MAC Layer Design and Analysis for Cooperative Communications in Wireless Networks

July 2013

Xiaoyan Wang

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Graduate School of Systems and Information Engineering
University of Tsukuba

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Abstract

Cooperative communication, which utilizes neighboring nodes to relay the overhearing information, has been employed as an effective technique to deal with the multi-path fading by achieving the diversity gain. Recent studies have shown that cooperative communication can obtain significant performance improvement in various kinds of networks. This dissertation focuses on the MAC layer design and analysis for cooperative communications. We contribute to the advancement of cooperative communications by proposing and analyzing Cooperative MAC (CMAC) protocols, with the goal to enhance the performance of network throughput, delay and energy efficiency.

We first analyze the transmission rate for reactive CMAC, which has not been well addressed yet in the previous work. For a given transmitting power level and a desired probability of success, we investigate how much average transmission rate can be increased by reactive CMAC. Moreover, we study the impact of maximal ratio combiner and energy constraint on reactive CMAC. The extensive evaluation results reveal that the average transmission rate can be substantially improved through such adaptive cooperation.

Secondly, we propose a proactive CMAC protocol with the purpose of improving the network lifetime of mobile ad-hoc networks. A practical energy consumption model is utilized, which takes the energy consumption on both transceiver circuitry and transmit amplifier into account. A distributed utility-based best relay selection strategy is incorporated, which selects the best relay based on location information and residual energy. Furthermore, with the purpose of enhancing the spatial reuse, an innovative network allocation vector setting is provided to deal with the varying transmitting power of the source and relay terminals. We show that the proposed protocol significantly prolongs the network lifetime under various circumstances even for high circuitry energy consumption cases by comprehensive simulation study.

Finally, we propose a network coding aware reactive CMAC protocol for wireless ad-hoc networks. Introducing network coding technique into the cooperative retransmission process, enables the relay node to assist other nodes while serving its own traffic simultaneously. The design objective is to increase the throughput and reduce the delay. We propose a network coding-aware utility-based best relay selection strategy, which takes the coding opportunity, achievable throughput and estimated delay into consideration. To avoid the possible collision, we further improve the relay selection process by incorporating two collision free relay selection schemes. Simulation results reveal that the proposed scheme can improve the network performance under general circumstances comparing with two benchmarks.

Acknowledgements

Completing my Ph.D. dissertation is a milestone in my career that would not have been possible without the help and support of my advisor, Prof. Jie Li. I would like to express my deepest gratitude to Prof. Li, who provided me the opportunity to study at the University of Tsukuba. His outstanding supervision and guidance play a critical role in my research or even in my life.

It is an honor for me to thank Prof. Hiroaki Nishikawa, Prof. Daisuke Takahashi, Prof. Kazuki Katagishi, and Prof. Shigetomo Kimura for being my dissertation committee members and providing constructive advices and comments on my researches.

I would like to thank all the members in Operating Systems and Distributed Processing (OSDP) laboratory for their kind help: Dr. Ruidong Li, Dr. Ghada Ahmed Abdel Monaim Khoriba, Dr. Yu Gu, Dr. Wei Li, Dr. Xiaofei Xing, Dr. Yongsheng Liu, Huang Lu, Wei Jing, Dan Li, Daichi Hiroki, Yasuo Okamoto, Biao Han, Xiucai Ye, Shuai Fu, Atsushi Nagashima, Liwen Xu, Ou Wang, Zhongping Dong, Li Qiang, Yajun Tian, Kei Ebana, Zichen Jin, Zhengxu Li, Yujie Hu, Naoto Ishizuka, Cheng Sun, Ke Tang and Serigne Mbacke Ndiaye. Also, it is my pleasure to thank Prof. Hisao Kameda (at University of Tsukuba), Prof. Yuguang Fang (at University of Florida), Prof. Kui Wu (at University of Victoria), Prof. Mohsen Guizani (at Qatar University), Prof. Jiannong Cao (at Hong Kong Polytechnic University), Prof. Lasheng Yu (at Central South University), Prof. Li Xu (at Fujian Normal University) and Prof. Jianping Pan (at University of Victoria) for their kind advices and support on my researches.

I am deeply indebted to my parents and my wife for their support, understanding and love. Thank you for everything. Finally, I would like to thank all my friends in Japan.

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Chapter 1

Introduction

This chapter begins with discussions of motivation and the problems studied in this dissertation. A summary of the main contributions is included in Section 1.2, and the organization of the dissertation is provided in Section 1.3

1.1 Motivation and Overview

Wireless communication evolves rapidly since the three-dot Morse code for the letter ‘S’ was transmitted using electromagnetic waves in 1895. The demands of high throughput, low transmission delay, efficient energy consumption motivate the development of Wireless Sensor Networks (WSNs) [1], green cellular networks [2], and Wireless Ad-hoc NETworks (WANETs) [3]. The main obstacles to achieve high performance in these wireless applications are fading, shadowing, interference and other impairments that associated with the wireless channel. Among the most severe impairments to wireless communications is fading, which results from the multipath propagation [4].

The key technique to realize the reliable wireless transmission over fading channel is diversity [4]. Diversity is defined as the technique by which multiple copies of the signal are delivered to the receiver via independent fading channels. Among several diversity techniques, spatial diversity [5] attracts particularly attention since it does not need additional bandwidth or a reduction of transmission rate. To achieve the spatial diversity, Multiple-Input Multiple-Output

(MIMO) systems [6–9] have been researched extensively in the last decade. In MIMO systems, both the transmitter and the receiver are equipped with multiple antennas. In order to obtain the signals that fade independently, the antennas must be equipped separately by at least a few wavelengths in one terminal. Unfortunately, it might be infeasible in some applications due to cost and space constraints.

To solve such problems, Cooperative Communication (CC) [10] has gained much interest recently as a new design paradigm to make terminals help each other in a distributed fashion so that the same diversity as in MIMO systems can be obtained. The broadcast nature of wireless medium is exploited in cooperative fashion, different nodes in the network share their antennas and resources for distributed transmission. CC has the potential of improving the throughput, transmission delay, energy efficiency and coverage range. Both WiMAX and LTE-Advanced envisage including cooperative relay features or relay-enabled model into the forthcoming standards.

The theory behind cooperative communications has been studied extensively, and significant physical layer performance improvement has been demonstrated in terms of transmission rate, outage probability and transmitting power efficiency. However, when we implement the cooperative communications into a real network, MAC layer design is indispensable as well. Without considering the MAC layer interactions and signaling overhead due to cooperation, the performance gain through physical layer cooperation may not improve end-to-end performance. In this dissertation, we focus on Cooperative MAC (CMAC) protocol design by jointly considering the issues in MAC layer and physical layer. As shown in Fig. 1.1, the challenges facing in cooperative MAC design includes:

- *Hybrid cooperative network coding*

  One of the main disadvantages in cooperative communications is that the relay nodes must help the source node in advance, thus their own data must be postponed. To enable a relay node to retransmit the data for the source node, while delivering its own data simultaneously, hybrid cooperative network coding technique is becoming a growing concern recently. In order to introduce network coding into cooperative communication, the corresponding MAC layer design should be considerably modified.

- *Relay selection.*

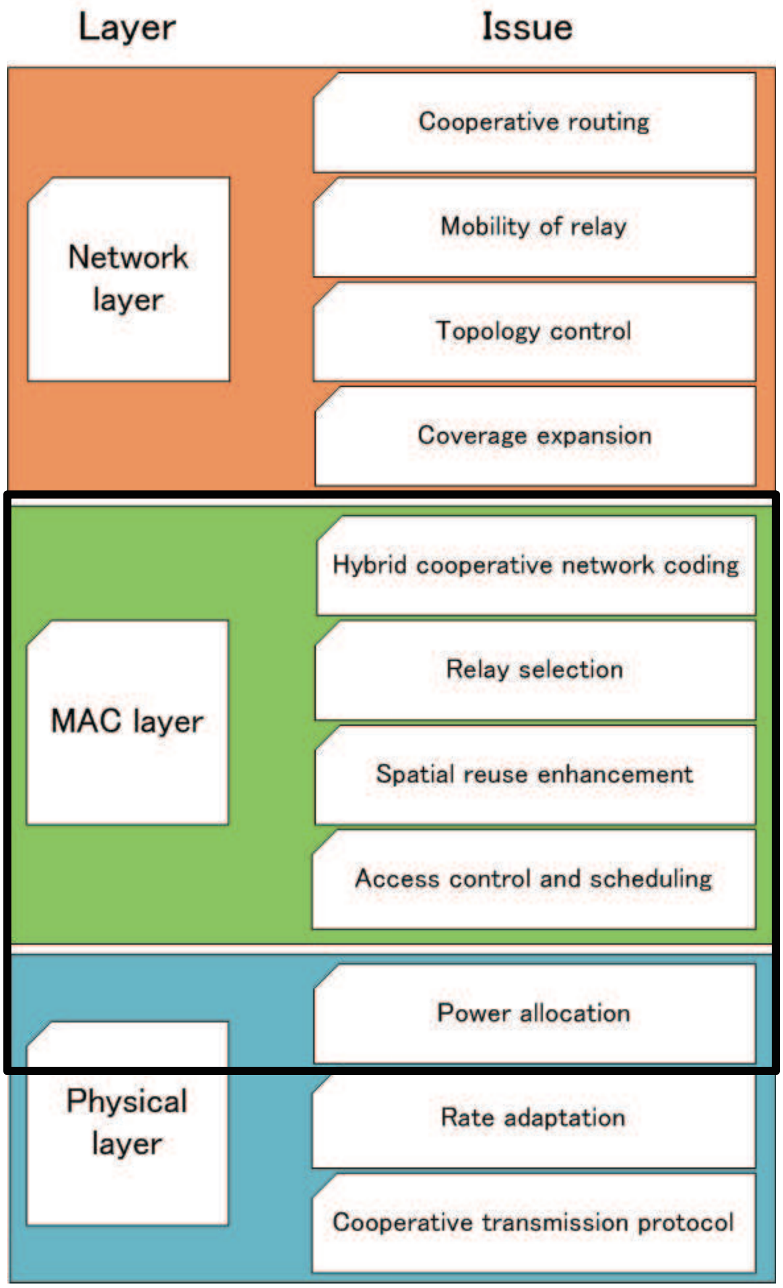

FIGURE 1.1: The research issues we focused.

Best relay selection is vital for reaping the performance benefit of cooperative communication. It is a challenging task to share channel information in timely and distributed manner and at the same time select the best relay in a time varying radio environment.

- *Spatial reuse enhancement*

  As the involvement of relaying and varying transmitting power, the interference ranges in cooperative communication are changing during one transmit session. In order to avoid the interference and enhance the spatial reuse simultaneously, delicate MAC layer setting is required.

- *Access control and scheduling*

  Due to the introducing of the relay node, the medium access control and scheduling become more complicated compared to the direct transmission. All the ongoing cooperative transmission should be protected against potential collisions from any other nodes in the vicinity.

- *Power allocation.*

  The transmitting power of cooperating signals should be properly controlled since energy is a scarce resource. Increasing the energy efficiency and keeping the quality of the transmission at the same time is a critical task for the work aims at improving the network lifetime.

1.2 Contributions

This dissertation focuses on the CMAC protocol design, and addresses the related issues mentioned in the previous section. The main contributions of this dissertation are summarized as follows.

1.2.1 Transmission Rate Analysis for Reactive CMAC (Chapter 3)

CMAC schemes can be generally categorized into proactive CMAC and reactive CMAC. The average transmission rate of reactive CMAC, however, has not been well addressed in the previous work. Under a given probability of success, we analytically derive the average transmission rate for reactive CMAC [11, 12]. Moreover, we investigate the impact of Maximum Ratio Combiner (MRC) and energy constraint for direct transmission and cooperative transmission. Numerical results reveal that the average transmission rate can be substantially improved by reactive CMAC, even when the energy constraint is taken into account.

1.2.2 Improving the Network Lifetime of WANETs through CMAC Design (Chapter 4)

We aim at extending the network lifetime for Wireless Ad hoc NETworks (WANETs) through CMAC protocol design. We propose a proactive CMAC protocol [13] considering the overheads and interference due to cooperation, as well as the energy consumption on both transceiver circuitry and transmit amplifier. A distributed energy-aware location-based best relay selection strategy is incorporated, which is more reasonable for WANETs comparing with the existing schemes based on channel condition. A cross-layer optimal transmitting power allocation scheme is designed to conserve the energy while maintaining certain throughput level. In addition, to deal with the presence of relay terminals and dynamic transmitting power, we provide an innovative Network Allocation Vector (NAV) setting to avoid the collisions and enhance the spatial reuse. Simulation results reveal that the proposed protocol can significantly prolong the network lifetime at the cost of relatively low throughput and delay degradation.

1.2.3 Network Coding Aware CMAC Design for WANETs (Chapter 5)

To enable a relay node to retransmit the data for the source node, while delivering its own data simultaneously, we investigate introducing Network Coding (NC) technique into CC. We propose a novel network coding aware reactive CMAC protocol [14, 15] that coordinates the relay involved cooperative coded retransmission process. We also propose a coding opportunity aware relay selection strategy to choose the best relay in an efficient, distributed and collision free manner. Furthermore, instead of the simple utility-based backoff scheme, we further incorporate two collision free relay selection strategies to improve the relay selection process. Simulation results demonstrate that the proposed protocol can substantially improve the throughput, delay and Packet Delivery Ratio (PDR).

1.3 Organization of the Dissertation

- **Chapter 2** gives the general background information related to this dissertation. We start from the introduction of multipath fading and diversity technique. Then we present the subject of cooperative communication and outline the common cooperative transmission protocols as well as different signal combining techniques. At last, the cooperative MAC protocol design for contention based wireless networks is addressed.
- **Chapter 3** analyzes the average transmission rate for reactive CMAC under a given probability of success. A closed-form expression for average transmission rate is derived and the impacts of MRC and energy constraint are investigated.
- **Chapter 4** proposes a CMAC protocol named DEL-CMAC based on IEEE 802.11 Distributed Coordination Function (DCF). DEL-CMAC aims at improving the network lifetime of WANETs by jointly exploiting energy advantage and location advantage.
- **Chapter 5** proposes a network coding aware CMAC protocol named NCAC-MAC based on IEEE 802.11 Carrier Sense Multiple Access (CSMA) policy without channel negotiation. The goal of NCAC-MAC is to improve the throughput and delay of the WANETs by introducing the NC technique into the cooperative coded retransmission.
- **Chapter 6** summarizes the dissertation and discusses the directions of our future work.

Chapter 2

Cooperative Communications and Cooperative MAC Design

In this chapter, we give a brief overview of the cooperative communication and cooperative MAC design related issues. We begin with the introduction of multipath fading in Section 2.1. Then, the details of diversity techniques are provided in Section 2.2. The concept of cooperative communication is addressed in Section 2.3, and the MAC layer design of cooperative communication is presented in Section 2.4.

2.1 Multipath Fading

Wireless applications are becoming an indispensable parts of our daily life. The main challenge in achieving the demands of these wireless applications is the unpredictability associated with the wireless channel. Wireless channels feature path loss, noise, fading, shadowing, interference, and other impairments that affect the communication performance.

Among the most severe impairments to wireless communications is signal fading. Fading is defined as the time variation of received signal power caused by changes in the wireless medium. As illustrated in Fig. 2.1, in wireless communication, the signal travels from the sender to the receiver through multiple reflective paths (the so-called multipath propagation). The fluctuations in amplitude, phase and angel of arrival of the signal result in multipath fading. The multiple copies of the signal arriving at the receiver may add together in destructive way and result in temporary failure of the communication [16, 17].

In a system with L paths between the transmitter and the receiver, the signal at the receiver is modeled as

$$y(t) = \sum_{i=1}^{L} h_i(t)x(t - \tau_i(t)) + n(t), \tag{2.1}$$

where $h_i(t)$ is the channel coefficient for the i−th path at time t, $\tau_i(t)$ is the corresponding path delay, and $n(t)$ is the additive noise. The channel delay spread is defined as the time difference between the first received path and the last received path as follows

$$\Delta = \max_{i,j\in\{1,\ldots,L\}} \tau_i - \tau_j. \tag{2.2}$$

Depending on Δ, the multipath fading can be divided into two categories:

- *Frequency selective fading*

  Δ is greater than a small fraction of the symbol period T_s, which means the delay spread of the channel. In this case, the coherence bandwidth of the channel is smaller than the bandwidth of the signal. Different frequency components of the signal therefore experience uncorrelated fading.

- *Flat fading*

  Δ is far lesser than T_s, in which we consider that all of the paths are received simultaneously. In this case, the coherence bandwidth of the channel is larger than the bandwidth of the signal. Therefore, all frequency components of the signal will experience the same magnitude of fading.

2.2 Diversity Techniques

To combat fading and enable reliable wireless communications, diversity techniques have attracted lots of attentions recently. The basic idea of diversity is to transmit and receive uncorrelated signal components. Diversity can be defined as any technique by which multiple copies

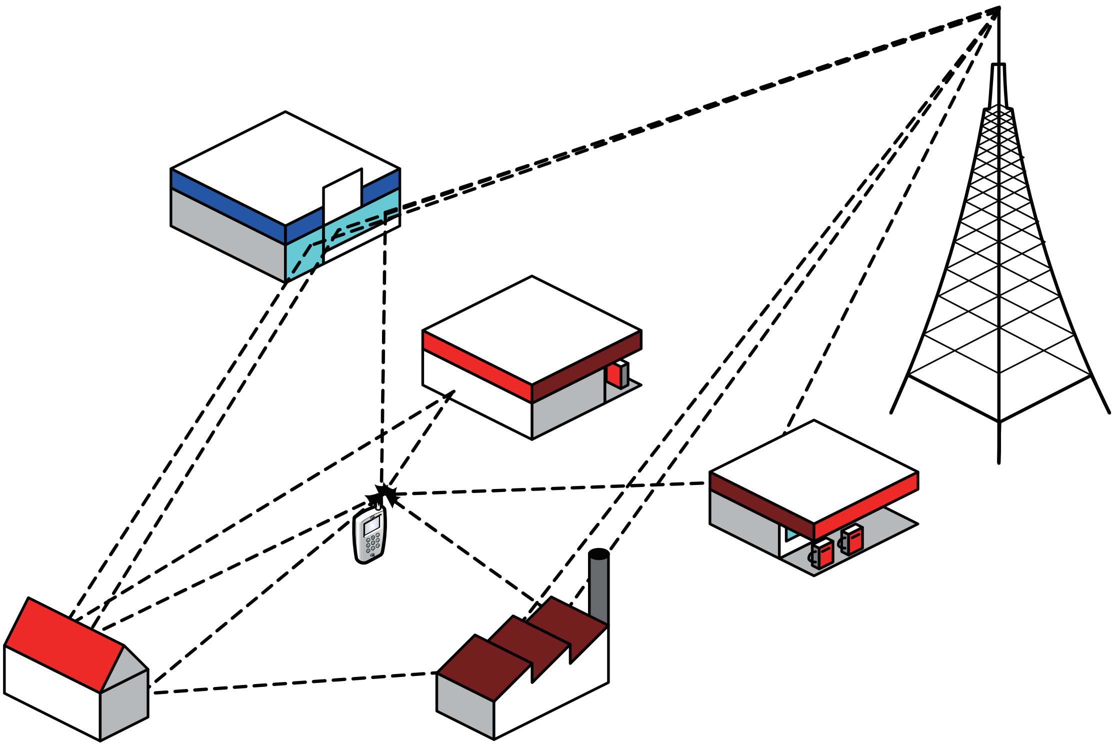

FIGURE 2.1: Multipath propagation.

of the signal are delivered to the receiver via independently fading channels [17]. Based on the fact that individual channels experience independent fading events, diversity can reduce the error rates significantly. If d denotes the number of copies of the message received through independent fading channels and p denotes the probability that one channel is in outage, then the probability for d channels are all in outage is p^d.

The diversity gain is defined in [17] as the rate of decay of the probability of error with the Signal to Noise Ratio (SNR) when using log-log scale,

$$Diversity\ gain = -\lim_{SNR\to\infty} \frac{\log P_e}{\log SNR}, \tag{2.3}$$

where P_e is the error probability. Eqn. (2.3) indicates that when P_e decays like SNR^{-d}, the diversity gain is d. For instance, P_e for a Single Input and Single Output (SISO) transmission decays like SNR^{-1}, thus the diversity gain is 1. And P_e for a Single Input and Multiple Output (SIMO) system with 2 receiving antennas scales like SNR^{-2}, thus the diversity gain is 2. Since increasing SNR is generally difficult due to transmitting power constraint, increasing the diversity gain is often the only way of reducing the error probability in systems over fading channels.

Depending on the physical domains which independent channels can be generated, diversity techniques can be divided into time, frequency and spatial diversities.

2.2.1 Time Diversity

As shown in Fig. 2.2, time diversity is realized by transmitting multiple copies of the same signal at different time instants. When the interval of the time instants is greater than the coherence time of the wireless channel, the replicas are considered to be received by different channels. Thus, the probability that one replica can be successfully decoded increases as the number of the received replicas. While advanced time diversity techniques exist, e.g., channel coding with interleaving, which are more efficient than simply repetition. The main disadvantages with time diversity are the poor spectral efficiency and the reduced transmission rate.

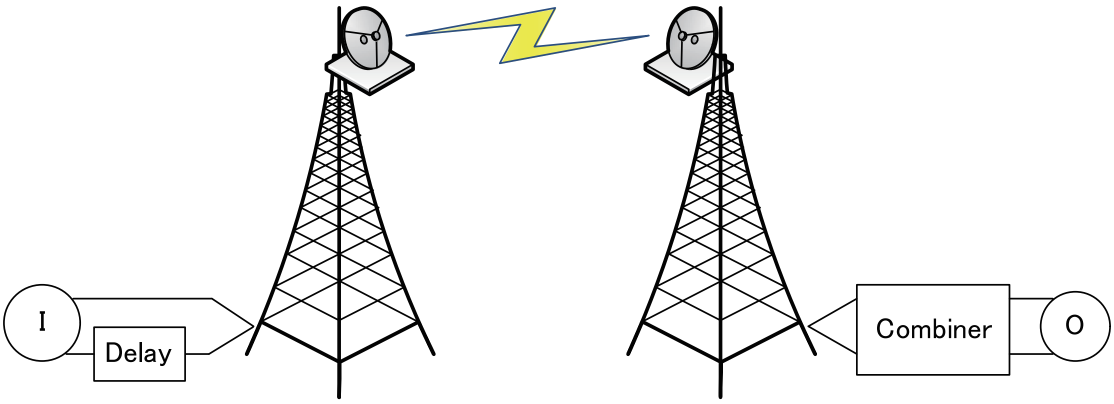

FIGURE 2.2: Time diversity.

2.2.2 Frequency Diversity

As illustrated in Fig. 2.3, frequency diversity involves the simultaneous use of multiple frequencies to transmit information since the wavelength for different frequencies result in uncorrelated fading characteristics. Orthogonal Frequency-Division Multiplexing (OFDM) is a popular scheme to achieve frequency diversity. The high data rate stream is divided into multiple low data streams and, each stream is transmitted over a sub-channel. Thus, the overall data stream is transmitted over sub-channels that are independently attenuated by the wireless channel. The shortcoming in frequency diversity is the requirement of additional bandwidth or the high bandwidth losses.

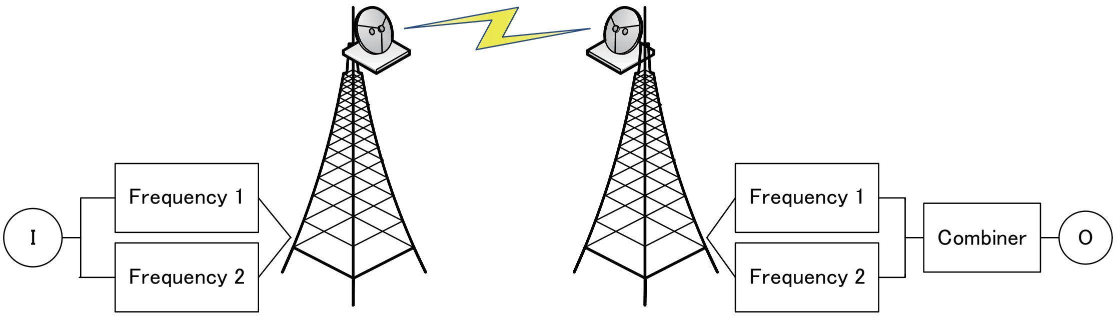

FIGURE 2.3: Frequency diversity.

2.2.3 Spatial Diversity

As shown in Fig. 2.4, spatial diversity technique achieves the diversity gain by sending the same signal by different antennas, and receiving the redundant information on multiple antennas, e.g., Multiple Input and Multiple Output (MIMO) systems [18, 19]. Space-time coding technique [7–9] for MIMO have been shown to achieve a maximum diversity gain which equals to the product for the number of transmit and receive antennas [20]. For instance, for a MIMO system with 3 transmit antennas and 3 receive antennas, the diversity gain is 9. The primary appeal of spatial diversity is that it does not require additional bandwidth or reduce the transmission rate, while improves the performance of the communication in terms of capacity, throughput, error performance, and energy efficiency. However, the downside is that antennas with sufficient separation may be impossible for many wireless terminals due to the space or cost constraint.

2.3 Cooperative Communications

To avoid the problems introduced in the previous section, cooperative communication has been recently introduced [10, 21–24]. Cooperative communications create a virtual MIMO environment where nodes collaborate and share their antennas to form a distributed MIMO system. The

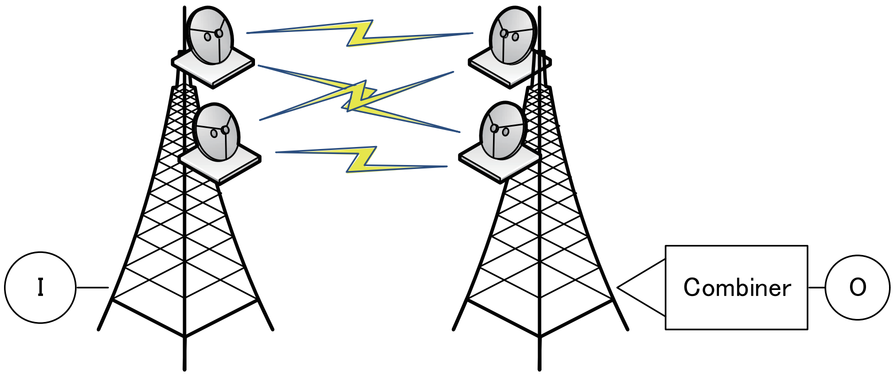

FIGURE 2.4: Spatial diversity.

same advantages as in MIMO systems can be obtained by exploiting the broadcast nature of wireless medium.

Cooperative communication is initially inspired by the research on relay channel model in the presence of Additive White Gaussian Noise (AWGN) [25, 26]. It extends the traditional point-to-point channel by including a relay whose purpose is to help transfer information from the source to the destination. As shown in Fig. 2.5, the relay channel can be decomposed into a broadcast channel from the viewpoint of the source, and a multiple access channel from the viewpoint of the destination.

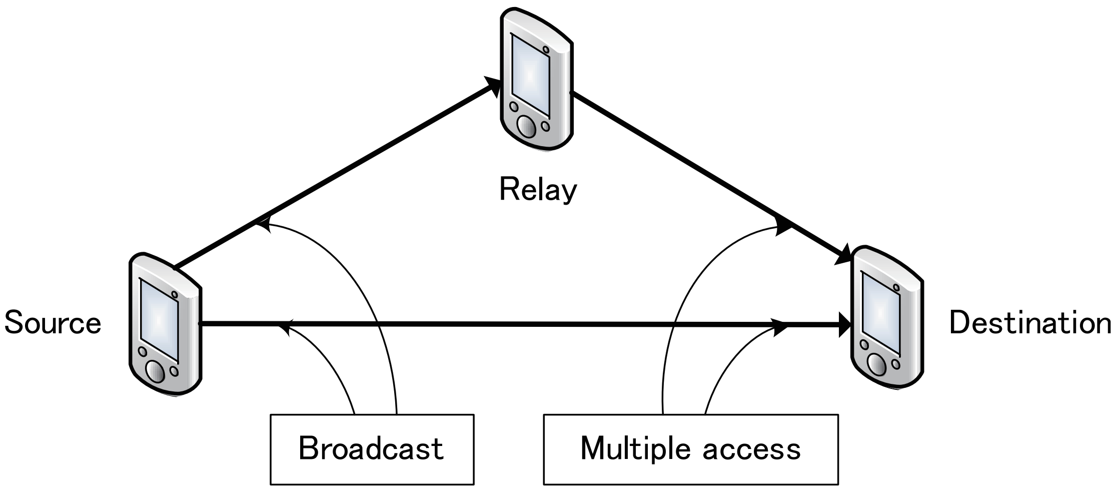

FIGURE 2.5: The relay channel.

In [21], the concept of user cooperation diversity was firstly presented. Then, many theoretic studies and results came out. A detailed information theoretic study of two-source transmit cooperation in a mobile uplink scenario was analyzed in [10, 22], which also exploited several practical implementation issues. And several practical cooperative transmission protocols in fading environments were proposed in [23, 24]. Novel information theoretic results and new insights into information theoretic coding was investigated in [27]. Prominent literature on the use of space-time codes with relays were addressed in [23, 28, 29]. Besides the previous researches on information theory aspects, a variety of contributions to power allocation [30, 31], power saving [32], coverage expansion [33], topology control [34], relay selection and deployment [35–38] were proposed.

The key idea in cooperative communication is that relay nodes can help the source node forward its information to the destination node, and the destination node receives several replicas of the same information via independent channels. Thus, the overall network performance can be improved by these kinds of sharing power and computation with neighboring nodes. As illustrated in Fig. 2.6, cooperative communication can be utilized in various wireless applications, includes cellular networks, wireless ad-hoc networks, wireless sensor networks and cognitive radio networks.

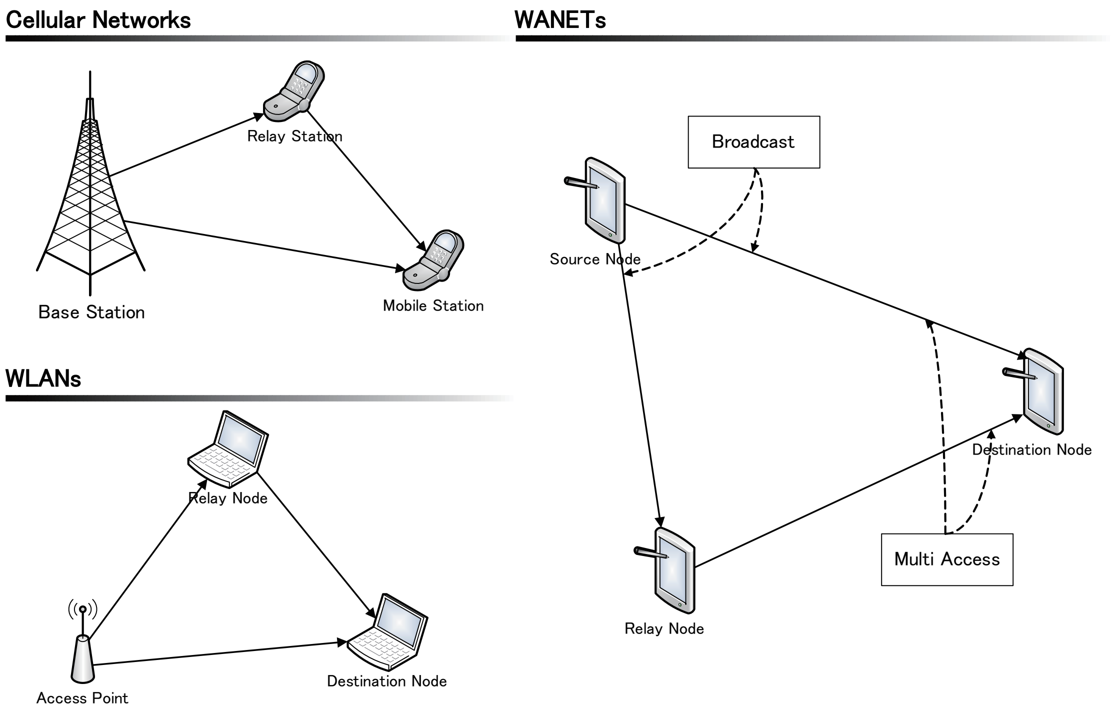

FIGURE 2.6: Applications of cooperative communications in wireless networks.

2.3.1 Cooperative Transmission Protocols

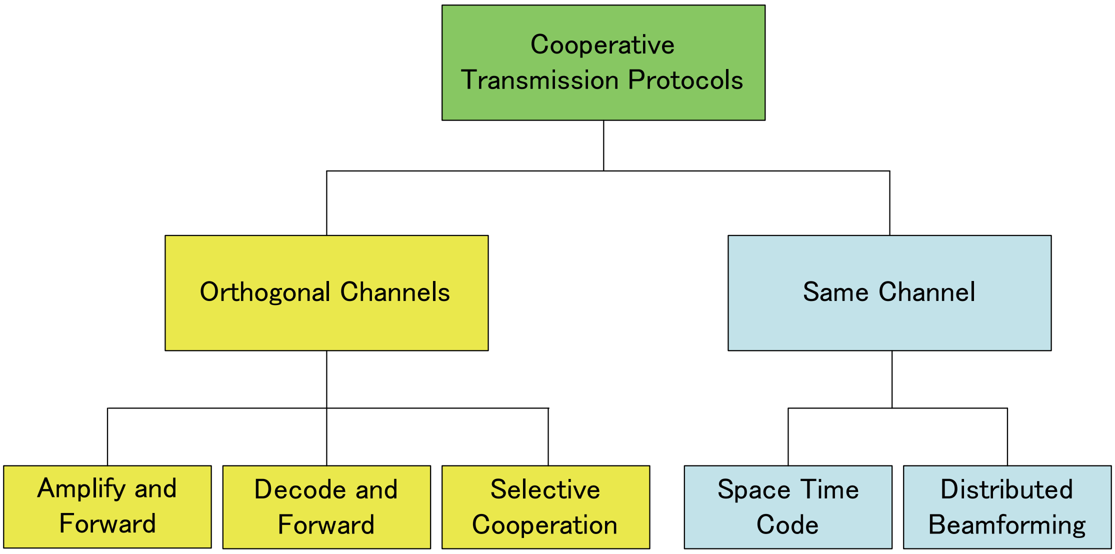

FIGURE 2.7: Classification of cooperative transmission protocols based on channel usage.

