = \sum_{m \in R_1} \lambda_{m,d} s_j + \sum_{m \in R_2} \lambda_{m,d} s_{j+1} + n_{ji}, \tag{3.12}$$

$$r_{(j+1)i} = -\sum_{m \in R_1} \lambda_{m,d} s^*_{j+1} + \sum_{m \in R_2} \lambda_{m,d} s^*_j + n_{(j+1)i}, \tag{3.13}$$

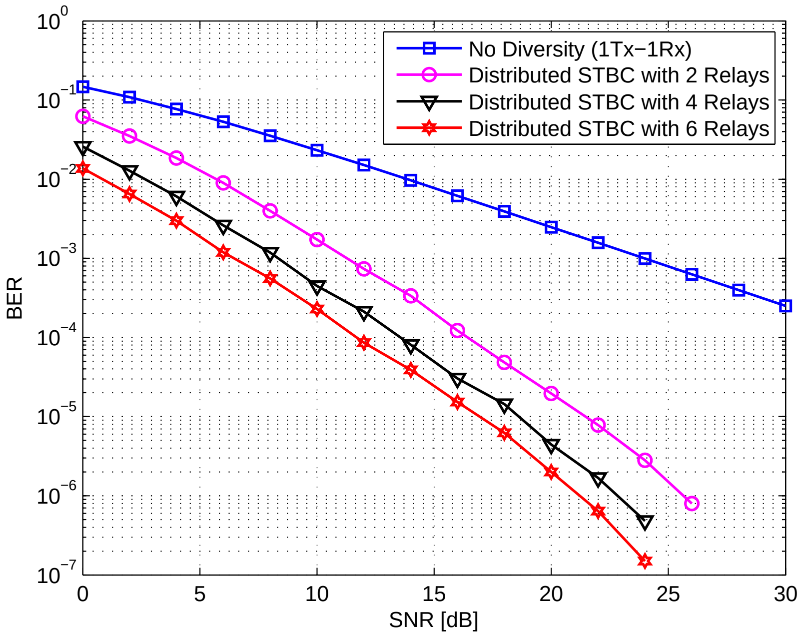

Figure 3.6: Distributed STBC encoding with different number of relay nodes.

where $\lambda_{m,d} = \sqrt{P_t T_s}\beta_{m,d}h_{m,d}$ is channel response between the m-th relay node and the destination node. R_1 and R_2 are the set of relay nodes transmitting the STBC encoding patterns 1 and 2, respectively. At the destination, the decoded signals of the s_j and s_{j+1} symbols are derived according to equation 3.8 as follows,

$$\begin{aligned}\tilde{s}_j &= \sum_{m\in R_1}\lambda^*_{m,d}r_{ji} + \sum_{m\in R_2}\lambda_{m,d}r^*_{(j+1)i} \\ &= (\left|\sum_{m\in R_1}\lambda_{m,d}\right|^2 + \left|\sum_{m\in R_2}\lambda_{m,d}\right|^2)s_j + \sum_{m\in R_1}\lambda^*_{m,d}n_{ji} + \sum_{m\in R_2}\lambda_{m,d}n^*_{(j+1)i},\end{aligned} \tag{3.14}$$

$$\begin{aligned}\tilde{s}_{j+1} &= \sum_{m\in R_2}\lambda^*_{m,d}r_{ji} - \sum_{m\in R_1}\lambda_{m,d}r^*_{(j+1)i} \\ &= (\left|\sum_{m\in R_1}\lambda_{m,d}\right|^2 + \left|\sum_{m\in R_2}\lambda_{m,d}\right|^2)s_{j+1} - \sum_{m\in R_1}\lambda_{m,d}n^*_{(j+1)i} + \sum_{m\in R_2}\lambda^*_{m,d}n_{ji}.\end{aligned} \tag{3.15}$$

As a result, the cooperative diversity gain can be obtained if the channel response is known exactly at the destination node. Then the decoded signals of the two $\tilde{s}_j$ and $\tilde{s}_{j+1}$ symbols can be detected. The figure 3.6 shows the performance of distributed STBC encoding with different number of relay nodes in the relay phase.

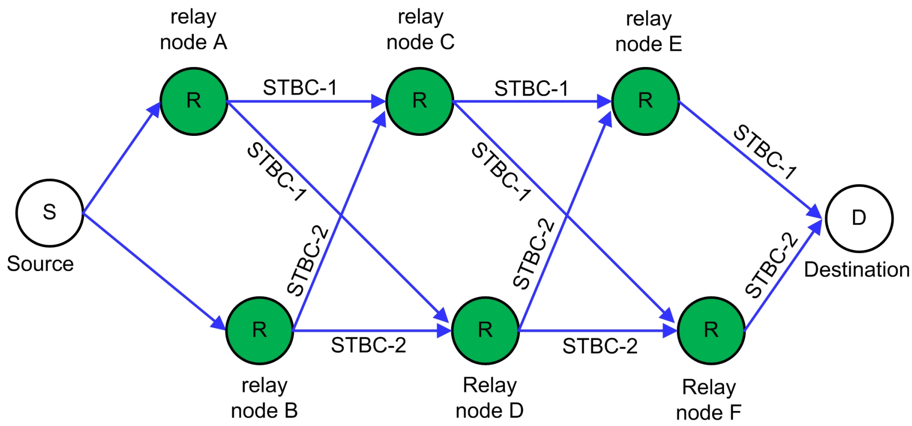

Figure 3.7: Distributed cooperative diversity in wireless multi-hop relay networks.

3.4 OFDM Cooperative Diversity in Multi-hop Wireless Relay Networks

Distributed user cooperative diversity schemes in multi-hop relay wireless communications have a problem that is difficult to establish the path routes from the source node to the destination node with the effectively cooperative relay nodes. As mentioned in Section 2.5, in wireless multi-hop ad-hoc networks, there are two main broad categories of routing protocols, proactive and reactive protocols, used to establish the route from the source node to the destination node before transmission. While proactive schemes have the large overhead for the control packet and it is difficult to establish the appropriate route when network topology is large and often changed since route information is generally kept in the routing tables and is periodically updated, reactive protocols have the large delay because these protocols search for the route from the source node to the destination node in an on-demand manner [20]. To overcome this problem, [21] has proposed a scheme called STBC distributed ARQ as shown in Fig. 3.8. In this scheme, the source node first broadcast the data packet to the destination node without finding the path routes in advance. The transmission procedure of the STBC distributed ARQ scheme can be summarized as follows: First, the data packet is broadcasted from the source node. The data packet is then received and detected by the surrounding relay nodes and the destination node. In the

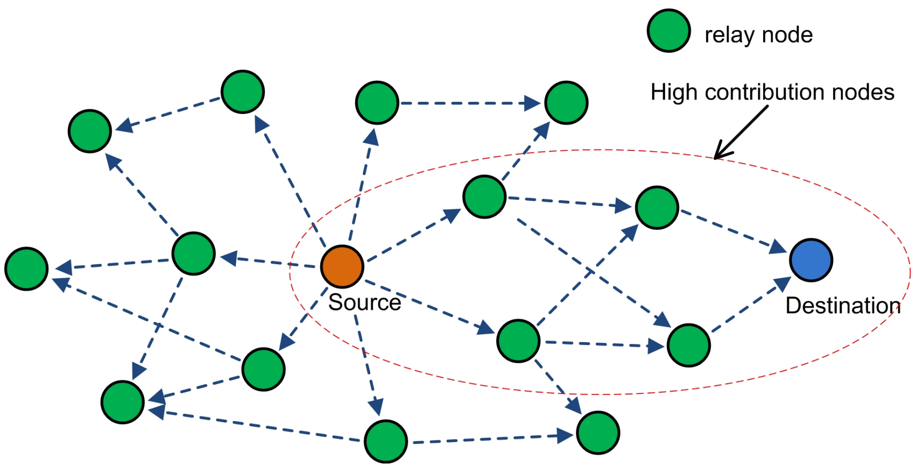

Figure 3.8: STBC Distributed ARQ scheme.

next step, if the destination node does not receive the data packet correctly, the data packet is simultaneously retransmitted by all the source node and the surrounding nodes which have already received the error-free data packet. A control packet is broadcasted from the source node to trigger the transmission timing for the surrounding nodes. Finally, when the destination node received the error-free data packet, an ACK packet is sent back to the source node according to the same method with the transmission of the data packet.

Thanks to the cooperative diversity gain from the distributed relay nodes and the source node, this method achieves significant improvement of the packet loss probability with a small average number of hops. However, drawback of this scheme is that the number of transmitted packets in network increases significantly. This is because the data packet in STBC distributed ARQ scheme is transmitted toward all direction, which is cause of the redundant broadcast packets which do not highly contribute to the communication direction between the source node and the destination node. This can lead to increasing in the average power consumption and collision in the network. In addition, the STBC Distributed ARQ scheme cannot select the best relays with high contribution according to the transmission direction.

In wireless communications, OFDM is well known as an efficient and effective technique to achieve high data transmission rates and better transmission quality, and to enhance frequency spectrum efficiency. In addition, by using many narrowband subcarriers instead of one wide-band carrier for transmission and inserting a guard period or cyclic prefix, the OFDM signal has robustness against the frequency selective fading, shadowing and multipath fading, and inter-symbol interference (ISI). As a result, the OFDM signal has more tolerant to delay spread because of the guard interval [71]. Due to these advantages, OFDM technique is used widely in many wireless communication standards such as IEEE 802.11a/g WLAN standard, 4G and LTE cellular systems.

In distributed cooperative diversity communications, timing and frequency synchronizations for distributed STBC encoding systems are a challenging task in highly dynamic communication environment. They are still open problems and should be investigated in the future. Recently, there are several papers that have already proposed the solution to solve these problems [23][24][25]. Therefore, it is assumed that the perfect synchronizations can be achieved by using a control packet in this thesis. In addition, the guard interval of OFDM has tolerance to not only the influence of the delay spread but also the transmitting timing offset among distributed relay nodes, the OFDM technique is also used and combined with STBC encoding in this thesis.

In addition to diversity gain, coding gain is also exploited to reduce bit error rate (BER) and improve system performance in wireless communications. In coding theory, coding gain is defined as the measure in the difference between the signal-to-noise ratio (SNR) levels between the uncoded system and coded system required to reach the same BER levels. When E_b/N_0 is in dB, the coding gain G_c is also defined as [72],

$$G_c = \left(\frac{E_b}{N_0}\right)_{uncoded} - \left(\frac{E_b}{N_0}\right)_{coded}, \tag{3.16}$$

where E_b and N_0 are energy per bit and the noise power density, respectively. The diversity gain indicates relationship between the magnitude of the slope of the average BER curve and an increase in the SNR. The magnitude is higher when the SNR increases. However, coding gain generally just shifts the average BER curve to the left [73]. In order to obtain reliable data transfer, convolutional codes are used widely in applications in wireless communications [74]. Convolutional codes are commonly specified by three parameters (n, k, m), which are the number of output bits, input bits, and memory registers, respectively. They are also a measure of the efficiency of the code. As mentioned in Table 2.2 including the information of the different code rate, the code rate is equal to k/n. The operation in detail of convolutional encoders can be found in [75]. The Viterbi algorithm which is well known can be used decode the convolutional codes. The operation of the Viterbi decoding scheme is described in detail in [76] [74].

3.5 Chapter Summary

This chapter provides the information and analysis of the features of the background techniques in cooperative wireless communications. In order to improve the reliability and performance of system in wireless multi-hop relay networks, the advantages of these techniques such as cooperative diversity gain, spatial multiplexing gain, array gain, coding gain must be exploited via distributed relay nodes. More specifically, distributed STBC encoding scheme and convolutional codes are considered in the proposed method. In addition, OFDM technology is also considered to use in this thesis to enhance frequency spectrum efficiency and reduce interference.

Chapter 4

A proposal of Cooperative Diversity method for STBC-OFDM Multi-hop Relay Wireless Networks

4.1 Introduction

In wireless communications, the advantages of MIMO technology have been widely acknowledged such as diversity gain, spatial multiplexing gain, and array gain [16]. However, it is difficult to install multiple antennas in a small wireless mobile node because of size and hardware limitations. In order to overcome the problems and to obtain diversity gain in wireless multi-hop ad-hoc networks, the user cooperative diversity has been proposed [17][18]. The cooperative diversity is known as technique allowing single-antenna nodes to reap some of the benefits of MIMO systems. In the cooperative diversity, STBC encoding is often applied in order to obtain the higher cooperative diversity gain without channel state information (CSI) at the transmitting node [19]. In addition, this encoding scheme can achieve both full diversity order and full data transmission rate with simple decoding algorithm at the receiving node. In this system, relays simultaneously transmit the signals encoded by one of the STBC encoding patterns in a cooperative manner. At the receiving node, because the STBC encoded signals with different encoding patterns are received, the cooperative diversity gain can be obtained by decoding STBC as shown in [19]. However, the user cooperative diversity schemes in multi-hop relay communications have a problem that is difficult to establish the path routes from the source node to the destination node with selecting the efficient cooperative relays.

In wireless multi-hop ad-hoc networks, there are two main broad categories of routing protocols, proactive and reactive protocols, used to establish the path routes from the source node to the destination node before transmitting data packets. Proactive schemes posed a negligible delay since route information is generally kept in the routing tables and is periodically updated. However, the overhead of the control packets is large. In addition, it is difficult to establish the efficient path routes when network topology is large and frequently changed. In contrast, reactive protocols search for the path routes from the source node to the destination node in an on-demand manner. Therefore, these routing protocols are suitable for the network topology which is frequently changed. However, the delay of this type of routing protocols is large since the information of routing is not stored at each node [20].

To overcome this problem, [21] has proposed a scheme called STBC distributed ARQ. In this scheme, the source node first broadcast the data packet to the destination node without finding the path routes in advance. Then, if the destination node does not receive the data packet correctly from the source node, the data packet is simultaneously retransmitted by all the source node and the surrounding nodes which have already received the error-free data packet. A control packet is broadcasted from the source node to trigger and synchronize the transmission timing for the surrounding nodes. As a result, this method achieves significant improvement of the performance with a small average number of hops. However, a drawback of this scheme is that the number of transmitted packets in network increases significantly. This is because the data packet and control packets in STBC distributed ARQ scheme are transmitted toward all direction, which is cause of the redundant broadcast packets which do not highly contribute to the communication direction from the source node to the destination node. This can lead to increasing in the average power consumption and collision in the network.

In addition, this scheme cannot select the best relay nodes with high contribution according to the transmission direction in each hop.

Therefore, a cooperative diversity transmission method is proposed to reduce the power consumption normalized by one data packet transmission power consumption with keeping the performance improvement for wireless multi-hop ad-hoc networks in this chapter. The power consumption is reduced by limiting the number of transmitting relay nodes in each hop and the number of repetition of packet transmission at each node, which in turn makes the reduction of the number of transmitted packets in network. As a result, this can lead to the reduction of interferences in network and better efficiency frequency utilization. More specifically, it is assumed that the current and future locations of nodes are available. After limiting the number of potential relay nodes based-on the predictable future location of distributed relay nodes, a relay selection algorithm is proposed to select the two distributed relay nodes in each hop with high contribution according to the transmission direction from the source node to the destination node by installing a new timer which is set according to distance between a potential relay node and the destination node at each node in network. This timer is also used to assign the STBC encoding pattern to the two distributed relay nodes. In order to obtain coding gain and higher performance improvement, the convolutional code is also employed at each node. The remainder of this chapter is organized as follows. In Section 4.2, system model and the analysis of signal model are provided. Next, the proposed method is described in detail in Section 4.3. In Section 4.4, performance evaluation through computer simulations and results are presented. Finally, Section 4.5 summarizes this chapter.

4.2 System Model

In order to obtain diversity gain, the cooperative diversity is applied in multi-hop wireless relay networks. The original STBC transmit diversity technique is proposed by Alamouti [19]. Here, we consider distributed STBC cooperative diversity for OFDM multi-hop wireless relay networks. The image of this model is shown in Fig. 4.1, where R_{x1} and R_{x2} are first and second relay nodes selected in the xth hop, respectively, $x = (1, 2, ..., n)$. In this model, the two selected

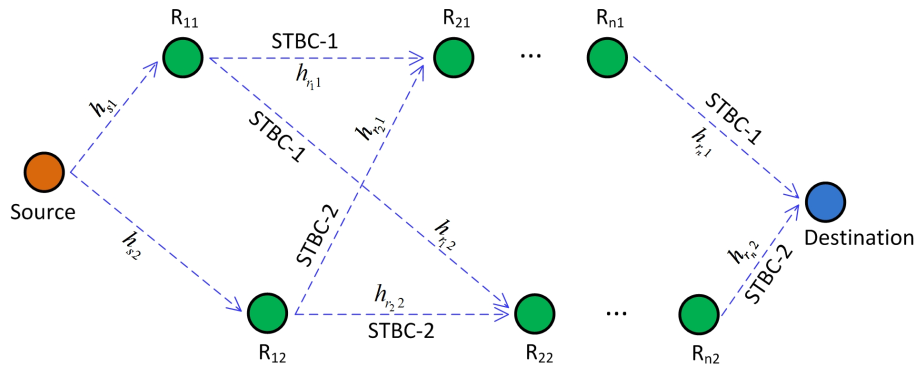

Figure 4.1: System model of the proposed method.

relay nodes in each hop broadcast the same data packet simultaneously to the surrounding nodes in the next hop and the destination node. As a result, the cooperative diversity gain of the MRC (maximum ratio combing) scheme can be obtained by using the STBC encoding at each relay node.

In the proposed method, the input signal for the jth symbol is denoted as s_j, and the input signal for the next symbol is denoted as s_{j+1}, where $j = 2a$ and a is the even number. The two symbols s_j, s_{j+1} are encoded and simultaneously transmitted from the two selected relay nodes in each hop. The transmitted STBC encoding patterns are shown in Table 4.1, where * is the complex conjugate operation. In this Table, the original STBC encoding patterns as shown in Table 3.1 are modified in order to avoid interference and collision when the transmitted signals from the relay nodes combining with the retransmitted signals from the source node. In user cooperative diversity schemes, one of the STBC encoding patterns is assigned to one distributed node for the cooperative transmission. In this proposed method, the branch 0 and 1 are assigned to the first and second relay nodes, respectively. At the receiver, the signals are received and combined with the different path losses and fading fluctuations. The transmitting timing and frequency synchronizations are adjusted according to a beacon packet transmitted by the previous link node. In order to keep the explanation simple, we focus on a sub-carrier of OFDM technique. The first received signal of the s_j symbol at the ith relay node and the destination node at the first transmission is given by,

$$r_{ji} = \sqrt{P_t}\beta_{si}h_{si}s_j + n_{ji}, \tag{4.1}$$

Table 4.1: Modified STBC Encoding Patterns.

data symbol (period)	Symbol j (t)	Symbol $j+1$ ($t+T$)
branch 0	s_j	s_{j+1}
branch 1	-s_{j+1}^*	s_j^*

where P_t is transmission power. h_{si} and β_{si} are fading channel coefficient and path loss gain between the source node and the i-th relay node or the destination node at the first transmission, respectively. s_j is the transmitted signal of the jth symbol and n_{ji} is the noise component of the jth symbol.

At the next transmission or the first relay transmission, if the two selected relay nodes receive the beacon packet, the two relay nodes broadcast the same data packet simultaneously with the different STBC encoding patterns. Data packet transmission procedure for this case is shown in Fig. 4.2. In this model, we denote K is the number of repetition of the same data packet transmission at each node. $K = 1$ means that each node only transmits the same data packet once. We consider the case of $K = 1$. The received signals of the s_j and s_{j+1} symbols at the ith relay and the destination node can be expressed as follows,

$$r_{ji} = \lambda_{r_1 i} s_j - \lambda_{r_2 i} s_{j+1}^* + n_{ji}, \tag{4.2}$$

$$r_{(j+1)i} = \lambda_{r_1 i} s_{j+1} + \lambda_{r_2 i} s_j^* + n_{(j+1)i}, \tag{4.3}$$

where $\lambda_{r_1 i} = \sqrt{P_t}\beta_{r_1 i} h_{r_1 i}$ and $\lambda_{r_2 i} = \sqrt{P_t}\beta_{r_2 i} h_{r_2 i}$ are the channel responses from the first and second relay node transmitting the different STBC encoding patterns of branch 0 and 1 to the ith relay or the destination node, respectively. At the receiver, the decoded signals of the s_j and s_{j+1} symbols at the ith relay and the destination node are derived according to STBC decoding algorithm as follows,

$$\begin{aligned} \widetilde{s}_j &= \lambda_{r_1 i}^* r_{ji} + \lambda_{r_2 i} r_{(j+1)i}^* \\ &= \left(|\lambda_{r_1 i}|^2 + |\lambda_{r_2 i}|^2\right) s_j + \lambda_{r_1 i}^* n_{ji} + \lambda_{r_2 i} n_{(j+1)i}^*, \end{aligned} \tag{4.4}$$

$$\begin{aligned} \widetilde{s}_{j+1} &= \lambda_{r_1 i}^* r_{(j+1)i} - \lambda_{r_2 i} r_{ji}^* \\ &= \left(|\lambda_{r_1 i}|^2 + |\lambda_{r_2 i}|^2\right) s_{j+1} + \lambda_{r_1 i}^* n_{(j+1)i} - \lambda_{r_2 i} n_{ji}^*. \end{aligned} \tag{4.5}$$

Here, the transmitting timing and frequency are adjusted for synchronous transmission between the relay nodes and the source node by using the predefined bit patterns for synchronization in the received beacon packet. When K value is greater than one, the received signals of the s_j and s_{j+1} symbols are given by,

$$r_{ji}^{(k)} = \lambda_{si}^{(k-1)} s_j + \sum_{m \in R_1} \lambda_{r_m i}^{(k)} s_j - \sum_{m \in R_2} \lambda_{r_m i}^{(k)} s_{j+1}^*, \tag{4.6}$$

$$r_{(j+1)i}^{(k)} = \lambda_{si}^{(k-1)} s_{j+1} + \sum_{m \in R_1} \lambda_{r_m i}^{(k)} s_{j+1} + \sum_{m \in R_2} \lambda_{r_m i}^{(k)} s_j^*, \tag{4.7}$$

where λ_{si} is channel response between the source node and the i-th relay in the next hop. R_1 and R_2 are denoted as the set of relay nodes transmitting the different STBC encoding patterns 0 and 1, respectively. In these equations, the noise components are omitted to keep the presentation simple. The number on the right shoulder denotes the number of the k-th transmission of the signal $(k = 1, 2, ..., K)$. At the receiver, the decoded signals of the s_j and s_{j+1} symbols are derived as follows,

$$\widetilde{s}_j^{(k)} = \left(\left| \lambda_{si}^{(k-1)} + \sum_{m \in R_1} \lambda_{r_m i}^{(k)} \right|^2 + \left| \sum_{m \in R_2} \lambda_{r_m i}^{(k)} \right|^2 \right) s_j, \tag{4.8}$$

$$\widetilde{s}_{(j+1)i}^{(k)} = \left(\left| \lambda_{si}^{(k-1)} + \sum_{m \in R_1} \lambda_{r_m i}^{(k)} \right|^2 + \left| \sum_{m \in R_2} \lambda_{r_m i}^{(k)} \right|^2 \right) s_{j+1}. \tag{4.9}$$

As a result, by using the user cooperative diversity scheme combining with STBC encoding, if the channel impulse response is estimated exactly at the receiver, cooperative network diversity gain can be obtained with the MRC decoding scheme. Then, the signals $\widetilde{s}_j^{(k)}$ and $\widetilde{s}_{j+1}^{(k)}$ can be decoded.

4.3 Cooperative Diversity Method for STBC-OFDM Multi-hop Relay Wireless Networks

In the proposed method, it is assumed that the transmission power for all the nodes are fixed and the nodes know their own position. The information about the coordinate of the destination node will be attached in the data packet. It is also assumed that the current and future locations of nodes in network are available and can be predicted. In this method, there are three control packets: Beacon packet, Confirm to Become Relay packet (CBR), Acknowledgment packet (ACK). The beacon packet shown in [21] is also used to synchronize and trigger the transmitting timing of relay nodes in each hop. The beacon packet includes an ID of the source node, an ID of the destination node, IDs of the first and second relay, pilot symbols for synchronous transmission of the source node and the relay nodes. The CBR packet is used to select the two relay nodes in each hop. An ACK packet is sent from the destination node to the source node to confirm that the data packet is received successfully. In the proposed method, N is denoted as the maximum number of iterative steps for data transmission. Let n be a count down of the current iterative step of a particular data packet. At the first step, $n = N$ and n value is decreased one unit and is stored in the packet in the next step. When the data packet with $n = 0$ is received, the data packet is not forwarded. $N = 0$ means that the data packet is transmitted once by only the source node and not forwarded by any relay nodes. We also consider limiting the number of repetition of the same data packet transmission at each node as K value. If the number of transmission times of the same data packet transmission at a particular node is more than K, the data packet is not transmitted by the node. It is worth noting that N value is the number of hops if there are always at least one selected relay node in each hop. In the case that there is no relay node in the next transmission, the iterative step is the retransmission from the nodes in the current hop. The detail of the proposed method is described in Subsections 4.3.1 and 4.3.2.

4.3.1 Transmission Procedure of the Proposed Method

The data packet transmission procedure of the proposed method with $K = 1$ and $N = 2$ is shown in Figs. 4.2 and 4.3.

1. First, the source node broadcasts a data packet attached the position of the destination node. The destination node and surrounding relays receive and detect the data packet.

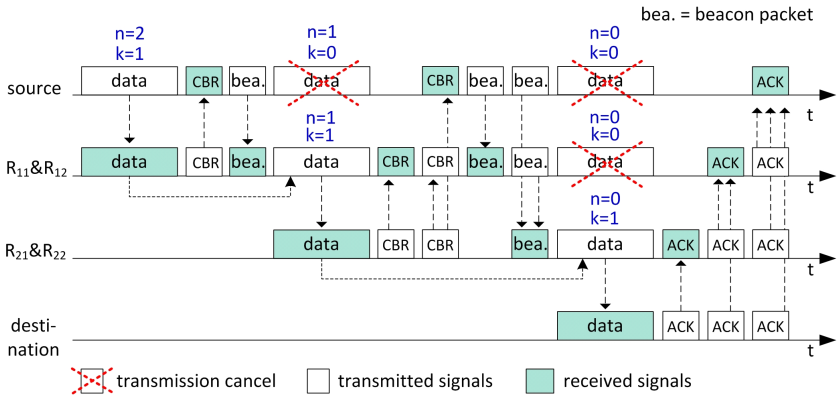

Figure 4.2: Data packet transmission procedure with $K = 1$ and $N = 2$.

2. In order to confirm the successful transmission, when the error-free data packet is received at the destination node, an ACK packet from the destination node is sent back to the source node.

3. At the source node, if the ACK packet from the destination node is not received, but the CBR packets from the two selected relays are received then a beacon packet is transmitted to trigger and synchronize the transmitting timing for the two selected relays. If both the ACK and CBR packets are not received within the period of pre-determined time and the number of the retransmission of the data packet is less than N, the data packet will be retransmitted. In this case, K value is not applied.

4. At the distributed relay nodes, if the error-free data packet is received then these relay nodes will use a new timer to contend with other relays in the same hop to access medium. The branch 0 and 1 of STBC encoding pattern are assigned to the first and the second relay nodes to transmit the same data packet, respectively. The detail of the relay selection method is explained in Subsection 4.3.2.