As shown in Fig. 2.7, depending on the channels used by the cooperation, there are two types of cooperative transmission protocols in the physical layer: cooperation uses orthogonal channels and cooperation uses same channel.

2.3.1.1 Cooperation via Orthogonal Channels

In this kind of approaches, the cooperative nodes use orthogonal channels to avoid interference among the cooperating signals. The orthogonal channels can be obtained by different time slots, different frequency bands, or different spreading codes. We introduce three basic cooperative transmission protocols in this category as follows.

- *Amplify and forward*

  One simple protocol is the amplify and forward method [39] shown in Fig. 2.8. At the first time slot, the source node transmits the signal to the destination, the relay node receives this signal at the same same. At the next time slot, the relay node simply amplifies the signal received from the source and retransmits it to the destination. The destination node receives two independently faded versions of the signal, and combines them in order to

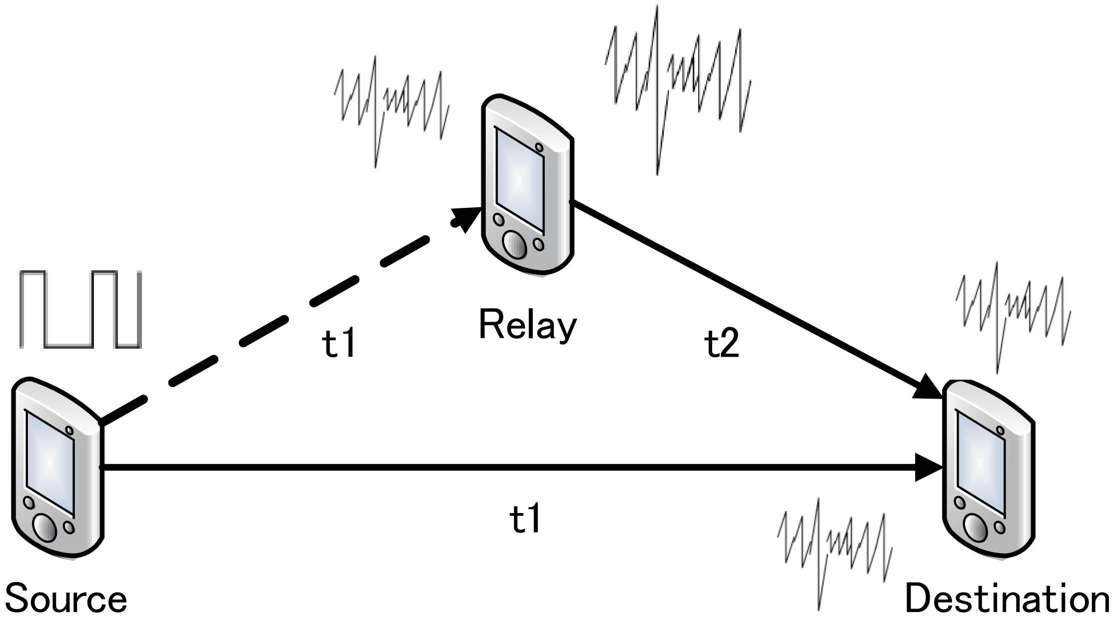

FIGURE 2.8: Amplify and forward.

make better probability to decode the information. The main downfall of this method lies in the fact that noise contained in the signal is amplified at relay node as well.

- *Decode and forward*

  In decode and forward scheme [40], instead of being amplified, the received signal transmitted by the source node is decoded at the relay node. Then, the relay node re-encodes the data and forwards it to the destination node, as shown in Fig. 2.9. It is the most often preferred method to process data in the relay node, since there is no amplified noise in the forwarded signal. However, considerable computing time and resources are required.

- *Selective cooperation*

  In the previous two schemes, a problem exists when the channel from the source node to the relay node is poor. In the amplify and forward method, a low quality signal at the relay node does not help at the destination due to the amplified noise. And a similar situation exists in the decode and forward method, when the relay node cannot decode the signal correctly. To overcome this problem, in selective cooperation method [24], the relay node retransmits the received signal only when it is decoded correctly. However, this scheme requires sharing channel information between the source node and the relay node.

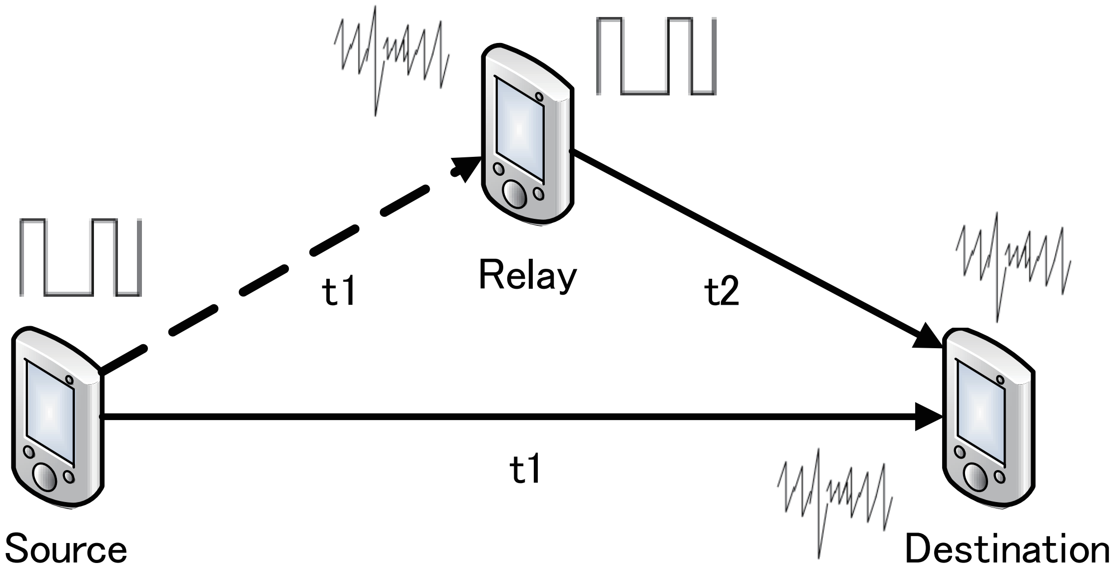

FIGURE 2.9: Decode and forward.

2.3.1.2 Cooperation via Same Channel

The cooperative transmission protocols considered in Section 2.3.1.1 require orthogonal signal dimensions, which result in reduced bandwidth efficiency. In this category, we introduce two kind of cooperative transmission protocols that all relay nodes transmit the same or different signals at the same time through the same channel.

- *Distributed space time code*

  Distributed Space Time Code (STC) is firstly proposed in [23]. As illustrated in Fig. 2.10, in distributed STC, the source node broadcasts the signal at the first time slot, and the STC transmission is performed at the second time slot through multiple relay nodes. As the number of relay nodes increases, however, the design of orthogonal space time block code is difficult and a rate loss is unavoidable.

- *Distributed beamforming*

  The basic idea of distributed beamforming is that the received signals from multiple nodes are summed coherently at the destination by multiplying a proper weight at each relay node [41]. The main issues in distributed beamforming includes phase synchronization [42], and power allocation [43].

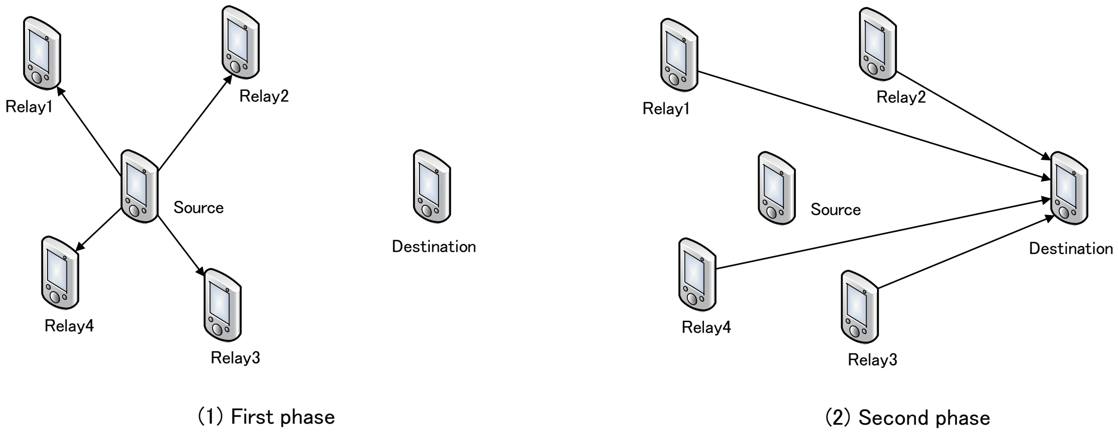

FIGURE 2.10: Cooperative transmission with distributed space time code.

2.3.2 Signal Combining Techniques

Combining techniques are used in the destination node which combine the multiple received signals into a single improved signal. We introduce two representative signal combining schemes as follows.

- *Equal ratio combining*

  Equal Ratio Combining (ERC) is the simplest combing method for signals. All received signals are just added up [44] as

$$y_d(n) = \sum_{i=1}^{k} y_{i,d}(n), \tag{2.4}$$

  where $y_d(n)$ denotes the total signal received at the receiver, and $y_{i,d}(n)$ is the signal from the i^{th} channel. Since the lack of estimation to the channel quality, the performance of ERC is considerably low.

- *Maximal ratio combining*

  Better performance can be achieved if the incoming signals are weighted wisely. In Maximal Ratio Combining (MRC), an approximation of the channel quality is utilized to weight the signal. Specifically, each input signal is multiplied by its corresponding conjugated channel gain [44] as

$$y_d(n) = \sum_{i=1}^{k} h^*_{i,d}(n) y_{i,d}(n), \tag{2.5}$$

where $h^*_{i,d}(n)$ is the approximating channel gain. For MRC, the receiver does not need to have knowledge of the exact channel characteristics, an approximating channel quality is sufficient.

2.4 Cooperative Medium Access Control (CMAC)

Recently, extensive work on CC has been investigated in physical layer, while less attention has been devoted to the Medium Access Control (MAC) layer. However, without considering the MAC layer interactions due to cooperation, the performance of the network may not be improved. Since the communication overhead and collision induced by relaying may affect the performance negatively. An efficient and holistic Cooperative MAC (CMAC) protocol design is indispensable. Many of applications based on IEEE 802.11, 802.15.4 are using contention-based medium access control protocols, i.e., Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA). Thus, in this dissertation, we are particularly interested in CMAC design for contention-based wireless networks.

For CMAC design, there are three important questions we should consider, i.e., when to cooperate, whom to cooperate with, and how to protect the ongoing transmission. Firstly, a source node may not always need the relay node to help the current transmission, i.e., when the channel condition is good or the distance between source and destination is short. Involving the relay node needs additional control overhead and coordination, thus cooperate or not needs to be investigated. Secondly, one or more relay nodes need to be selected among multiple relay candidates in the network. Selecting the best relay node or relay sets in an efficient and distributed way affects the overall performance substantially. Thirdly, as the introducing of the relay node, the interference range of the ongoing transmission becomes more complicated than the point-to-point transmission. Protecting all ongoing transmission sequences against collisions from other nodes in the vicinity is indispensable.

In the context of CMAC, the protocols can generally be divided into two categories: proactive CMAC and reactive CMAC.

2.4.1 Proactive CMAC

The proactive CMAC protocols aim at using the relay nodes to mitigate the throughput bottleneck. They trigger the relay selection process before the direct transmission. Each source node chooses either the direct transmission or the cooperative transmission in order to enhance the throughput. The proactive CMAC schemes [45–49] initiate the relaying when the combined data rates on the source-relay link and relay-destination link is higher than the data rate on the direct link. A shortcoming is that they introduce a constant overhead to all transmissions whatever the cooperative transmission is used or not.

2.4.2 Reactive CMAC

The reactive CMAC protocols devote the cooperation to the retransmission process. The cooperation is initiated only when the direct transmission fails. The reactive CMAC schemes [50–52] utilize the distributed cooperative Automatic Repeat-reQuest (ARQ) to trigger the cooperative retransmission. A disadvantage is that all the potential relay nodes have to listen to the transmission of the source node, which consumes additional energy.

Chapter 3

Transmission Rate Analysis for Reactive CMAC

In wireless communications, there is a dilemma between better reliability and higher data rates. Generally speaking, reliability is inversely proportional to the data rates. Then, the following question has been raised: can we improve data rates without reducing transmission reliability? The answer is yes, and the solution is cooperative communication technique. Recently, the cooperative communication has been employed as an effective technique to combat the effects of channel fading. In this chapter, we address the transmission rate enhancement issue via reactive CMAC in wireless networks. For a given transmitting power level and a desired probability of success, we investigate how much average transmission rate can be increased by reactive CMAC. Moreover, we study the impact of maximal ratio combiner and energy constraint on reactive CMAC. The extensive evaluation results reveal that the average transmission rate can be substantially improved through such adaptive cooperation.

This chapter is organized as follows. Section 3.1 introduces the background and motivation of this work. Section 3.2 presents the system and transmission models. In Section 3.3, we formulate the average transmission rates of direct transmission and cooperative transmission through the typical three-node model. In Section 3.4, we investigate the impact of MRC and energy constraint on adaptive relaying. We show evaluation results in Section 3.5, and finally, conclusion in Section 3.6.

3.1 Introduction

Transmission rate enhancement is one of the fundamental requirements for wireless networks, e.g., Wireless Mesh Networks (WMNs) [53] and Wireless Multimedia Sensor Networks (WMSNs) [54]. For WMNs, the users hope they could download fast and surf the internet smoothly. For WMSNs, the requirement of transmission rate is higher than the traditional wireless sensor networks, specifically, at least one order of magnitude higher data rate may be required [54]. Hence, enhancing the transmission rate becomes one of the primary objectives in the design of such wireless networks.

To improve the transmission rate over wireless links, either the bandwidth, or the spectral efficiency needs to be increased. Multi-Input and Multi-Output (MIMO) technology [55] can drastically increase the spectral efficiency via parallel transmissions over multiple transmitters when the bandwidth is fixed or limited [19]. Implementing multiple antennas on a wireless terminal, unfortunately, might be infeasible due to the cost and space constraints.

Cooperative communication [10] has gained much interest recently as a new design paradigm to make terminals help each other in a distributed fashion so that the same advantages as in MIMO systems can be obtained. The broadcast nature of wireless medium (the so-called wireless broadcast advantage) is exploited in cooperative fashion. The wireless transmission between a pair of terminals can be received and processed at other terminals for a performance gain, rather than be considered as the interference traditionally. Specifically, the relay nodes help the source node forward its information to the destination node. Thus, the destination node receives several replicas of the same information via different independent channels, which can significantly mitigate the effects of channel fading and achieve the diversity gain.

Cooperative Medium Access Control (CMAC) schemes can be generally categorized into proactive CMAC and reactive CMAC [24]. Proactive CMAC schemes include fixed Amplify-and-Forward (AF) and fixed Decode-and-Forward (DF) protocols. They are different from the process at the relay node. In fixed AF, the relay node simply amplifies the analogy signal and forwards it to the destination node. In fixed DF, the relay node decodes the received signal, re-encodes it and then transmits it to the destination node. Although fixed DF has the advantage over AF in reducing the additive noise, it may forward erroneous signals to the destination. Note that fixed relaying schemes are easy to implement but the bandwidth efficiency is low.

The reason is that half of the channel resources are allocated to the relay node, which leads to the reduction of the average transmission rate. To overcome this disadvantage, two reactive CMAC schemes are proposed in [24]. One is selection relaying, which applies a threshold test on the channel state to decide whether to cooperate or not. Another is incremental relaying, which employs the feedback from the destination in the form of ACKnowledgement (ACK) and Negative ACK (NACK). In this chapter, we focus on the reactive CMAC, and in the remainder of this chapter, the incremental relaying is utilized as the cooperative transmission scheme.

Lately, cooperative communication has attracted a lot of attention for its potential to increase spatial diversity. In [35, 36, 56–58], relay selection and assignment issues both in one-hop and multi-hop scenarios are studied. Optimal power allocation and energy efficiency of cooperation systems are investigated in [59] and [30], respectively. In addition, the coverage expansion issue for cooperative networks has been explored in [33], and the cooperative routing algorithms have been proposed in [60, 61].

The previous work mainly focus on the diversity gain or the reduction of average transmitting power through cooperation. The efficient transmission rate of cooperative communication (especially of by reactive CMAC), however, has not been well addressed yet. In this chapter, we explore the average transmission rate enhancement issue via reactive CMAC. In addition, the impact of Maximal Ratio Combiner (MRC) and energy constraint on reactive CMAC are analyzed. The performance metric for comparison is the average transmission rate which is measured by bits per second per hertz (b/s/Hz).

We summarize our contributions as follows.

- We derive a closed-form expression of the average transmission rate for reactive CMAC under a given probability of success.
- We investigate the impact of MRC and energy constraint on reactive CMAC in wireless networks.
- Our numerical results reveal that the average transmission rate can be substantially improved by adaptive cooperation under general scenarios.

3.2 System and Transmission Models

We consider a scenario that consists of one source-destination pair and a single potential relay as depicted in Fig. 3.1. In practice, a terminal cannot listen and transmit signals simultaneously, which will cause severe interference. Thus, a half-duplex constraint is assumed. We consider the link between any two terminals is subject to narrowband Rayleigh fading, and the noise components are modeled as Additive White Gaussian Noise (AWGN). Moreover, we assume that the fading of different channels are mutually independent, since the terminals are usually well separated.

Traditionally, Direct Transmission (DT) is widely used for the wireless communication. As we mentioned above, Cooperative Transmission (CT) becomes more and more popular nowadays. Thus, in this chapter, we focus on the average transmission rates of DT and CT under a desirable probability of success and a certain level of transmitting power.

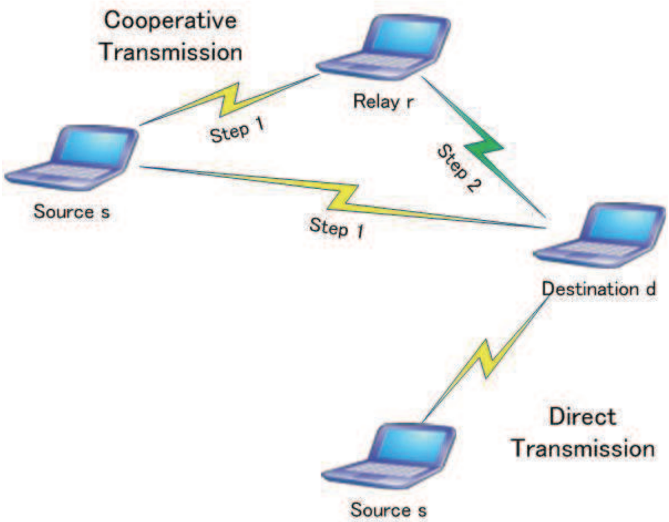

FIGURE 3.1: A simple scenario comprises of one source-destination pair and a single relay node.

For traditional DT, the signal received at the destination node d from source node s is given by [30] as

$$y_{sd} = \sqrt{Pd_{sd}^{-\alpha}}h_{sd}x + n_{sd}, \tag{3.1}$$

where P is the transmitting power, x is the transmitted data with unit power, d_{sd} is the distance between the source node and the destination node, α is the path loss exponent (generally from 2 to 4 according to the channel conditions), h_{sd} is the channel fading gain between two terminals and n_{sd} is the additive noise.

For CT, as aforementioned, the incremental relaying scheme proposed in [24] is employed in this chapter. Suppose that at the current time slot, the source node sends its data to the destination node. Due to the broadcast nature of the wireless medium, the relay node r can overhear this signal. The signal received at the destination node is given in Eqn. (3.1) and the signal received at the relay node is

$$y_{sr} = \sqrt{Pd_{sr}^{-\alpha}} h_{sr} x + n_{sr}. \tag{3.2}$$

Depending on the reception at the destination node, there exist two cases for the following processes. Case (i), the destination node is able to decode the signal correctly. It sends an ACK frame back to the source node. The source node handles the new data in queue at the next time slot, and the relay node keeps idle. Case (ii), the destination node cannot decode the signal correctly. It broadcasts a NACK frame. The relay node re-encodes the source's data and retransmits it on behalf of the source at the next time slot. The signal received at the destination node from the relay node in the second time slot is

$$y_{rd} = \sqrt{Pd_{rd}^{-\alpha}} h_{rd} x + n_{rd}. \tag{3.3}$$

According to the processing performed at the destination node, CT with no-MRC and CT with MRC can be considered separately. For CT with no-MRC scheme, the destination node only uses the relay's signal for decoding. For CT with MRC scheme, in the analog domain, the destination node coherently combines the two copies of the data x, i.e., y_{sd} from the source and y_{rd} from the relay, as follows [30]

$$y_d = a_{sd} y_{sd} + a_{rd} y_{rd}, \tag{3.4}$$

where $a_{sd} = \sqrt{Pd_{sd}^{-\alpha}} h_{sd}^*$ and $a_{rd} = \sqrt{Pd_{rd}^{-\alpha}} h_{rd}^*$.

The CT model can provide the spatial diversity because the source's signal can be transmitted by two independent channels, which implies that if one channel encounters a deep fading or strong shadowing, the signal can be transmitted by another one.

3.3 Transmission Rate Enhancement via Reactive CMAC

In this section, we compare cooperative transmission (i.e., adaptive relaying) with direct transmission, and derive their achievable average transmission rates under the same probability of success.

3.3.1 Direct Transmission (DT)

In information theory, the mutual information of two random variables is defined as a quantity that measures the mutual dependence of the two variables. For DT, the mutual information between source s and destination d is formulated by

$$I_{sd} = \log_2\left(1 + \frac{Pd_{sd}^{-\alpha}\,|h_{sd}|^2}{N_0}\right), \tag{3.5}$$

where $\frac{Pd_{sd}^{-\alpha}|h_{sd}|^2}{N_0}$ is the Signal-to-Noise Ratio (SNR). Note that in Eqn. (3.5), without loss of generality, the unit bandwidth is assumed and the noise components are modeled as AWGN with variance N_0.

Outage event is defined as the set of channel realizations that cannot support reliable transmission rate R. And outage probability is calculated as the one associated with the outage event, specifically, the probability that the mutual information is less than the transmission rate R. Thus, the outage probability in DT is calculated as

$$\mathcal{P}_D^O = \mathcal{P}\left(I_{sd} < R_D\right), \tag{3.6}$$

where R_D denotes the reliable transmission rate for DT. Substituting Eqn. (3.5) into Eqn. (3.6), we obtain

$$\mathcal{P}_D^O = \mathcal{P}\left(|h_{sd}|^2 < \frac{\left(2^{R_D} - 1\right) N_0 d_{sd}^{\alpha}}{P}\right). \tag{3.7}$$

We assume that the channel coefficient h_{sd} follows the Gaussian zero mean distribution, thus $|h_{sd}|^2$ can be modeled as the exponential random variable. Utilizing the probability density function of $|h_{sd}|^2$, Eqn. (3.7) is converted to

$$\begin{aligned}\mathcal{P}_D^O &= \int_0^{(2^{R_D}-1)N_0 d_{sd}^{\alpha}/P} \exp\left(-|h_{sd}|^2\right) d\left(|h_{sd}|^2\right) \\ &= 1 - \exp\left(-\frac{\left(2^{R_D}-1\right) N_0 d_{sd}^{\alpha}}{P}\right).\end{aligned} \tag{3.8}$$

In order to meet a desired probability of success $\mathcal{P}_D^S$, which is equal to $1-\mathcal{P}_D^O$, the achievable transmission rate in DT is expressed as

$$R_D = \log_2\left(1 - \frac{P\ln\left(\mathcal{P}_D^S\right)}{N_0 d_{sd}^{\alpha}}\right). \tag{3.9}$$

3.3.2 Cooperative Transmission (CT)

In this subsection, we derive the average transmission rate of the CT with no-MRC, in which the destination node only uses the signal received from the relay to decode when the direct transmission is failed.

The outage probability for CT with no-MRC is given by

$$\begin{aligned}\mathcal{P}_C^O &= \mathcal{P}(I_{sd} < R_C)\mathcal{P}(I_{sr} < R_C) \\ &\quad + \mathcal{P}(I_{sd} < R_C)(1 - \mathcal{P}(I_{sr} < R_C))\mathcal{P}(I_{rd} < R_C),\end{aligned} \tag{3.10}$$

where R_C is the transmission rate at each time slot for CT with no-MRC. In Eqn. (3.10), the first term corresponds to the case that both the source-destination and the source-relay channels are in outage, and the second term corresponds to the case that the source-destination and relay-destination channels are in outage but the source-relay channel is not. Then, we can derive and simplify the probability of success in CT with no-MRC as

$$\begin{aligned}\mathcal{P}_C^S &= 1 - \mathcal{P}_C^O \\ &= \exp\left(-\lambda_C d_{sd}^{\alpha}\right) + \exp\left(-\lambda_C\left(d_{sr}^{\alpha} + d_{rd}^{\alpha}\right)\right) \\ &\quad - \exp\left(-\lambda_C\left(d_{sd}^{\alpha} + d_{sr}^{\alpha} + d_{rd}^{\alpha}\right)\right),\end{aligned} \tag{3.11}$$

where

$$\lambda_C = \frac{\left(2^{R_C} - 1\right) N_0}{P}. \tag{3.12}$$

Approximating the exponential function above as $\exp(-x) \approx 1 - x + x^2/2$, Eqn. (3.11) can be simplified to

$$\mathcal{P}_C^S \approx 1 - \left(d_{sd}^{\alpha} d_{sr}^{\alpha} + d_{sd}^{\alpha} d_{rd}^{\alpha}\right) \lambda_C^2. \tag{3.13}$$

Thus, R_C is expressed as

$$R_C \approx \log_2\left(\frac{P}{N_0}\sqrt{\frac{1 - \mathcal{P}_C^S}{d_{sd}^{\alpha} d_{sr}^{\alpha} + d_{sd}^{\alpha} d_{rd}^{\alpha}}} + 1\right). \tag{3.14}$$

In order to obtain the average transmission rate for CT with no-MRC, we should calculate the probability that the source node transmits only, which is

$$\mathcal{P}(\Omega) = 1 - \mathcal{P}\left(I_{sd} < R_C\right) + \mathcal{P}(I_{sd} < R_C)\mathcal{P}(I_{sr} < R_C). \tag{3.15}$$

Using $\mathcal{P}(\Omega)$, the average transmission rate for CT with no-MRC is obtained by

$$\begin{aligned} \overline{R_C} &= R_C \mathcal{P}(\Omega) + \frac{R_C}{2}\left(1 - \mathcal{P}(\Omega)\right) \\ &\approx \tfrac{1}{2}\log_2\left(\lambda_C \tfrac{P}{N_0} + 1\right) \\ &\quad \left(2 - \exp\left(-\lambda_C d_{sr}^{\alpha}\right) + \exp\left(-\lambda_C\left(d_{sr}^{\alpha} + d_{sd}^{\alpha}\right)\right)\right), \end{aligned} \tag{3.16}$$

where

$$\lambda_C = \sqrt{\frac{1 - \mathcal{P}_C^S}{d_{sd}^{\alpha} d_{sr}^{\alpha} + d_{sd}^{\alpha} d_{rd}^{\alpha}}}. \tag{3.17}$$

In Eqn. (3.16), the first term corresponds to the case that the source node transmits only, which occupies one time slot. And the second term corresponds to the case that the relay node cooperates with the source node, which occupies two time slots, thus the transmission rate decreases to $R_C/2$.

3.4 The Impact of MRC and Energy Constraint on Reactive CMAC

In this section, we elaborate the impact of MRC and energy constraint on cooperative communication (i.e., adaptive relaying).

3.4.1 Cooperative Transmission with MRC

In CT with MRC, the destination node combines the two signals that received from the source node and from the relay node together, to obtain a resulting signal with better probability to successful decoding.

In CT with MRC, the instantaneous mutual information at destination node is

$$I_d = \log_2\left(1 + \frac{P d_{sd}^{-\alpha} |h_{sd}|^2 + P d_{rd}^{-\alpha} |h_{rd}|^2}{N_0}\right). \tag{3.18}$$

The outage probability of CT with MRC is calculated by

$$\begin{aligned} \mathcal{P}_M^O = & [\mathcal{P}(I_{sr} < R_M) + (1 - \mathcal{P}(I_{sr} < R_M)) \\ & \mathcal{P}(I_d < R_M \mid I_{sd} < R_M)] \cdot \mathcal{P}(I_{sd} < R_M), \end{aligned} \tag{3.19}$$

where R_M is the transmission rate at each timeslot for CT with MRC. Within the square brackets of Eqn. (3.19), the first term $\mathcal{P}(I_{sr} \leq R_M)$ corresponds to the case that the source-relay channel is in outage, the second term corresponds to the case that the source-relay channel is not in outage, but the output of the MRC cannot support the reliable transmission rate R_M, in which the outage also occurs. We add the above two terms together because they are exclusive events. After some mathematical manipulation, the probability of success can be expressed as

$$\begin{aligned} \mathcal{P}_M^S = & \exp\left(-\lambda_M d_{sd}^{\alpha}\right) + \frac{d_{sd}^{\alpha}}{d_{sd}^{\alpha} - d_{rd}^{\alpha}} \\ & \left(\exp\left(-\lambda_M\left(d_{sr}^{\alpha} + d_{rd}^{\alpha}\right)\right) - \exp\left(-\lambda_M\left(d_{sr}^{\alpha} + d_{sd}^{\alpha}\right)\right)\right), \end{aligned} \tag{3.20}$$

where

$$\lambda_M = \frac{\left(2^{R_M} - 1\right) N_0}{P}. \tag{3.21}$$

Using the same approximate function, Eqn. (3.20) is simplified to

$$\mathcal{P}_M^S \approx 1 - \frac{2d_{sd}^\alpha d_{sr}^\alpha + d_{sd}^\alpha d_{rd}^\alpha}{2}\lambda_M^2. \tag{3.22}$$

Thus R_M is expressed as

$$R_M \approx \log_2\left(\frac{P}{N_0}\sqrt{\frac{2\left(1-\mathcal{P}_M^S\right)}{2d_{sd}^\alpha d_{sr}^\alpha + d_{sd}^\alpha d_{rd}^\alpha}} + 1\right). \tag{3.23}$$

Finally, similar to Eqn. (3.16), the average transmission rate for CT with MRC is expressed as

$$\begin{aligned}\overline{R_M} &\approx \tfrac{1}{2}\log_2\left(\lambda_M \tfrac{P}{N_0} + 1\right)\\ &\left(2 - \exp\left(-\lambda_M d_{sr}^\alpha\right) + \exp\left(-\lambda_M\left(d_{sr}^\alpha + d_{sd}^\alpha\right)\right)\right),\end{aligned} \tag{3.24}$$

where

$$\lambda_M = \sqrt{\frac{2\left(1-\mathcal{P}_M^S\right)}{2d_{sd}^\alpha d_{sr}^\alpha + d_{sd}^\alpha d_{rd}^\alpha}}. \tag{3.25}$$

Comparing Eqn. (3.14) with Eqn. (3.23), we can observe that under the same desirable probability of success, R_M always performs better than R_C. However, from Eqn. (3.16) and Eqn. (3.24), it is hard to tell that $\overline{R_M}$ strictly dominates $\overline{R_C}$.

3.4.2 Cooperative Transmission with Energy Constraint

All the previous analysis is based on the assumption that the terminals (including the source node and relay node) transmit the data with maximum transmitting power P. However, in some kinds of wireless networks, e.g., WMSNs, energy is still a scare resource since the wireless devices are battery powered. Thus, in this subsection, we derive the average transmission rates of CT while keeping the total transmitting power of DT and CT in the same level, i.e., no more energy is consumed due to the relaying in CT.

To keep the total energy consumption of CT and DT in the same level, the following constraint must be satisfied.

$$P = P_s\mathcal{P}(\Omega) + (P_s + P_r)(1 - \mathcal{P}(\Omega)), \tag{3.26}$$

where P is the transmitting power at the source node in DT, P_s and P_r are the transmitting power at the source node and relay node in CT, respectively. $\mathcal{P}(\Omega)$ is the probability that the source node transmits only, which is given in Eqn. (3.15).

To simplify this issue, we assume the transmitting power at the source node is equal to the one at the relay node in CT, i.e., $P_s = P_r = P'$. Then, from Eqn. (3.26), the transmitting power used in CT is calculated as

$$P' = \frac{P}{2 - \mathcal{P}(\Omega)}. \tag{3.27}$$

Replacing P of Eqn. (3.16) with P', we can obtain the average transmission rate of CT with energy constraint. The results in Section 3.5 reveal that the average transmission rate of CT with energy constraint still has a substantial increase compared to DT.

3.5 Evaluation Results

In this section, we evaluate the reactive CMAC by considering the impact of MRC and energy constraint. The evaluation metric in this chapter is the average transmission rate. Note that there are various system parameters that can affect the performance, among which are the transmitting power, the distance between source and destination, the position of the relay node and the required probability of success. In order to study the effect of each of these parameters, we investigate the performance by varying one of these parameters and fixing the rests. In all the evaluations, the noise power and path loss exponent are fixed as $N_0 = -80$ dBm and $\alpha = 4$.

3.5.1 DT, CT with no-MRC and CT with MRC

We first present the evaluation results of the average transmission rate enhancement via cooperative transmission with and without MRC.