5. At the receiver, the STBC encoded signals are decoded and the data packet is recovered. Repeating steps from 3 to 5 until the ACK packet is correctly received at the source node or the current iterative step (n) of the data packet reaches to zero. If the error-free data packet is received at the

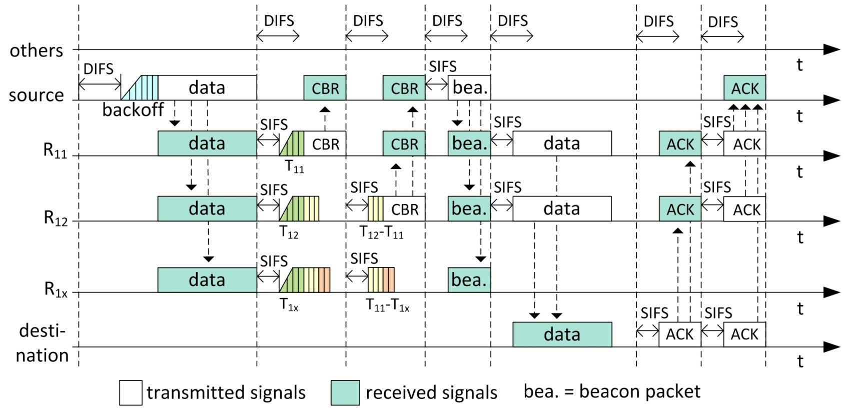

Figure 4.3: Timing and medium access procedure for the proposed method.

destination node, an ACK packet is transmitted from the destination node to the source node according to the same way of transmitting data packet but K value is not also applied. In the other words, the number of the retransmission of the ACK packet at each node and from the destination node is the same as that of the data packet from the source node. If the ACK packet is not received at the source node after the number of N times transmission at the destination node, the data packet transmission is repeated from step 3 to 5, until the ACK packet is correctly received at the source node or until the number of the data packet retransmission exceeds the maximum N value.

4.3.2 Timer and Relay Selection of the Proposed Method

After limiting the number of potential relay nodes based-on the predictable future location of distributed relay nodes, a relay selection method is proposed to select the two optimal relay nodes in each hop, called the first and second relay node. The relay selection method is based-on a new timer which is set according to distance between a potential relay node and the destination node.

After receiving the data packet without error from the source node or the relay nodes in the previous hop, the relay nodes which have the distance from their future location to the destination node less than the distance from the source node to the destination node become potential relay nodes. The potential relay nodes then initialize the proposed timer as given in equation 4.10. The two relay nodes with the first and second shortest duration of timer become the first and second relay nodes, respectively. This timer is also used to contend to access medium among relay nodes in the same hop.

$$T_i = \Delta \times \frac{d_i}{d_{Max}} \frac{(DIFS - SIFS)}{aSlottime}, \tag{4.10}$$

where T_i is timer of the ith potential relay node. Δ is the normalized factor of the timer. The factor can be adjusted to be compatible with different systems. d_i is the distance from the ith potential relay node to the destination node. d_{Max} is the maximum distance between the relay nodes and the destination node. This value is set such that fraction d_i/d_{Max} is always less than one. $DIFS$ and $SIFS$ are distributed inter-frame space and short inter-frame space, respectively [33]. In the legacy IEEE 802.11 standard in wireless communications, after sensing medium idle, a node can only transmit data packet when interval of $DIFS$ and its back-off time has expired [33]. In order to guarantee that the relaying will not be interrupted by other nodes in the network, T_i must be less than interval of $(DIFS - SIFS)$. The operation of the timer and medium access control procedure is shown in Fig. 4.3. In the same hop, the timer of the potential relay node closest to the destination node will finish first. The first relay node then transmits a CBR packet to the source node. During the period of time, the timer of the other potential relay nodes will be frozen and then run the remainder of the timer when the CBR packet transmission from the first relay node has already completed. The potential relay node with the second shortest period of timer becomes the second relay node. The second relay node then also sends a CBR packet to the source node. After the CBR packets are transmitted, both the first and second relays will be in the state of waiting for a beacon packet from the source node. If the beacon packet is received, the data packet with STBC encoding from the first and second relay nodes be transmitted simultaneously to relay nodes in the next hop and the destination node. The other relays will stop and discard the received data packet after receiving the CBR packet from the second relay or the beacon packet from the source node.

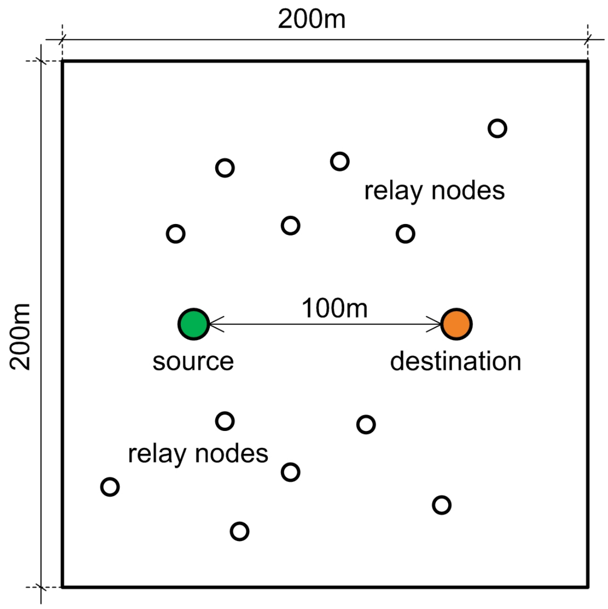

Figure 4.4: Simulation area.

4.4 Performance Evaluation

4.4.1 Simulation conditions

Simulation area is set to be a 200 [m] by 200 [m] square as shown in [21]. In the simulation area, the relay nodes is located randomly. The distance between the source node and the destination node is 100 [m]. The position of the nodes are fixed and set to be at the center of the simulation area as shown in Fig.4.4. The other simulation conditions are listed in Table 4.2. In order to keep the simulation simple, the non-line of sight environment is applied in this simulation. It is assumed that the delay of all paths from all distributed nodes are received within the guard interval of OFDM technique, therefore the performance of the proposed method is not effected by ISI. In order to evaluate the basic performance, it is also assumed that channel estimation is perfect for each STBC branch. In this simulation, the data packet is considered as lost if the ACK packet is not received at the source node when n value reaches to zero. N value is varied from 0 to 6. No multi-hop means $N = 0$ so that the only direct communication is considered. In this simulation, the performance of a conventional on-demand routing protocol

Table 4.2: The simulation parameters of the computer simulation.

Modulation method	QPSK
Number of subcarriers	52
FFT size	64
Length of guard interval	16 samples
Length of pilot	4 symbols
Length of data packet	96 symbols
Length of ACK, CBR, beacon packets	6 symbols
Number of nodes (include the source and destination nodes)	102
Frequency band	5 [GHz]
Path loss exponent	3
d_{Max}	100 [m]
Normalized factor (Δ)	1
Channel model (Rayleigh)	5-path fading
Noise level	95 [dBm]
Channel estimation	Perfect
Antenna gain	0 [dBi]

as AODV protocol in [11] is considered to compare to the performance of the proposed method. The path route from the source node to the destination node is established by using the route request packet (RREQ) and the route reply packet (RREP). First, the RREQ packet is broadcasted from the source node. The surrounding nodes then rebroadcast the packet and finally the packet is correctly received at the destination node. Next, the RREP is replied to the source node by using the route information including in the RREQ packet. In order to establish the reliable path route, a threshold SNR of the received signal power is required when RREQ packet is received at the intermediate nodes due to the fading channel and the difference between the length of the data packet and RREQ packet. The threshold SNR is set to be 10[dB] at each node in this simulation. It is assumed that the established links are sufficient link margin to allow that the data packet is received correctly.

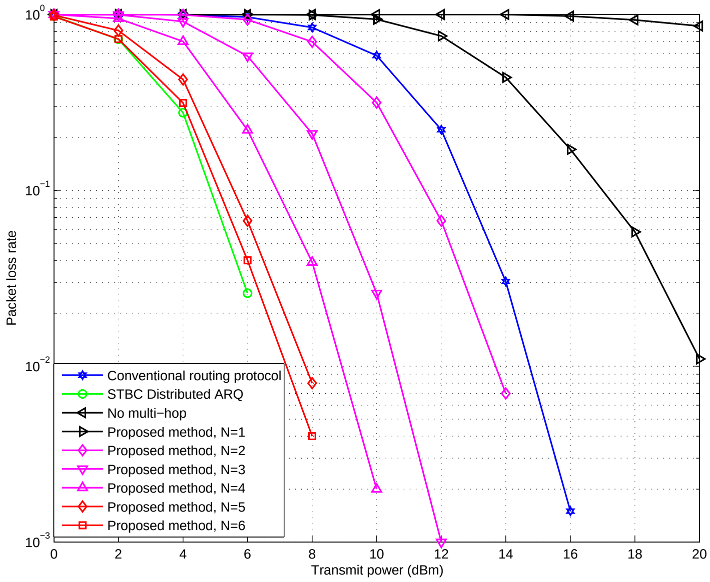

Figure 4.5: Packet loss rate with different N values and $K = 3$.

4.4.2 Simulation Results

First, the performance of packet loss probability as a function of the transmit power per node is shown in Fig. 4.5. It can be seen from the figure that when N value increases, the performance is improved significantly. However, the improvement is almost saturated when $N = 6$ in this simulation. By using all of relay nodes to retransmit the data packet to the destination node in each hop and without limiting the number of retransmission of data packet of each node ($K = N$), STBC Distributed ARQ scheme always has the better performance with the same number of retransmission. However, due to two optimal relay nodes are selected to obtain diversity gain by using the proposed procedure of relay selection, the performance degradation of the proposed method is negligible. In this simulation, the performance of the proposed method with $N = 6$ and $K = 3$ is almost as same as that of STBC Distributed ARQ with $N = 4$. In comparison with the direct communication and the conventional routing, the performance of the proposed method can be improved significantly. The conventional routing can reduce the packet error rate compared to the direct communication. However,

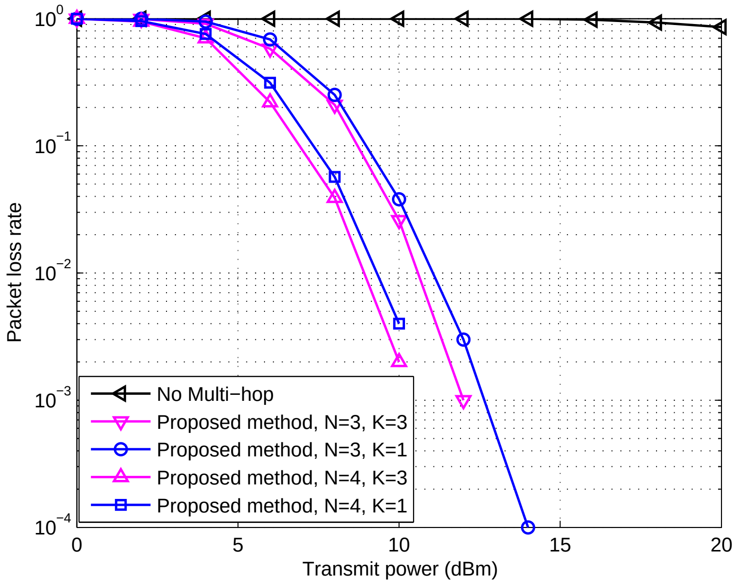

Figure 4.6: Packet loss rate with $K = 3$ and $K = 1$.

since STBC cooperative diversity gain cannot be obtained in the conventional routing, the proposed method with $N = 2$ has better performance.

Next, the performance with $K = 3$ and $K = 1$ is shown in Fig. 4.6. When K value increases, not only the selected relays in the current hop but also the selected relays in the previous hops transmit the data packet simultaneously to the destination node. As a result, the performance is improved when K value increases since higher cooperative diversity gain can be obtained. However, the improvement is small. This is because the relay nodes in the previous hops is further from the destination node than the relay nodes in the current hop. As a result, K value is not contributing too much to the performance improvement.

Next, in order to improve the performance of the proposed method, the convolutional code ($R = 1/2$ and $K_R = 7$) and combining signal are considered to used at each node. Since coding gain can be obtained, the performance of the proposed method is improved significantly as shown in Fig. 4.7. By using the signal combining technique between previous received signal and the current received signal during the transmission process, the time diversity gain can be obtained. However, the improvement is not much as shown in Fig. 4.8. In addition, this

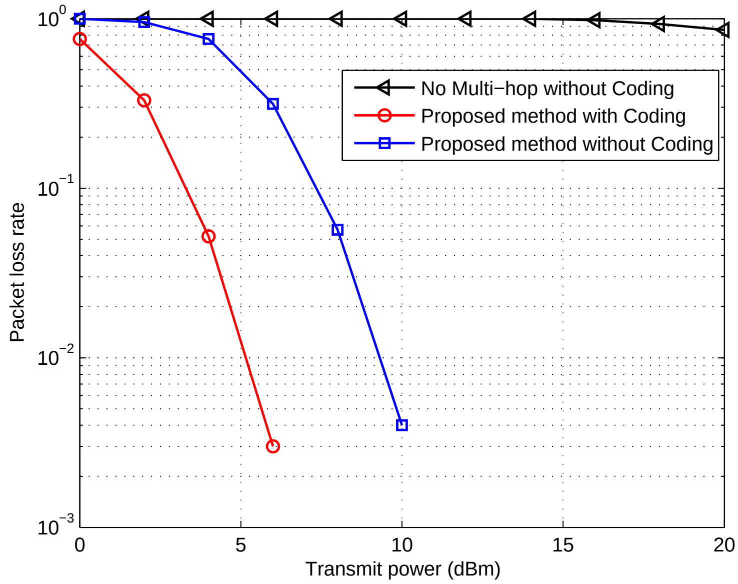

Figure 4.7: Packet loss rate with and without coding ($N = 4$ and $K = 1$).

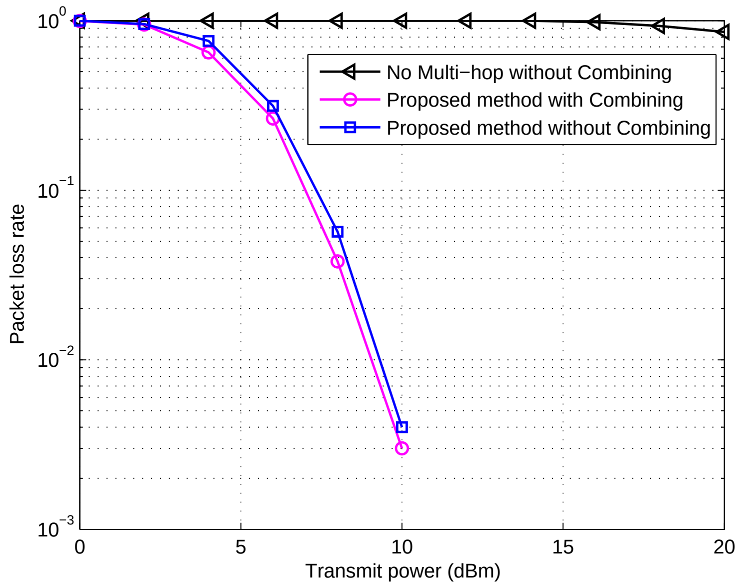

Figure 4.8: Packet loss rate with and without combining ($N = 4$ and $K = 1$).

technique requires a large memory and high complexity processing at each node.

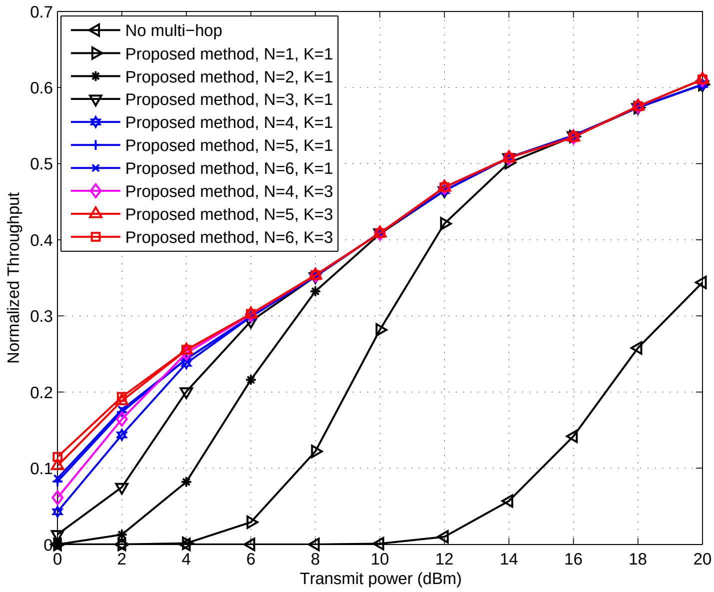

Figure 4.9: Normalized throughput performance.

Next, Fig. 4.9 shows the normalized throughput of proposed method. In this simulation, the normalized throughput is calculated as a ratio of the number of correctly received data packets to the number of transmitted data packets. It is assumed that the full load packets are generated at the source node. From the figure, the normalized throughput of the proposed method increases when K value or N value increases. However, the throughput is almost saturated when $N = 4$ and $K = 1$. Due to using ACK packet, the transmission is stopped after ACK is received correctly at the source node. Therefore, when transmit power increases, the performance of the direct transmission is improved. As a result, with $N = 2$ and transmit power is about 14 [dBm], the throughput increases to more than 0.5.

Finally, the power consumption normalized by one data packet transmission power consumption is evaluated as shown in Fig. 4.10. Since the power consumption is directly proportional to the number of transmitted packet in network and in order to avoid the impact of types of device power consumption, we normalized the power consumption by one data packet transmission power consumption. Therefore, the receiver power consumption is ignored in this case. In this simula-

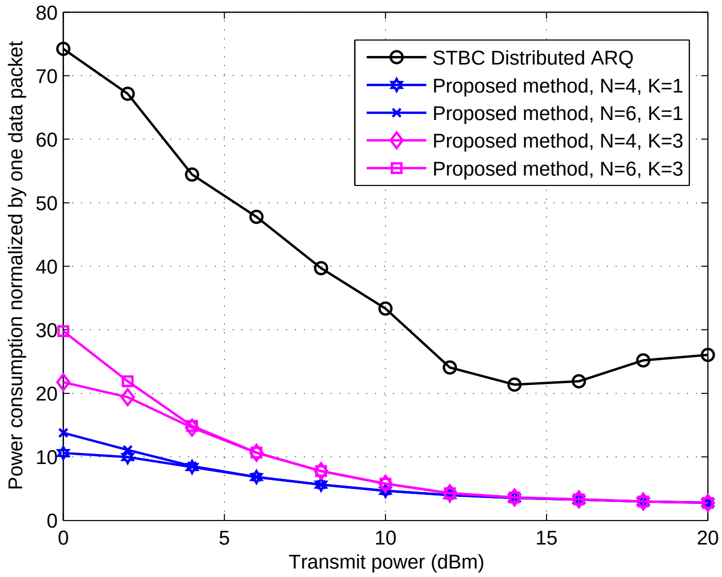

Figure 4.10: Power consumption normalized by one data packet.

tion, data packet transmission power consumption is derived as the total number of transmitted bits of the data packet and control packets summed up and then normalized by the size of the data packet. From the figure, because the data packet is broadcasted toward the all direction and without limiting the number of repetition of the same data packet transmission at each node, the power consumption of the STBC Distributed ARQ scheme increases significantly due to the redundant packets. We can confirm that the power consumption of the proposed method can be reduced considerably by using only the two relay nodes in each hop and limiting the number of repetition of the same data packet transmission at each node.

4.5 Chapter Summary

In this chapter, a cooperative diversity transmission method for wireless multi-hop ad-hoc networks is proposed. In this method, the new timer is installed to select the two relay nodes with high contribution according to the transmission direction in each hop. In order to obtain higher cooperative diversity gain in each hop, the data packet is encoded by using STBC code matrix in a distributed manner and transmitted simultaneously to the next hop and the destination node. The timer is also used to assign the STBC encoding pattern to the two distributed relay nodes in each hop. From simulation results, When N value increases, the performance is improved significantly. However, the improvement is almost saturated when $N = 6$. In addition, K value is not contributing too much to the performance improvement. Since coding gain can be obtained, the performance of proposed method is improved significantly. However, the improvement is not much for signal combining technique. By selecting the only two distributed relay nodes in each hop and limiting the number of repetition of packet transmission at each node, we can confirm that the proposed method can achieve considerable improvement of the power consumption normalized by one data packet transmission power consumption in network with keeping the significant improvement of performance. As a result, this can lead to the reduction of interferences in network and better efficiency frequency utilization, which in turn can achieve high reliability in wireless communications.

Chapter 5

Cooperative Distributed STBC Transmission Method for Multi-hop V2V Communications

5.1 Introduction

In recent years, in order to provide road safety, comfortable driving with entertainment applications, and distribution of updated information about the roads, etc., for ITS systems, a solution that has attracted researchers' attention is the use of the vehicular communications. In vehicular communications and VANETs, the current standards can be applied for safety related message exchange but in the future world, other new applications like autonomous controlled vehicles require more reliability and capacity with small delay. In addition, wireless multi-hop data delivery for emergency situations on road is not explicitly supported in the current standards.

In vehicular communications, VANETs have some attractive characteristics as follows. First, the movement of vehicles is limited in road trajectory. As a result, if the information of road maps, current position, speed, and direction of movement are available then the future position of vehicles in network can be predicted. In addition, since the vehicle nodes can provide continuous power to communication devices by themselves, transmission power in VANETs is not a significant constraint as in the conventional ad-hoc or sensor networks. Finally, the vehicle nodes have usually higher computational capability because of the no limitation of device size. However, the network topology changes frequently and very fast due to high vehicle mobility and different movement direction of each vehicle. As a result, inter-vehicle connectivity can be impacted significantly from a network perspective in comparison with low-velocity mobile communication systems. Moreover, the harsh communication environment is also one of the most difficult challenges in VANETs, the line-of-sight (LoS) component of the signal in inter-vehicle connectivity is often blocked by obstacles as buildings at intersections or trucks on highway scenarios. Consequently, Consequently, signal attenuation is large [6].

The existing routing protocols in MANETs [11][12][13] are not suitable for most application scenarios in multi-hop vehicular communications due to the distinctive characteristics. This is also because one or multiple paths from a source node to a particular destination node should be discovered before transmitting data packet in these routing protocols. Therefore, these protocols are not suitable for the scenario with more than one destination node. Furthermore, problems of redundant broadcast messages and the broadcast storm [14][15] can make the design of routing protocols further complicated. As a result, a design of effective and efficient routing protocol in VANETs is still a critical challenge and requirement.

As earlier mentioned in Section 2.5, location based routing protocols are designed to meet the requirements of highway safety applications. In the protocols, it is assumed that nodes use a global positioning system (GPS) device for obtaining position information. A sender broadcasts safety-related messages to all receivers in its communication range. Whether the messages are rebroadcasted or not depends on the relative position between the receiver and the transmitter. One of the conventional protocols suitable for VANETs is Multi-Hop Vehicular Broadcast (MHVB) [46]. In MHVB, the farthest relay vehicle station is selected to rebroadcast the message in each hop. Therefore, this method significantly improves the performance of data dissemination in VANETs. Figure 5.1 shows the transmission procedure of MHVB protocol. In this figure, the data packet is considered as the safety-related message. When the error-free message is received at vehicle station, the distance between the sender and itself is calculated. The distance is used to calculate the waiting time before retransmitting the message.

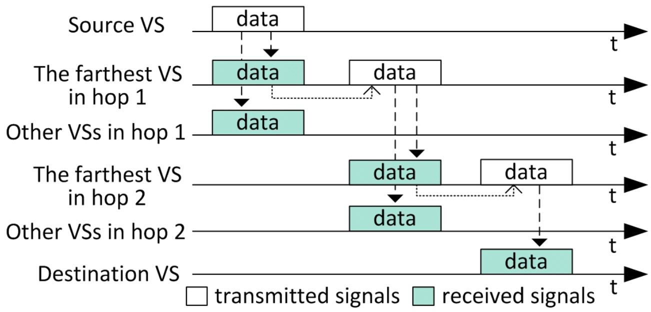

Figure 5.1: Conventional routing protocol based-on location.

Consequently, a farther relay vehicle station waits less time and retransmits the message sooner than the others. However, the function of the waiting time is not explicitly given in [46]. In this method, because only one relay node is selected to forward the packet in each hop, the signal attenuation and packet loss rate caused by the obstacles like buildings or trucks can be large. The performance of MHVB is compared with that of the proposed method.

In this chapter, we consider to exploit the attractive characteristics in vehicular communications. Thanks to the digital road maps and the exchange of routine messages in current ITS systems, the information of position, speed, and movement direction of vehicles are available. In order to achieve high reliability and reducing redundant broadcast messages in multi-hop vehicular communications, we first propose a relay selection algorithm based-on position, speed and direction of movement, combining with the digital map equipped on the vehicles to select a group of distributed vehicle stations which have high contribution according to the transmission direction to forward the same data packet simultaneously to the further vehicle stations in the next hop. In addition, we install another new timer to select a master vehicle station (MVS) which manages the transmission of whole network, triggering and synchronizing transmit timing of vehicle relay stations in each hop. This timer is set according to the information of relative location between the potential MVSs in the next hop and the current MVS. In order to obtain cooperative diversity gain, the STBC encoding is applied at the group of distributed vehicle relay stations in each hop. In the proposed method, the STBC encoding pattern of each sub-carrier is randomly assigned at the distributed vehicle relay stations in each hop. The complicated STBC encoding pattern assignment is therefore not required.

In this method, we focus on the emergency messages in multi-hop V2V communications. The emergency information is provided to the behind vehicles on the same way in the emergency situations such as traffic congestion, traffic accidents, and road hazards to avoid chain collisions on highway for ITS systems. In the proposed method, a vehicle station which can first detect the emergency situations broadcasts the warning messages to the behind vehicle stations on the same way. By communicating between vehicles, it can be predicted possible collision and automatically speed down or alert drivers. The proposed method can also be used in applications for emergency vehicles (e.g., ambulances and fire trucks) to disseminate alarm messages to the other vehicles in the forward direction by simply changing the conditions of position, speed and direction of movement to select intermediate vehicle stations in each hop.

The remainder of this chapter is organized as follows. In Section 5.2, system model of the proposed method is provided. Next, the proposed method is described in detail in Section 5.3. In Section 5.4, performance evaluation through computer simulations and results are presented. Finally, Section 5.5 summarizes this chapter.

5.2 System Model

In order to achieve high reliability, the only vehicle stations (VSs) which have high contribution according to the transmission direction and already received the data packet correctly are selected to transmit the same data packet simultaneously to the VSs in the next hop as shown in Fig. 5.2. In the proposed method, a VS can be in four states: Transmit VS (TVS), Relay VS (RVS), Master Relay VS (MVS), or Ordinary VS (OVS). A TVS is the first VS transmitting the data packet in the network. An RVS is a VS that receives the error-free data packet in each hop. An MVS is a VS that is selected to transmit a control packet to trigger and synchronize transmitting timing of RVSs in each hop. Initially, the MVS is assigned to the TVS for triggering the timing of transmission and this function is transferred to the next MVS. Therefore, there is always an MVS in the network. An OVS is a VS that is not a TVS, an RVS, or an MVS. In this

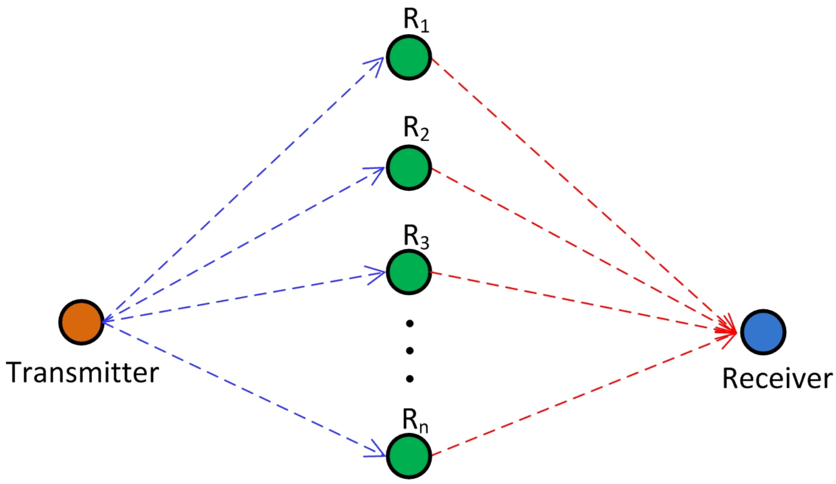

Figure 5.2: System model for two-hop transmission.

method, after receiving the error-free data packet from the TVS, OVSs which are near the location of the emergency situations only work as an RVS or an MVS even if they can identify the situations by themselves. Therefore, we also assume that there is only one TVS during transmission process.