Recall the average transmission rate expression in Eqn. (3.16) and Eqn. (3.24), it is straightforward that for any d_{rd}, the minimum d_{sr} is optimal. This means the optimal position of the relay node lies on the straight line connecting the source and destination. Fig. 3.2 depicts the results of the average transmission rate versus the position of the relay node when setting the transmitting power at -10 dBm, distance of source-destination at 20 m, outage probability at

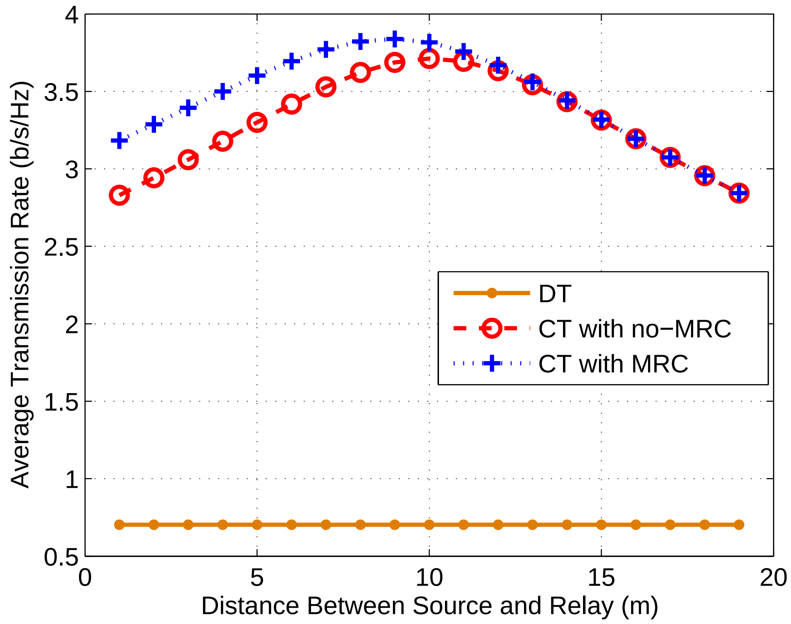

FIGURE 3.2: DT, CT with no-MRC and CT with MRC: average transmission rate versus the position of relay

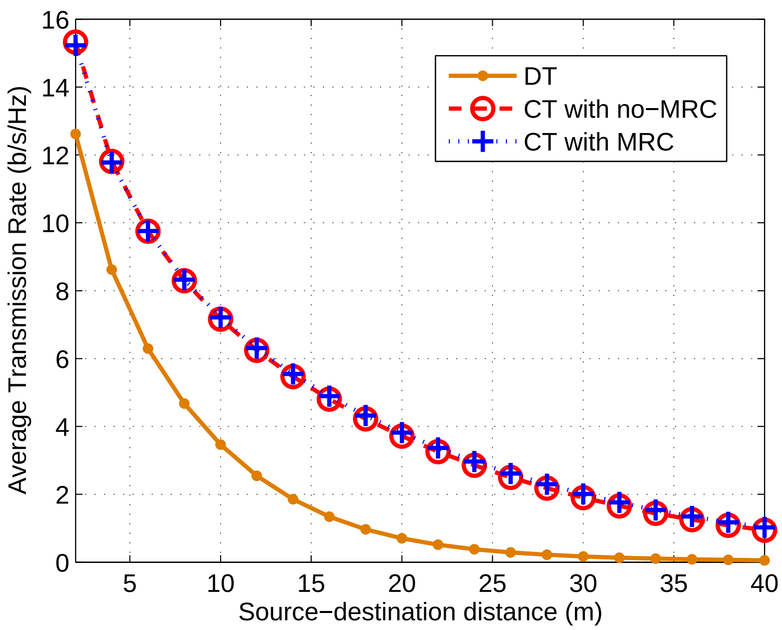

FIGURE 3.3: DT, CT with no-MRC and CT with MRC: average transmission rate versus the distance between source and destination

1%. The relay node locates at the line connecting the source and destination, and moves from the source node towards the destination node. From this figure, it is clear that CT can enhance the average transmission rate up to nearly 550% compared with DT. By varying the position of the relay node, the plotted curves reveal that when $d_{sr} \leq 10m$, CT with MRC performs much better than CT with no-MRC. However at $d_{sr} > 10m$, the two schemes have no much difference. It means that for CT with MRC, the optimal position of the relay node is closer to the source node than to the destination node.

Next, we vary the distance between the source node and the destination node from 2 m to 40 m while fixing the position of relay node at the middle of the line connecting the source and destination. Fig. 3.3 shows that the further the distance between source and destination, the more performance gain we can obtain through CT, e.g., 20% enhancement for d_{sd} = 2 m, and 1100% enhancement for d_{sd} = 30 m. However, the difference between CT with no-MRC and CT with MRC is negligible. Thus, we raise a question: is it necessary to use the MRC to enhance the average data transmission rate when we utilizing the adaptive relaying? As we know, MRC needs additional hardware requirements to maximize the overall SNR. Specifically, MRC requires a coherent detector that has the knowledge of all the channel coefficients. Moreover, it requires the destination node to store an analog version of the signal from the source node, which costs storage capacity. Unfortunately, as the figure shows, the performance gain through MRC in reactive CMAC is limited.

Finally, in Figs. 3.4 and 3.5, we study the effect of changing the outage probability from 10^{-1} to 10^{-5} and changing the transmitting power from −20 dBm to −10 dBm, respectively. The distance between the source node and the destination node is fixed at 20 m, the position of the relay node is located at the midpoint of the source-destination pair. It can be seen that through reactive CMAC, around 1 ∼ 3 b/s/Hz average transmission rate can be increased.

3.5.2 DT, CT without energy constraint and CT with energy constraint

In this subsection, we present the evaluation results of the impact of energy constraint on average transmission rate of CT.

Fig. 3.6 depicts the average transmission rates of DT, CT without and with energy constraint when we vary the position of the relay node. The setting used in Fig. 3.6 is the same as in

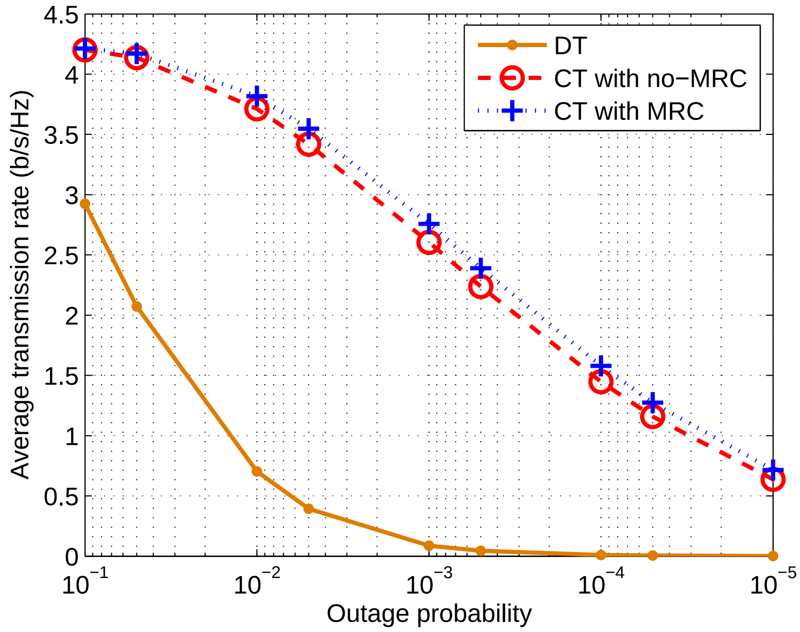

FIGURE 3.4: DT, CT with no-MRC and CT with MRC: average transmission rate versus the outage probability

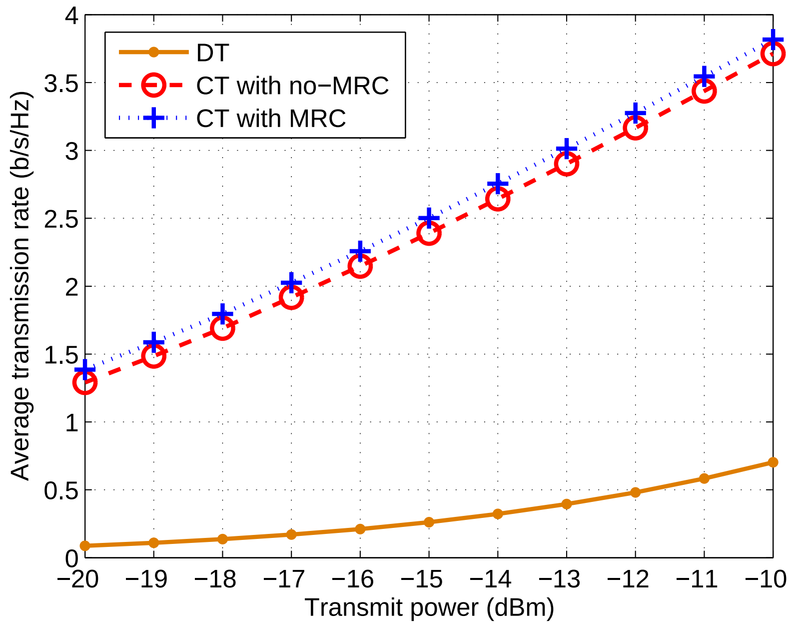

FIGURE 3.5: DT, CT with no-MRC and CT with MRC: average transmission rate versus the transmitting power

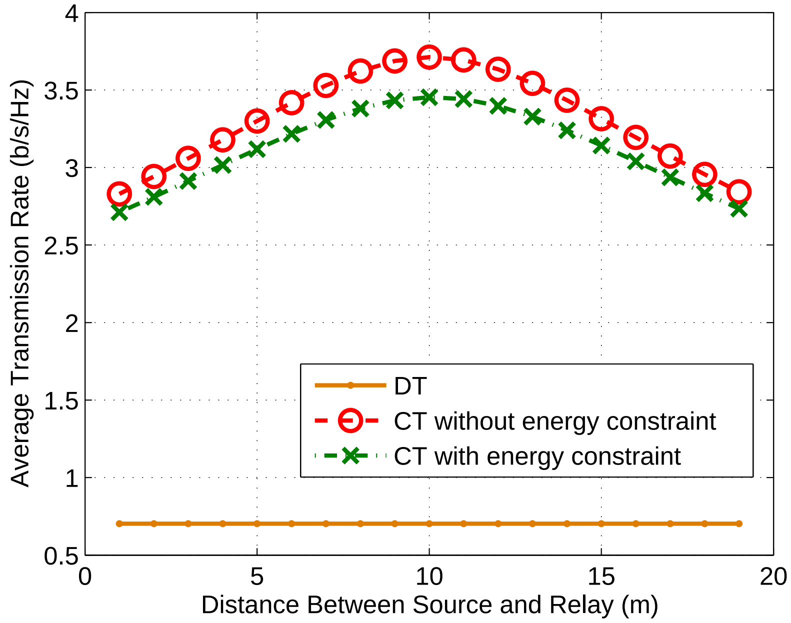

FIGURE 3.6: DT, CT without energy constraint and CT with energy constraint: average transmission rate versus the position of relay

Fig. 3.2. From the figure, we observe that much more gain on average transmission rate can be achieved through maximum transmitting power when the relay node locates near the midpoint of the source-destination pair. And the impact of energy constraint becomes comparatively small when the relay node moves toward the source node or the destination node.

In Fig. 3.7, we show the average transmission rate varying with the outage probability. The plotted curves reveal that the reduction of average transmission rate due to energy constraint is obvious when the desired outage probability is comparatively large, i.e., 11% reduction on outage probability 0.1. And the impact of energy constraint becomes minor as the outage probability decreases.

At last, in Figs. 3.8 and 3.9, we change the distance of source-destination pair from 2 m to 40 m, and the transmitting power from −20 dBm to −10 dBm, respectively. We observe that the average transmission rate of CT with energy constraint only has a limited reduction compared with the one of CT without energy constraint. Those evaluation results reveal that the average transmission rate can be enhanced via adaptive relaying even taking the energy constraint into account.

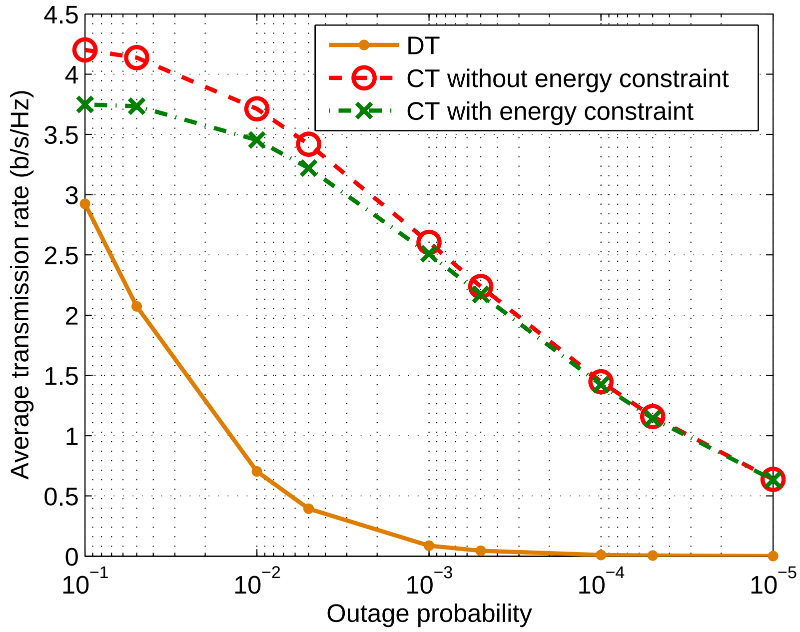

FIGURE 3.7: DT, CT without energy constraint and CT with energy constraint: average transmission rate versus the outage probability

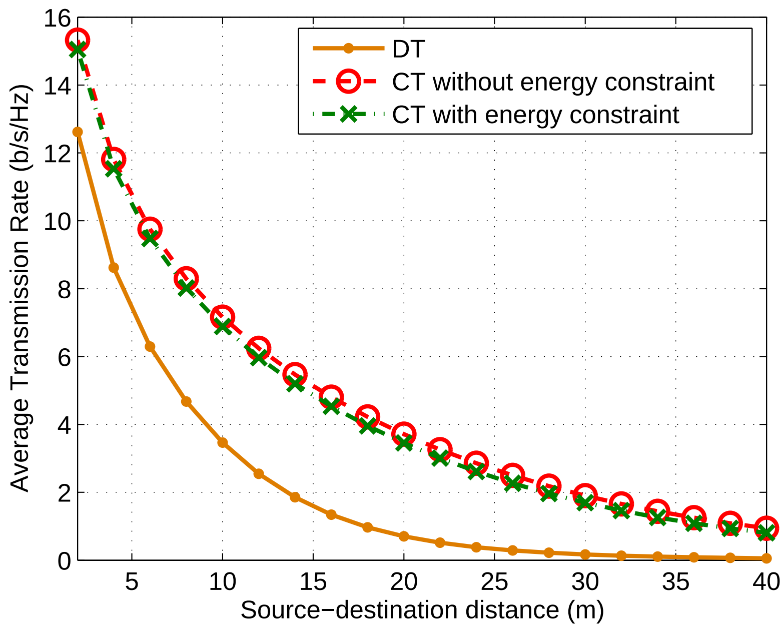

FIGURE 3.8: DT, CT without energy constraint and CT with energy constraint: average transmission rate versus the distance between source and destination

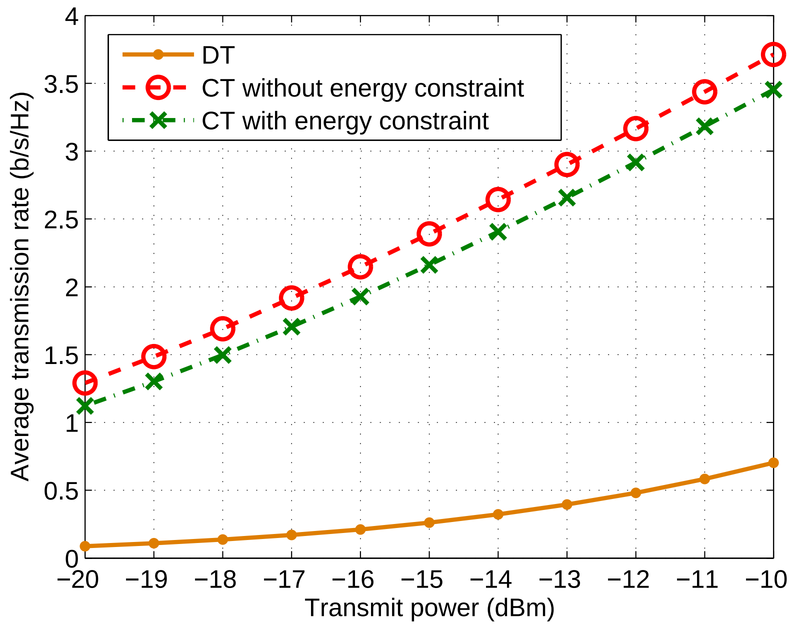

FIGURE 3.9: DT, CT without energy constraint and CT with energy constraint: average transmission rate versus the transmitting power

3.6 Summary

In this chapter, we have addressed the transmission rate enhancement issue in reactive CMAC for wireless networks. For a given probability of success, we formulate the average transmission rate for DT and CT. In addition, we have studied the impact of MRC and energy constraint on average transmission rate. Our evaluation results reveal that CT can enhance the average transmission rate substantially, e.g., around 1 $\sim$ 3 b/s/Hz can be increased when the source-destination distance is 20 m. We also show that the benefit brought from MRC is limited in reactive CMAC, and the average transmission rate can be improved even when the energy constraint is taken into account.

Chapter 4

Improving the Network Lifetime of WANETs through CMAC Design

In this chapter we aim at extending the network lifetime of Wireless Ad-hoc NETworks (WANETs) via cooperative communication. To deal with the complicated medium access interactions induced by relaying and leverage the benefits of such cooperation, an efficient Cooperative Medium Access Control (CMAC) protocol is needed. We propose a novel cross-layer Distributed Energy-adaptive Location-based CMAC protocol, namely DEL-CMAC, for WANETs. The design objective of DEL-CMAC is to improve the performance of the WANETs in terms of network lifetime and energy efficiency. A practical energy consumption model is utilized in this work, which takes the energy consumption on both transceiver circuitry and transmit amplifier into account. A distributed utility-based best relay selection strategy is incorporated, which selects the best relay based on location information and residual energy. Furthermore, with the purpose of enhancing the spatial reuse, an innovative network allocation vector setting is provided to deal with the varying transmitting power of the source and relay terminals. We show that the proposed DEL-CMAC significantly prolongs the network lifetime under various circumstances even for high circuitry energy consumption cases by comprehensive simulation study.

This chapter is organized as follows. We introduce the related work and our motivation in Section 4.1. We present preliminaries and model in Section 4.2. In Section 4.3, we describe the proposed DEL-CMAC protocol. In Section 4.4, we further elaborate the detail of the DEL-CMAC, including the best relay selection strategy, the cross-layer power allocation scheme and the NAV setting. Simulation results and discussions are addressed in Section 4.5. Conclusions are drawn in Section 4.6.

4.1 Introduction

A Wireless Ad-hoc NETwork (WANET) is a self-configured network of terminals connected by wireless links. Wireless terminals such as cell phones, portable gaming devices, PDAs (Personal Digital Assistants) and tablets all have wireless networking capabilities. By participating in WANETs, these terminals may reach the Internet when they are not in the range of Wi-Fi access points or cellular base stations, or communicate with each other when no networking infrastructure is available. This is why the future cellular systems have started considering taking WANET mode into their design, formed the so-called multi-hop cellular networks [62]. WANETs can also be utilized in the disaster rescue and recovery described in [63]. One primary issue with continuous participation in WANETs is the network lifetime, because the aforementioned wireless terminals are battery powered, and energy is a scarce resource.

Cooperative Communication (CC) [10] is a promising technique for conserving the energy consumption in WANETs. The broadcast nature of the wireless medium (the so-called wireless broadcast advantage) is exploited in cooperative fashion. The wireless transmission between a pair of terminals can be received and processed at other terminals for performance gain, rather than be considered as an interference traditionally. CC can provide gains in terms of the required transmitting power due to the spatial diversity achieved via user cooperation. However, if we take into account the extra processing and receiving energy consumption required for cooperation, CC is not always energy efficient compared to direct transmission. There is a tradeoff between the gains in transmitting power and the losses in extra energy consumption overhead.

CC has been researched extensively from the information theoretic perspective [10, 23, 24, 32, 34] and on the issues of relay selection [35–38, 56]. Recently, the work on CC with regard to cross-layer design by considering cooperation in both physical layer and MAC layer attracts more and more attention. Without considering the MAC layer interactions and signaling overhead due to cooperation, the performance gain through physical layer cooperation may not improve end-to-end performance.

Cooperative MAC (CMAC) protocol considering the practical aspect of CC is vital. Liu *et al.* have proposed a CMAC protocols named CoopMAC [45] to exploit the multi-rate capability and aimed at mitigating the throughput bottleneck caused by the low data rate nodes, so that the throughput can be increased. With the similar goal, Zhu *et al.* [46] have proposed a CMAC protocol for wireless ad hoc network. However, beneficial cooperation considering signaling overhead is not addressed in [45] and [46]. A busy-tone-based cross-layer CMAC protocol [64] has been designed to use busy tones to help avoiding collisions in the cooperative scenario at the cost on transmitting power, spectrum, and implementation complexity. A reactive network coding aware CMAC protocol has been proposed by Wang *et al.* [15], in which the relay node can forward the data for the source node, while delivering its own data simultaneously. But the network lifetime is not addressed in [15]. A distributed CMAC protocol [65] has been proposed to improve the lifetime of wireless sensor networks, but it is based on the assumption that every node can connect to the base station within one hop, which is impractical for most applications. A CMAC protocol for vehicular networks, particularly for gateway downloading scenarios, has been designed by Zhang *et al.* [50]. A drawback in [50] is that it can only be utilized in the scenario that all the vehicles are interested in the same information. Moreover, Moh *et al.* [47] have designed a CMAC protocol named CD-MAC which lets the relay transmit simultaneously with the source using space-time coding technique. Shan *et al.* [48] have explored a concept of cooperation region, whereby beneficial cooperative transmissions can be identified. However, energy consumption is not evaluated for both of them.

The existing CMAC protocols mainly focus on the throughput enhancement while failing to investigate the energy efficiency or network lifetime. While the works on energy efficiency and network lifetime generally fixate on physical layer [30] or network layer [35]. Our work focuses on the MAC layer, and is distinguished from previous protocols by considering a practical energy model (i.e., energy consumption on both transceiver circuitry and transmit amplifier), with the goal to enhance energy efficiency and extend network lifetime. The tradeoff between the gains promised by cooperation and extra overhead is taken into consideration in the proposed protocol. In addition, in the previous works, very little attention has been paid to the impact brought by varying transmitting power in CC on the interference ranges, since constant transmitting power is generally used. The interference ranges alteration in both space and time will significantly affect the overall network performance. We also address the issue of effective coordination over multiple concurrent cooperative connections with dynamical transmitting power in this chapter.

In this chapter, we propose a novel Distributed Energy-adaptive Location-based CMAC protocol, namely DEL-CMAC, for WANETs. DEL-CMAC is designed based on the IEEE 802.11 Distributed Coordination Function (DCF), which is a widely used standard protocol for most of wireless networks. DEL-CMAC comprises a relay-involved handshaking process, a cross-layer power allocation scheme, a distributed utility-based best relay selection strategy, and an innovative Network Allocation Vector (NAV) setting. From the perspective of information theory, higher diversity gain can be obtained by increasing the number of relay terminals. From a MAC layer point of view, however, more relays lead to the enlarged interference ranges and additional control frame overheads. We employ single relay terminal in this chapter to reduce the additional communication overhead. DEL-CMAC initiates the cooperation proactively, and utilizes the decode and forward protocol [24] in the physical layer. We summarize our contributions as follows.

- We propose DEL-CMAC that focuses on the network lifetime extension, which is a less explored aspects in the related work. By considering the overheads and interference due to cooperation, as well as the energy consumption on both transceiver circuitry and transmit amplifier, DEL-CMAC can significantly prolong the network lifetime.
- A distributed energy-aware location-based best relay selection strategy is incorporated, which is more reasonable for WANETs comparing with the existing schemes based on channel condition.
- For a desired outage probability requirement, a cross-layer optimal transmitting power allocation scheme is designed to conserve the energy while maintaining certain throughput level.
- To deal with the presence of relay terminals and dynamic transmitting power, we provide an innovative NAV setting to avoid the collisions and enhance the spatial reuse.
- Extensive simulation results reveal that DEL-CMAC can significantly extend the network lifetime under various scenarios at the cost of relatively low throughput and delay degradation, compared with IEEE standard DCF and throughput-aimed scheme CoopMAC [45].

4.2 Models and Preliminaries

In this section, we present the employed system and energy models, and the background knowledge about DCF and decode and forward protocol.

4.2.1 System and Energy Models

As shown in Fig. 4.1, a multi-hop WANET with randomly deployed mobile terminals is considered, where all terminals have the capability to relay. To come up with a reasonable system model, we assume that data connections among terminals are randomly generated and the routes are established by running Ad hoc On-demand Distance Vector (AODV) [66], which is a widely used conventional routing protocol for WANETs. There are two types of relay terminals in our network, i.e., routing relay terminals and cooperative relay terminals. In the system model, AODV builds the route in a proactive manner by selecting the routing relay terminals firstly. When a route is established, DEL-CMAC initiates the cooperation in a hop-by-hop manner by selecting the cooperative relay terminals. In this chapter, the *source and destination terminals* are referred to the terminals at MAC layer, and the *relay terminals* indicate the cooperative relay terminals. For convenience, we use term *source*, *relay* and *destination* in the remainder of the chapter to denote the *source terminal, relay terminal and destination terminal* respectively.

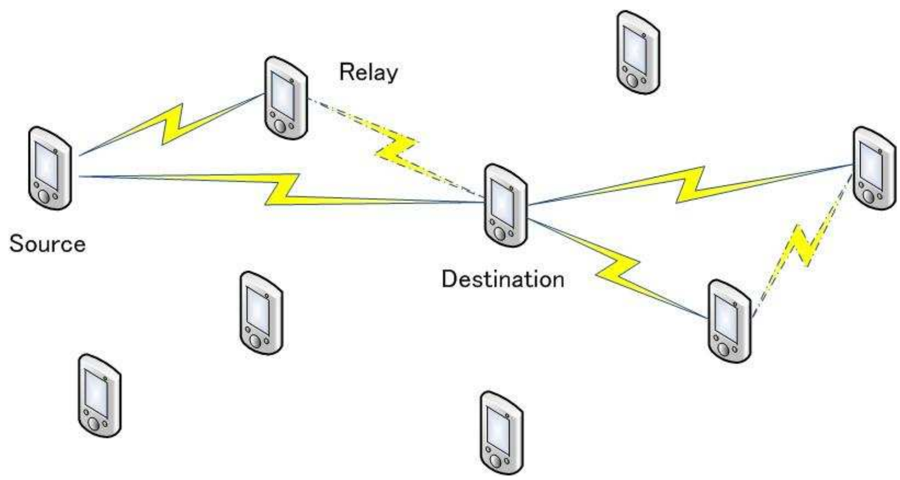

FIGURE 4.1: Multi-hop WANET scenario.

It is reasonable to assume that the energy is consumed both on transmitting and receiving the data, similar energy consumption model is used in previous work, e.g., [67]. To transmit a packet, the energy cost is $C_t = (P+P')T$. And to receive a packet, the energy cost is $C_r = P'T$. P refers to the power consumption at transmit amplifier (also denotes as transmitting power in this chapter), and P' refers to the power consumption at transceiver circuitry. To study the effect of energy consumption on transceiver circuitry, the cases $P'/P = 0.5, 1, 2$ are generally examined. Low P'/P ratio indicates that the energy consumption on transmit amplifier accounts for great proportion of the total energy consumption. And high P'/P ratio indicates the high circuitry energy consumption case.

4.2.2 DCF

The basic operations of the proposed DEL-CMAC are based on the IEEE 802.11 DCF [68] (Distributed Coordination Function). In DCF, after a transmitting terminal senses an idle channel for a duration of Distributed InterFrame Space (DIFS), it backs off for a time period that chosen from 0 to its Contention Window (CW). After the backoff timer expires, the well-known RTS-CTS-DATA-ACK procedure is carried out (Fig. 4.2). Any terminal overhearing either the RTS or the CTS extracts the information contained in the MAC frame header, and sets its NAV to imply the time period during which the channel is busy.

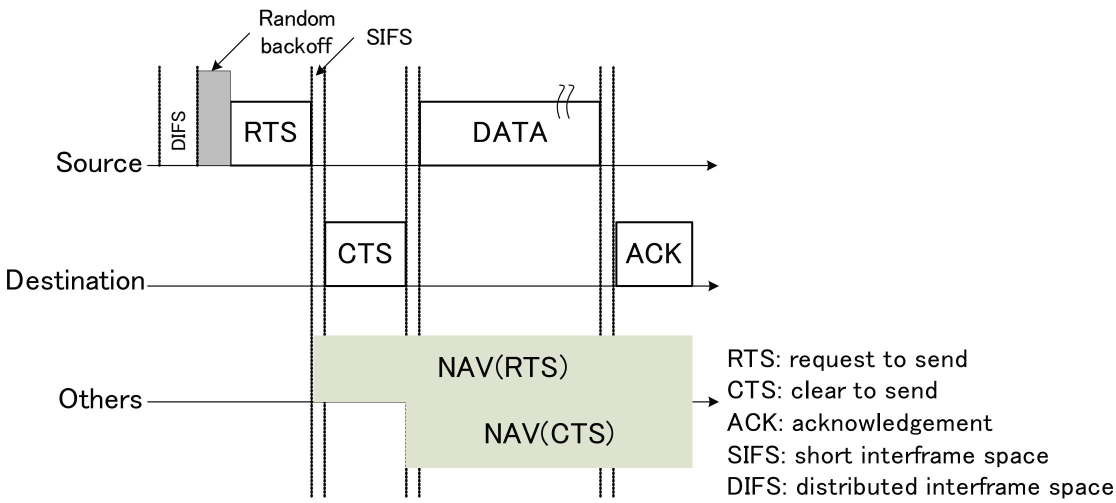

FIGURE 4.2: IEEE 802.11 DCF.

4.2.3 Decode and Forward

DEL-CMAC utilizes the Decode and Forward (DF) protocol [24] with Maximum-Ratio-Combiner (MRC) in the physical layer. The process can be divided into two phases. In the first phase (solid link in Fig. 4.1), the source sends its data to the destination. Due to the broadcast nature of the wireless medium, the relays can overhear this signal. The signals received at the destination and relay, y_{sd} and y_{sr}, are given in Eqns. (4.1) and (4.2), respectively.

$$y_{sd} = \sqrt{P_s d_{sd}^{-\alpha}} h_{sd} x + n_{sd}, \tag{4.1}$$

$$y_{sr} = \sqrt{P_s d_{sr}^{-\alpha}} h_{sr} x + n_{sr}. \tag{4.2}$$

Here, P_s is the transmitting power at the source, x is the transmitted data with unit power, d_{sd} and d_{sr} are respectively the distances of source-destination and source-relay, α is the path loss exponent, h is the channel gain between two terminals and n is the additive noise. In the second phase (dashed link in Fig. 4.1), if the relay can decode this signal, it retransmits the data to the destination; otherwise, it keeps silence. The signal from the relay to the destination, y_{rd}, in the second phase is

$$y_{rd} = I(\sqrt{P_r d_{rd}^{-\alpha}} h_{rd} x + n_{rd}), \tag{4.3}$$

where I is equal to 1 or 0, depending on whether the relay can decode the message correctly or not. In the analog domain, the destination coherently combines y_{sd} transmitted from the source in the first phase and y_{rd} transmitted from the relay in the second phase by MRC as [30]

$$y_d = a_{sd} y_{sd} + a_{rd} y_{rd}, \tag{4.4}$$

where $a_{sd} = \sqrt{P_s d_{sd}^{-\alpha}} h_{sd}^*$ and $a_{rd} = \sqrt{P_r d_{rd}^{-\alpha}} h_{rd}^*$. Comparing with direct transmission, CC with MRC reduces the receiving threshold, which benefits at two folds: (1) The transmission range is extended while the transmitting power is kept constant, (2) The transmitting power is decreased while serving the same transmission range. In this chapter, our DEL-CMAC takes advantage of the second benefit.

4.3 The Proposed DEL-CMAC Protocol

In this section, with the objective of prolonging the network lifetime and increasing the energy efficiency, we present a novel CMAC protocol, namely DEL-CMAC, for multi-hop WANETs. When cooperative relaying is involved, the channel reservation needs to be extended in both space and time in order to coordinate transmissions at the relay. To deal with the relaying and dynamic transmitting power, besides the conventional control frames RTS, CTS and ACK, additional control frames are required. DEL-CMAC introduces two new control frames to facilitate the cooperation, i.e., *Eager-To-Help* (ETH) and *Interference-Indicator* (II). The ETH frame is used for selecting the best relay in a distributed and lightweight manner, which is sent by the winning relay to inform the source, destination and lost relays. In this chapter, the best relay is defined as the relay that has the maximum residual energy and requires the minimum transmitting power among the capable relay candidates. The II frame is utilized to reconfirm the interference range of allocated transmitting power at the winning relay, in order to enhance the spatial reuse. Among all the frames, RTS, CTS, ETH and ACK are transmitted by fixed power. And the transmitting power for the II frame and data packet are dynamically allocated. We denote the time durations for the transmission of RTS, CTS, ETH, ACK and II frames by T_{RTS}, T_{CTS}, T_{ETH}, T_{ACK} and T_{II}, respectively.