In order to obtain diversity gain, the user cooperative diversity is applied in multi-hop wireless relay networks. The original STBC transmit diversity technique is proposed in [19]. In this chapter, we consider using distributed STBC model with two transmit antennas and one receive antenna. If multiple RVSs transmit the same STBC encoding pattern, the received signal is combined just as increasing the number of multi-paths of OFDM system. We do not need prepare more pilot symbols for channel estimation by increasing the number of transmitters. The system model using distributed STBC encoding for multi-hop V2V communications is shown in Fig. 5.3, where x, y, and z are the number of RVSs in the first, second, and n-th hop, respectively. In this model, the selected RVSs transmit the same data packet simultaneously toward the RVSs in the next hop. By using the different STBC encoding patterns at each RVS, the cooperative diversity gain of the maximum ratio combing (MRC) can be obtained in the receiver. It is assumed that the input signal for the j-th symbol is denoted as s_j, and the next symbol is denoted as s_{j+1}, where $j = 2a$ and a is the even number. The s_j and s_{j+1} symbols are encoded and simultaneously transmitted

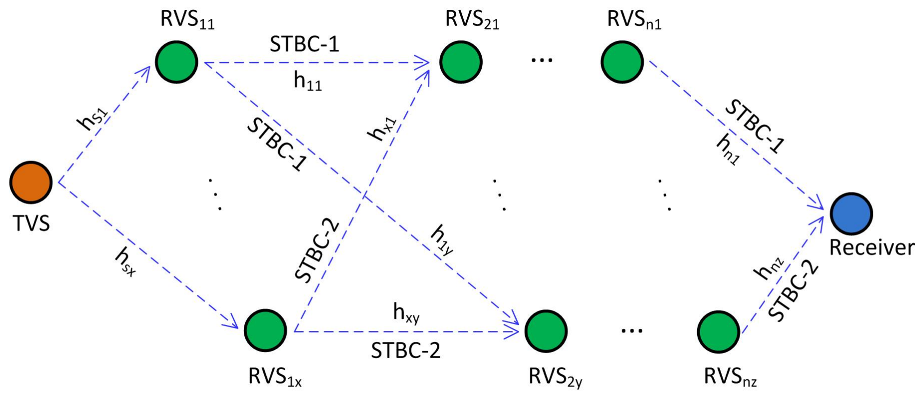

Figure 5.3: System model of the proposed method.

from RVSs in each hop. The transmitted STBC encoding patterns are shown in Table 4.1, where * is the complex conjugate operation. At the receiver, the signals are received and combined with the different path losses and fading fluctuations. We have to adjust the transmitting timing and frequency according to a control packet named SYNT transmitted by MVS in each hop. In order to keep the explanation simple, we focus on an OFDM sub-carrier signal for explanation.

At the first transmission, the received signal of the s_j symbol at the i-th RVS is given by,

$$r_{ji} = \sqrt{P_t}\beta_{ti}h_{ti}s_j + w_{ji}, \tag{5.1}$$

where P_t is transmission power. h_{ti} and β_{ti} are fading channel coefficient and path loss gain between the source node named Transmit VS (TVS) and the i-th RVS, respectively. The path loss gain is calculated with α the path loss exponential as described in Subsection 2.3. w_{ji} is noise component of the s_j symbol.

At the next transmission or the first relay transmission, if the SYNT packet from the current MVS is correctly received at the RVSs, both the MVS and RVSs simultaneously transmit the same data packet with the different STBC encoding patterns. The simultaneous transmission procedure with distributed STBC encoding in each hop is shown in Fig. 5.2. In the proposed method, we denote K is the number of repetition of the same data packet transmission at each node. $K = 1$ means that each node only transmits the same data packet once. The received signals of the s_j and s_{j+1} symbols with $K = 1$ at the i-th

RVS are expressed as follows,

$$r_{ji} = \sum_{m \in R_1} \lambda_{mi} s_j - \sum_{m \in R_2} \lambda_{mi} s_{j+1}^* + w_{ji}, \tag{5.2}$$

$$r_{(j+1)i} = \sum_{m \in R_1} \lambda_{mi} s_{j+1} + \sum_{m \in R_2} \lambda_{mi} s_j^* + w_{(j+1)i}, \tag{5.3}$$

where $\lambda_{mi} = \sqrt{P_t}\beta_{mi}h_{mi}$ is channel response between the m-th RVS in the current hop and the i-th RVS in the next hop. R_1 and R_2 are denoted as the set of RVSs transmitting the different STBC encoding patterns 0 and 1, respectively. At the receiver, the decoded signals of the s_j and s_{j+1} symbols are derived according to STBC decoding as follows,

$$\begin{aligned} \tilde{s}_j &= \sum_{m \in R_1} \lambda_{mi}^* r_{ji} + \sum_{m \in R_2} \lambda_{mi} r_{(j+1)i}^* \\ &= \Big(\Big| \sum_{m \in R_1} \lambda_{mi} \Big|^2 + \Big| \sum_{m \in R_2} \lambda_{mi} \Big|^2 \Big) s_j, \end{aligned} \tag{5.4}$$

$$\begin{aligned} \tilde{s}_{j+1} &= \sum_{m \in R_1} \lambda_{mi}^* r_{(j+1)i} - \sum_{m \in R_2} \lambda_{mi} r_{ji}^* \\ &= \Big(\Big| \sum_{m \in R_1} \lambda_{mi} \Big|^2 + \Big| \sum_{m \in R_2} \lambda_{mi} \Big|^2 \Big) s_{j+1}. \end{aligned} \tag{5.5}$$

In these equations, the noise components are omitted to keep the presentation simple. When K value is greater than one, the received signals of the s_j and s_{j+1} symbols are given by,

$$r_{ji}^{(k)} = \lambda_{ti}^{(k-1)} s_j + \sum_{m \in R_1} \lambda_{mi}^{(k)} s_j - \sum_{m \in R_2} \lambda_{mi}^{(k)} s_{j+1}^*, \tag{5.6}$$

$$r_{(j+1)i}^{(k)} = \lambda_{ti}^{(k-1)} s_{j+1} + \sum_{m \in R_1} \lambda_{mi}^{(k)} s_{j+1} + \sum_{m \in R_2} \lambda_{mi}^{(k)} s_j^*, \tag{5.7}$$

where λ_{ti} is channel response between the TVS and the i-th RVS in the next hop. In these equations, the noise components are also omitted to keep the presentation simple. The number on the right shoulder denotes the number of

Table 5.1: Direction and speed converter.

Direction bits	Direction	Speed bits	Speed [km/h]
00	North	00	0-60
01	South	01	60-80
10	West	10	80-100
11	East	11	100-+

the k-th transmission of the signal ($k = 1, 2, ..., K$). At the receiver, the decoded signals of the s_j and s_{j+1} symbols are derived as follows,

$$\begin{aligned}\tilde{s}_j^{(k)} &= (\lambda_{ti}^{(k-1)} + \sum_{m\in R_1} \lambda_{mi}^{(k)})^* r_{ji}^{(k)} + (\sum_{m\in R_2} \lambda_{mi}) r_{(j+1)i}^{(k)*} \\ &= (\left|\lambda_{ti}^{(k-1)} + \sum_{m\in R_1} \lambda_{mi}^{(k)}\right|^2 + \left|\sum_{m\in R_2} \lambda_{mi}^{(k)}\right|^2) s_j,\end{aligned} \tag{5.8}$$

$$\begin{aligned}\tilde{s}_{j+1}^{(k)} &= (\lambda_{ti}^{(k-1)} + \sum_{m\in R_1} \lambda_{mi}^{(k)})^* r_{(j+1)i}^{(k)} - (\sum_{m\in R_2} \lambda_{mi}) r_{ji}^{(k)*} \\ &= (\left|\lambda_{ti}^{(k-1)} + \sum_{m\in R_1} \lambda_{mi}^{(k)}\right|^2 + \left|\sum_{m\in R_2} \lambda_{mi}^{(k)}\right|^2) s_{j+1}.\end{aligned} \tag{5.9}$$

As a result, by using the user cooperative diversity scheme combining with STBC encoding, if the channel impulse response is estimated exactly at the receiver, cooperative network diversity gain can be obtained with the MRC decoding scheme. Then, the decoded signals $\widetilde{s}_j^{(k)}$ and $\widetilde{s}_{j+1}^{(k)}$ can be detected.

Although timing and frequency synchronization for distributed STBC systems is a challenging task in highly dynamic communication environment, some papers have proposed the solution to solve these problems [23][24][25]. Therefore, it is assumed that the synchronization can be obtain by using the SYNT packet and OFDM technology.

5.3 Cooperative Distributed STBC Transmission Method for Multi-hop V2V Communications

In the proposed method, it is assumed that transmission power of all VSs is fixed and VSs know their own position and are equipped with an electronic map. The information about position, speed and direction of the TVS and MVS is attached in the safety-related messages. The information can be converted by using two bits for speed and two bits for direction as shown in Table 5.1. In this method, there are three control packets: Synchronize and trigger the transmitting timing of RVSs (SYNT), Request to broadcast SYNT (RTBS), Clear to broadcast SYNT (CTBS). The SYNT packet shown in [21] is also used to synchronize and trigger the transmitting timing of RVSs in each hop. The RTBS and CTBS packets are used to select an MVS in each hop for transferring network management function from the previous MVS to the new MVS. In this method, it is reminded that N is denoted as the number of maximum iterative steps for data transmission. Let n be a count down of the current iterative step of a particular data packet. At the first step, $n = N$ and n value is decreased one unit and is stored in the packet in the next step. When the data packet with $n = 0$ is received, the data packet is not forwarded. $N = 0$ means that the data packet is transmitted once by only the TVS and not forwarded by any RVSs. It is worth noting that this method is used to broadcast the information of emergency situation to all behind vehicles, therefore the current iterative step (n) always reaches to zero for all data packets in due to no destination node. We also consider limiting the number of repetition of the same data packet transmission at each VS as K value. If the number of transmission times of the same data packet transmission at a particular VS is more than K, the data packet is not transmitted by the VS. It is also worth noting that N value is the number of hops if there are always one selected MVS in each hop. In the case that there is no MVS in the next transmission, the iterative step is only the retransmission from the nodes in the current hop.

The transmission sequence of the proposed method is shown in Fig. 5.4. The proposed method is described in detail in Subsections 5.3.1 and 5.3.2.

5.3.1 Transmission Procedure of the Proposed Method

The transmission algorithm at the TVS and RVS are shown in Figs. 5.5 and 5.6, respectively. The figures also show the transmission algorithm at MVS. First, the TVS broadcasts the data packet and the surrounding OVSs receive and detect the packet. If an error-free data packet is received, an OVS then

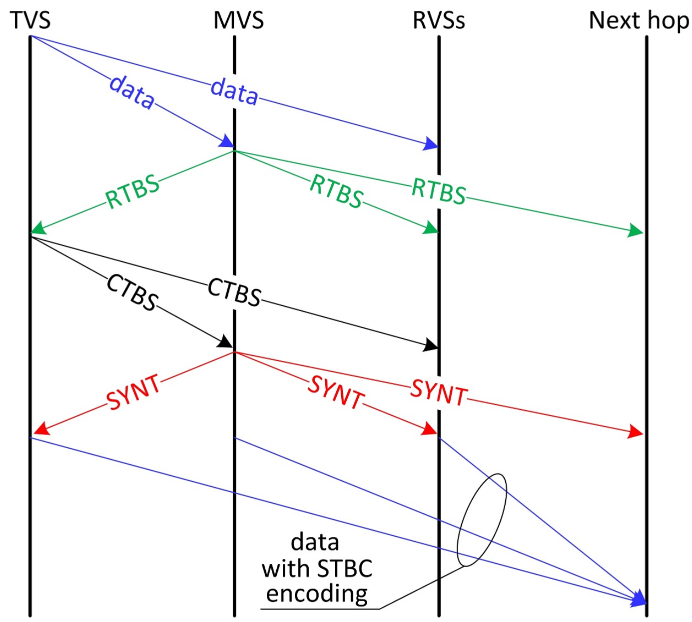

Figure 5.4: Transmission procedure at the first hop.

becomes an RVS and ready to rebroadcast the data packet. At the next iterative step, the information about position, speed and movement direction of the TVS will be checked at RVSs. In the proposed method, RVSs process only the data packets transmitted by the TVS in front of them. An MVS is then selected from the RVSs in each hop. In order to become potential MVSs, the distance and speed deviation between the RVS and TVS must be less than predetermined thresholds. The speed threshold ($v_{thr.}$) is set such that carrier frequency offset caused by Doppler-effect is acceptable in vehicular environment. The distance threshold ($d_{thr.}$) is set according to the transmission range of VSs in the network. In this method, the thresholds are only used at the RVSs to select the potential MVSs in each hop as shown in Fig 5.6. After transmitting the SYNT and data packets at the current MVS or at the TVS, the thresholds are not used as shown in Fig 5.5. In order to improve the transmission performance, the RVSs with opposite direction of movement with the TVS do not become potential MVSs. The impact of the thresholds of distance and speed deviation on the performance of the proposed method is planned for future work. After that, the potential MVS uses the proposed timer to contend with the others in the same hop. The

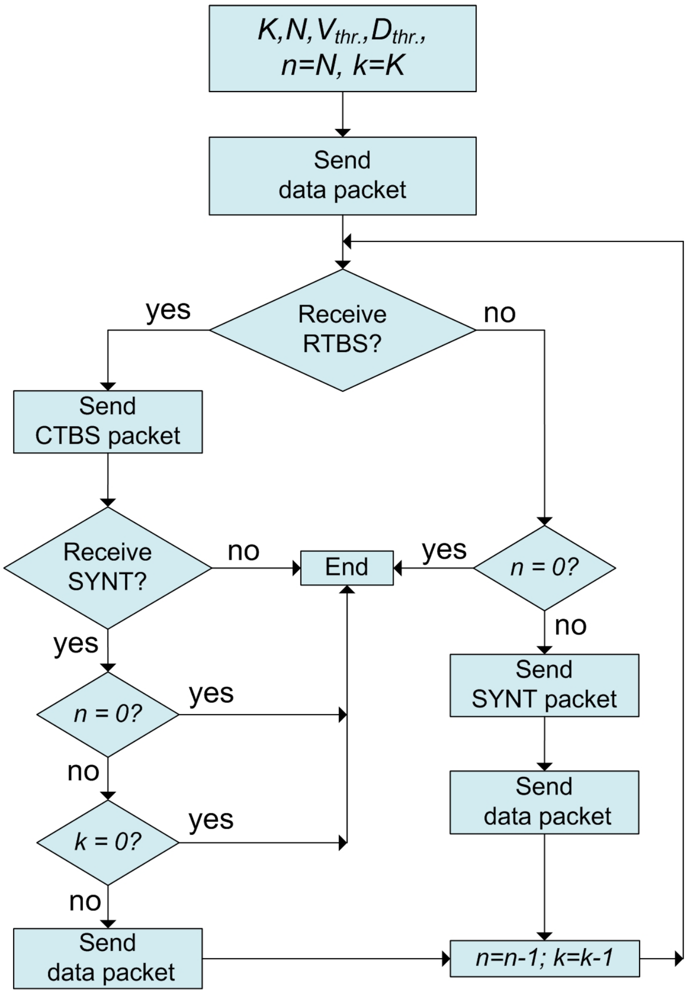

Figure 5.5: Transmission algorithm at the TVS.

potential MVS with the shortest timer will transmit an RTBS packet sooner than the others. If an error-free CTBS packet is received from the TVS, the potential MVS becomes MVS in the hop by transferring the MVS function from the TVS. A SYNT packet then is broadcasted from the MVS to trigger and synchronize transmitting timing of RVSs in the hop. If the SYNT packet is correctly received at RVSs, both the MVS and RVSs simultaneously rebroadcast the same data packet with the different STBC encoding patterns.

At the next iterative step, the MVS has the same role as the TVS for transferring the function of MVS to the next candidate of MVS. In the proposed method, the transmission at the other VSs will be stopped if the control packets are re-

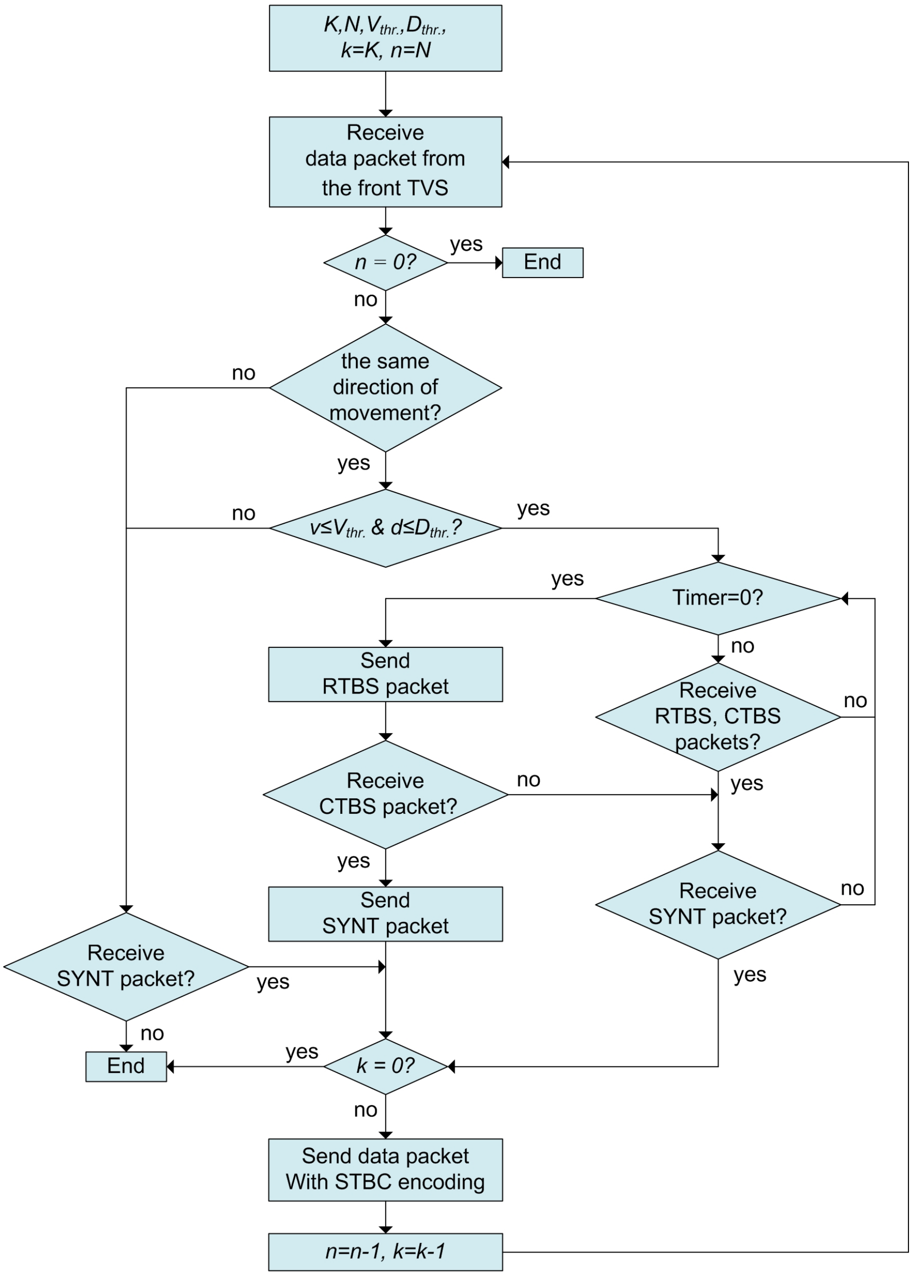

Figure 5.6: Transmission algorithm at RVS.

ceived. Therefore, interference and collision in the network can be reduced. In the proposed method, each RVS synchronizes the transmitting timing and frequency according to the SYNT packet. The timing offset due to the distributed position of RVSs can be absorbed by the guard interval of OFDM technology.

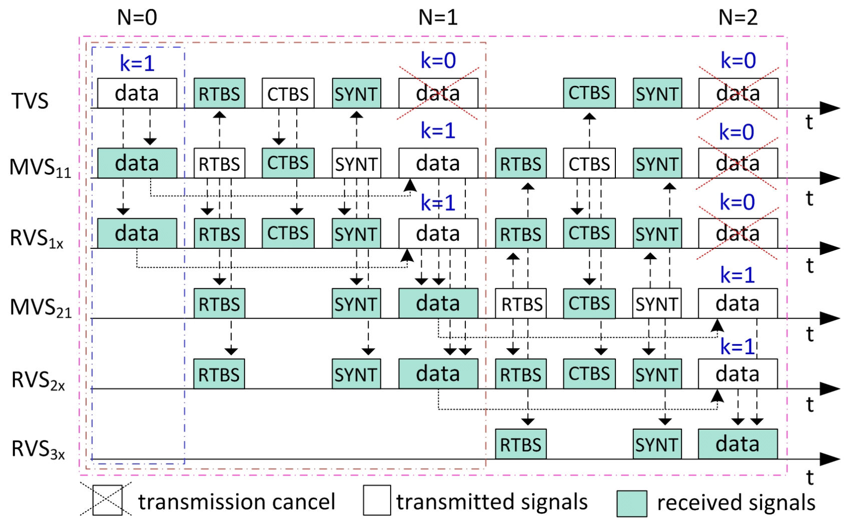

Figure 5.7: Transmission procedure for the cases with $K = 1$.

Finally, if the conditions are satisfied, the data packet and SYNT packet with STBC encoding will be transmitted based-on K and N values. The different STBC encoding pattern is selected randomly in each RVS. The control packets include N and K values, the packet ID for retransmission, the predetermined bit pattern for synchronization, and so on. Transmission procedure of the proposed method for the cases with different N values and $K = 1$ is summarized in Fig. 5.7. In the figure, MVS_{n1} and RVS_{nx} are the MVS and RVSs in the n-th hop, respectively.

5.3.2 Timer and Relay Selection Method

In the proposed method, a novel procedure of relay selection is used to select RVSs and MVS with high contribution according to the transmission direction in each hop. The procedure is based-on history data of position, speed and direction of movement of RVSs. RVSs process only the data packets received from the TVS in front of them. After receiving an error-free data packet, the data packet is re-broadcasted simultaneously by RVSs, if a SYNT packet is correctly received from MVS. In order to become potential MVSs, RVSs must be satisfied the conditions of position, speed and direction of movement described in Subsection 5.3.1. The potential MVSs then initialize the proposed timer as equation (5.10). This timer

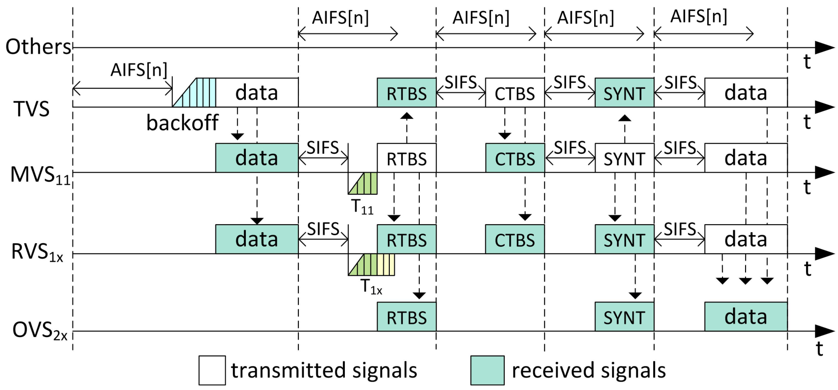

Figure 5.8: Timing and medium access procedure.

is used to select an MVS among the potential MVSs to send the SYNT packet at the next iterative step. It is also used to contend to access medium in the network.

$$T_i = \Delta \times \frac{PRIO[n]}{d_i} \times \frac{(AIFS[n] - SIFS)}{aSlottime}, \tag{5.10}$$

where T_i is timer of the i-th potential MVS in microseconds. Δ is the normalized factor of the timer. The factor can be adjusted to be compatible with different systems. $PRIO[n] = n + 1$ $(0 \leq n \leq 3)$ is the priority of the different access categories (ACs). The lower value of the $PRIO$ is the higher priority of the AC is. D_i is the distance in meter from the i-th potential MVS to the TVS or current MVS. $AIFS[n]$ and $SIFS$ are arbitration inter-frame space and short inter-frame space, respectively. $aSlottime$ is the length of one slot.

After sensing medium idle, a node can only transmit data packet for each AC when at least interval of the $AIFS[n]$ has expired [32]. In order to guarantee that the relaying will not be interrupted by other VSs in the network, T_i must be less than interval of $(AIFS[n] - SIFS)$. The $AIFS[n]$ is a duration derived by the relation,

$$AIFS[n] = AIFSN[n] \times aSlottime + SIFS, \tag{5.11}$$

where $AIFSN[n]$ is arbitration inter-frame space number, which is set to determine the length of an $AIFS$ interval corresponding to each AC [32]. The operation of the timer and medium access control procedure is shown in Fig. 5.8. In the same hop, the timer of the potential MVS farthest to the TVS or current

MVS will finish first. The potential MVS then sends an RTBS packet and waits for a CTBS packet from the TVS or current MVS. During the time, the timer of the other potential MVSs will be frozen. In the case that the CTBS packet is not received, the potential MVS does not become MVS for avoiding existence of multiple MVSs. After a predetermined waiting time, if the SYNT packet is not received, the other potential MVSs run the remainder of their timer. When the timer has expired, an other RTBS packet is transmitted to the TVS or current MVS. The process of the MVS selection is similar to the first time. At the TVS or current MVS, if the RTBS packet is not received, after a predetermined time period, a SYNT packet then is broadcasted. In this case, K value is not applied, the data packet also is retransmitted. For example, $d_1 = 200$ [m] and $d_2 = 100$ [m] are the distance from the first and second potential MVS to the TVS, respectively. In this chapter, we consider the data packet with the highest priority ($n = 0$, $AIFSN[0] = 2$) [32]. From equations (5.10) and (5.11), the timer of the first and second potential MVS are derived $T_1 = 0.01\Delta$ [μs] and $T_2 = 0.02\Delta$ [μs], respectively. If Δ is set to be 500, then $T_1 = 5$ [μs] and $T_2 = 10$ [μs]. As a result, after waiting the interval of $(SIFS + T_1)$, the first potential MVS transmits the RTBS packet to the TVS sooner than the second one.