4.3.1 Protocol Description

The frame exchanging process of DEL-CMAC is shown in Fig. 4.3. Similar to the IEEE 802.11 DCF protocol, the RTS/CTS handshake is used to reserve the channel at first. As we know, the cooperative transmission is not necessary in the case that the transmitting power is small [69], because the additional overhead for coordinating the relaying overtakes the energy saving from diversity gain. Those inefficient cases are avoided by introducing a transmitting power threshold Λ_p. In DEL-CMAC, upon receiving the RTS frame, the destination computes the required transmitting power for the direct transmission P_s^D (given in Section 4.4.2). There are two cases depending on the calculated P_s^D.

- *Case (i)*: $P_s^D \leq \Lambda_p$. The destination sends a CTS frame with flag field (FLAG_P) equal to 0, which implies that the direct transmission is adequate. Thus, when the transmitting

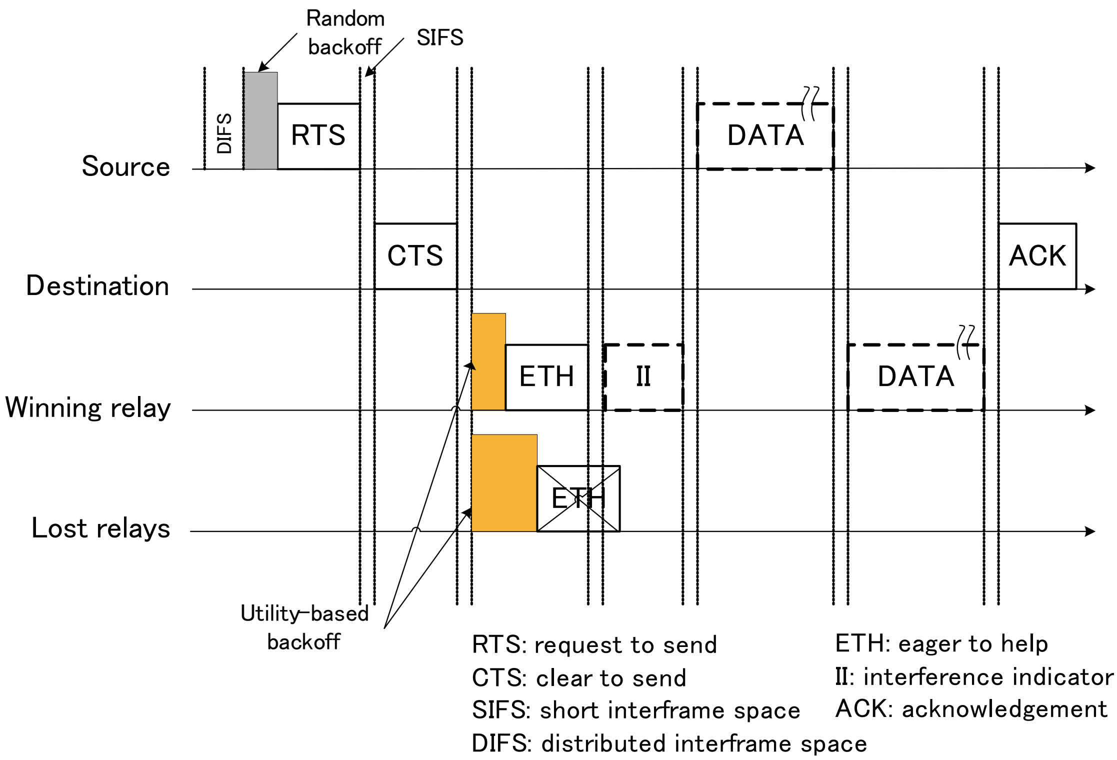

FIGURE 4.3: The frame exchanging process of DEL-CMAC.

power for the direct transmission is sufficiently low, DEL-CMAC is reduced to the DCF protocol and thus has backward compatibility with the legacy 802.11 standard.

- *Case (ii)*: $P_s^D > \Lambda_p$. FLAG_P in the CTS frame is set to 1, which indicates that the cooperative relaying is desired. All the terminals having overheard RTS and CTS, and not interfere with other ongoing transmissions are considered as the relay candidates. After the relay candidates check if they are able to reduce the energy consumption (given in the Eqn. (4.5)), the capable relay candidates contend for relaying by sending ETH after a utility-based backoff (utility function is provided in Section 4.4.1). Notice that there may exist the case that two relay candidates hidden with each other (outside the transmission range). However, they can still sense the message sent from each other (within the sensing range which is set at 1.9 times of the transmission range in the simulator by default). The case that multiple ETH frames collide due to hidden would not exist. After SIFS (short interframe space), the winning relay broadcasts the II message to reconfirm the interference range of the allocated transmitting power at relay, which is used in the NAV setting (Section 4.4.3). After the above control frame exchanging, the source and relay cooperatively send the same data frames to the destination in two consecutive time intervals using the allocated transmitting power (Section 4.4.2). Finally, the destination sends an ACK back to the source if it decodes the message successfully.

The detailed protocol operations and flow charts (shown in Figs. 4.4 and 4.5) are provided from the perspective of different terminals:

4.3.1.1 Operations at the Source

i. When a source wants to initiate the data transmission with payload length L bytes, it first senses the channel to check if it is idle. If the channel is idle for DIFS, the source chooses a random backoff timer between 0 and CW. When the backoff counter reaches zero, the source sends out a RTS to reserve the channel. Notice that different from DCF, the location information of the source is carried in the RTS, which is used in the optimal power allocation.

ii. If the source does not receive a CTS within $T_{RTS} + T_{CTS} + SIFS$, a retransmission process will be performed. Otherwise, in the case that FLAG_P of CTS is 0, the DEL-CMAC is reduced to DCF protocol, and we omit its operations in the following. In the case that FLAG_P is 1, the source waits for another $T^{max}_{Backoff} + T_{ETH} + SIFS$, where $T^{max}_{Backoff}$ is the maximum backoff time for the relay (given in Section 4.4.1). If ETH is not received, which means that no capable relay exist, the source sends the data by direct transmission with data rate R.

iii. If both CTS and ETH are received, after waiting for $T_{II} + SIFS$, the source initiates a cooperative transmission with data rate $2R$ using the optimal transmitting power P^C_s which is piggybacked in the ETH. Notice that in order to maintain the end-to-end throughput, doubled data rate is employed in the cooperative transmission mode. We assume that the terminal can support two transmission rates by different coding and modulation schemes.

iv. If an ACK is not received after $16(L + L_h)/2R + T_{ACK} + 2SIFS$, where L_h is the header length (in bytes), the source would perform a random backoff same as DCF. Otherwise, the transmission process succeeds and the source handles the next packet in the buffer if any.

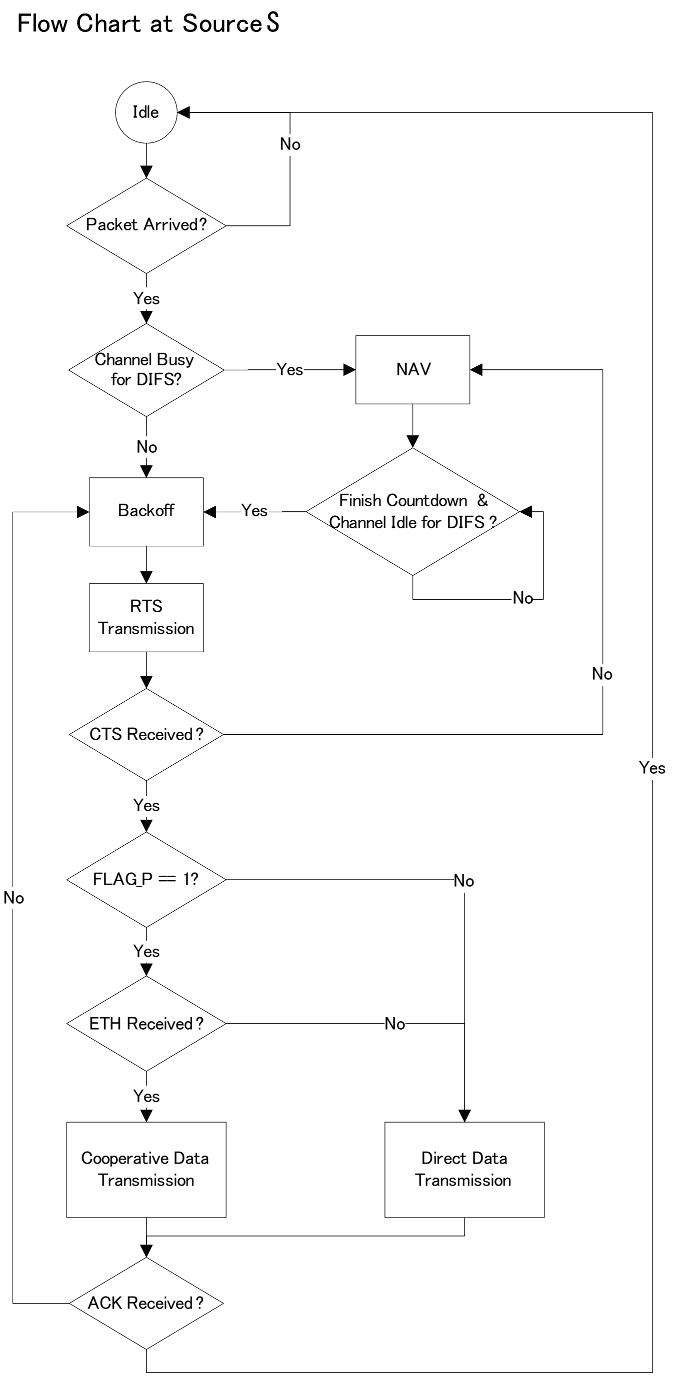

FIGURE 4.4: Flow chart at the source S.

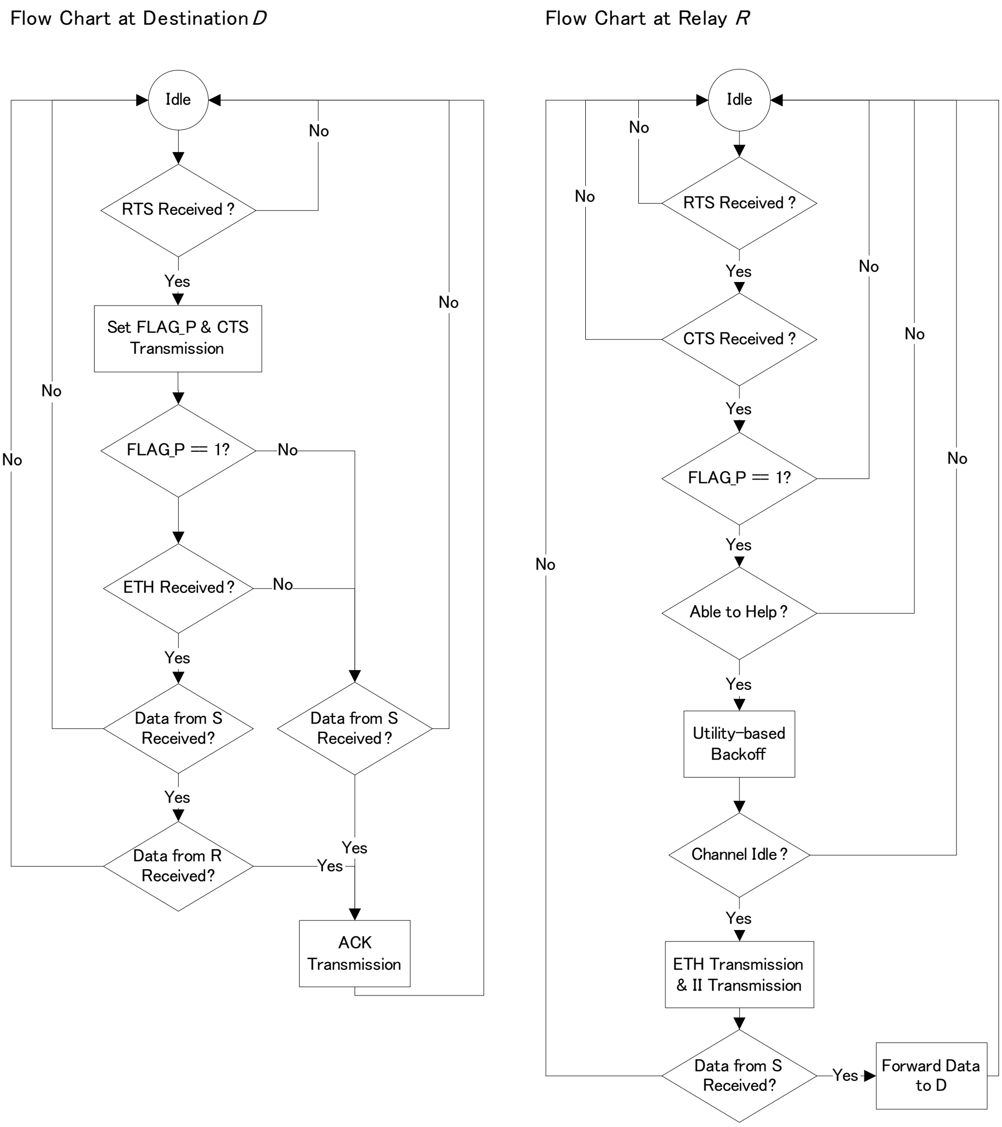

FIGURE 4.5: Flow chart at the destination D and relay R.

Notice that the unit for L and L_h is byte, and the unit for data rate is bits per second, thus the transmission time for one data frame is $8(L + L_h)/2R$.

4.3.1.2 Operations at the Destination

i. Upon receiving the RTS, the destination sends a CTS back after SIFS. The CTS contains the location information of the destination, the FLAG_P, and the transmitting power for the direct transmission P_s^D (in the form of dBm, occupying 4 bytes), which is used for the possible relay contention.

ii. In the case that FLAG_P is 1, if the destination has not heard any ETH within $T_{Backoff}^{max} + T_{CTS} + T_{ETH} + SIFS$, it assumes that the direct transmission will be performed and waits for the data packet from the source.

iii. Otherwise, the destination waits for the data packets from the source and winning relay. If the destination can decode the combined signals correctly, it sends back an ACK. Otherwise, it just lets the source timeout and retransmit.

4.3.1.3 Operations at the Relay

i. Any terminal that receives both RTS and CTS (with FLAG_P equals 1) and does not interfere with other transmissions in its vicinity can be regarded as a relay candidate. Upon receiving the CTS, each relay candidate checks whether it is able to reduce the total energy consumption by

$$\begin{aligned}&(2P_s^D - P_s^C - P_r^C - 2P') \times (L + L_h)/2R - \\ &(P_r^C + P') \times T_{II} - (P + 3P') \times T_{ETH} > 0.\end{aligned} \tag{4.5}$$

P_s^C and P_r^C refer to the transmitting power in the cooperative transmission mode for source and relay (given in Section 4.4.2), P_s^D and P refer to the transmitting power in the direct transmission mode for source and the fixed transmitting power respectively. Term $(2P_s^D - P_s^C - P_r^C - 2P') \times (L + L_h)/2R$ denotes the saved energy consumption in transmitting the data by CC, term $(P_r^C + P') \times T_{II}$ and $(P + 3P') \times T_{ETH}$ denotes the additional energy consumption on control overhead. By Eqn. (4.5), the relay checks whether CC can reduce the total energy consumption both on transmitting and receiving, compared to direct transmission. Every capable relay candidate (satisfies Eqn. (4.5)), starts a backoff timer after SIFS interval. The specific utility-based backoff scheme is given in Section 4.4.1.

ii. Intuitively, the backoff at a better relay expires earlier, hence the best relay will send out an ETH first. The lost relays give up contention when sensing the ETH. The ETH contains the optimal transmitting power P_s^C for the source (in the form of dBm, occupying 4 bytes).

iii. After SIFS, the winning relay broadcasts the II message using power P_r^C. II message is used to reconfirm the interference range of the relay with the objective to enhance the spatial reuse. The detail of the NAV setting will be explained in Section 4.4.3. Then, the winning relay waits for the data packet from the source to arrive. Upon receiving the data packet, the winning relay forwards it to the destination with data rate $2R$ using transmitting power P_r^C.

4.3.2 Further Discussions

Compared with the IEEE 802.11 DCF, the proposed DEL-CMAC has additional control message overhead in the case that the FLAG_P is 1 and the capable relay candidates are absent. The duration of this overhead is a constant time equal to $T_{Backoff}^{max} + T_{ETH} + SIFS$. It is undesirable but inevitable if we try to coordinate multiple connections with cooperative relaying and choose the best relay in a distributed fashion. However, notice that the probability of no capable relay candidate exists is quite small given a general node density deployment (addressed in Section 4.4.3). In addition, this overhead duration is relatively short comparing with the payload transmission duration. From the simulation results provided in Section 4.5, we observe that the performance of throughput and delay only decreases by around 5%, which may be acceptable when considering the significant increase in the network lifetime.

Another issue in DEL-CMAC is the hidden terminal problem due to the terminal mobility. Consider a situation as follows. After the exchanges of RTS, CTS and ETH, a terminal located outside the transmission range originally moves into the range. Due to the lack of NAV setting, this terminal may interfere with the ongoing transmission, leading to a collision. However, the hidden terminal issue caused by the terminal mobility is not unique for our DEL-CMAC, and it already exists in the original IEEE 802.11 DCF. In this work, we consider the probability that hidden terminal issue occurs is considerably low, and we leave it as our future work.

4.4 Detail and Supplement of DEL-CMAC

In this section, we elaborate the detail and the supplement of the proposed DEL-CMAC. Specifically, we address the optimal power allocation scheme, the utility-based best relay selection strategy, and the NAV (network allocation vector) setting in the following subsections.

4.4.1 Utility-based Best Relay Selection

Selecting the best relay distributed and efficiently affects the performance of the CMAC protocol significantly. The existing relay selection schemes that incorporated into the CMAC protocols, largely depend on the instantaneous channel condition, which based on the assumption that the channel condition is invariant during one transmit session. For WANETS that deployed in heavily built-up urban environments or heavy traffic environments, this assumption is hard to guarantee [70]. This implies that the "best" selected relay terminal according to channel condition during the route construction or handshaking period, may not be the best one in the actual data transmission period. Selecting the best relay terminal based on the instantaneous location instead of instantaneous channel condition may be more reasonable for WANETs. In this chapter, we propose a distributed energy-aware location-based best relay selection strategy which is incorporated into the control frame exchanging period in DEL-CMAC. The location information of individual wireless devices can be obtained through GPS or other localization algorithms [71]. The required location information of source and destination is carried by RTS and CTS frames. Thus no additional communication overheads are involved. DEL-CMAC chooses the best relay based on a utility-based backoff, which depends on the required transmitting power to meet certain outage probability (related to individual location) and the residual energy of individual terminals. It is carried out in a distributed, lightweight and energy-efficient fashion, in which the backoff of the relay that has the minimum utility value expires first.

We define the Backoff Utility function BU_r for relay r as

$$BU_r = \tau \min(\frac{E}{E_r}, \delta) \times \frac{P_r^C}{P_s^D/2}, \tag{4.6}$$

where E_r is the current residual energy of relay r, P_r^C is the transmitting power at relay r in cooperative mode, and P_s^D is the transmitting power at source s in direct mode (both obtained through the equations in Section 4.4.2). The parameters in Eqn. (4.6) include the energy consumption threshold δ, the constant unit time τ, and the initial energy E. Intuitively, the terminal with high residual energy and low transmitting power (i.e., small BU_r value), has a comparatively short backoff time. The terminal whose backoff expires first will be selected as the winning relay. The threshold δ is to restrict the maximum backoff time within an acceptable range. Since when the residual energy is very low, E/E_r will be extremely large, leading to a very long backoff time that we should prevent. The term P_r^C is strictly upper bounded by $P_s^D/2$, i.e., the term $\frac{P_r^C}{P_s^D/2}$ is always less than 1. Thus, BU_r is upper bounded by the maximum backoff time $T_{Backoff}^{max}$ which is equal to $\tau \cdot \delta$.

We observe that there is a tradeoff between the probability of collision (due to extremely close utility value) and the time spent in the relay selection process. The value of τ cannot be made too large to postpone the time to find out the best relay, or too small to raise the probability of collision. In our simulation, τ is set to 0.1 ms. However, setting τ properly can only depress the collision probability but cannot avoid the collision completely. Considering to incorporate the collision free relay selection strategies [48, 72] into our utility-based backoff scheme is our future work.

Different from the existing best relay selection schemes, the proposed strategy utilizes the location information and takes the residual energy into considerations. Besides, it is completely distributed and every terminal makes the decision independently. Using the proposed relay selection strategy, the energy consumption rate among the terminals can be balanced, and the total energy consumption can be reduced.

4.4.2 Optimal Power Allocation

Optimal power allocation is indispensable for a cross-layer CMAC protocol that aims at increasing energy efficiency. In this subsection, we address the power allocation for CC and direct transmission under the given outage probability. We start with deriving the transmitting power at source in the direct transmission mode, which is calculated by the destination after it receives the RTS. Then, under the same outage probability and end-to-end data rate, the optimal transmitting power at source and relay in the cooperative transmission mode is calculated by individual relay candidates after the RTS/CTS handshake.

4.4.2.1 Direct Transmission

The mutual information of two random variables is defined as a quantity that measures the mutual dependence of the two variables. For wireless communication, the mutual information between source s and destination d is defined as

$$I_{sd} = \log_2\left(1 + \frac{P_s^D d_{sd}^{-\alpha} |h_{sd}|^2}{N_0}\right), \tag{4.7}$$

where P_s^D is the transmitting power at the source in the direct transmission mode, d_{sd} is the distance between the source and the destination, α is the path loss exponent, h_{sd} is the channel fading gain and N_0 is variance of the noise component. Outage event is defined as the set of channel realizations that cannot support reliable transmission rate R. Thus outage probability of direct transmission is the probability that I_{sd} falls below the transmission rate R, which is calculated as

$$\mathcal{P}_D^O = \mathcal{P}(I_{sd} \leq R) = \mathcal{P}\left(|h_{sd}|^2 < \frac{\left(2^R - 1\right) N_0 d_{sd}^{\alpha}}{P_s^D}\right). \tag{4.8}$$

Based on the assumption that the channel coefficient h_{sd} follows the Gaussian zero mean distribution, $|h_{sd}|^2$ can be modeled as the exponential random variable. Utilizing the probability density function of $|h_{sd}|^2$, Eqn. (4.8) is converted to

$$\begin{aligned} \mathcal{P}_D^O &= \int_0^{(2^R-1)N_0 d_{sd}^{\alpha}/P_s^D} \exp\left(-|h_{sd}|^2\right) d\left(|h_{sd}|^2\right) \\ &= 1 - \exp\left(-\frac{\left(2^R - 1\right) N_0 d_{sd}^{\alpha}}{P_s^D}\right). \end{aligned} \tag{4.9}$$

Thus, in order to meet the desired outage probability, the minimum transmitting power in the direct transmission mode is given as

$$P_s^D = -\frac{(2^R - 1)N_0 d_{sd}^{\alpha}}{\ln(1 - \mathcal{P}_D^O)}. \tag{4.10}$$

4.4.2.2 Cooperative Transmission

Under the same outage probability and end-to-end data rate requirements, we compute the optimal transmitting power at source and relay in the cooperative transmission mode with MRC.

The instantaneous mutual information at the destination is

$$I_d = \log_2\left(1 + \frac{P_s^C d_{sd}^{-\alpha} |h_{sd}|^2}{N_0} + \frac{P_r^C d_{rd}^{-\alpha} |h_{rd}|^2}{N_0}\right), \tag{4.11}$$

where P_s^C and P_r^C are the transmitting power at source and relay in the cooperative transmission mode, respectively. Due to the doubled transmitting duration for the data packet in DF, the required data rate in one time interval is set to $2R$ in order to support an end-to-end data rate R. Thus, the total outage probability of DF with MRC can be calculated as

$$\mathcal{P}_C^O = \mathcal{P}\left(I_{sr} \leq 2R\right) + \left(1 - \mathcal{P}\left(I_{sr} \leq 2R\right)\right)\mathcal{P}\left(I_d \leq 2R\right). \tag{4.12}$$

In Eqn. (4.12), the first term corresponds to the case that the source-relay channel is in outage, while the second term corresponds to the case that the source-relay channel succeeds, but the combined signal in the destination cannot support reliable transmission rate $2R$. Substituting Eqn. (4.11) into Eqn. (4.12), we obtain the total outage probability as a function of P_s^C and P_r^C after some mathematical manipulation,

$$\begin{aligned}\mathcal{P}_C^O = \mathscr{F}(P_s^C, P_r^C) &= 1 - \frac{d_{rd}^\alpha}{d_{rd}^\alpha - d_{sd}^\alpha} \exp\left(-\frac{(2^{2R}-1)N_0(d_{sr}^\alpha + d_{sd}^\alpha)}{P_s^C}\right) \\ &- \frac{d_{sd}^\alpha}{d_{rd}^\alpha - d_{sd}^\alpha} \exp\left(-\frac{(2^{2R}-1)N_0 d_{sr}^\alpha}{P_s^C}\right) \exp\left(-\frac{(2^{2R}-1)N_0 d_{rd}^\alpha}{P_r^C}\right).\end{aligned} \tag{4.13}$$

The optimization problem of power allocation can be stated as follows,

$$\begin{aligned}&\min\ (P_s^C + P_r^C), \\ &\text{s.t. } \mathscr{F}(P_s^C, P_r^C) = \mathcal{P}_C^O.\end{aligned} \tag{4.14}$$

The optimal solution exists when $P_s^C = P_r^C$, and $P_s^{C^*}$ is the solution to the following equation

$$d_{sd}^\alpha \mathscr{G}(d_{sd}^\alpha + d_{rd}^\alpha) - d_{rd}^\alpha \mathscr{G}(d_{sr}^\alpha + d_{sd}^\alpha) + (1 - \mathcal{P}_C^O)(d_{rd}^\alpha - d_{sd}^\alpha) = 0, \tag{4.15}$$

where

$$\mathscr{G}(d) = \exp\left(-\frac{(2^{2R} - 1)N_0 d}{P_s^C}\right).$$

Notice that the required distances information can be easily obtained by the location information piggybacked in the RTS and CTS. Although nonlinear equation Eqn. (4.15) can be solved by iteration method, the complexity is high. To avoid the additional calculation overhead, we approximate the exponential function as $\exp(-x) \approx 1 - x + x^2/2$. Then $\mathcal{G}(d) = \exp(-xd)$, where $x = \frac{(2^{2R}-1)N_0}{P_s^C}$, can be simplified to $1 - dx + (d^2/2)x^2$. Finally, Eqn. (4.15) is approximated by

$$Ax^2 + Bx + C = 0, \tag{4.16}$$

where

$$\begin{aligned} A &= (d_{sd}^{\alpha} d_{sr}^{2\alpha} + d_{sd}^{\alpha} d_{rd}^{2\alpha} - d_{rd}^{\alpha} d_{sr}^{2\alpha} - d_{rd}^{\alpha} d_{sd}^{2\alpha})/2, \\ B &= d_{rd}^{\alpha} d_{sr}^{\alpha} - d_{sd}^{\alpha} d_{sr}^{\alpha}, \\ C &= \mathcal{P}_C^O (d_{sd}^{\alpha} - d_{rd}^{\alpha}). \end{aligned}$$

This quadratic equation can be easily solved, and the calculation overhead is light for ordinary wireless terminal. Using the calculated P_s^C and P_r^C, each relay candidate checks whether it can conserve the energy consumption or not by Eqn. (4.5). If the equation holds, the relay candidate initiates a backoff timer to contend for the winning relay, otherwise, it keeps silence.

4.4.3 Spatial Reuse Enhancement

As the involvement of relaying and varying transmitting power, the interference ranges in DEL-CMAC are changing during one transmit session. In order to avoid the interference and conserve the energy, delicate NAV setting is required. NAV limits the use of physical carrier sensing, thus conserves the energy consumption. The terminals listening on the wireless medium read the duration field in the MAC frame header, and set their NAV on how long they must defer from accessing the medium. Taking IEEE 802.11 DCF for instance, the NAV is set using RTS/CTS frames (Fig. 4.2). No medium access is permitted during the blocked NAV durations.

Comparing with the simple NAV setting in DCF, the setting in DEL-CMAC needs to be considerably modified. The presence of relays will enlarge the interference ranges and the dynamic transmitting power makes the interference ranges vary during one transmit session. Improper NAV setting induces energy waste and collisions. Specifically, setting the NAV duration too short will wake up the terminal too soon, which results in energy waste due to medium sensing. On the other hand, setting it too long will reduce the spatial efficiency, which results to the

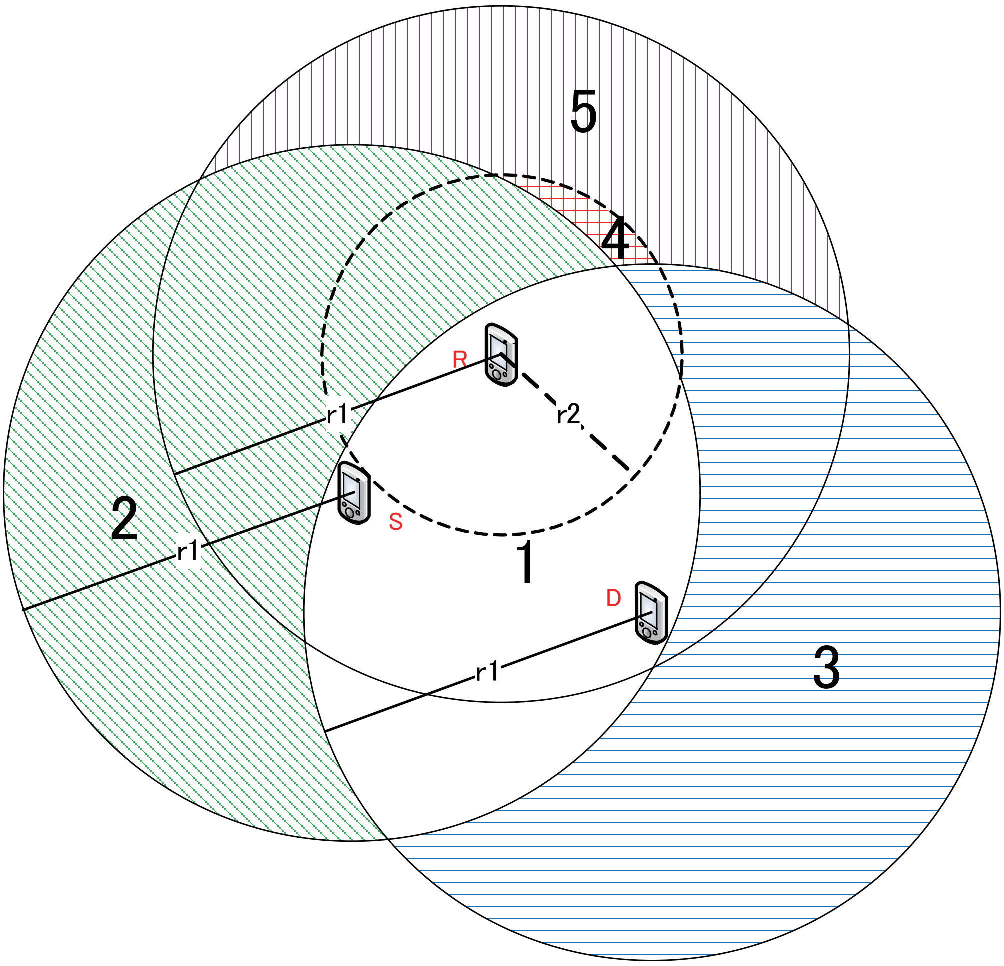

FIGURE 4.6: An illustration for the NAV setting ranges for the cooperative communication with varying transmitting power.

performance degradation in terms of throughput and delay. Thus, effective NAV setting is necessary and critical. Unfortunately, most of the previous works does not address the NAV setting issue in CC [47, 64], not to mention the one with varying transmitting power. In this chapter, we divide the transmission ranges for the source, destination and relay to five different regions (Fig. 4.6). Since different transmitting power lead to different transmission ranges, there exist two ranges for the relay. As shown in Fig. 4.6, the solid circle denotes the transmission range for fixed transmitting power (with radius r_1), and the dashed circle denotes the transmission range for the allocated transmitting power (with radius r_2). Notice that it is not necessary to consider the transmission range with allocated transmitting power at the source, since all the terminals lie inside the solid circle of the source will interfere with the ACK. Thus, they must defer accessing the medium until the very end of the whole session. In the following, we address the specific NAV setting for our DEL-CMAC from the perspective of different regions by Fig. 4.7.