5.3.3 Transmission Time of the Proposed Method

The transmission time of the proposed method can be it be calculated as follows. At the first step in transmission process, the sender delay of the data packet from the TVS is derived as equation (5.12).

$$T_{S_0} = T_c + T_d + T_{prop}, \tag{5.12}$$

where T_c is time needed for the TVS to acquire the channel before it transmits the data packet, which may include the back-off time, Arbitration Inter-frame Space ($AIFS[n]$). T_d is data packet transmission time, which is equal to protocol heads transmission time (T_h) plus data payload transmission time (T_{pl}) as shown in equation (5.13). T_{prop} is the time for the signal propagating from the TVS to the RVSs at the first transmission, which can be ignored when electromagnetic wave is transmitted in the air.

$$T_d = T_h + T_{pl}, \quad (5.13)$$

At the next step, let $T_m(i_n)$ be the time needed for selecting the i-th MVS candidate and suppressing the other potential MVSs at the n-th iterative step, $n = (N, ..., 2, 1)$ as described at the beginning of Section 5.3. Note that $T_m(i_n)$ is an increasing function of i_n, since the lower-priority MVS candidate with the longer timer always needs to wait and confirm that no higher-priority MVS candidates with the shorter timer have been selected to transmit SYNT packet. Combining with the Figs. 5.8 and 5.7, $T_m(i_n)$ is calculated as follows,

$$T_m(i_n) = T_{SIFS} + T_{i_n} + (T_{RTBS} + T_{SIFS})i_n + T_{CTBS} + T_{SIFS}, \quad (5.14)$$

$$T_m(i_n) = T_{SIFS} + T_{i_n} + (T_{RTBS} + T_{SIFS} + T_{CTBS} + T_{SIFS})i_n, \quad (5.15)$$

where equations (5.14) and (5.15) are $T_m(i_n)$ for the cases of the failed RTBS and CTBS packets, respectively. T_{i_n} is the proposed timer of the i-th MVS as shown in equation (5.10) at the n-th iterative step. The transmission time needed for forwarding the data packet at the n-th iterative step is given as follows,

$$T_{S_n} = T_m(i_n) + T_{SYNT} + T_{SIFS} + T_d + 4T_{prop}. \quad (5.16)$$

From equations (5.12) and (5.16), the total transmission time of the proposed method can be derived as follows,

$$T_{Tran} = T_{S_0} + \sum_{n=1}^{N} T_{S_n}. \quad (5.17)$$

Substituting (5.12) and (5.16) into (5.17) and after some tedious manipulations, the the total transmission time can be determined as follows,

$$T_{Tran} = T_c + \sum_{n=1}^{N} T_m(i_n) + N(T_{SYNT} + T_{SIFS}) + (N+1)T_d, \quad (5.18)$$

where T_{prop} is omitted to keep the presentation simple.

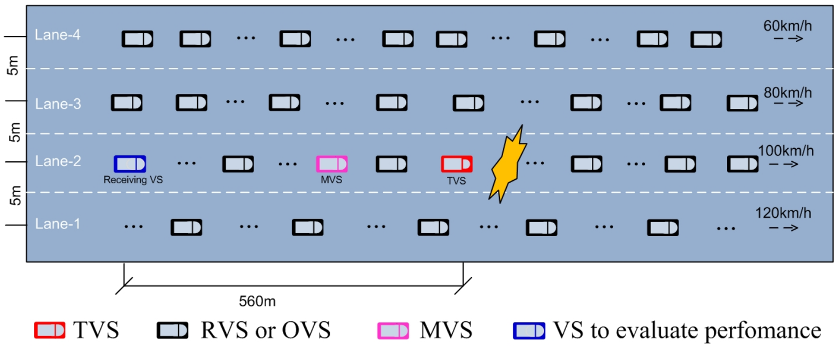

Figure 5.9: Vehicular simulation scenario.

5.4 Performance Evaluation

5.4.1 Simulation conditions

In order to evaluate the performance of the proposed method, one group of vehicles on highway is configured as shown in Fig. 5.9 [77][78]. In this scenario, the distance between vehicles in lane-1, lane-2, lane-3, and lane-4 are 90 [m], 80 [m], 70 [m], and 60 [m], respectively. The speed of vehicles is from 60 to 120 [km/h] depending on the lanes on the highway. In this simulation, the distance between the TVS and the position to evaluate the performance named Receiving VS is 560 [m]. The position of vehicles is randomized but still guarantees the parameters of the distance and speed on the different lanes. The other simulation conditions are listed in Table 5.2. In this simulation, STBC Distributed ARQ and MHVB schemes are selected to compare with the proposed method. In STBC Distributed ARQ, the data packet is broadcasted from the source node to the destination node without finding the path route in advance [21]. Therefore, this scheme can be used in the scenario with more than one destination node. Since the TVS and all RVSs both behind and in front of the TVS are selected to simultaneously retransmitted the data packet without limiting the number of repetition of the same data packet transmission at each VS to obtain STBC cooperative diversity gain in each hop, STBC Distributed ARQ scheme is considered as the upper bound of the performance. On the other hand, only one RVS is selected to forward the data packet in each hop in MHVB without diversity. In MHVB, the data packet is also transmitted from the source node to the destination node

Table 5.2: The simulation parameters of the computer simulation.

Modulation method	OFDM QPSK
Number of sub-carriers	52
Length of FFT	64
Length of guard interval	16 samples
Length of pilot signal	4 symbols
Length of data packets	16 symbols
Length of SYNT, RTBS, CTBS packets	4 symbols
Frequency band	760 [MHz]
Threshold of speed ($v_{thr.}$)	60 [km/h]
Threshold of distance ($d_{thr.}$)	560 [m]
Channel model	Rayleigh
Noise level	-90 [dBm]
Channel estimation	Perfect
Antenna gain of each VS	0 [dBi]
Height of Antennas	1.5 [m]
Direction of antenna	Omnidirectional
Normalized factor (Δ)	500
$PRIO[0]$	1
$AIFSN[0]$	2
$SIFS$	$32[\mu s]$
$aSlottime$	$13[\mu s]$
Transmit power	Variable
Number of generated packets in each transmit power	5000 packets

without finding the path route in advance. Therefore, MHVB is also suitable for the scenario with more than one destination node. In the original STBC Distributed ARQ scheme, the data packet transmission is repeated until the ACK packet is correctly received at the source node or the number of retransmission exceeds the maximum N value. In this simulation, in order to be suitable for this scenario, no ACK packet is used, the data and control packets transmission

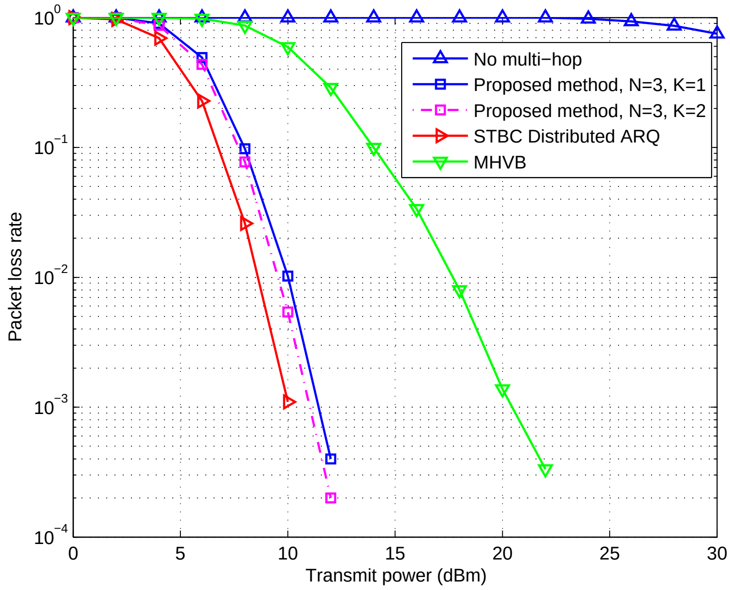

Figure 5.10: Packet loss rate with 64 RVSs.

is continuously repeated until the current number of iterative steps of the data packet is equal to zero ($n = 0$). The other parameters are set to be the same as the proposed method. In this simulation, it is also assumed that the delay of all paths from the distributed RVSs is received within the guard interval of OFDM technology, therefore the ISI (inter-symbol interference) is not consider. In the proposed method, STBC encoding patterns of each distributed node are selected randomly in each sub-carrier. Therefore, the complicated task of assigning STBC encoding pattern for transmitting RVSs is not required.

5.4.2 Simulation results

First, the packet loss rate of the proposed method with the different K and N values as a function of the transmission power per VS is shown in Fig. 5.10. In this simulation, the number of RVSs is 64 including 32 RVSs in front of the TVS and 32 RVSs between the TVS and Receiving VS which is VS to evaluate the performance of the proposed method. The number of iterative steps for data packet transmission is varied from $N = 0$ to 3. $N = 0$ means that the

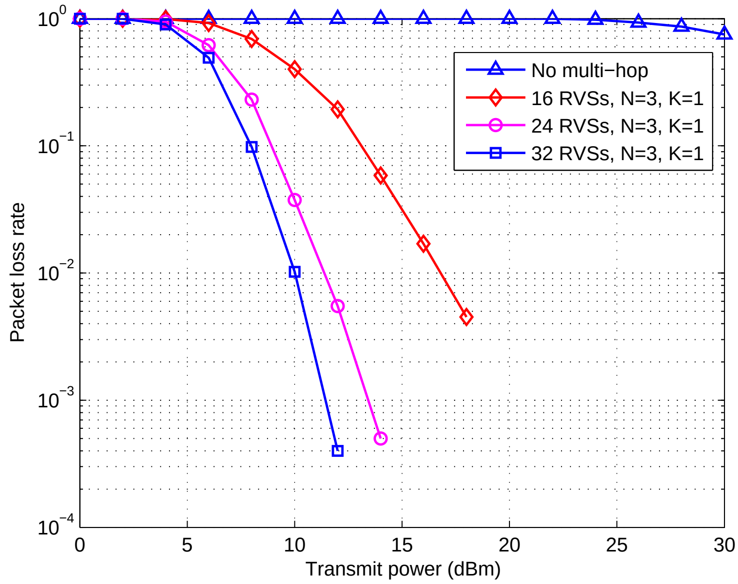

Figure 5.11: Packet loss rate with the different number of RVSs.

data packet is not retransmitted so that the only direct communication from the TVS to the Receiving VS is considered. It can be seen from the figure that the proposed method achieves a good performance when N value increases. MHVB routing protocol can reduce the packet error rate compared to the direct communication of the proposed method. However, since there is only one RVS selected to forward the data packet in each hop and STBC cooperative diversity gain cannot be obtained in MHVB, the performance of the proposed method is improved significantly in comparison with MHVB routing protocol. In this simulation, $K = 1$ means that each VS only transmits the data packet once. When the K value is more than one, the data packet is retransmitted by not only RVSs at the current hop but also RVSs at the previous hops. Therefore, the higher diversity gain can be obtained. From the figure, the performance of the proposed method is improved when K increases. However, this improvement is negligible because the RVSs at the previous hops are farther from the Receiving VS than the RVSs at the current hop. In this simulation, the performance of the proposed method is also compared with that of the transmission scheme in [21]. From this figure, STBC Distributed ARQ has better performance with the same

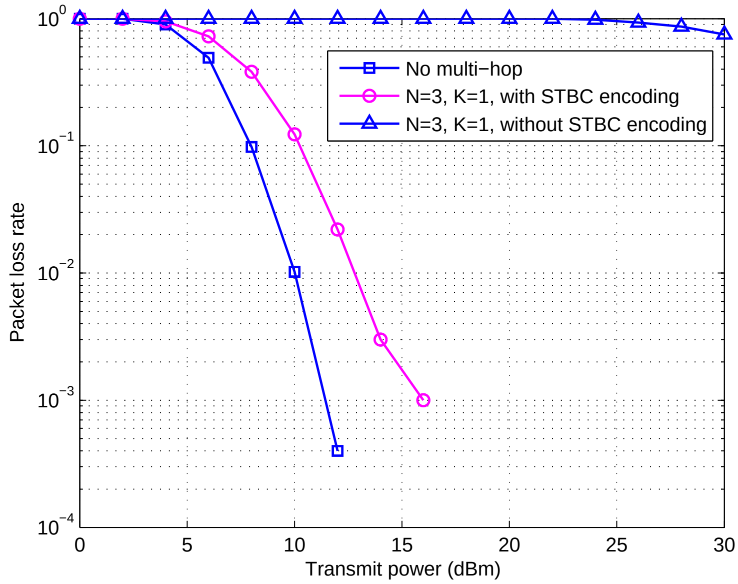

Figure 5.12: Packet loss rate with and without STBC encoding.

number of iterative steps for data packet transmission. This is because, in STBC Distributed ARQ, the data packet is simultaneously retransmitted by all of RVSs in both behind and in front of the TVS in each hop while only RVSs in behind the TVS is selected to rebroadcast the data packet in the proposed method. In addition, the number of repetition of the same data packet transmission at each VS is not limited ($K = N$). However, since RVSs with high contribution according to the transmission direction are selected to obtain cooperative diversity gain, the performance increase of the proposed method is negligible.

Next, Fig. 5.11 shows the performance of the proposed method with the different number of RVSs. As a system assumption in this simulation, we evaluate the performance by choosing the number of RVSs is 16, 24, and 32 between the TVS and the Receiving VS. When the number of RVSs increases, the data packets are simultaneously rebroadcasted by the more number of RVSs in each hop. Therefore, the higher diversity gain can be achieved. As a result, the proposed method has significant improvement of the performance when the number of RVSs increases. Therefore, it is better for the proposed method in the environment with the higher vehicle density. Next, the performance with and without

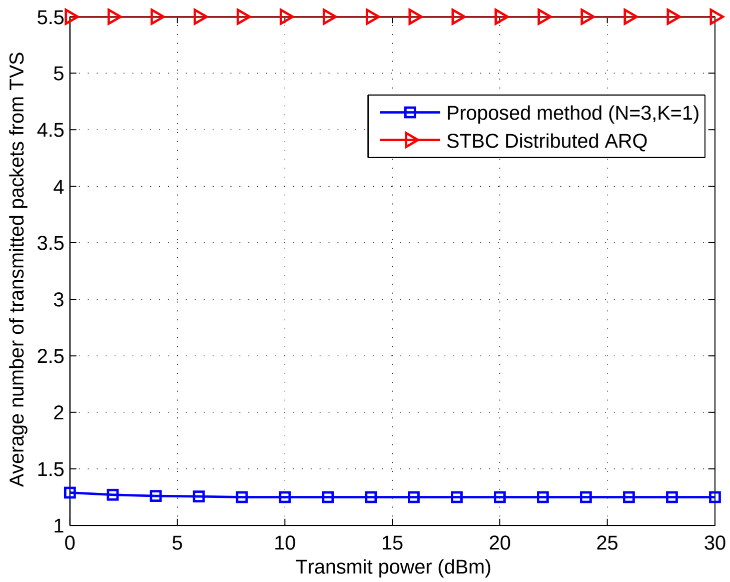

Figure 5.13: Average number of transmitted packets from the TVS.

using STBC encoding is shown in Fig. 5.12. From the figure, due to the STBC cooperative diversity gain, the performance of the proposed method with using STBC encoding for retransmitting the data packet at each VS is much better than that without using STBC encoding.