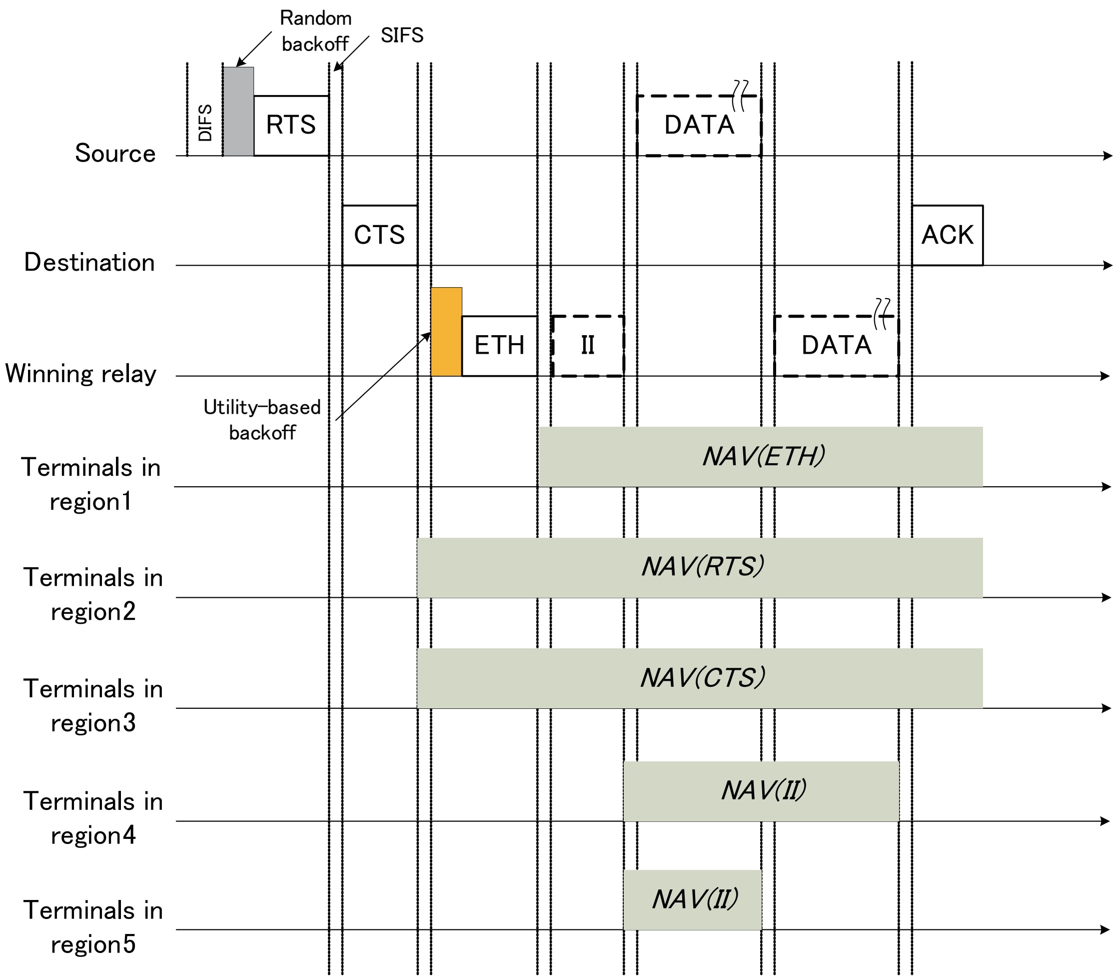

FIGURE 4.7: NAV setting for DEL-CMAC.

4.4.3.1 Region 1 (The terminals that can receive both the RTS and CTS)

The terminals in this region are the relay candidates. According to our DEL-CMAC, they contend for the winning relay after the RTS/CTS exchange. Upon receiving the ETH, all the lost relays should keep silence until the whole transmit session is finished. Notice that for the sake of the relay selection, the terminals cannot set their NAVs as soon as they receive the RTS as in the IEEE 802.11 DCF. All the neighboring terminals have to wait until the end of the CTS and then make their decisions. Thus, the NAV duration in region 1 is $T_{II}+T_{ACK}+16(L+L_h)/2R+4SIFS$. Given that the distance between the source and destination is l_{sd}, the area of region 1 is

$$S_{sd}(l_{sd}) = 2r_1^2 \arcsin(h/r_1) - hl_{sd}, \tag{4.17}$$

where

$$h = \sqrt{4r_1^2 l_{sd}^2 - l_{sd}^4}/2l_{sd}.$$

Assume that the terminals are uniformly distributed, the probability that a terminal is located in region 1 is

$$\mathcal{P}_1 = \frac{S_{sd}(l_{sd})}{\pi r_1^2}. \tag{4.18}$$

And the probability that no available relay candidate exists is $1 - \mathcal{P}_1$. In the worst case, which the source and destination locate at the maximum distance, i.e., $l_{sd} = r_1$, the probability of no relay candidate exists is 60.9%.

4.4.3.2 Region 2 (The terminals that can receive the RTS but not the CTS)

Those terminals set their NAV durations until the end of the ACK, which is $T_{Backoff}^{max} + T_{ETH} + T_{II} + T_{ACK} + 16(L + L_h)/2R + 5SIFS$.

4.4.3.3 Region 3 (The terminals that can receive the CTS but not the RTS)

The same as the terminals in region 2, they set their NAV until the end of the ACK.

4.4.3.4 Region 4 (The terminals that can receive the II)

As we mentioned before, according to different transmitting power, there exist two transmission ranges at the relay. One is the transmission range for the ETH message with fixed transmitting power (large solid circle with radius r_1 in Fig. 4.6), the other is the transmission range for the II message and data with allocated transmitting power (small dashed circle with radius r_2 in

Fig. 4.6). The terminals in region 4 fall inside the small transmission range at the relay, they should defer the medium access until the end of the data transmissions (two phases). Recall that in 802.11 DCF, the nodes outside the transmission ranges of source and destination do not set NAV, they use physical carrier sensing to avoid the possible collision. Thus, same as the setting in 802.11 DCF, the NAV duration for nodes in region 4 ends before the ACK frame. The NAV duration for them is $16(L + L_h)/2R + 2SIFS$. Region 4 exists only when conditions $l_{sr} > r_1 - r_2$ and $l_{rd} > r_1 - r_2$ are both satisfied. The area of region 4 can be calculated as

$$S_4 = \pi r_2^2 - S^c_{sr}(l_{sr}) - S^c_{rd}(l_{rd}) + S^c_{srd}(l_{sd}, l_{sr}, l_{rd}), \tag{4.19}$$

where $S^c_{sr}(l_{sr})$ and $S^c_{rd}(l_{rd})$ are the intersection of the transmission ranges of source-relay and relay-destination, and $S^c_{srd}(l_{sd}, l_{sr}, l_{rd})$ is the intersection of the transmission ranges of source, relay and destination. Notice that the superscript c indicates that the small transmission range at the relay is used. The area of intersection of two ranges can be calculated by using the similar formula like Eqn. (4.17). And the area of intersection of three ranges can be easily calculated by definite integral. Their specific expressions are omitted in this chapter due to limited space.

4.4.3.5 Region 5 (The terminals that can receive the ETH but not the II)

The terminals in this region fall inside the large transmission range at the relay but outside the small one. Those terminals have a relatively short NAV duration comparing to the terminals in region 4, which is only $8(L + L_h)/2R$. Since when the source finishes its data transmission, the terminals in region 5 and the relay may not interfere with each other. By utilizing II frame, the nodes in this region may initiate their transmission in advance given they are outside the interference range of the destination. The area of region 5 can be calculated as

$$S_5 = \pi r_1^2 - S_{sr}(l_{sr}) - S_{rd}(l_{rd}) + S_{srd}(l_{sd}, l_{sr}, l_{rd}) - S_4, \tag{4.20}$$

Under the uniform distribution assumption, the probability that a terminal is located in region 5 is obtained by

$$\mathcal{P}_5 = \frac{S_5}{\pi r_1^2}. \tag{4.21}$$

The transmission of the queuing packets at nodes in region 5 can be moved up. The delay can be reduced by $(L + L_h)/2\text{R}+\text{SIFS}$, which results to a 45.5% improvement in the throughput with probability $\mathcal{P}_5$.

4.5 Performance Evaluation

In this section, we evaluate DEL-CMAC via extensive simulations comparing with IEEE 802.11 DCF and CoopMAC [45]. Since the purpose of our scheme is to prolong the network lifetime and increasing the energy efficiency, the evaluation metrics in this chapter are the transmitting power, total energy consumption, network lifetime, aggregated throughput and average delay. The transmitting power denotes the power consumed at transmit amplifier (without the power consumed at transmit circuitry). The total energy consumption is the summation of the transmitting (including both transmit amplifier and circuitry) and receiving energy cost at the source, destination and relay. The lifetime is defined as the duration from the network initialization to the time that the first terminal runs out of power. To validate the performance improvements in DEL-CMAC, we utilize both the single-hop scenario and the multi-hop multi-connection scenario. The simulation is carried out in QualNet network simulator [73].

TABLE 4.1: Simulation parameters

RTS	160 bits	Noise power	−60 dBm
CTS	144 bits	Fixed transmit power	10 dBm
ACK	112 bits	Data rate	1 Mbps
ETH	192 bits	Path loss exponent α	3
II	80 bits	Initial energy E	1 J
PHY header	192 bits	Energy threshold δ	10
MAC header	272 bits	Power threshold Λ_p	0 dBm
Unit time τ	0.1 ms	Circuitry power	7, 10, 13 dBm

The initial energy of all the terminals are set to 1 J. The propagation channel of two-ray path loss model is adopted. Constant data rate with 1 Mbps is used in DEL-CMAC and DCF, while adapted data rates with 1, 2, 5.5 Mbps are used in CoopMAC. The fixed transmitting power used for control frames is set to 10 dBm and, the fixed transmitting power used for data frame in CoopMAC is set to 15 dBm due to the high data rate (the transmitting power for the data frames in DEL-CMAC and DCF is dynamically allocated). The simulation settings and parameters are listed in Table I.

4.5.1 Single-hop Scenarios

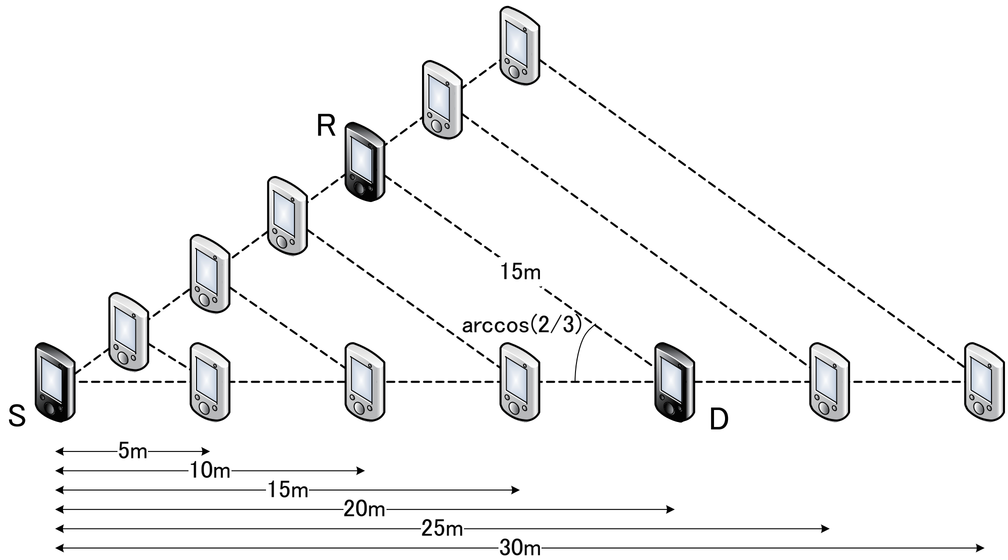

FIGURE 4.8: A illustration of the single-hop scenario.

We first compare our DEL-CMAC with the IEEE 802.11 DCF in a single-hop scenario that only consists of three terminals (one source, one destination and one relay), to show the differences between cooperative and non-cooperative communication on energy consumption. As shown in Fig 4.8, the distance between source and destination changes from 5 m to 30 m, and angles $\angle SDR$ and $\angle DSR$ keep at arccos(2/3).

Fig. 4.9 shows the variance of the transmitting power to satisfy different outage probability requirements, when the distance between source and destination is 20 m. It is straightforward that high outage probability requirement leads to high cost in terms of transmitting power. We observe that for the required data rate and outage probability, the transmitting power for cooperative transmission is far less than the one for direct transmission. Since the probability of success 99.9% is acceptable for most of the wireless network applications, the simulation study in the remainder of this chapter are all based on the outage probability 0.1%.

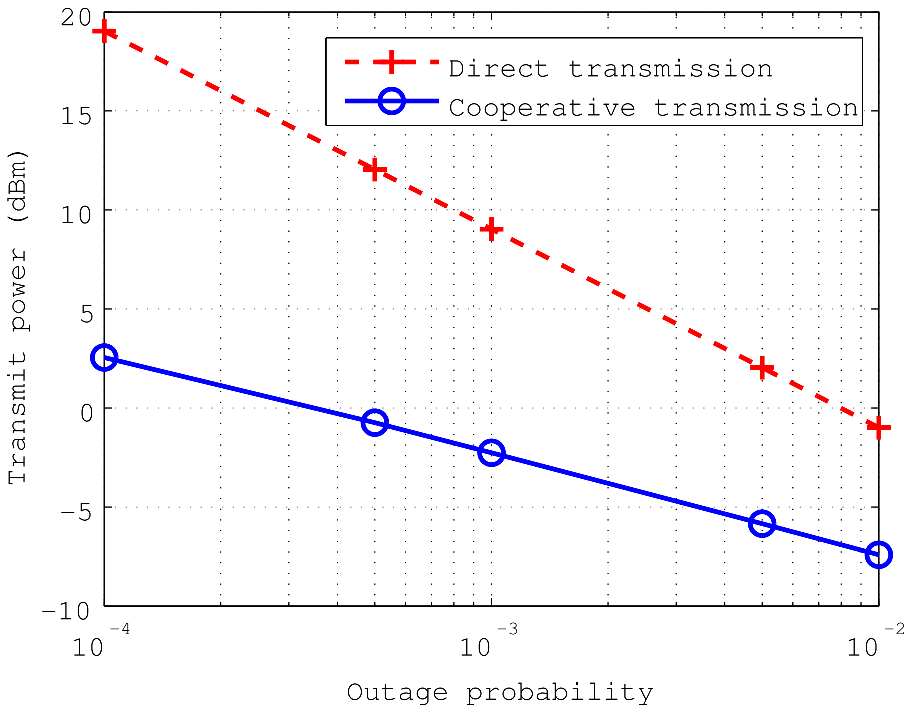

FIGURE 4.9: Transmitting power versus outage probability.

To validate the efficiency of the cooperative communication, only investigating transmitting power is not enough. The processing and receiving energy consumption at relay and destination should also be taken into account. In Fig. 4.10, we compare the total energy consumption in one transmit session. The ratio of the energy consumption on transceiver circuitry to transmit amplifier, i.e., P'/P, at $0.5, 1, 2$ are investigated. We plot the energy consumption at different distances for different P'/P ratios. For short distance, the direct transmission is more efficient in all cases, since the overhead for control frames dominates the energy saving from cooperative diversity. Notice that due to the transmitting power threshold check and the energy consumption check by Eqn. (4.5), inefficient cases for cooperative transmission (i.e., when the direct channel condition is good or the distance is short) are ruled out in DEL-CMAC. The energy consumption of DCF, however, is dramatically increased as the distance raises (around 7 meters for case $P'/P = 0.5$ and 11 meters for case $P'/P = 2$). While the energy cost by DEL-CMAC remains in the same level even for farther distances. The energy consumption of DEL-CMAC is significantly below DCF for medium to long distances, considering the circuit energy consumption at both sender

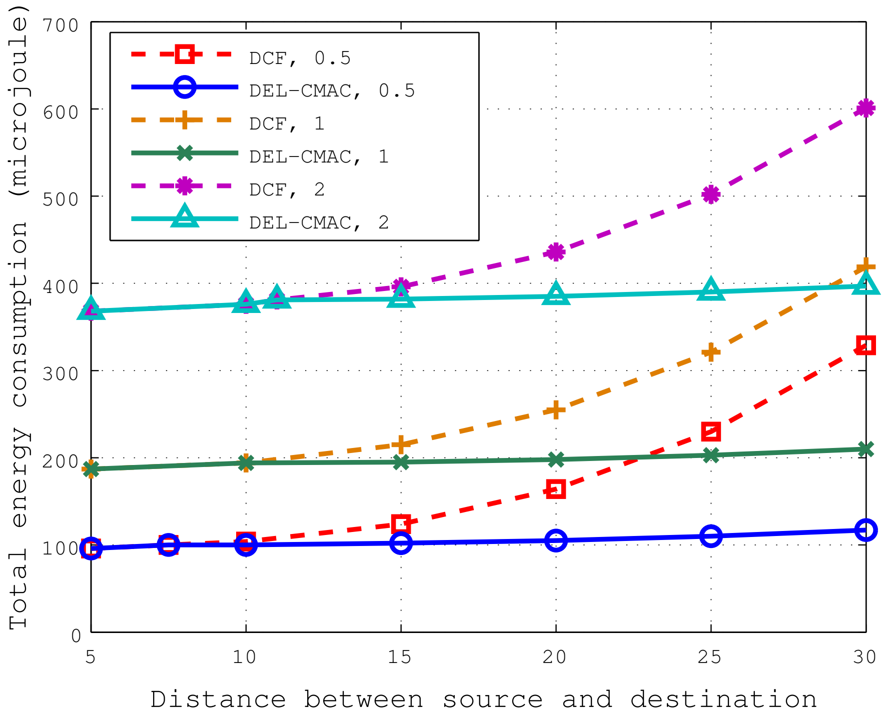

FIGURE 4.10: Energy consumption versus source-destination distance.

and receiver.

4.5.2 Multi-hop Multi-connection Scenarios

Next, we illustrate the performance of DEL-CMAC in a realistic multi-hop multi-connection scenario along with IEEE 802.11 DCF and CoopMAC. This complex scenario takes the interference and collision caused by different connections into account.

As shown in Fig. 4.11, terminals are randomly placed in a square area of $200 \times 200m^2$. The dashed lines indicate that all the terminals belong to the same subnet. The 5 solid lines indicate that 5 Constant Bit Rate (CBR) connections, in which sources (nodes $1, 11, 21, 31, 41$) transmit UDP-based traffic at 1 packet per 100 milliseconds to the destinations (nodes $20, 30, 40, 50, 10$) through multi-hop. The data payload length is set to 1024 bytes (unless stated otherwise). AOD-V [66] routing protocol is used to establish the routing paths, which is widely used in WANETs.

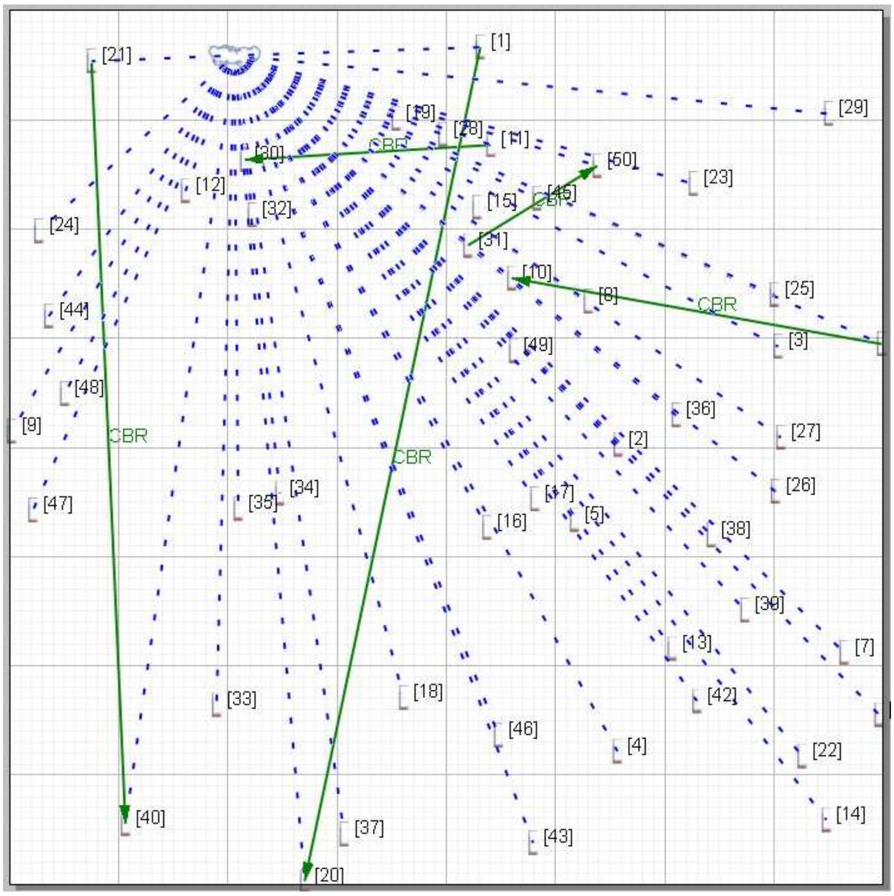

FIGURE 4.11: A snapshot of the multi-hop multi-connection network.

Other routing protocols as DSR or energy aware routing protocol can also be used, the performance of the proposed MAC layer scheme is independent of network layer schemes.

We vary the number of terminals in the area from 20 to 60 while keeping the number of CBR to 5. In Fig. 4.12, we compare the network lifetime of DEL-CMAC with IEEE 802.11 DCF and CoopMAC in a static network. It is clear that our DEL-CMAC always outperforms DCF and CoopMAC in all cases. CoopMAC [45] is designed to increasing the throughput, in which fixed transmitting power and adapted data rates are utilized. It is reasonable that the network lifetime of CoopMAC is the shortest, due to the lacking of power control and the additional control overhead for cooperative communication. The performance gain of DEL-CMAC over DCF and CoopMAC raises as the number of terminals increases. The reason can be explained

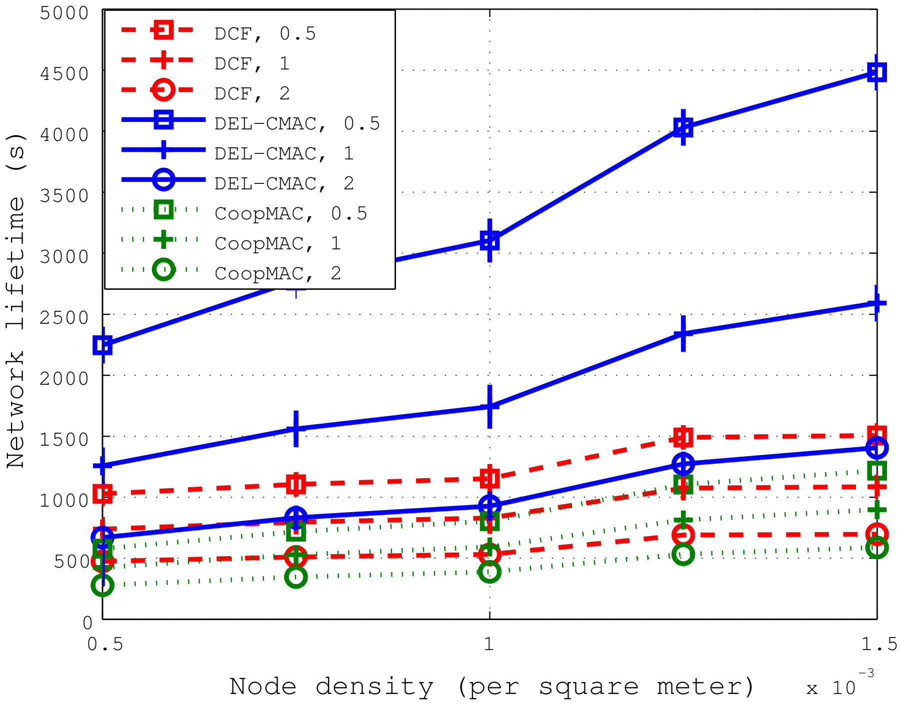

FIGURE 4.12: Network lifetime versus the node density in a static environment (with 95% confidence interval).

from the following two aspects. First, if the node density is low, some terminals have to play the role as the source and cooperative relay alternately. This additional relay energy cost is expected to impact the performance negatively. The growing availability of relay candidates results in balanced energy consumption. To be more specific, if the node density is high enough, the terminals having their own data to send or serving as routing relay, are rarely selected as the cooperative relay for other connections. Because their residual energy is lower than the others. Second, the higher the node density is, the higher the probability that relay candidates are located in the ideal positions for the existing source-destination pairs. Thus, high node density leads to a transmitting power reduction for both source and relay by our optimal power allocation scheme. To be specific, at least 2.2 and 3.9 times lifetime improvements for case $P'/P = 0.5$, and 1.4 and 2.4 times lifetime improvements for cases $P'/P = 2$, can be obtained by DEL-CMAC over DCF and CoopMAC, respectively.

Next, we study the impact of mobility on the network lifetime. We incorporate the random

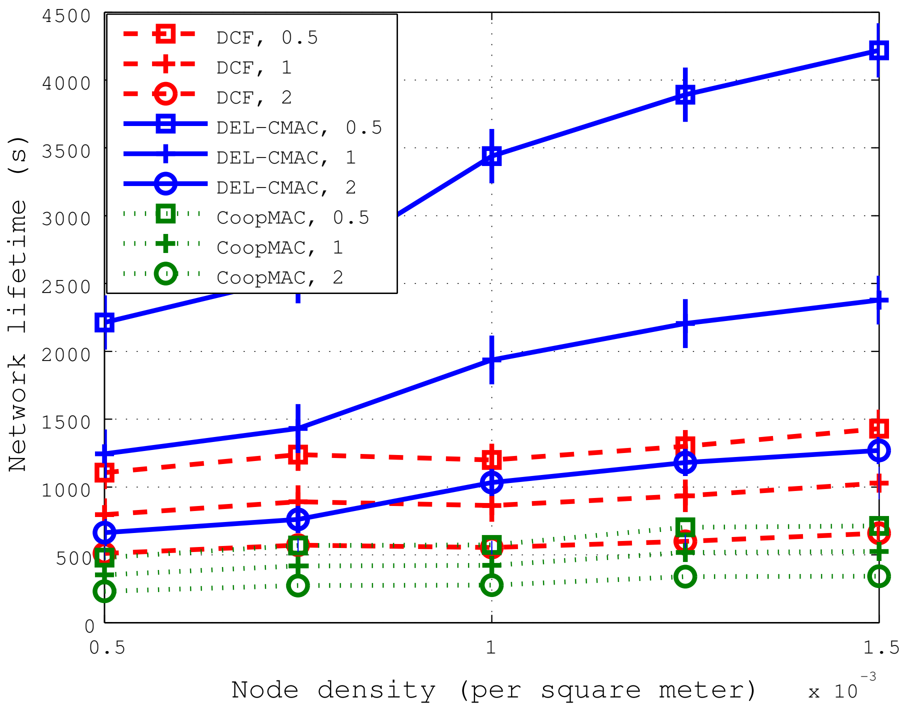

FIGURE 4.13: Network lifetime versus the node density in mobile environment (with 95% confidence interval).

waypoint model [74] in our simulation. Each terminal selects a random position, moves towards it in a straight line at a constant speed that is randomly picked from a range, and pauses at that destination. The terminal repeats this process throughout the simulation. We set the maximum speed at 10mps and the pause time at 10s. From Fig. 4.13, we can observe the similar result as in static scenario. Our DEL-CMAC prolongs the network lifetime by at least 2 and 4.8 times for case $P'/P = 0.5$, and 1.3 and 2.8 times for case $P'/P = 2$, compared with DCF and CoopMAC respectively. Thus, we conclude that our DEL-CMAC performs well both in stationary and mobile scenarios in terms of network lifetime.

An examination on the relationship between the network lifetime and the data payload size for DEL-CMAC is provided in Fig. 4.14. We observe that when the node density is low and payload size is small, the transmitting power saved by cooperative transmission is greatly canceled out by the overhead entailed by the cooperative relaying, e.g., only 1.26 times lifetime enhancement for 20 terminals and 128 bytes payload. However, as the node density and payload

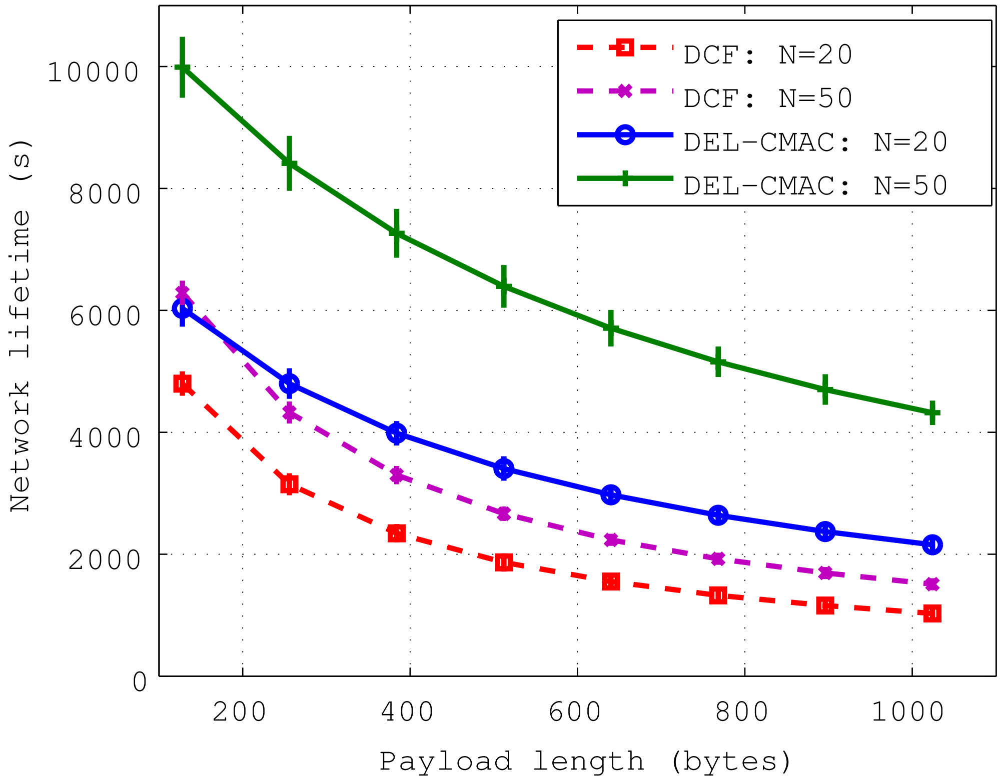

FIGURE 4.14: Relation between the data payload size and the network lifetime ($P'/P = 0.5$ and with 95% confidence interval).

size raise, the lifetime gain that our DEL-CMAC can achieve becomes more and more significant, e.g., 2.87 times enhancement for 50 terminals and 1024 bytes payload. Thus, we conclude that DEL-CMAC is more suitable for the networks with large payload size and fairly high node density.

Finally, Figs. 4.15, 4.16 and Figs. 4.17, 4.18 depict the aggregated throughput and average delay for the 3 schemes both in static and mobile environments. The CoopMAC outperforms the two others in both throughput and delay due to the utilization of multiple data rates. And the performance of CoopMAC decreases considerably in the mobile scenario, since the table-based proactive relay selection may not adapt to moving networks. For DEL-CMAC, the throughput of the network decreases by at most 7.89% in static environment and, 4.04% in mobile environment, compared to DCF. And the delay increases by at most 5.61% and 3.93% in static and mobile environments, respectively. These results are expected since the additional control

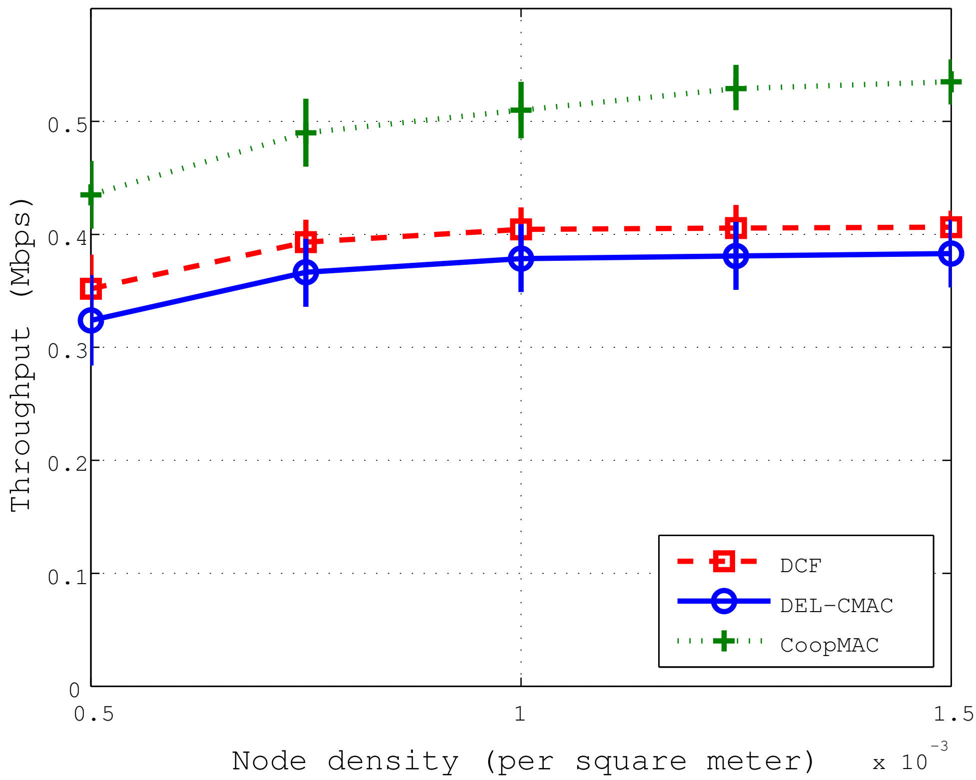

FIGURE 4.15: Throughput performance versus node density in static environment(with 95% confidence interval).

frame overhead is required to coordinate the cooperative transmission. Besides, the utility-based backoff used for choosing the best relay, and the enlarged interference range by relaying also affect the throughput and delay negatively. However, comparing to the network lifetime gain, we consider that the performance reduction around 5% in throughput and delay is acceptable. Notice that CoopMAC enhances the throughput and delay at the cost of considerably network lifetime degradation. The proposed scheme is particularly suitable for the WANETs in which the network lifetime is the primary requirement, e.g., the WANETs utilized in the disaster rescue. For instance, when an earthquake hits someplace, to search for survivors, a large number of small robots, equipped with various sensors and a camera, can be deployed all over the rubble. The robots form a WANET to forward the sensing data to the base stations and to coordinate their movements so that the entire area is searched. In order to maximize the chance of finding survivors, the network lifetime is much more important than the throughput and delay in this

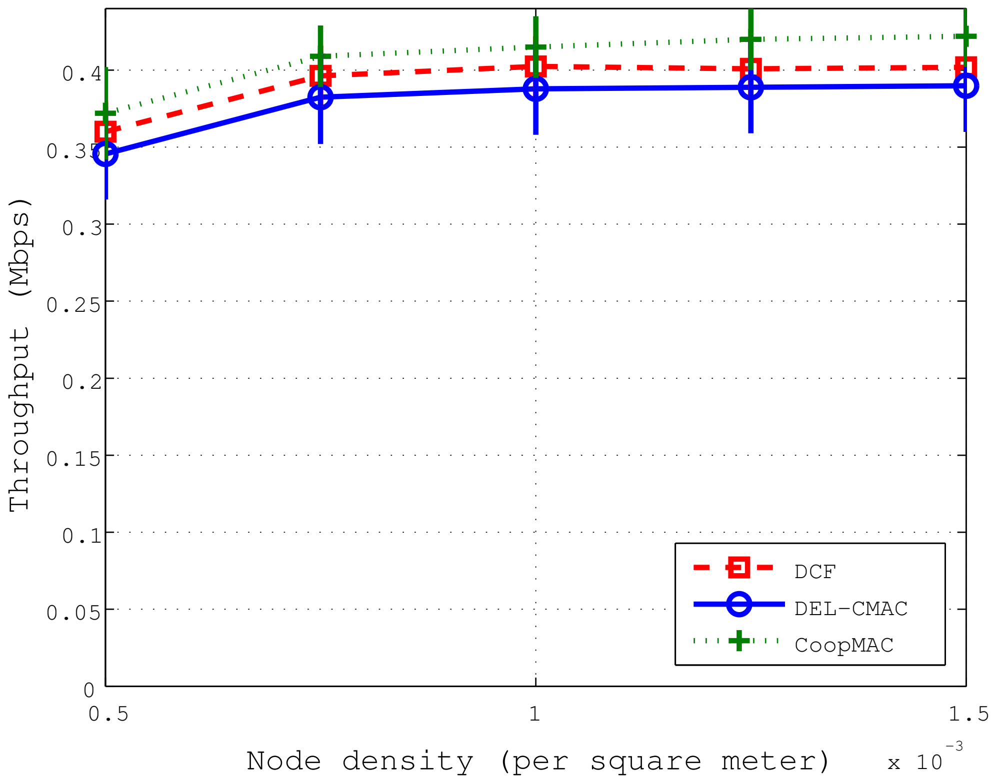

FIGURE 4.16: Throughput performance versus node density in mobile environment(with 95% confidence interval).

kind of applications.

4.6 Summary

In this chapter, we have proposed a novel distributed energy-adaptive location-based cooperative MAC protocol for WANETs. By introducing DEL-CMAC, both energy advantage and location advantage can be exploited thus the network lifetime is extended significantly. We have also proposed an effective relay selection strategy to choose the best relay terminal and a cross-layer optimal power allocation scheme to set the transmitting power. Moreover, we have enhanced the spatial reuse to minimize the interference among different connections by using novel NAV settings. We have demonstrated that DEL-CMAC can significantly prolong the network lifetime

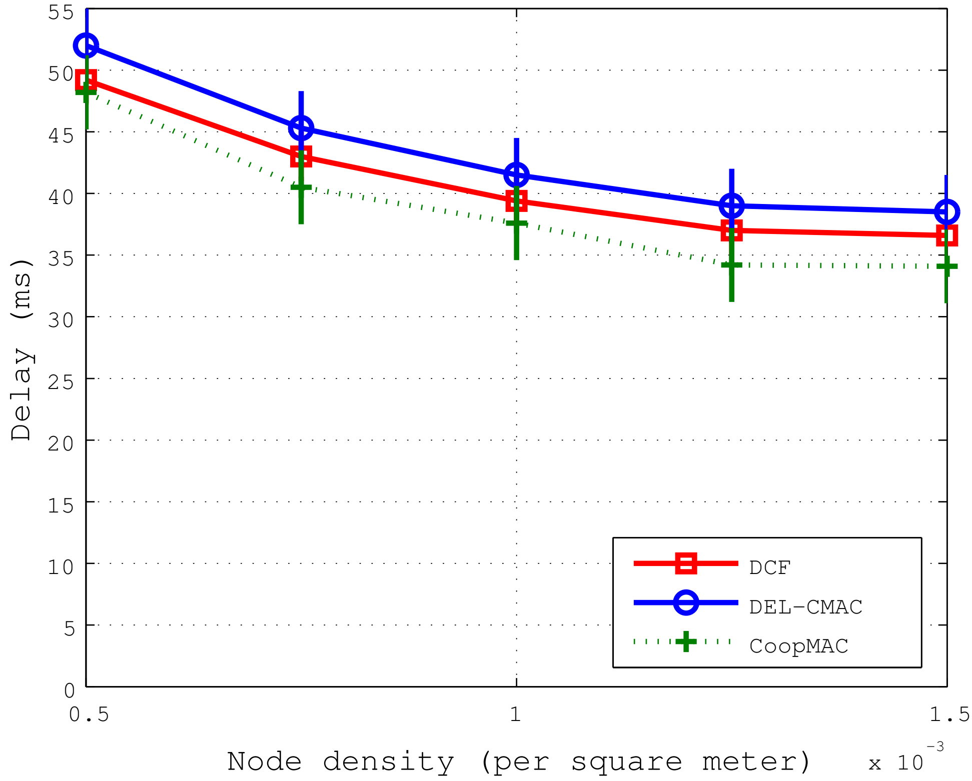

FIGURE 4.17: Delay performance versus the node density in static environment(with 95% confidence interval).

comparing with the IEEE 802.11 DCF and CoopMAC, at relatively low throughput and delay degradation cost.

As a future work, we will investigate our DEL-CMAC for larger scale network size and with high mobility. We will also consider to develop an effective cross-layer cooperative diversity-aware routing algorithm together with our DEL-CMAC to conserve energy while minimizing the throughput and delay degradation.

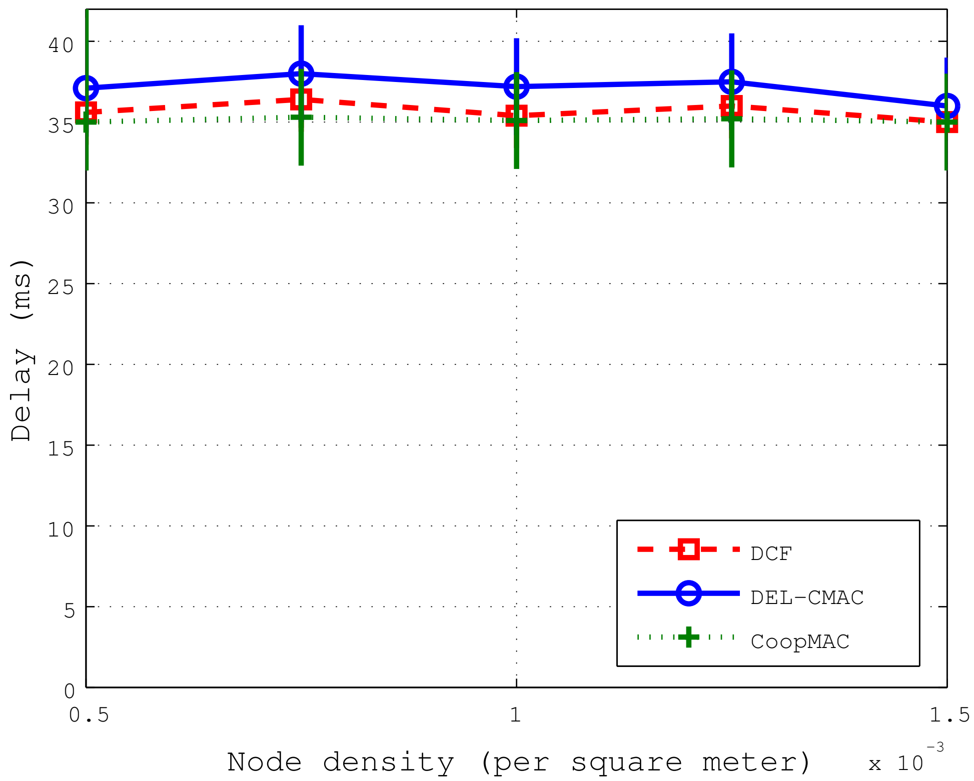

FIGURE 4.18: Delay performance versus the node density in mobile environment(with 95% confidence interval).

Chapter 5

Network Coding Aware CMAC Design for WANETs

In most of the wireless applications, the users are selfish and prefer to serve their own traffic prior to others. However, in cooperative communication, the relay nodes should help the source before delivering their own data. To enable a relay node to retransmit the data for the source node, while delivering its own data simultaneously, we introduce network coding technique into the cooperative communications in this chapter. To leverage the benefits brought by both of them, an efficient Medium Access Control (MAC) protocol is needed. In this chapter, we propose a novel network coding aware cooperative MAC protocol, namely NCAC-MAC, for wireless ad hoc networks. The design objective of NCAC-MAC is to increase the throughput and reduce the delay. Simulation results reveal that NCAC-MAC can improve the network performance under general circumstances comparing with two benchmarks.

This chapter is organized as follows. We introduce the related work and our contribution in Section 5.1. We present the preliminaries and main problems of HCNC based retransmission process in Section 5.2. In Section 5.3, we describe the proposed NCAC-MAC protocol in detail. We further develop two collision free relay selection strategies in Section 5.4 to improve the original NCAC-MAC on the relay selection process. Analysis and simulation results are addressed in Section 5.5. And finally Section 5.6 draws the conclusions and future work.

5.1 Introduction

Cooperative Communication (CC) has gained much interest recently as a new design paradigm to make terminals help each other in a distributed fashion so that the diversity gain is achieved via the user cooperation in wireless ad hoc networks. The broadcast nature of the wireless medium (the so-called wireless broadcast advantage) is exploited in cooperative fashion. The wireless transmission between a transmitter-receiver pair can be received and processed at neighboring nodes for performance gain, rather than be considered as the interference traditionally. Several replicas of the same data can be received at the destination node through different independent channels, which results in higher transmission rate, lower transmission delay, more efficient power consumption, or even increased coverage range.

Recently, extensive work on CC has been investigated in physical layer [10, 23, 24], and theoretic fields (including power allocation [30, 31], power saving [32], coverage expansion [33], topology control [34], relay selection and deployment [35–38]), while less attention has been devoted to the Medium Access Control (MAC) layer. However, without considering the MAC layer interactions due to cooperation, the gain through physical layer cooperation may not improve the performance. Since the communication overhead and collision induced by relaying are generally overlooked in the physical layer protocol design. An efficient and holistic Cooperative MAC (CMAC) protocol is required.

CMAC can generally be categorized into two classes: the proactive CMAC [45–49] and the reactive CMAC [50–52]. The proactive CMAC schemes trigger the relay selection process before the direct transmission. Thus, they introduce a constant overhead to all transmissions whatever the cooperative communication is needed or not. On the other hand, the reactive C-MAC schemes select the relay node only when the direct transmission fails. A disadvantage is that all the potential relay nodes have to listen to the transmission of the source node, which consumes additional energy. In this chapter, we focus on the reactive CMAC protocol which initializes the cooperative retransmission when the direct transmission fails. Most of the previous researches on reactive CMAC assume that the relay nodes are willing to help the source without pursuing their own interest (delivering their own data or getting rewarded). For majority of the wireless ad hoc network applications, however, the users are selfish and prefer to serve their own traffic prior to others.

In order to enable a relay node to retransmit the data for the source node, while delivering its own data simultaneously, Hybrid Cooperative Network Coding (HCNC) technique is becoming a growing concern in recent years. The key idea of HCNC is to employ the Network Coding (NC) technique [75, 76] into the cooperative transmission process and, gain the advantages of both NC and CC. Besides the related works on HCNC that focus on the information theoretic metrics or physical layer protocols [77–80], Munari *et al.* proposed a reactive CMAC policy, namely Phoenix [81], based on HCNC. By Phoenix, relay nodes can assist other nodes and serve their own traffics simultaneously during the retransmission processes. In Phoenix [81], the relay node is selected randomly. When the direct transmission fails, the neighboring node sensing free medium at the end of a random backoff time, wins the contention and performs the retransmission on behalf of the source node. Phoenix has the following drawbacks. (i) The coding opportunity is not guaranteed. Whether the randomly selected relay node holds the packets that can be coded with the retransmitting packet is uncertain. (ii) The multirate capability of the network is not exploited. Since nodes support different data rates depending on different channel conditions. Whether the randomly selected relay node is in the best channel condition that can transmit the coded packet with the maximum data rate to the destination is unsure. (iii) The packet queuing conditions at different relay candidates are not considered. In order to reduce the overall delay, the relay node with large queuing packets in the buffer should have a high priority to perform the coded retransmission.

To address the above issues and facilitate CC and NC on the MAC layer, in this chapter, we propose a novel *Network Coding Aware Cooperative Medium Access Control* (NCAC-MAC) protocol [15] based on IEEE 802.11 CSMA policy without channel negotiation. The contributions of this work are summarized as follows. (i) We propose a CMAC protocol based on HCNC, which coordinates the relay-involved cooperative coded retransmission process. (ii) We propose a network coding-aware utility-based best relay selection strategy. To the best of our knowledge, this is the first study on cooperative relay selection that takes the coding opportunity, achievable throughput and estimated delay into consideration. (iii) Instead of the simple utility-based backoff scheme, we further incorporate two collision free relay selection strategies to improve the relay selection process. (iv) We reveal that the proposed scheme can improve the throughput, delay and packet delivery ratio of the network comparing to the previous work.

5.2 Network Coding Meets Cooperative Communication

At first, we illustrate how the traditional cooperative retransmission (i.e., without network coding) works. Suppose that the source node A sends a packet x to the destination node B. Due to the broadcast nature of the wireless medium, some neighbor node (say node C) may decode x successfully. In the case of a failed transmission between nodes A and B (i.e., node B receives a corrupted version of x, say x'), node C can perform a retransmission on behalf of node A immediately. Cooperative retransmission significantly benefits from diversity gain, that is from transmission via multiple uncorrelated or loosely correlated channels. In such traditional scheme, however, the relay node helps the source node without serving its own traffic. Such a behavior requires the node to postpone its own queuing packets and thus, is not encouraged in a real network, especially under a heavy traffic scenario.

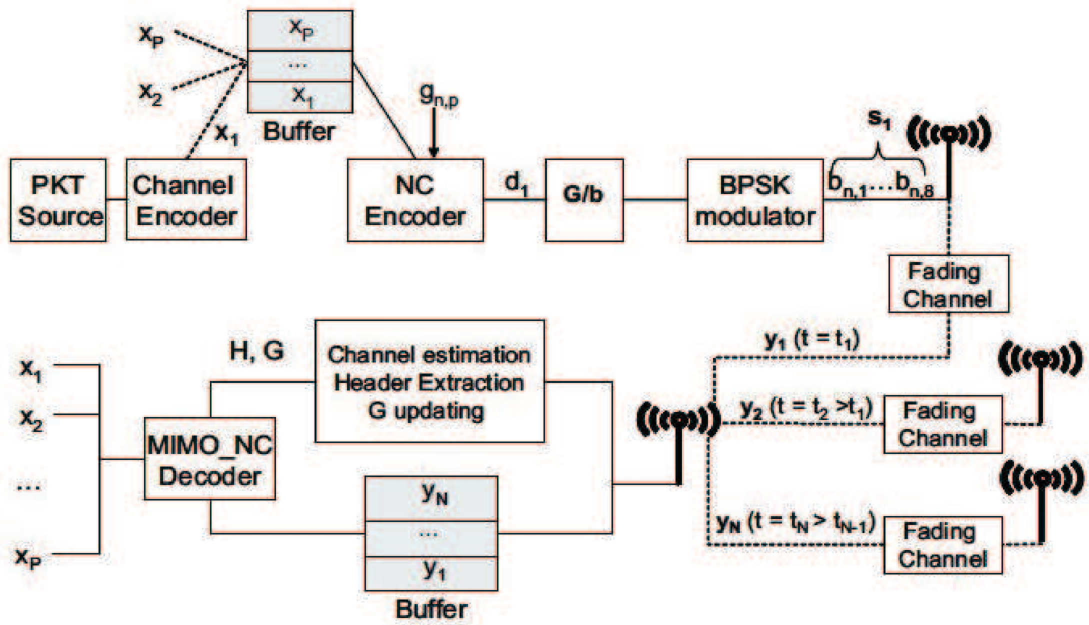

FIGURE 5.1: The MIMO_NC encoding/decoding procedure.

Then the following question is raised: is it possible to enable the relay node to help other nodes retransmit packet x, while delivering its own data y simultaneously? To solve the question, it is necessary to combine frames x and y (i.e., to $F(x, y)$) together. NC technique is very useful in this context [75], however, classical NC [76] shows a threshold behavior in the presence of packet losses. It cannot decode packets x and y from $F(x, y)$ and x', since to retrieve the P

original packets, it must have P linearly independent coded packets. To realize the network coding with corrupted packets, Fasolo *et al.* proposed an approach named MIMO_NC [82], which moves network coding functionalities towards the physical layer and designs a different decoding phase based on soft decoding rather than on the inversion of linear systems. By MIMO_NC, packets x and y can be retrieved by a corrupted packet x' and, an encoded packet $F(x, y)$ which is a linear combination of vectors in a Galois field according to NC principles. The complete flow of the encoding/decoding procedure is presented in Fig. 5.1. The details of the network coding scheme MIMO_NC is presented as follows, which are cited from [82].

- *Encoding*: The encoding phase starts at the channel encoder, where the MAC layer packets are coded. These bits are clustered into Galois symbols. The encoded PDUs are called Information Units (IUs). The number of available IUs is P, and the the IU symbols are denoted as $x_p^{(t)}$, where $1 \leq p \leq P$ is the packet index and t is the symbol index inside the packet. These IUs are linearly combined so as to create a Coded Packet (CP), whose Galois symbols are turned into bits, and the bits are modulated into BPSK symbols $b_n^{(t)}$.

- *Decoding*: The receiver performs coherent channel estimation and extracts the NC coefficients from the header. The receiver stores the packet into a buffer and updates its estimate of the G matrix. These CPs have been received in different times and from different sources. The number of received packets that can be used for detection is denoted as N. The received samples are gathered into column vectors of 8 elements y_n. The N vectors $y_j^{(t)}$ that belong to the same generation are stacked on top of each other, so as to build a $8N$ vector y. The channel matrix, G and y are passed to the MIMO_NC decoder. Let us focus on the $N = 2$ case for simplicity, and with no loss in generality. From now on we shall focus on a specific t, thus we shall drop the time index. Then the system to decode is:

$$\begin{pmatrix} y_1 \\ y_2 \end{pmatrix} = \begin{pmatrix} H_1 & 0 \\ 0 & H_2 \end{pmatrix} \begin{pmatrix} s_1 \\ s_2 \end{pmatrix} + \begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix}$$

  where H_n is the 8×8 identity matrix multiplied by h_n, s_n is the vector of 8 BPSK symbols that represents the Galois symbol d_n, and η_n is a vector of 8 independent Gaussian random variables with zero mean and variance σ^2. Therefore, for any combination of input Galois elements x_1, x_2, there is a well defined set of output modulated waveforms. The maximum likelihood criterion picks the x_1, x_2 that minimize the distance between the expected received symbols $[H_1 s_1(x_1, ..., x_p); H_2 s_2(x_1, ..., x_p)]$ and the actual samples y_1,y_2.

In summary, each node will collect the packets, decode the header, extract the NC coefficients and then keep the received soft samples. The node tries to decode as many transmitted packets as possible with the collected frames. Should it fail it will store the received samples and keep them so as to help the decoding of the next packets.

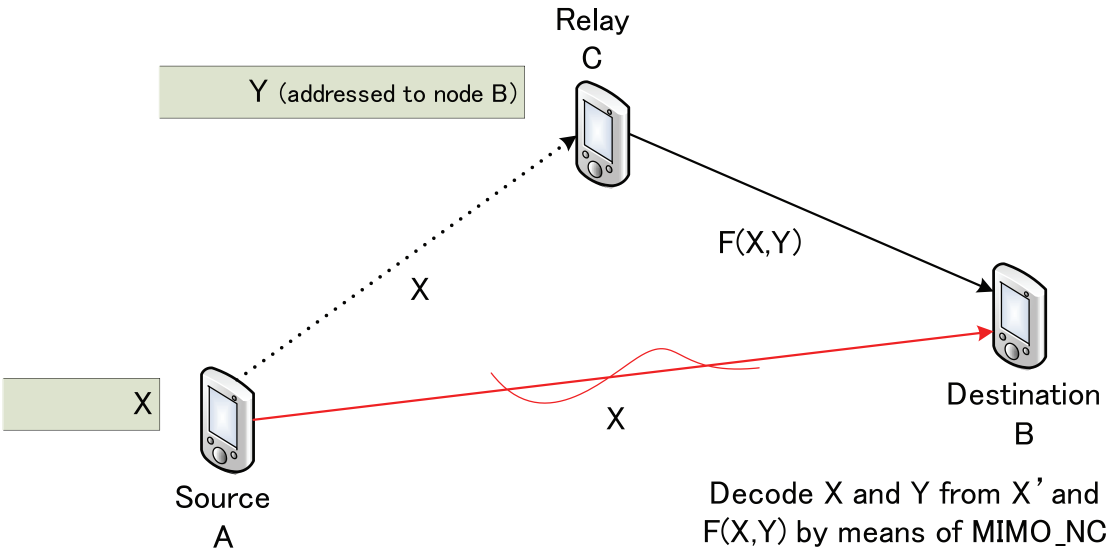

FIGURE 5.2: A scenario of HCNC based retransmission. Case (i): the packet y at the relay node has the same destination with the packet x from the source node.

With the support of MIMO_NC, the HCNC based retransmission can be realized. Under the condition that the transmission of packet x from node A to node B is failed, there are two cases in HCNC based retransmission, depending on the addressee of the packet to combine (say packet y) at the relay node C.

- *Case (i)*: As depicted in Fig. 5.2, node C has a packet y in its buffer, which is also addressed to node B. If the quality of the cached corrupted packet x' in node B is not too poor (i.e., the average Signal to Interference and Noise Ratio (SINR) is above a given threshold Λ_{th}), coded retransmission by means of MIMO_NC [82] can be supported. By MIMO_NC, the destination node has the capability to decode both x and y even if only the corrupted packet x' and the linear combination of x and y, i.e., $F(x,y)$, are available. Through HCNC, node C can forward $F(x,y)$ to node B instead of simply retransmitting x. It is straightforward that the throughput and average delay of the network can be substantially improved by HCNC in this case.

- *Case (ii)*: As depicted in Figs. 5.3 and 5.4, node C has no packet addressed to node B, but has a packet y to another node (say node D). In such a case, the appropriateness of HCNC depends on whether node D has cached packet x or not during the previous direct transmitting session.
  - *Case (ii)-1*: Node D has overheard and decoded x during the direct transmission (Fig. 5.3). Then, node C can retransmit $F(x,y)$ to serve nodes B and D once for all. Node B obtains x by decoding x' and $F(x,y)$ using MIMO_NC, and node D obtains y by decoding x and $F(x,y)$ using ordinary NC policy.
  - *Case (ii)-2*: Node D has not overheard and decoded x due to long distance or bad channel condition between nodes A and D (Fig. 5.4). Without x, node D would not be able to extract y from $F(x,y)$. Thus, node C cannot successfully serve its traffic by HCNC during the retransmission. In this case, node C should retransmit packet x directly.

Notice that the key issue in case (ii) is to judge whether node D (the addressee of packet y) has cached packet x or not. We denote this issue as *cached issue* in the chapter. In Phoenix, cached issue is solved by additional RTS/CTS exchange between nodes C and D and thus, generates undesired communication overheads and interference. In the NCAC-MAC, we utilize a connectivity table to predict the condition of node D in advance (addressed in Section 5.3.1.2).

5.3 The Proposed NCAC-MAC Protocol

In this section, we present the proposed NCAC-MAC protocol in detail. We introduce the frame exchanging process of NCAC-MAC first, and two collateral approaches: *Network Coding Supported-Cooperative Retransmission* (NCS-CR) and *Pure-Cooperative Retransmission* (P-CR) in the following subsections.

In order to take full advantages of NC and CC in wireless ad hoc networks, two ingredients are indispensable [81]. First, a physical layer protocol that can handle coded retransmission. As we mentioned in Section 5.2, HCNC technique, e.g., MIMO_NC [82] or others as [77], [78] can leverage incorrect received frames. Second, a MAC policy that can coordinate the cooperation process. In this chapter, we focus on the MAC layer protocol design, which is

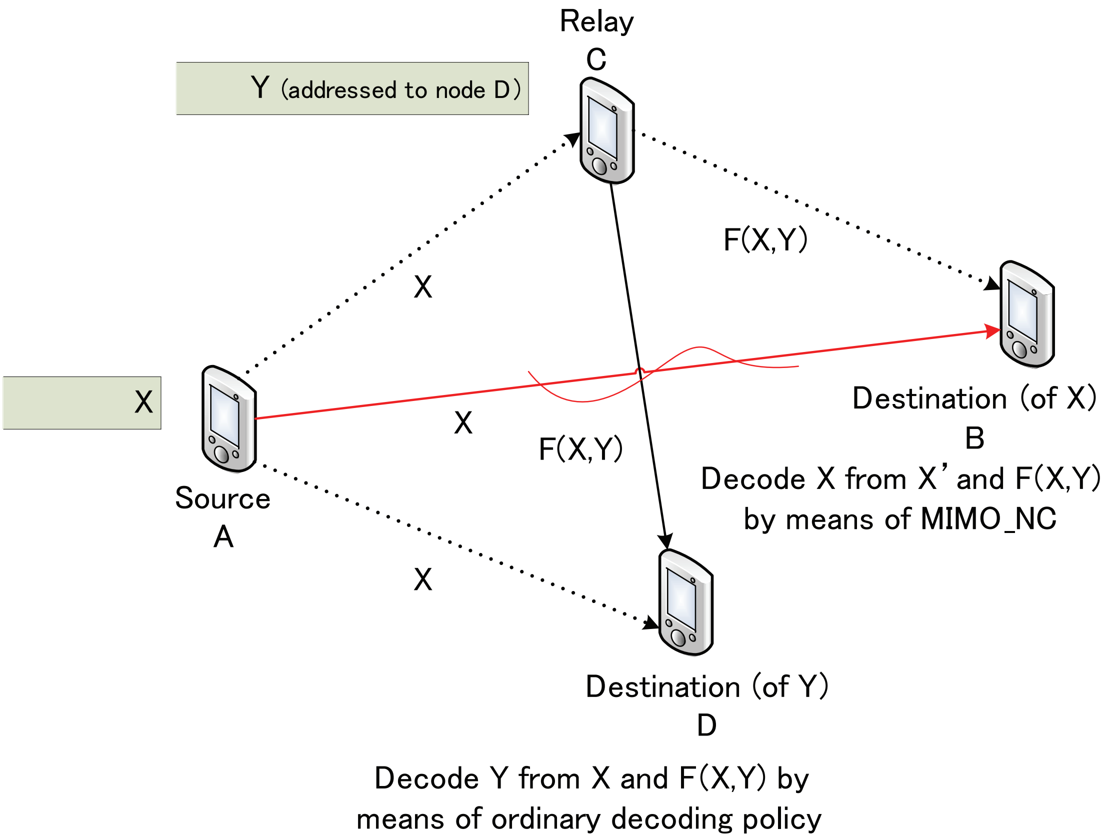

FIGURE 5.3: A scenario of HCNC based retransmission. Case (ii)-1: the packet y at the relay node has a destination (say node D) other than node B, and node D has cached packet x in the previous direct transmitting session.

critical to reap the performance gains brought from the physical layer. With the design objective of increasing the throughput and reducing the delay, we propose a novel HCNC based reactive CMAC policy, namely NCAC-MAC, based on the IEEE 802.11 CSMA policy without channel negotiation, for wireless ad hoc networks. We assume that the network consists of multiple wireless terminals having the same capability in terms of transmitting power, data rates and buffer size, which is a common assumption that can be found in many previous works [46, 47]. Besides the conventional ACKnowledgement (ACK) frame and Negative ACK (NACK) frame, a new control frame named *Eager-To-Help* (ETH) is introduced in our scheme to enable the efficient and distributed best relay selection.

The frame exchanging process of NCAC-MAC is depicted in Fig. 5.5. Before attempting to transmit, the source node checks the surrounding medium. If the channel is idle for a Distributed

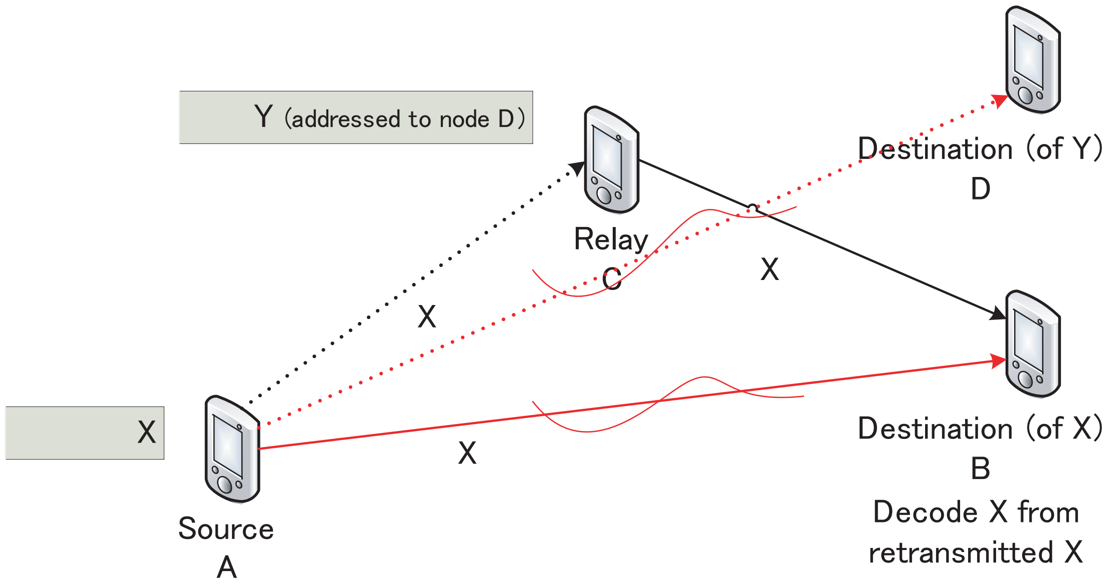

FIGURE 5.4: A scenario of HCNC based retransmission. Case (ii)-2: the packet y at the relay node has a destination (say node D) other than node B, but node D has not cached packet x in the previous direct transmitting session.

InterFrame Space (DIFS), the source node chooses a random backoff time between 0 and its contention window. Otherwise, the source node persists on monitoring the channel until it is idle. Once the backoff counter reaches zero, the packet (say payload x) will be transmitted. According to the packet reception at the destination node, the following processes are divided into four cases.

Case 1: the payload is decoded successfully. The destination node sends back an ACK frame, and the source node handles next packet in the buffer if any.

Case 2: the payload is corrupted but the received SINR is above the threshold Λ_{th}. The destination node sends back a NACK frame with the *SINR_FLAG* equal to 1, which indicates the coded retransmission can be supported. Nodes that receive the NACK and have correctly decoded packet x, are regarded as the relay candidates. The following processes are performed according to the collateral approach NCS-CR presented in Subsection 5.3.1.

Case 3: the payload is corrupted and the received SINR is below the threshold Λ_{th}. The destination node sets the SINR_FLAG of the NACK frame to 0. Coded retransmission is not

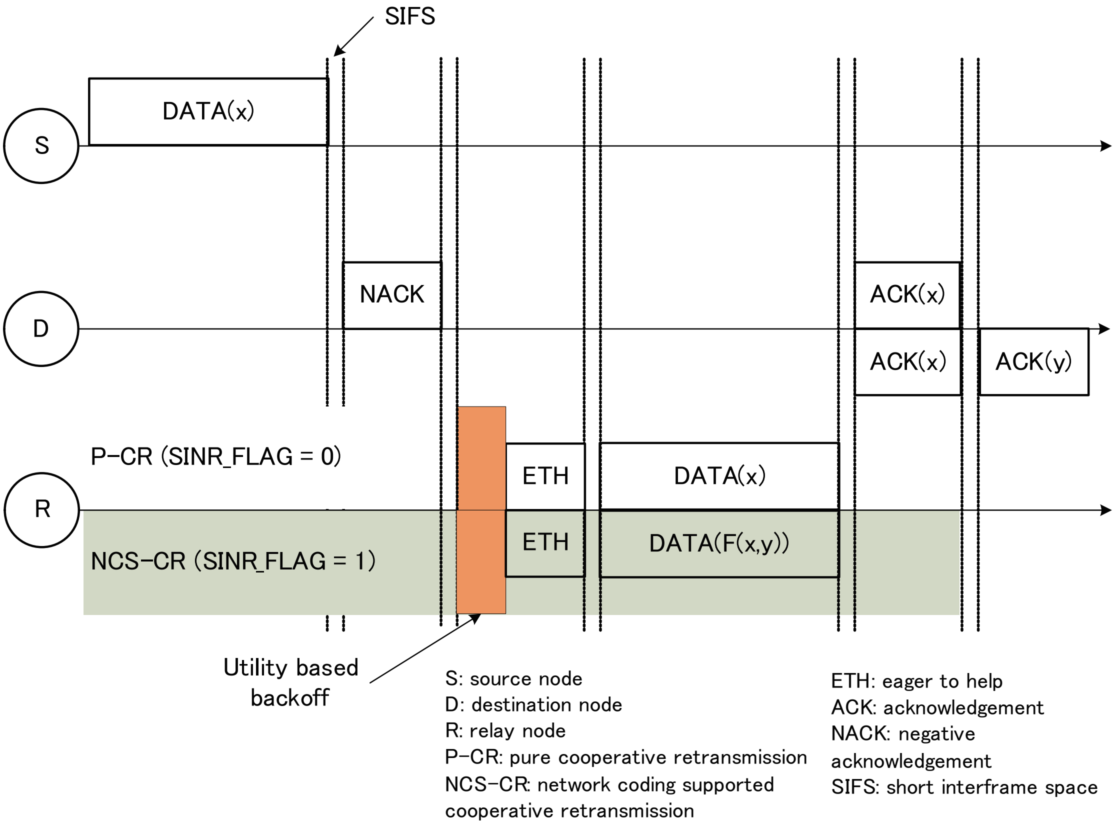

FIGURE 5.5: The frame exchanging process of NCAC-MAC, under the condition that the direct transmission of packet x fails.

encouraged due to the low SINR. The traditional cooperative retransmission is performed based on the collateral approach P-CR presented in Subsection 5.3.2.