Next, the average number of transmitted packets from the TVS is shown in Fig. 5.13. In this simulation, the size of the SYNT, RTBS, and CTBS packets is set to be 1/4 of the data packet. We evaluate the total number of transmitted bits included in the data packet and the control packets are summed up and are normalized by the size of the data packet. The total number then is averaged by the number of generated packets. From the figure, the average number of transmitted packets from the TVS is much lower than that of STBC Distributed ARQ scheme. This is because the data and SYNT packets are always retransmitted from the TVS without limiting the number of repetition of the same data packet transmission at each VS in STBC Distributed ARQ scheme. Consequently, the power consumption of the TVS is large and the transmission process completely depends on the TVS. In the proposed method, an MVS is selected to broadcast the SYNT packet in each hop. At the next iterative step, the MVS has the same

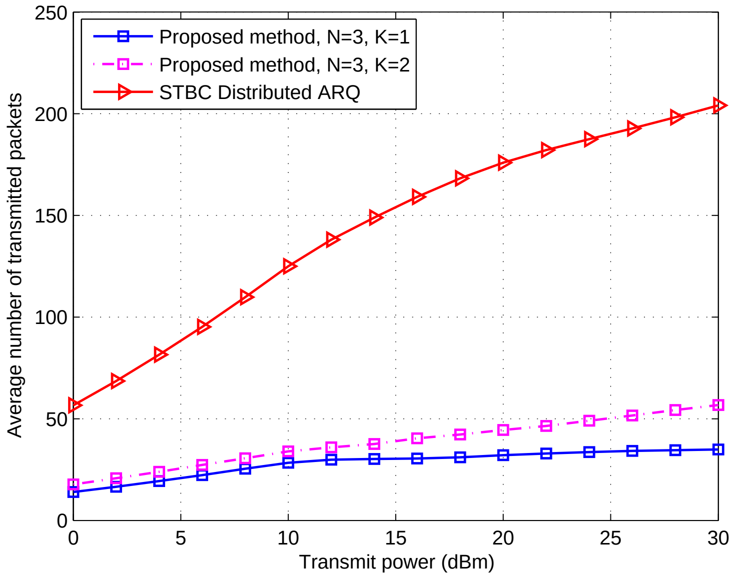

Figure 5.14: Average number of transmitted packets.

function as the TVS. When the transmit power is low, the selection of the MVS can be not successful. In this case, both SYNT and data packets are transmitted by the TVS. As a result, the average number of transmitted packets from the TVS is high. However, the number decreases considerably at high transmit power because the MVS can be easily selected.

Next, the average number of transmitted packets in the whole network is shown in Fig. 5.14. From the figure, since the data and control packets are broadcasted toward all direction and the number of repetition of the same data packet transmission at each VS is not limited, the average number in STBC Distributed ARQ increases significantly. In the proposed method, in order to reduce the redundant packets, the only RVSs with high contribution according to the transmission direction are selected to rebroadcast the packets. We also consider limiting the number of repetition of the same data packet transmission at each VS as K value. As a result, the average number of transmitted packets in the network with $K = 1$ decreases significantly. Combining with the simulation results in Fig. 5.10, when $K = 1$, the increase of the packet loss probability is small. Therefore, $K = 1$ is a better choice for the proposed method.

Table 5.3: Packet success rate and average transmission time.

	MHVB	STBC Distributed ARQ	The proposed method
PDR	0.712	1.000	1.000
Time [ms]	1.661	1.671	2.242
ANTP	3.949	63.343	21.721

Finally, the end-to-end packet delivery rate (PDR) and the transmission time evaluated by the average number of transmitted packets (ANTP) are shown in Table 5.3. In this simulation, the PDR is defined as the probability of receiving a data packet correctly at the Receiving VS, which is 560 [m] far from the TVS. In order to evaluate the transmission time, the maximum number of iterative steps for data transmission is set to be $N = 3$ for all methods and $K = 1$ for the proposed method. The transmission of a particular data packet is stopped when the data packet is correctly received at the Receiving VS or the current number of iterative step of the data packet is equal to zero ($n = 0$), the transmission time is then derived. In order to compare the transmission time between the methods, we use the IEEE 802.11p (OFDM) parameters as listed in Table 5.2. It is assumed that bit rate is set to be 6 Mbps for both data and control packets (including both headers and payload), back-off time and propagation delay are ignored. In this simulation, the transmit power of all VSs is set to be 12 [dBm] which is chosen based-on the point without error detected in Fig. 5.10 and satisfying the current standards of transmit power. From the table, although there is no control packets used in MHVB, the transmission time of MHVB is approximated with that of STBC Distributed ARQ. This is because with the lowest PDR=0.712 of MHVB, the transmission is only stopped when the data packet is correctly received at the Receiving VS with the required average number of iterative steps is approximately the maximum N value or n value of the data packet is equal to zero. Due to only one RVS forwarding the data packet in each hop and no control packets, the required ANTP in MHVB is the lowest in this simulation. Since the time needed for selecting an MVS in each hop, the transmission time of the proposed method is higher than that of STBC Distributed ARQ with the same PDR = 1. However, due to only the RVSs with high contribution according to the transmission direction selected to forward the data packet and limitation of K value in the proposed method, the required ANTP in the proposed method is much lower than that in STBC Distributed ARQ scheme.

5.5 Chapter Summary

In this chapter, we have proposed a cooperative diversity transmission scheme for dissemination of the emergency messages in multi-hop V2V communications. First, in order to exploit the attractive characteristics in vehicular communications, a relay selection algorithm based-on position, speed and direction of movement to select a group RVSs with high contribution according to the transmission direction to forward the emergency messages in each hop has been proposed. In addition, we have installed a new timer to select a master vehicle station which manages a packet transmission of whole network in each hop. In the proposed method, the STBC encoding scheme is used at the distributed RVSs to obtain cooperative diversity gain in each hop. The analysis of signal model and transmission time of the proposed method is also provided in this chapter. From the simulation results, we can confirm that the proposed method can reduce the number of transmitted packets in network while keeping the significant improvement of packet loss probability by selecting the only RVSs high contribution according to the transmission direction in each hop and limiting the number of repetition of packet transmission at each vehicle station. In comparison with the single-hop direct communication system and the conventional simple location based routing protocol as MHVB, the packet loss probability of the proposed method can be improved significantly. As a result, the proposed method can achieve high reliability in wireless multi-hop V2V communications.

Chapter 6

Conclusion

This chapter concludes our research work based on the studies of distributed cooperative diversity for multi-hop V2V communications. First, the advantages and contributions of the proposed method are summarized. The potential future research direction is then discussed and shown.

6.1 Contributions and Advantages

In recent years, ITS is a natural trend in order to reduce the potential driving risk, enhance road safety, and bring out comfortable driving with infotainment applications. In Japan, ITS systems is also considered as a foundation for overcoming society problems. Due to challenging characteristics of vehicular communications, the current protocols and standards can be applied for safety-related message exchange but in the future world, other new applications like autonomous controlled vehicles require more reliability and capacity with small delay. In addition, multi-hop data delivery for emergency situations on road is not explicitly supported in the current standards.

Therefore, in this thesis, we have researched characteristics, challenges and requirements of ITS communications. The overview of propagation model, the IEEE 802.11p standard (PHY and MAC specifications), the routing protocols, frequency band allocations and DSRC technology are also given in this thesis. We have also researched the cutting-edge techniques in wireless communications such as MIMO systems, cooperative communications, and distributed cooperative diversity techniques, etc. In order to achieve high reliability in wireless multi-hop communications, the efficient cooperative relays must be selected to forward the packet in each hop. Distributed STBC encoding should be also applied to obtain higher cooperative diversity gain. In addition, the number of transmitted packet and the power consumption in network must be reduced while still maintaining the performance improvement of system, which can reduce the mutual interference in the shared radio channel.

From the background knowledge, cooperative diversity transmission methods are proposed. In the proposed methods, the data packet is transmitted from the source node without finding the route in advance and high reliability can be achieved without complicated routing algorithms. STBC encoding is implemented in a distributed manner to obtain user cooperative diversity gain. The analysis of signal model and transmission time are also provided. Furthermore, by selecting the only distributed relay nodes with high contribution according to the transmission direction and limiting the number of repetition of the same message transmission at each node, the proposed methods can reduce redundant broadcast messages and the power consumption normalized one data packet transmission power consumption significantly while keeping the high performance improvement in comparison with the other methods. This can lead to the reduction of interferences in network and better efficiency frequency utilization, which in turn can achieve high reliability in wireless communications.

As a result, the proposed method can partly meet the requirements and challenges in vehicular communications. The emergency information is provided to the behind vehicles on the same way in the emergency situations by using wireless multi-hop V2V communications. By communicating between vehicles, it can be predicted possible collision and automatically speed down or alert drivers. The proposed method can also be used in applications for emergency vehicles (e.g., ambulances and fire trucks) to disseminate alarm messages to the other vehicles in the forward direction by simply changing the conditions of position, speed and direction of movement to select intermediate vehicle stations in each hop.

In the future, when fully automated driving systems are implemented in real transport systems, the movement of vehicles is fully automatic, without operation of drivers. The information about location, speed, direction of movement, and the start and destination points of vehicles, as well as the digital road maps, etc., are available. Therefore, our investigation of distributed cooperative diversity transmission schemes have provided some new research directions for the next generation of multi-hop V2V communications. These studies can be also an efficient approach to support multi-hop data delivery for new standards, protocols, and practical applications in vehicular communications in the future. By using many distributed relay nodes with high contribution according to the transmission direction and combining STBC encoding in a distributed manner to broadcast the same packet simultaneously, the performance of packet transmission is improved significantly.

6.2 Future Research Work

In this thesis, we have studied on distributed cooperative diversity transmission methods for wireless multi-hop vehicular communications. First, the performance of our proposed methods is compared with STBC Distributed ARQ scheme in which the data packet is broadcasted toward all direction by all relay nodes. Therefore, STBC Distributed ARQ scheme is considered as the upper bound of the performance. The performance of our proposed methods is also compared with conventional on-demand routing protocol such as AODV or MHVB protocols which only one relay is selected to forward the data packet in each hop, thus cooperative diversity gain can not be obtained. The importance to compare the performance with the routing protocols is the difference compared with schemes which can not obtain diversity gain. Therefore, finding out the analytical bounds of the performance of the proposed methods is also an open work. Moreover, in the proposed methods, it is assumed that plural frequency channels is used for avoiding interference in network. The impact of interference on performance of systems should be considered in the future. In addition, it is also assumed that the timing and frequency synchronizations are perfect in our proposed methods since some papers have proposed the solution to solve these problems. However, the synchronizations for distributed STBC systems is still a challenging task in highly dynamic communication environment. Therefore, the synchronization problems should be investigated in the future. Finally, The proposed method can achieve high reliability due to reducing the number of transmitted packets in network while keeping the significant improvement of packet loss probability. When the number of transmitted packets is reduced by limiting the number of transmitting relays and limiting the number of repetition of packet transmission at each vehicle station, the interference in network and efficiency frequency utilization can be improved. However, the proposed method have high transmission time due to the period of selecting MVS and transferring the function of networking management in each hop. How to reduce the transmission time for the proposed method is also an open work.

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Publications

List of Publications Directly Related to The Dissertation

Journal Papers

1. Cong-Hoang Diem, Koya Sato, and Takeo Fujii,**"Cooperative Distributed STBC Transmission Scheme for Multi-Hop V2V Communications,"** IEICE TRANSACTIONS on Fundamentals of Electronics, Communications and Computer Sciences, Vol.E99-A, no. 1, pp. 252 - 262, Jan. 2016. (**Related to Chapter 5, Published**)

International Conference Papers

1. Cong-Hoang Diem, Takeo Fujii, **"A novel distributed STBC cooperative diversity scheme for OFDM multi-hop relay networks,"** in Proceedings of 2015 12th Annual IEEE Consumer Communications and Networking Conference (CCNC), pp.154 - 155, Las Vegas, NV., Jan. 2015. (**Related to Chapter 4**)

List of Publications For References

International Conference Papers

1. Cong-Hoang Diem, Takeo Fujii, **"Distributed STBC for vehicular communications on highway,"** in Proceedings of ITS World Congress 2015,

Bordeaux, France, Oct. 2015. (**Related to Chapter 5**)

2. Cong-Hoang Diem, Takeo Fujii, **“An efficient cooperative transmission scheme for vehicular communications,”** in Proceedings of 2015 14th International Conference on ITS Telecommunications (ITST), pp. 12 - 16, Copenhagen, Denmark, Dec. 2015. (**Related to Chapter 5**)

Domestic Conference Papers

1. Cong-Hoang Diem, Takeo Fujii, **“An Efficient Distributed Cooperative Diversity Method for STBC-OFDM Multi-hop Networks,”** IEICE Technical conference on Radio Communication Systems (IEICE 2014/12 NS/RCS), IEICE Technical Report, vol. 114, no. 372, RCS2014-258, pp. 225-229, Dec. 2014. (**Related to Chapter 4**)

2. Cong-Hoang Diem, Koya SATO, Takeo Fujii, **“A Highly Efficient Transmission Scheme for Multi-hop V2V Communications on Highway,”** IEICE Technical conference on Software Radio (IEICE SR 2015), IEICE Technical Report, vol. 115, no. 161, SR2015-29, pp. 79-85, July 2015. (**Related to Chapter 5**)