Case 4: Both the payload and header are corrupted. The harsh channel conditions may lead to the loss of both payload and header. Due to the missing of the packet header, the destination node cannot gather any information to identify the source and request a retransmission. The only option is to let the source node timeout and restart the transmission.

5.3.1 Network Coding Supported-Cooperative Retransmission (NCS-CR)

When the SINR of the received corrupted packet x' is above the given threshold Λ_{th}, NCS-CR is performed to enable the relay node to retransmit the packet x for the source node while sending a packet y for its own simultaneously. In Phoenix [81], the relay node is selected by a random backoff scheme. To be specific, the node that wins the contention (the backoff counter reaches zero first) checks whether there exists a proper packet y in its buffer that can be combined with packet x. This random selection cannot guarantee the coding opportunity of the retransmission, since the relay node is determined before the coding check. In addition, Phoenix may cause additional RTS/CTS exchange, when the selected relay node has no packet addressed to the destination node but to other nodes (case (ii) in Section 5.2). As a matter of fact, the probability of case (ii) occurs is much higher than case (i). The relay selection strategy in NCS-CR, however, takes the coding opportunity, throughput and delay into consideration. It is performed in a distributed and efficient fashion, in which the node with the maximum utility value is allocated the minimum backoff time and thus, will be chosen as the relay node.

Any node that receives NACK and has correctly decoded packet x, can be regarded as a relay candidate. Upon receiving the NACK with SINR_FLAG equal to 1, each relay candidate starts a utility-based backoff to contend for the retransmission. Specifically, the relay candidate i calculates a utility value for every packet y queuing in its buffer (in the formulation, we consider the general case that the addressees of the individual queuing packets in the node are different), and the utility value of node i (denoted as U_i^{NCS}) is equal to the minimum one of them. The backoff time of node i (denoted as T_i^{NCS}) is inversely proportional to its utility value as

$$T_i^{NCS} = \frac{C}{U_i^{NCS}}, \tag{5.1}$$

where

$$U_i^{NCS} = \min_{y=1,2,\cdots L_i} \Big(\rho_y \cdot (\beta \cdot (S_{i,y} / S^{max}) + L_i / L^{max})\Big). \tag{5.2}$$

Here, L_i is the number of the packets queuing in the buffer at node i, L^{max} is the length of the buffer. $S_{i,y}$ is the estimated throughput for packet y, S^{max} is the upper bound for the estimated throughput. ρ_y $(0 \leq \rho_y \leq 1)$ is the probability that the addressee of packet y already has cached packet x. And constants C and β are the constant time and throughput weight, respectively. Notice that for every node i, L_i, $S_{i,y}$ and ρ_y vary depending on the individual conditions, and L^{max}, S^{max}, C and β are constant and identical since all the nodes have the same capability. Each relay candidate contends for the best relay with the same parameter settings, in terms of L^{max}, S^{max}, τ and β. Intuitively, high estimated throughput, large number of queuing packets and high cached probability lead to short backoff time. In addition, if there exist multiple packets having the same utility value in node i, for the sake of fairness, the packet in the front of the buffer is preferable. Next, we show how to calculate the estimated throughput $S_{i,y}$ and the cached probability ρ_y, respectively.

5.3.1.1 Estimated Throughput

Remind that HCNC based retransmission can be categorized into two cases as we addressed in Section 5.2. Depending on the addressee of the packet y queuing in the buffer at the relay node, $S_{i,y}$ can be calculated as

$$S_{i,y} = \begin{cases} S_{ij} & D(y) = j \\ \min(S_{ij}, S_{iD(y)}) & \text{otherwise.} \end{cases} \tag{5.3}$$

In case (i), the addressee of queuing packet y (denote as $D(y)$) is the same as the addressee of retransmitted packet x (denote as j). Thus, the estimated throughput over link (i, j) is employed when we calculate $S_{i,y}$. In case (ii), $D(y)$ is a node other than j, the minor estimated throughput between links (i, j) and $(i, D(y))$ is utilized. Since the throughput over a given link is defined as

Table 5.1: Relation between data rates and ranges

Data rate	11Mbps	5.5Mbps	2Mbps
Range	48.2m	67.1m	74.7m

the number of successfully transmitted bits per second. The throughput over a given link (i, j), S_{ij}, can be calculated as

$$S_{ij} = p^s_{ij} \times R_{ij}, \tag{5.4}$$

where p^s_{ij} and R_{ij} are the probability of success transmission and the data rate, respectively. Three different data rates are considered in this work, i.e., 11, 5.5 and 2 Mbps. Data rates that the link can support are generally adapted depending on the distance between the sender and the receiver. We assume that the distance or location information can be obtained by hardware (GPS) or computation (localization algorithm). The relation between the rates and the ranges is shown in Table 1, which is set according to [45].

In this work, we assume that the link is subject to Rayleigh fading, and the noise components are modeled as Additive White Gaussian Noise (AWGN). The mutual information of two random variables is defined as a quantity that measures the mutual dependence of the two variables.

For wireless communication, the mutual information between nodes i and j is formulated by

$$I_{ij} = \log_2\left(1 + \frac{P_i d_{ij}^{-\alpha} \left|h_{ij}\right|^2}{N_0}\right), \tag{5.5}$$

where P_i is the transmitting power at node i, d_{ij} is the distance between nodes i and j, α is the path loss exponent, h_{ij} is the channel fading gain between two terminals and N_0 is variance of the noise component. $\frac{P_i d_{ij}^{-\alpha}|h_{ij}|^2}{N_0}$ denotes the Signal-to-Noise Ratio (SNR). Notice that in Eqn. (5.5), without loss of generality, the unit bandwidth is assumed.

Outage event is defined as the set of channel realizations that cannot support reliable transmission rate R_{ij}. Thus outage probability is calculated as

$$p_{ij}^o = \mathcal{P}\left(I_{ij} < R_{ij}\right), \tag{5.6}$$

where R_{ij} denotes the reliable transmission rate between nodes i and j. Substituting Eqn. (5.5) into Eqn. (5.6), we obtain

$$p_{ij}^o = \mathcal{P}\left(\left|h_{ij}\right|^2 < \frac{\left(2^{R_{ij}} - 1\right) N_0 d_{ij}^{\alpha}}{P_i}\right). \tag{5.7}$$

Based on the assumption that the channel coefficient h_{ij} follows the Gaussian zero mean distribution, $\left|h_{ij}\right|^2$ can be modeled as the exponential random variable. Utilizing the probability density function of $\left|h_{ij}\right|^2$, Eqn. (5.7) is converted to

$$\begin{aligned} p_{ij}^o &= \int_0^{\left(2^{R_{ij}}-1\right)N_0 d_{ij}^{\alpha}/P_i} \exp\left(-\left|h_{ij}\right|^2\right) d\left(\left|h_{ij}\right|^2\right) \\ &= 1 - \exp\left(-\frac{\left(2^{R_{ij}} - 1\right) N_0 d_{ij}^{\alpha}}{P_i}\right). \end{aligned} \tag{5.8}$$

Then, the probability of success transmission, p_{ij}^s can be obtained by $1 - p_{ij}^o$, and expressed as

$$p_{ij}^s = \exp\left(-\frac{\left(2^{R_{ij}} - 1\right) N_0 d_{ij}^{\alpha}}{P_i}\right). \tag{5.9}$$

We observe that S_{ij} is upper bound by R^{max}, which is equal to 11 Mbps in this work. Notice that to estimate the throughput, the distances between the relay node and the addressees of the queuing packets in it is needed. This information is conserved in a connectivity table, which is addressed in the following subsection.

5.3.1.2 Cached Probability

As mentioned in Section 5.2, for HCNC based retransmission, the key issue in case (ii) is the so called cached issue. Take an instance that depicted in Figs. 5.3 and 5.4, cached issue is to judge whether the addressee of packet y that queuing at the relay node (node D), has cached packet x (the retransmitted packet) or not. Thus, obtaining the condition of node D in terms of whether cached packet x is critical. In Phoenix, the relay node C transmits a RTS to node D, and node D replies with a CTS only if the RTS is decoded and the node has in its cache either a correct copy of x or a corrupted version with SINR above threshold Λ_{th}. This RTS/CTS exchanging process leads to additional communication overhead and may cause undesired interference.

In order to solve the cached issue in an efficient way, in NCAC-MAC, we utilize a connectivity table for each node to estimate the cached probability. The connectivity table stores the connectivity information for itself and its one-hop neighbors. The distances and corresponding channel capacities over the links between itself and its neighbors, and the links between the neighbors and their corresponding neighbors (neighbors' neighbors) are stored in each node. Let us take the scenario depicted in Figs. 5.3 and 5.4 for an instance. Whether node D has cached packet x is determined by the channel condition over link (A, D). Given that node C has correctly decoded x already, the cached probability ρ_y for node D is high if the capacity over link (A, D) is better than the one over link (A, C). This comparison can be easily done by looking up the connectivity table at node C. As the routing table that used in routing protocol, the connectivity table is created at the network initialization phase. In this chapter, we focus on the static network. For the network with low mobility, our scheme can still work by updating the table periodically or reactively. However, for the network with high mobility, the connectivity table may estimate the distance and capacity inaccurately, which affects the performance of the proposed scheme. Solving the cached issue in a high mobility network is beyond the scope of this work, we will consider it as the future work.

We define the cached probability ρ_y as follows:

$$\rho_y = \begin{cases} 1 & D(y) = j, \\ \rho_{high} & C(source, D(y)) \geq C(source, relay), \\ \rho_{low} & \text{otherwise.} \end{cases} \quad (5.10)$$

In Eqn. (5.10), there are three different conditions. (i) The addressee of packet y is the same as the addressee of packet x, thus the cached probability is 100%. (ii) The capacity of the link over the source and addressee of packet y, i.e., C(source,D(y)), is better or equal than the one over the source and relay, i.e., C(source,relay). In this condition, the addressee of packet y has cached packet x with quite high probability. (iii) Otherwise, the cached probability is considerably low.

The values of ρ_{high} and ρ_{low} are set based on the following analysis. Notice that there are three factors in Eqn. (5.2), i.e., cached probability ρ_y, estimated throughput $S_{i,y}$, and number of queuing packets L_i. Among the three factors, the most important element we considered is the cached probability ρ_y. Since the coded retransmission is always preferable than the ordinary retransmission. And the coded retransmission can be performed only if a high cached probability can be guaranteed. Thus, we give the relay node with high cached probability a high priority to access the channel, regardless of the values of $S_{i,y}$ and L_i. Consider a boundary case that relay node A has maximum $S_{i,y}$ and L_i but low cached probability, and relay node B has minimum $S_{i,y}$ and L_i but high cached probability. We choose relay node B to retransmit the packet on behalf of the source. Since for node A, the coded retransmission cannot be guaranteed even though the $S_{i,y}$ and L_i are maximum. Thus, the principle of setting the values of ρ_{low} and ρ_{high} is

$$\begin{aligned} &\rho_{low} \cdot (\beta \cdot (S^{max} \,/\, S^{max}) + L^{max} \,/\, L^{max}) \\ &\qquad < \rho_{high} \cdot (\beta \cdot (S^{min} \,/\, S^{max}) + L^{min} \,/\, L^{max}). \end{aligned} \quad (5.11)$$

Substituting the parameter settings in Table 2 into the equation, we have $\rho_{low} \cdot ((1.25 \times 1) + 1) < \rho_{high} \cdot ((1.25 \times 2/11) + 1/20)$. Thus, the requirement becomes $\rho_{low}/\rho_{high} < 61/495$. According to the analysis above, in the simulation, we set ρ_{low} and ρ_{high} to 0.1 and 0.9, respectively.

Substituting the estimated throughput and cached probability obtained above into Eqn. (5.2), every relay candidate can easily calculate a backoff time individually. The node whose backoff timer expires first, claims to be the relay node by sending an ETH frame. The other relay candidates give up the contention as soon as they hear the ETH. After a duration of Short InterFrame

Space (SIFS), the selected relay node broadcasts a combination of packets x and y, to node j and node $D(y)$ (if $D(y) \neq j$). Upon successfully decoding packets x and y, nodes j and $D(y)$ send ACK frames back to the source node and relay node, respectively. By NCS-CR, the coding opportunity of the retransmission can be guaranteed, and the node with high estimated throughput and large number of backlogged queuing packets will be selected as the relay node.

5.3.2 Pure-Cooperative Retransmission (P-CR)

When the SINR of the received corrupted packet x' is below the given threshold Λ_{th}, the requirement of HCNC cannot be satisfied. Therefore, P-CR is employed in which the packets queuing in the buffer at relay node cannot be served during the retransmission process.

Upon receiving the NACK with SINR_FLAG equal to 0, each relay candidate contends for the relay node using a utility-based backoff time given by

$$T_i^P = \frac{C}{U_i^P}, \tag{5.12}$$

where

$$U_i^P = \beta \cdot (S_{ij} \, / \, S^{max}) + d^{min} \, / \, d_i. \tag{5.13}$$

Here, d_i is the estimated delay at node i, and d^{min} is the lower bound of the estimated delay. Same as to Eqns. (5.1) and (5.2), $S_{i,y}$ and d_i vary depending on the condition of individual nodes, and S^{max}, d^{min}, C and β are constant and identical for all the nodes. In P-CR, each relay candidate also contends for the best relay with the same parameter settings. The node with high estimated throughput and short estimated delay, i.e., with large utility value, will be selected as the relay node.

The relay node postpones all the packets queuing in its buffer when it serves the source node in P-CR. Thus, small estimated delay is preferable in P-CR. The estimated delay d_i is defined as the summation of medium access delay for all the packets queuing in the buffer at node i, and retransmitting time for the corrupt packet on behalf of the source by node i. The expression of estimated delay at relay node i is given as

$$d_i = \sum_{y=1}^{L_i} E_{iD(y)}^{R_{iD(y)}}(MAC) + E_i^{R_{ij}}(RET), \tag{5.14}$$

where y is the queuing packets at relay node i (from 1 to L_i). The first term $\sum_{y=1}^{L_i} E_{iD(y)}^{R_{iD(y)}}(MAC)$ denotes the sum of the medium access delay for every packet y (from node i to node $D(y)$ with data rate $R_{iD(y)}$) queuing in node i. And the second term $E_i^{R_{ij}}(RET)$ denotes the additional time for retransmitting the packet x on behalf of the source node. Notice that the two terms are independent. $E_i^{R_{ij}}(RET)$ can be calculated as

$$E_i^{R_{ij}}(RET) = T(ETH) + T_i^{R_{ij}}(DAT) + T(ACK) + 2SIFS + 3\delta, \tag{5.15}$$

where δ is the maximum propagation delay. Notice that d_i is lower bounded by the minimum estimated delay d^{min} when there is no queuing packet at node i. d^{min} is equal to $E_i^{(11Mbps)}(RET)$.

The calculation of the medium access delay for the queuing packets is based on the state transition, instead of the commonly used queuing theory as in [83]. Since the queuing theory can provide the analysis of the mean or distribution of the queuing delay for the whole network, but not the exact value for different relay nodes. In our scheme, a transmitting packet has three states: *arrival*, *backoff* and *freeze*. Fig. 5.6 shows the flow chart of the state transition for a transmitting packet. When the packet arrives (arrival state), if the surrounding medium is idle for DIFS, node i enters into the backoff state, otherwise, it enters into the freeze state. Thus, the medium access delay of a packet y is expressed as the sum of the time consumed in these two states, as

$$\begin{aligned} E_{iD(y)}^{R_{iD(y)}}(MAC) &= \mathcal{P}_i(AB) \cdot (DIFS + E_{iD(y)}^{R_{iD(y)}}(BAK)) \\ &+ \mathcal{P}_i(AF) \cdot (DIFS + E_{iD(y)}^{R_{iD(y)}}(FRZ)), \end{aligned} \tag{5.16}$$

where $E_{iD(y)}^{R_{iD(y)}}(BAK)$ is the estimated time consumed in backoff state, $E_{iD(y)}^{R_{iD(y)}}(FRZ)$ is the additional delay accumulated in freeze state. $\mathcal{P}_i(AB)$ and $\mathcal{P}_i(AF)$ are the probabilities of state transition from arrival to backoff and from arrival to freeze, respectively.

To formulate the estimated delay, we should consider the randomness of both packet arrival rate and service time. Using the most common description of Poisson statistics, the probability of exactly n packets arriving during time interval t is

$$p^n(t) = \frac{(\lambda t)^n}{n!} e^{-\lambda t}, \tag{5.17}$$

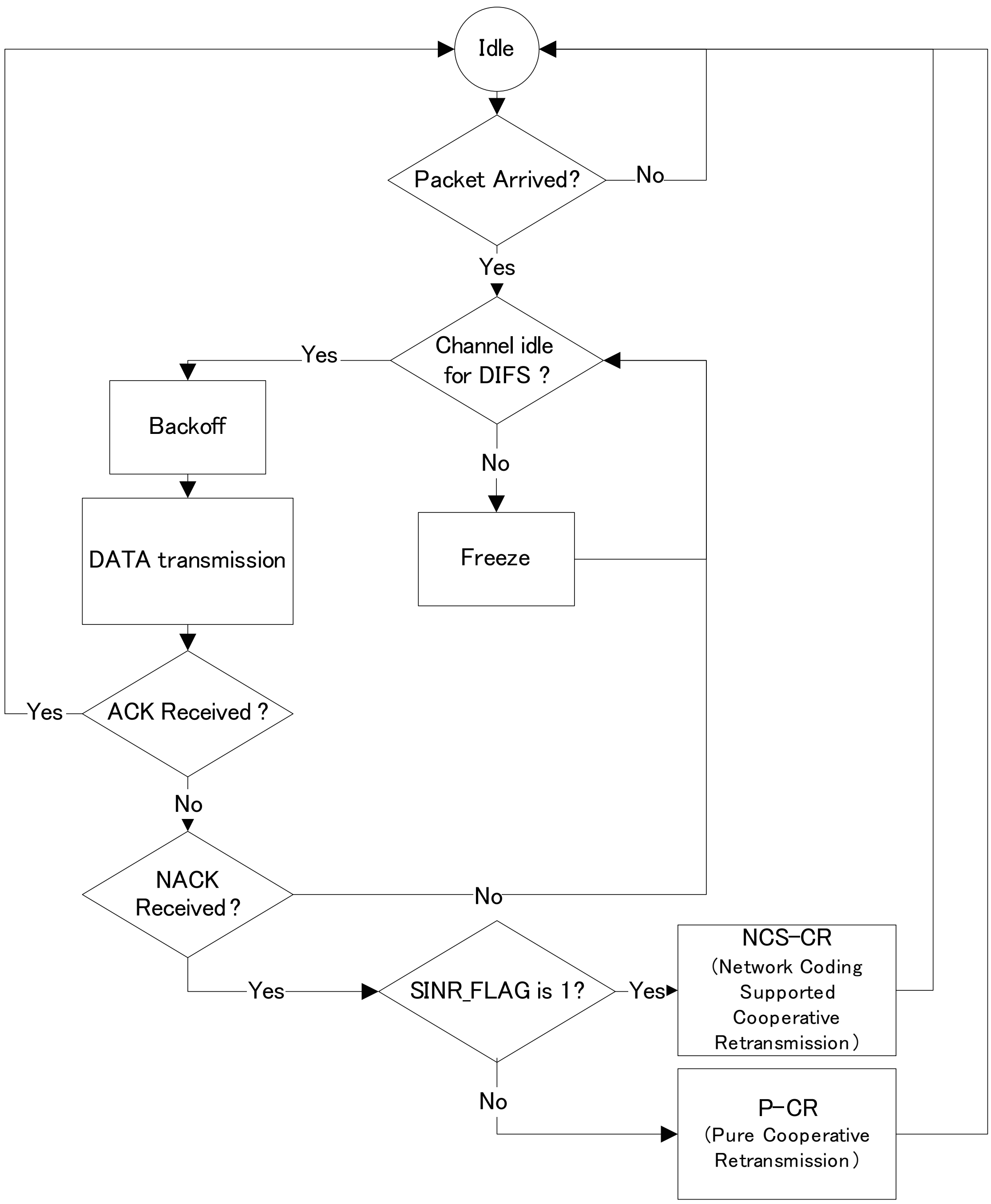

FIGURE 5.6: Flow chart of the state transition for a transmitting packet.

where λ is the mean packet arrival rate. Hence, the probability of channel is idle for time interval t can be derived by

$$p_i^{idle}(t) = e^{-\lambda(i)t}, \tag{5.18}$$

where $\lambda(i)$ is the total packet arrival rates within the transmission range at node i. $\lambda(i)$ is equal to $|NB_i| \cdot \lambda$, where $|NB_i|$ is the number of neighbors of node i. Using $p_i^{idle}(t)$, $\mathcal{P}_i(AB)$ and $\mathcal{P}_i(AF)$ in Eqn. 5.16 can be easily expressed as

$$\mathcal{P}_i(AB) = p_i^{idle}(DIFS) = e^{-\lambda(i)DIFS}, \tag{5.19}$$

$$\mathcal{P}_i(AF) = 1 - \mathcal{P}_i(AB) = 1 - e^{-\lambda(i)DIFS}. \tag{5.20}$$

The estimated time consumed in backoff state can be calculated by

$$E_{iD(y)}^{R_{iD(y)}}(BAK) = T_i^{R_{iD(y)}}(DAT) + T(ACK) + SIFS + 2\delta + \overline{B}. \tag{5.21}$$

The average random backoff time $\overline{B}$ is given by [84], as:

$$\begin{aligned}\overline{B} = \textstyle\sum_{n=0}^{N-1} &\left(p_i^{idle}(\eta)(1 - p_i^{idle}(\eta))^n \cdot 2^{n-1} W^{min}\right) \\ &+ (1 - p_i^{idle}(\eta))^N \cdot 2^{N-1} W^{min},\end{aligned} \tag{5.22}$$

where η is the time slot, W^{min} is the minimum backoff window size and N equal to $\log_2 (W^{max}/W^{min})$. Notice that in Eqn. (5.21) we use an optimistic estimation for the transmission time based on the assumption that no retransmission occurs.

On the other hand, the accumulated delay in freeze state $E_{iD(y)}^{R_{iD(y)}}(FRZ)$ is

$$\begin{aligned}E_{iD(y)}^{R_{iD(y)}}(FRZ) = &\mathcal{P}_i(FF) \cdot (DIFS + E_{iD(y)}^{R_{iD(y)}}(FRZ)) \\ &+ \mathcal{P}_i(FB) \cdot (DIFS + E_{iD(y)}^{R_{iD(y)}}(BAK)),\end{aligned} \tag{5.23}$$

where $\mathcal{P}_i(FF)$ and $\mathcal{P}_i(FB)$ denote the probabilities of staying in freeze state and transmitting from freeze state to backoff state, respectively. These probabilities are calculated by $\mathcal{P}_i(FB) = e^{-\lambda(i)DIFS}$ and $\mathcal{P}_i(FF) = 1 - \mathcal{P}_i(FB)$.

Substituting Eqn. (5.21) into Eqn. (5.23) leads to

$$\begin{aligned} E_{iD(y)}^{R_{iD(y)}}(FRZ) = &\frac{DIFS}{\mathcal{P}_i(FB)} + T_i^{R_{iD(y)}}(DAT) + T(ACK) \\ &+ SIFS + 2\delta + \overline{B}. \end{aligned} \tag{5.24}$$

Therefore, we can simplify Eqn. 5.16 into

$$\begin{aligned} E_{iD(y)}^{R_{iD(y)}}(MAC) = &\frac{DIFS}{\mathcal{P}_i(AB)} + T_i^{R_{iD(y)}}(DAT) + T(ACK) \\ &+ SIFS + 2\delta + \overline{B}. \end{aligned} \tag{5.25}$$

Finally, the estimated delay of node i can be expressed by

$$\begin{aligned} d_i = &\textstyle\sum_{y=1}^{L_i} T_i^{R_{iD(y)}}(DAT) + T_i^{R_{ij}}(DAT) + T(ETH) \\ &+ (L_i + 1) \cdot T(ACK) + \frac{L_i}{\mathcal{P}_i(AB)} \cdot DIFS \\ &+ (L_i + 2) \cdot SIFS + (2L_i + 3) \cdot \delta + L_i \cdot \overline{B}. \end{aligned} \tag{5.26}$$

Notice that in Eqn. (5.16), we do not take the possible retransmission of queuing packet y into account. Predicting the possible retransmission of the queuing packets is difficult, since the failed transmission may caused by bad channel condition or collision due to hidden terminal problem. We consider that in our utility function, the optimistic estimation of d_i is sufficient and fair enough to represent the condition at individual relay nodes.

The relay candidate with the minimum backoff time Tu_i^P wins the contention, and is selected as the relay node. After sending an ETH frame, it helps the source node by retransmitting the packet x to the destination. Upon correctly decoding the packet, the destination node sends an ACK frame back to the source node.

The utility functions in both NCS-CR and P-CR are easy to calculate and implement. The computation complexity is considerably low, thus we consider the proposed scheme is practical for most of the wireless terminals.

5.3.3 Throughput Analysis

For a better understanding, we give the throughput analysis of NCAC-MAC based on the analytical approach in [85]. To compute throughput S, firstly we need to calculate the probability of successful transmission by NCAC-MAC, which is given by

$$P_s = P_{sd} + (1 - P_{sd})P_{sr}P_{rd}, \tag{5.27}$$

where P_{sd}, P_{sr} and P_{rd} represent the link success probabilities of the source-destination, source-relay and relay-destination links, respectively. Next, for n active nodes, the probability that at least one node transmits is given by

$$P_{tr} = 1 - (1 - \tau P_s)^n, \tag{5.28}$$

where τ is the probability of each node transmits, whose expression can be found in [86]. Then, the probability of successful transmission, given that at least one node transmits, is given by

$$P_{trs} = n\tau(1 - \tau P_s)^{n-1}/P_{tr}. \tag{5.29}$$

Based on [85], the saturation throughput for NCAC-MAC can be expressed as

$$S = \frac{P_{tr}P_{trs}P_sE(payload)}{(1 - P_{tr})\eta + P_{tr}(1 - P_{trs})T_c + P_{tr}P_{trs}(T_s + T_f)}, \tag{5.30}$$

where $E(payload)$ is the average payload size, η is the time slot size, T_c is the average time due to collision, T_s is the average successful transmission time and T_f is the average failure time due to fading. In NCS-CR case, $E(payload)$ is equal to $P_{sd}W + (1 - P_{sd})2W$, while in P-CR case, $E(payload)$ is W, where W is the data payload length. In Eqn. (5.30), T_c is calculated as $W/R + DIFS + bo_f + SIFS$, where bo_f is the average backoff interval for failed transmission, whose calculation is given in [85]. T_s is expressed as

$$\begin{aligned} T_s = P_{sd}(T_c + bo_s + T(ACK)) + (1 - P_{sd})P_{sr}P_{rd}(T_c + bo_s + \\ T(NACK) + T_{ub} + T(ETH) + W/R^* + 2T(ACK) + 4SIFS), \end{aligned} \tag{5.31}$$

where bo_s is the average backoff interval for success transmission, T_{ub} is the utility-based backoff time in NCAC-MAC, R^* is the data rate used by the selected relay node, and T_c is $DIFS + W/R + SIFS$. Similarly, we can obtain T_f as

$$\begin{aligned} T_f = (1 - P_{sd})P_{sr}(1 - P_{rd})(T_c + bo_f + T(NACK) \\ + T_{ub} + T(ETH) + W/R^* + 2SIFS). \end{aligned} \tag{5.32}$$

Plugging calculated T_c, T_s and T_f into Eqn. (5.30), we can obtain the saturation throughput for NCAC-MAC.

5.4 Collision Free Relay Selection Strategies

In Section 5.3, the backoff time of the individual relay node varies inversely with its utility value. Thus, close utility value leads to similar backoff time and collision of the ETH and data frames. In the case of failure relay selection, the performance in terms of throughput and delay will considerably decrease. The collision probability can be depressed by raising the value of constant time C in Eqns. (5.1) and (5.12). However, large C postpones the time to find out the best relay node, which is inefficient and inadvisable. It is highly desirable that the process of relay selection is fast, decentralized and collision free. To achieve this goal, we consider to incorporate two attractive relay selection strategies, namely Group Contention-based Relay Selection (GC-RS) and Splitting Algorithm-based Relay Selection (SA-RS), into the NCAC-MAC scheme.

5.4.1 Group Contention-based Relay Selection (GC-RS)

In this subsection, we refer to an inter-intra group contention scheme proposed in [48], and modify it to GC-RS which is suitable for NCAC-MAC. In GC-RS, each relay candidate contends for retransmitting through three contention periods, i.e., inter-group contention, intra-group contention and re-contention (if necessary). The frame exchanging process is depicted in Fig. 5.7. The operation in each period is addressed in the following subsections.

5.4.1.1 Inter-group Contention

Upon receiving the NACK frame, all the relay candidates enter into the inter-group contention period. We evenly partition the inter-group contention period into G groups. Each relay candidate calculates its *group index* g $(0 \leq g \leq G-1)$ as follows

$$g = \left\lfloor \frac{G \cdot (U_{max} - U_i)}{U_{max} - U_{min}} \right\rfloor, \tag{5.33}$$

where U_i is the utility value of node i (U_i^{NCS} in NCS-CR or U_i^P in P-CR), U_{max} and U_{min} are the upperbound and lowerbound for the utility function (U_{max}^{NCS} and U_{min}^{NCS} for NCS-CR, or U_{max}^P and U_{min}^P for P-CR, respectively). $\lfloor x \rfloor$ is a floor function that maps x to the largest integer less than or equal to x. Utilizing Eqn. (5.33), each relay candidate obtains the group index distributively, which is inversely proportional to its utility value. Node with low group index is assigned a high priority to access the channel.

The nodes with group index g backoff for a period of time $T_{fb}(g) = g \cdot t_{fb}$, where t_{fb} is referred to as the backoff time slot. If no Group Indicator (GI) is overheard from lower index groups, the nodes in group g send GIs and enter into intra-group contention period. Thus, only the nodes with the lowest group index will keep contending in the next period, and the others quit the contention and keep silence.

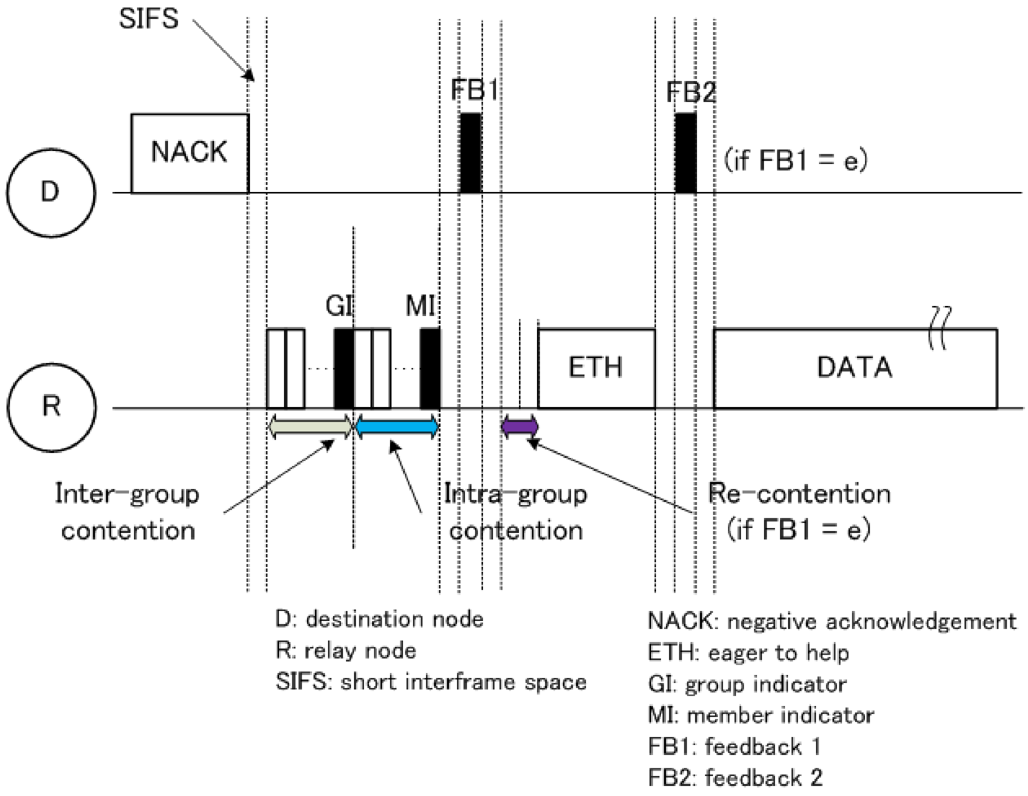

FIGURE 5.7: Group Contention-based Relay Selection Strategy

5.4.1.2 Intra-group Contention

Only the nodes have sent GI in the inter-group contention period will keep competing in the intra-group contention. Similarly, we evenly divide the intra-group contention period into M time slots. Each relay node in the selected group g calculates its *member index* m ($0 \leq m \leq M-1$) as

$$m = \left\lfloor \frac{GM \cdot (U_{max} - U_i)}{U_{max} - U_{min}} - gM \right\rfloor. \tag{5.34}$$

If a relay node with group index g and member index m does not overhear any Member Indicator (MI) during time $T_{fb}(g, m) = m \cdot t_{fb}$, it sends out a MI immediately.

There are two possible outcomes after the intra-group contention ends. The first outcome is that single relay node sends MI. In the case that there is only one node with group index g and member index m, the destination node sends out a feedback signal (denoted as FB1) equal to 1. Upon receiving FB1, the selected relay node broadcasts an ETH frame after SIFS, and performs the retransmission immediately. The second outcome is that multiple relay nodes send MIs. In the case that more than one relay node (denoted as collided optimal relay nodes) lie in the same intra-group time slot, re-contention is necessary.

The inter-intra group contention based strategy assures that the utility value(s) of the selected node(s) is(are) larger than that of any other nodes failed in the contention.

5.4.1.3 Re-contention

Since the utility values of the collided optimal relay nodes are quite close to each other, the performance gains achieved by them are similar. In the case of two or more relay nodes send MIs in the same time slot, we employ a re-contention period to randomly select a best relay node among the collided optimal relay nodes. Upon receiving the FB1 equal to e from the destination node, each collided optimal relay node sends an ETH frame after a backoff time $T_{fb}(k) = k \cdot t_{fb}$, where k is a randomly selected value from K time slots ($0 \leq k \leq K - 1$).

If the re-contention succeeds, the destination node sends back another feedback signal (denoted as FB2) equal to 1. Upon receiving FB2 and waiting for SIFS, the selected relay node retransmits the data on behalf of the source node. Otherwise (i.e., more than one node choose the same k), the relay selection process fails and thus, the retransmission is performed by the source node itself. The probability of ETH frame collision in re-contention depends on the value of K and the number of collided optimal relay nodes. Notice that a larger K gives a smaller collision probability, but induces much more time consuming in the relay selection period.

5.4.1.4 Parameter Optimization

To reduce the overhead in the inter-intra contention period and restrain the collision probability in the re-contention period, the system parameters, i.e., G, M and K, should be appropriately selected.

We utilize an optimized time slot reduction method, which is similar to the optimal grouping scheme proposed in [48], to set the values of G and M. We define $C_{|U|}$ as the number of reduced backoff time slots achieved by the inter-intra contention scheme compared with non-grouping scheme, where $|U|$ denotes the number of possible utility values. $C_{|U|}$ is calculated as

$$\begin{aligned} C_{|U|} &= \underbrace{(1-2)\times M}_{group(0)} + \underbrace{[(M+1)-3]\times M}_{group(1)} + \cdots \\ &\cdots + \underbrace{\Big[((G-1)\times M+1)-(G+1)\Big]\times M}_{group(G-1)} \\ &= \textstyle\sum_{j=1}^{G-1}\left[j\times M-(j+1)\right]\times M - M, \end{aligned} \tag{5.35}$$

where the nodes in group 0 take one more time slot than the non-grouping scheme (due to the additional time slot for the GI). The members in the following groups, however, can obtain a substantially saving on the number of backoff time slots.

Then, the optimization problem is given as

$$\begin{aligned} &\max\ C_{|U|} \\ &\text{s.t. } |U| = G\times M. \end{aligned} \tag{5.36}$$

Thus, at an expense of computation at the network initialization phase, the number of backoff time slots can be substantially saved by appropriately selected parameters G and M.

Then, let us focus on the setting of parameter K in the re-contention period. Consider the case that n relay nodes re-contend in K time slots. The probability that re-contending fails due to multiple relay nodes selecting the same time slot is given by

$$\begin{aligned} P_f = & \underbrace{\sum_{i=2}^{n} \binom{n}{i} \frac{1}{K^i} \left(\frac{K-1}{K} \right)^{n-i}}_{\text{fail probability at 1st time slot}} + \underbrace{\sum_{i=2}^{n} \binom{n}{i} \frac{1}{K^i} \left(\frac{K-2}{K} \right)^{n-i}}_{\text{at 2nd time slot}} \\ & + \cdots + \underbrace{\sum_{i=2}^{n} \binom{n}{i} \frac{1}{K^i} \left(\frac{1}{K} \right)^{n-i}}_{\text{at (K−1)th time slot}} + \underbrace{\frac{1}{K^n}}_{\text{at Kth time slot}} \\ = & \sum_{k=1}^{K-1} \left(\sum_{i=2}^{n} \binom{n}{i} \frac{1}{K^i} \left(\frac{K-k}{K} \right)^{n-i} \right) + \frac{1}{K^n}. \end{aligned} \tag{5.37}$$

The kth term in Eqn. (5.37) denotes the probability that re-contention fails due to more than one relay node selecting the kth time slot.

In order to properly set the value of K, given a desired failed probability P_f, the number of collided optimal relays n needs to be estimated. In practice, n can be estimated by letting the destination node observe the total receiving power of the MI frames. The estimated number of collided optimal relay $\tilde{n}$ is

$$\tilde{n} = \left\lceil \frac{\sum_{i=1}^{n} P_i + \sigma^2}{\bar{P}} \right\rceil, \tag{5.38}$$

where P_i is the signal power received from node i, n is the total number of signals that the destination node received, σ^2 is the noise power, and $\bar{P}$ is the average receiving power for a decodable signal which is obtained by the historical experience. $\lceil x \rceil$ is a ceiling function that returns the smallest integer not less than x. Using $\tilde{n}$ to estimate n in Eqn. (5.37), and setting a desired failed probability, the parameter K can be determined. For instance, for 5% failed probability and 2 re-contending relay nodes, K is set to 20. In NCAC-MAC, $\tilde{n}$ is piggyback by the FB1 frame to inform the collided optimal relay nodes. In the protocol implementation, the frame FB1 sent from the destination node is set to $\tilde{n}$ instead of e.

5.4.2 Splitting Algorithm-based Relay Selection

In this subsection, we present another efficient collision free relay selection method, i.e., splitting algorithm-based relay selection strategy, namely SA-RS. In SA-RS, only those relay nodes whose utility values lie between two thresholds transmit. And the threshold is updated in every node independently round by round, based on the feedback from the destination node. The frame exchanging process of SA-RS is depicted in Fig. 5.8. At every time slot, each relay candidate checks its utility value. If it lies between the current two thresholds, the node broadcasts a Relay Indicator (RI), otherwise, it keeps silence. When the current time slot ends, the relay candidates wait for the feedback (FB) from the destination node. If no feedback is received, it means that no relay node sends RI at the current time slot. Otherwise, in the case that the feedback is received, FB equal to e represents a collision due to multiple RI frames, and FB equal to 1 represents a successful relay selection by single RI frame. The thresholds are updated repeatedly according to Algorithm 1, until selecting the relay node successfully or reaching the maximum round number. ETH frame is sent by the optimal relay node, who performs the retransmission on behalf of the source node.

Algorithm 1: Splitting Algorithm

Input: $U_l = F_U^{-1}(1/n)$, $U_h = \infty$, $U_{ll} = 0$

while $m \neq 1$ *and* $k \leq K$ **do**
    Feedback $m = (0, 1, e)$ from last slot;
    if $m = e$ **then**
        $U_{ll} = U_l$; U_l =split(U_l, U_h);
    else if $m = 0$ **then**
        $U_h = U_l$;
        if $U_{ll} \neq 0$ **then**
            U_l =split(U_{ll}, U_l);
        else
            U_l =lower(U_l);
        end
    end
    $k = k + 1$;
end

The splitting algorithm which is utilized to adjust the thresholds in SA-RS, is originally proposed in [72]. The two thresholds, i.e., the lower threshold U_l and higher threshold U_h are updated periodically. A relay candidate i sends RI if and only if its utility value U_i satisfies $U_l \leq U_i \leq U_h$. Then, we explain the detail of the Algorithm 1 as follows.

- Line input: initialize the thresholds. Here, $F_U(u) = \Pr(U > u)$ denotes the Complimentary Cumulative Distribution Function (CCDF) of the utility. At the first time slot, the

FIGURE 5.8: Splitting Algorithm-based Relay Selection Strategy

thresholds are initialized as $U_l = F_U^{-1}(1/n)$, and $U_h = \infty$, so that the probability that one node's utility value is above U_l is $1/n$. Note that n is the number of relay candidates which can be obtained by the connectivity table. This setting minimizes the probability of a collision in the first round [72]. And U_{ll} tracks the largest utility value known up to the current round.

- Lines 1-2: m denotes the value of the feedback, which indicates the time slot was idle (0), collision (e), or success (1). And k and K are the number of time slots used so far and the maximum time slots, respectively.

- Lines 3-4: if a collision occurs ($m = e$), the range (U_l, U_h) splits into two parts by function split() given as

$$\text{split}(U_l, U_h) = F_U^{-1}\left(\frac{F_U(U_l) + F_U(U_h)}{2}\right). \tag{5.39}$$

  The nodes in the upper part send RI in the next time slot.

- Lines 5-8: if the time slot is idle ($m = 0$) and there has been a collision before ($U_{ll} \neq 0$), the best utility value lies between (U_{ll}, U_l). Thus, we split it into two parts again, the nodes lie in the upper part send RI in the next time slot.

- Lines 9-10: If the time slot is idle ($m = 0$) but there has never been a collision before (U_{ll} = 0), all the nodes' utility values are below U_l. Therefore, we lower the U_l using function lower() given as

$$\text{lower}(U_l) = \begin{cases} F_U^{-1}(F_U(U_l) + 1/n) & U_l > 0 \\ 0 & \text{otherwise.} \end{cases} \tag{5.40}$$

The algorithm ends when the outcome is a success ($m = 1$) or it reaches the maximum time slot ($k > K$).

According to [72], the best relay node can be found within 2.5 time slots on average. Thus, the average time consumed in relay selection process by SA-RS is $2\times2.5\times\eta+5\times SIFS$, where η denotes the time slot. This time consists of the time consumed by RI and the corresponding FB, and the SIFS time between them. For a comparison, the average time consumed on the best relay selection by GC-RS is $(G/2+M/2+1)\times\eta+2\times SIFS$ (here, we take a optimistic calculation without considering the re-contention, since it occurs with very low probability). $G/2$ and $M/2$ denote the average number of slots that inter and intra contentions need, and 1 denotes the additional time slot for FB1. Using the parameter settings in Table 2, we can observe that the average time on relay selection by GC-RS (4816 µs) is longer than the one by SA-RS (2940 µs). Besides comparison of the time consumption on relay selection, we also compare the transmission overhead between GC-RS and SA-RS. The average number of additional communication frames is 3 (GI, MI and FB1) by GC-RS , and 5 (RI and FB in every round, 2.5 rounds on average) by SA-RS. The additional communication overheads by GC-RS is less than the one by SA-RS. These results are also verified by our simulation in Section 5.5.

Utilizing GC-RS or SA-RS into NCAC-MAC, the best relay node can be selected in a collision free fashion. However, the avoidance of the collision is achieved at the cost of frame exchanging overhead. We will evaluate this tradeoff in Section 5.5, and show that the GC-RS and SA-RS can both achieve better packet delivery ratio and throughput at the cost of reasonable transmitting energy, comparing with the simple backoff scheme.

5.5 Performance Evaluation

In this section, we evaluate the proposed NCAC-MAC via simulations carried out in Omnet++ [87]. The evaluation metrics in this chapter are aggregated throughput, delay, Packet Delivery Ratio (PDR) and transmitting energy consumption. Firstly, we compare the NCAC-MAC with two remarkable schemes, namely CSMA and Phoenix. Then the benefits offered by the proposed collision free relay selection strategies, namely GC-RS and SA-GS, are evaluated. The simulation settings and parameters are summarized in Table 2.

We have simulated the NCAC-MAC in a scenario that 35 nodes are deployed in a 300×300 m^2 area. Each node generates packets addressed to its neighbors according to a Poisson traffic model with intensity λ. All the following evaluation results are obtained with 95% confidence interval.

We first illustrate the aggregated throughput versus the load per node in Fig. 5.9. We can observe that the NCAC-MAC outperforms CSMA by 23% and Phoenix by 10%, when a moderate load level is achieved. The impact of HCNC becomes evident as traffic in the network increases, since the large number of queuing packets leads to high coding opportunity. The throughput gain that brought by NCAC-MAC over Phoenix comes from two aspects. One is

TABLE 5.2: Simulation parameters and settings

Transmitting power	10 dBm
Noise floor	−102 dBm
Carrier sensing threshold	−100 dBm
Detection threshold	−96 dBm
Path loss exponent (α)	3.5
Payload size	2000 bits
Buffer size (L^{max})	20
SINR threshold (Λ_{th})	3 dB
Short Retry Limit - NCAC-MAC and Phoenix	2
Short Retry Limit - CSMA	3
Simulation time	12 s
Constant unit time (C)	0.1 ms
Throughput weight (β)	1.25
Time slot (η), DIFS and SIFS	20, 128 and 28 µs
High cached probability (ρ_{high})	0.9
Low cached probability (ρ_{low})	0.1
Group number (G) and member number (M)	5 and 10
ACK/NACK	112 bits
ETH	160 bits

the utilization of utility based relay selection. The node with high channel capability and coding opportunity is selected as the relay node in NCAC-MAC, whereas the relay is randomly selected in Phoenix. Another is the reduction of additional communication overhead. NCAC-MAC utilizes the connectivity table to solve the cached issue, whereas Phoenix uses additional RTS/CTS exchanges.

The second metric that we consider is the average delay. In Fig. 5.10, the curves show that the average delay raises as the load increases. And the NCAC-MAC reduces the average delay by 20% with respect to CSMA and, by 12% compared to Phoenix at saturation load. Due to the utilization of utility function and connectivity table, the time that packets queuing in the buffer can be reduced, and the delay due to additional communication overhead can be avoided.

Fig. 5.11 shows the result of PDR versus nominal load. First of all, we notice that the PDR of Phoenix is slightly improved over CSMA. This effect stems from the better failure recovery capabilities of HCNC with respect to plain ARQ [81]. However, Phoenix cannot guarantee the selected relay node is the best among all the relay candidates, or even is better than the original

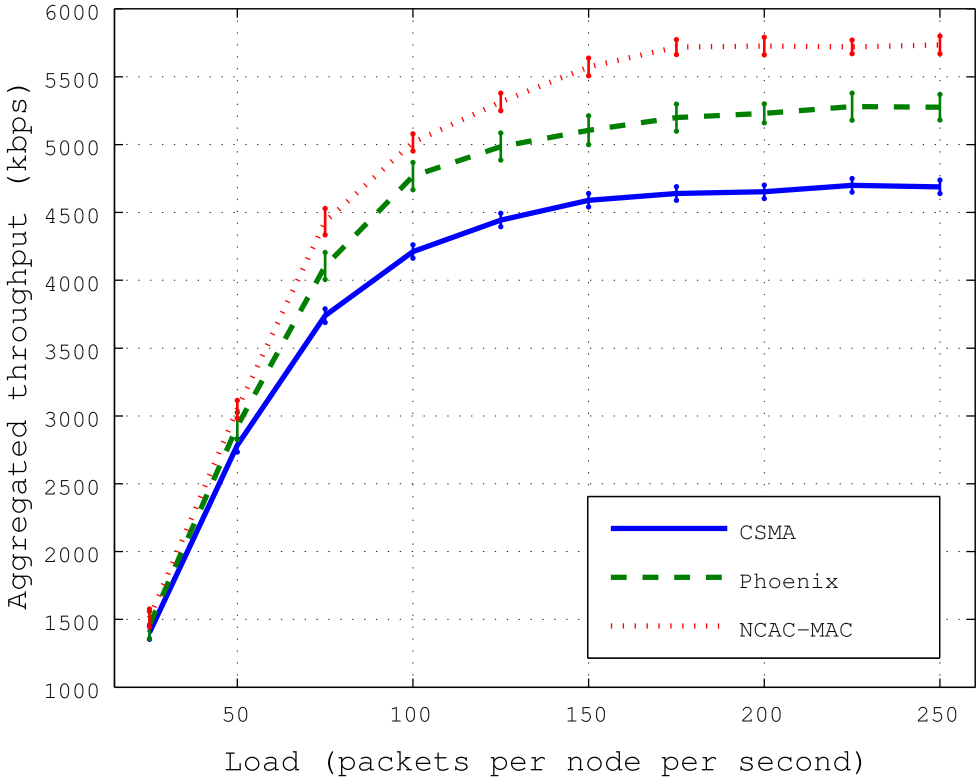

FIGURE 5.9: Aggregated throughput versus nominal load

source node. In contrast, the utility based relay selection scheme in NCAC-MAC can ensure high quality retransmission, i.e., coded retransmission with good channel condition. Thus, about 6% PDR improvement can be achieved by HCAC-MAC compared to Phoenix.

Next, we study the performance of GC-RS and SA-RS, which are imported into the relay selection process to avoid the possible collisions. Fig. 5.12 shows that around 1~2% PDR increment can be achieved by GC-RS and SA-RS, compared to original NCAC-MAC. The collision probabilities during relay selection for both GC-RS and SA-RS are extremely low, thus the PDR can be considerably improved.

Fig. 5.13 depicts the aggregated throughput of original NCAC-MAC, NCAC-MAC with GC-RS and NCAC-MAC with SA-RS. Although it is not obvious, we notice that GC-RS and SA-RS can achieve better aggregated throughput compared to original NCAC-MAC. We study that in GC-RS and SA-RS, on one hand, additional control messages are required, which is

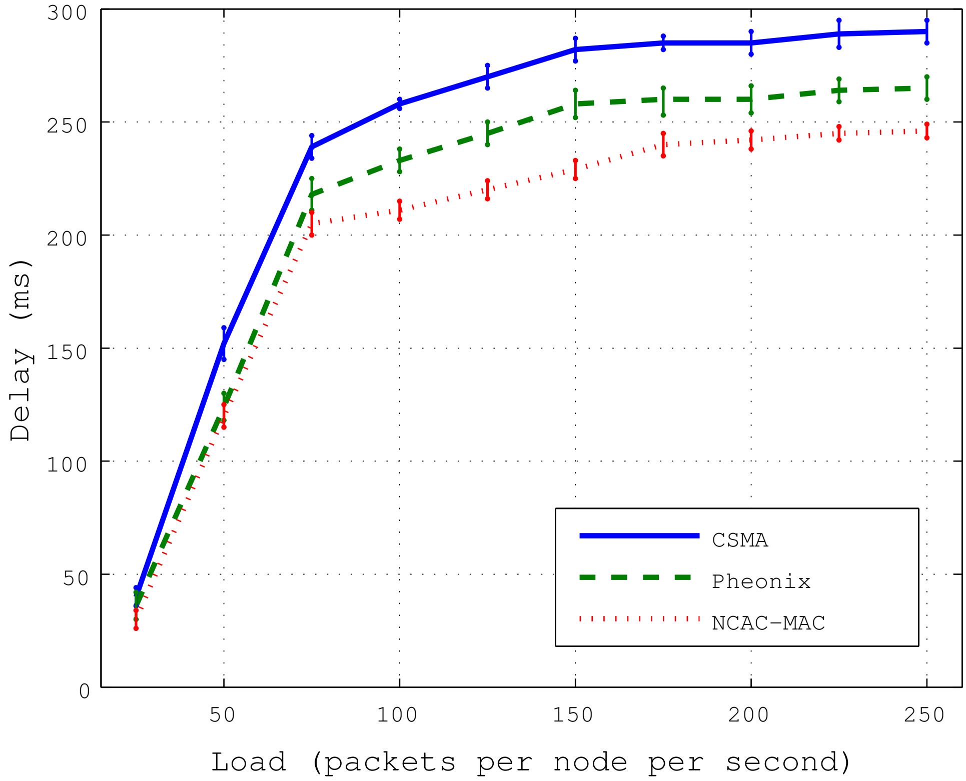

FIGURE 5.10: Delay versus nominal load

detrimental to the throughput. On the other hand, the number of time slots for relay selection is reduced, which benefits the throughput. The result is that the time spending on relay selection is reduced, although the reduction is quite small compared to the whole payload retransmitting time. Moreover, SA-RS performs slightly better than GC-RS, since the average time required to select the best relay for SA-RS is shorter than the one for GC-RS.

At last, Fig. 5.14 shows the average transmitting energy consumption per successfully accepted payload bit against different payload size at saturation load. The results of CSMA, Phoenix, NCAC-MAC, NCAC-MAC with GC-RS and NCAC-MAC with SA-RS are compared. Firstly, we observe that CSMA consumes much more energy than the other 4 schemes. The reason is that CSMA suffers from poor failure recovery capability and does not support coded retransmission. If the channel condition of the direct link is poor, the data payload may be retransmitted several times until reaches the short retry limit. For Phoenix, as we addressed

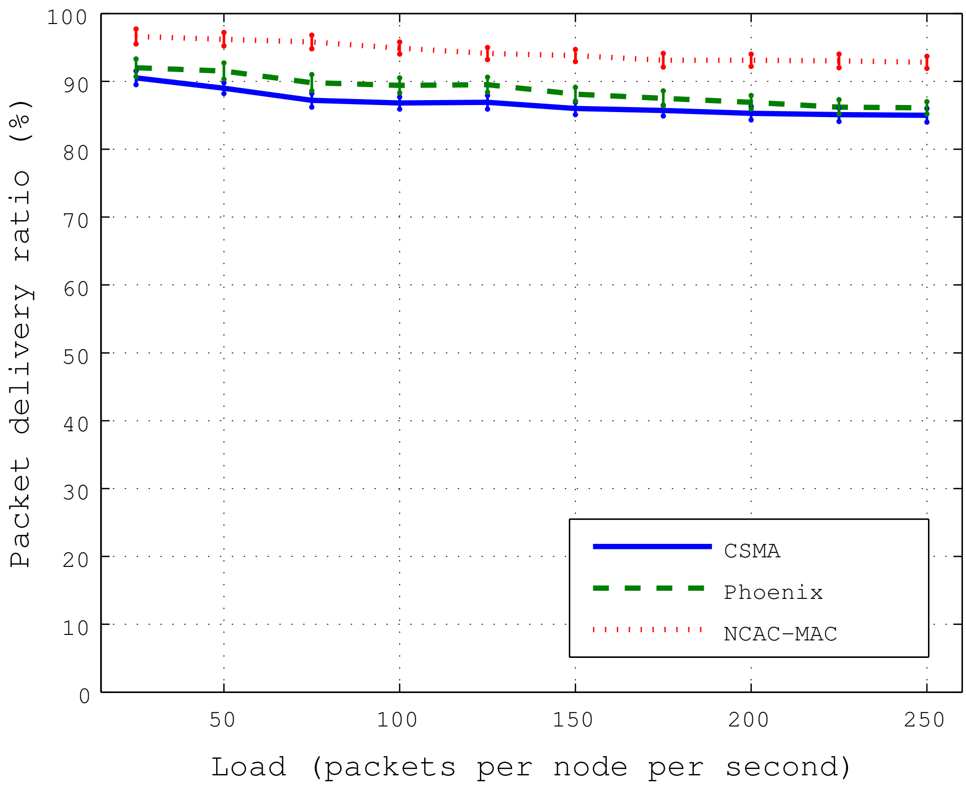

FIGURE 5.11: PDR versus nominal load

in Section 5.3.1.2, it requires additional RTS/CTS exchange to solve the cached issue. Consequently, additional communication overhead leads to additional energy consumption. The proposed NCAC-MAC has the lowest energy consumption among the 5 schemes. The saved energy comes from the reduced communication overhead and the better retransmission success probability. To avoid the collision during the relay selection period, additional control messages are needed. Specifically, frames GI, MI, FB are used in GC-RS, and frames RI, FB are used in SA-RS. Those addition communication overheads incurs extra transmitting energy consumption. Notice that we obtain better PDR and throughput performance by GC-RS and SA-RS, at the cost of reasonable additional energy consumption. And the additional transmitting energy consumption becomes obvious as the payload size reduces.

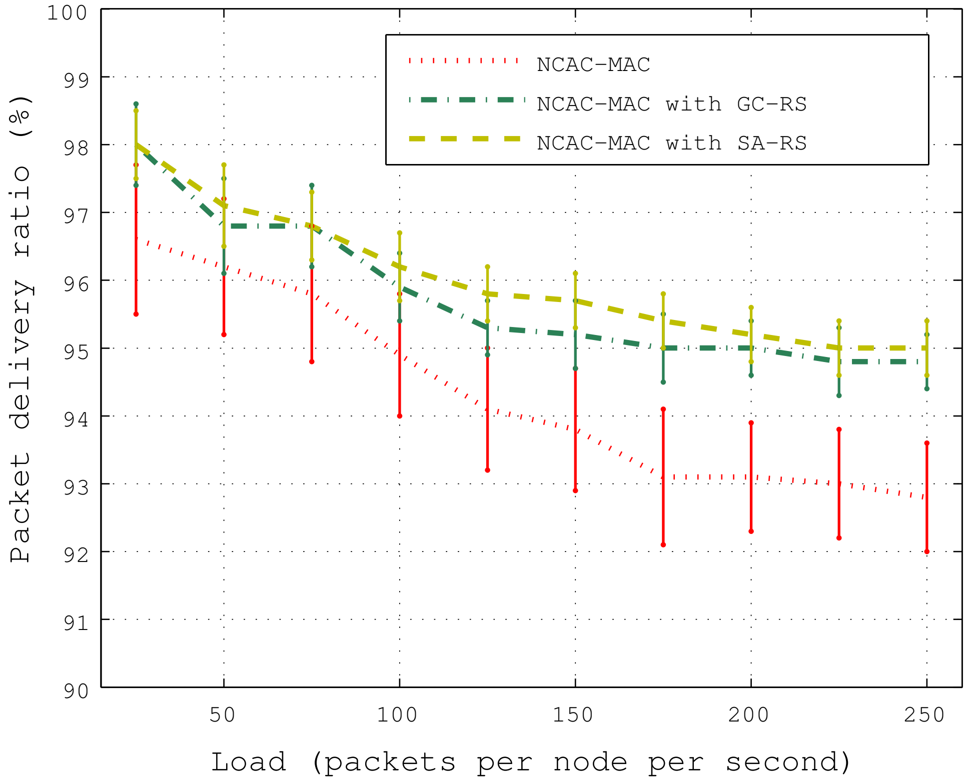

FIGURE 5.12: PDR versus nominal load, compared between original NCAC-MAC, NCAC-MAC with GS-RS and NCAC-MAC with SA-RS

5.6 Summary

In this chapter, we have proposed a novel network coding aware cooperative medium access control protocol, namely NCAC-MAC, for wireless ad hoc networks. By introducing NCAC-MAC, the advantages of both NC and CC can be exploited. We also have proposed a network coding aware utility-based relay selection strategy, to choose the best relay in an efficient and distributed manner. In addition, with the purpose of avoid collision, we have incorporated two collision free relay selection strategies, GC-RS and SA-RS, into NCAC-MAC. We have demonstrated that the NCAC-MAC can substantially improve the throughput, delay and PDR, comparing with IEEE 802.11 CSMA and Phoenix.

As a future work, we will investigate the NCAC-MAC for larger scale network size, and

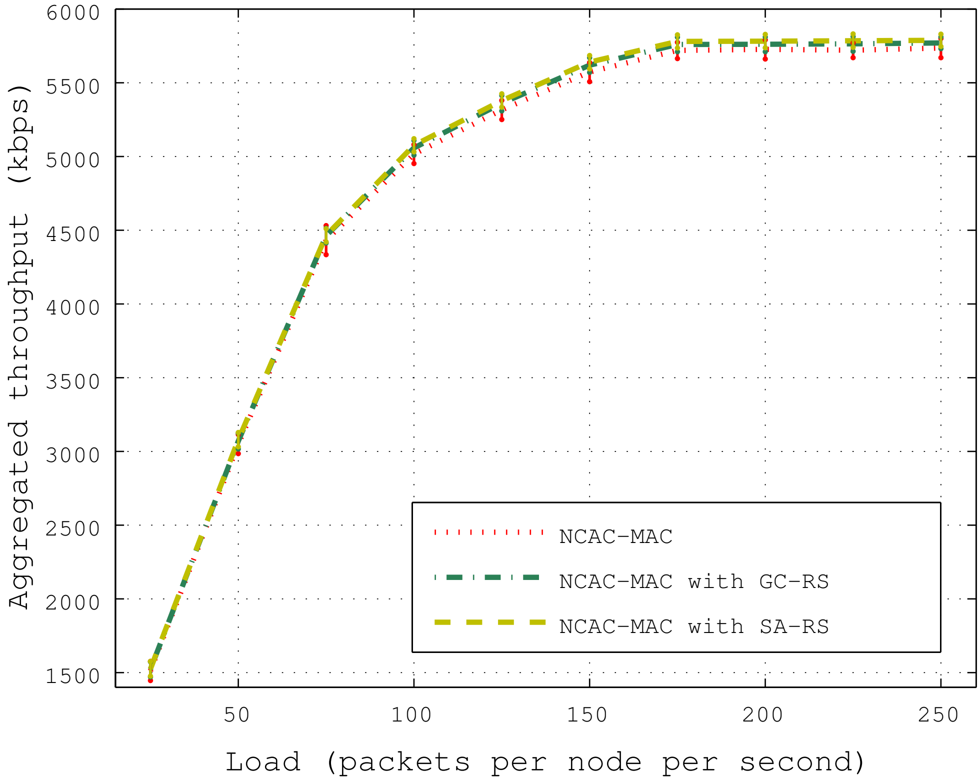

FIGURE 5.13: Aggregated throughput versus nominal load, compared between original NCAC-MAC, NCAC-MAC with GS-RS and NCAC-MAC with SA-RS

consider the efficient solution for the cached issue in a network with high mobility. It is also a promising future work to develop a network coding aware cooperative MAC protocol based on multichannel.

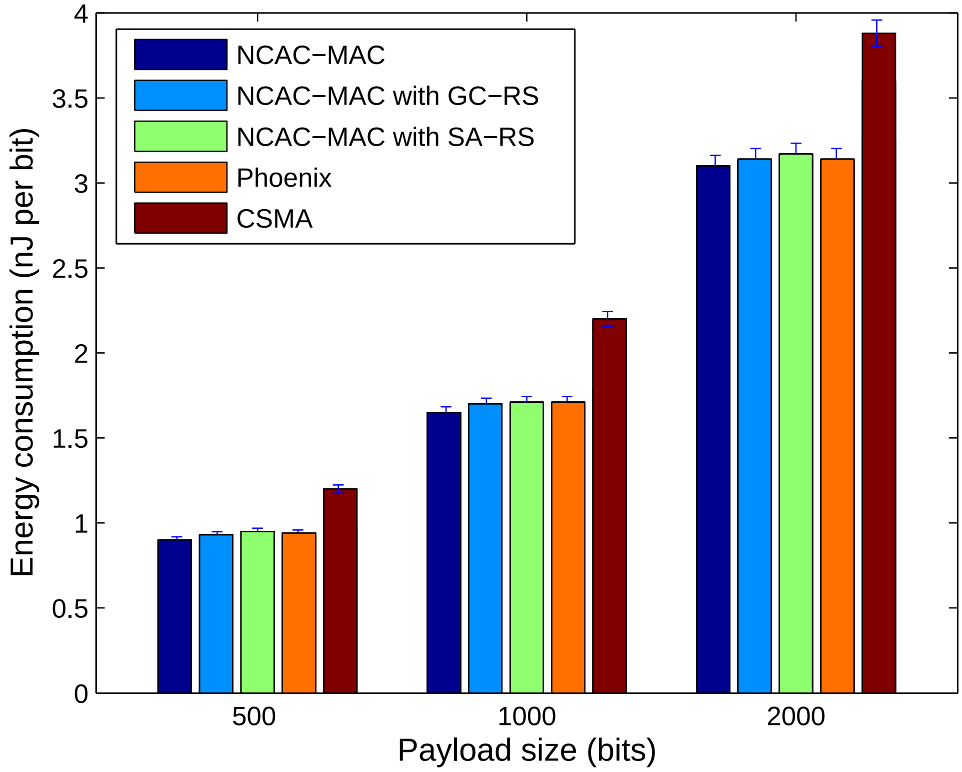

FIGURE 5.14: Average transmitting energy consumption per successfully accepted payload bit, compared between original NCAC-MAC, NCAC-MAC with GS-RS and NCAC-MAC with SA-RS

Chapter 6

Conclusions and Future Work

6.1 Conclusions

The essential idea of cooperative transmission in wireless systems is to exploit the broadcast nature and space diversity provided by the wireless medium. To obtain the diversity gain from the physical layer, the MAC layer design is critical and indispensable. In this dissertation, we focused on cooperative MAC protocol design and analysis. Our results indicated that by delicate MAC layer design, cooperative communication indeed can offer significant performance improvements in terms of data rate, energy efficiency, delay and packet delivery ratio. More specifically, we addressed the following three problems.

In Chapter 3, we presented the analytical results of average transmission rate for reactive CMAC protocols in wireless networks. For a user desired outage probability, we formulated the average transmission rate for reactive CMAC. In addition, we studied the impact of MRC and energy constraint on average transmission rate. Our evaluation results revealed that reactive CMAC can enhance the average transmission rate substantially compared to direct transmission. We also showed that the benefit brought from MRC is limited in reactive CMAC, and the average transmission rate can be improved even when the energy constraint is taken into account.

In Chapter 4, with the purpose to extend the network lifetime of WANETs, we proposed a novel distributed energy-adaptive location-based proactive CMAC protocol. Both energy advantage and location advantage were exploited in the proposed scheme, and thus the network lifetime was extended significantly. In addition, an effective relay selection strategy to choose the best relay terminal and a cross-layer optimal power allocation scheme to set the transmitting power were proposed. Finally, the spatial reuse issue was addressed to minimize the interference among different connections by using novel NAV settings. We demonstrated that the proposed scheme can significantly prolong the network lifetime comparing with the previous work, at relatively low throughput and delay degradation cost.

In Chapter 5, with the purpose of increasing the throughput and reducing the delay of the WANETs, we proposed a novel network coding aware reactive CMAC protocol. The proposed scheme took the advantages of both network coding and cooperative communication. We also proposed a network coding aware utility-based relay selection strategy, to choose the best relay in an efficient and distributed manner. In addition, in order to avoid possible collisions, we incorporated two collision free relay selection strategies. We demonstrated that the proposed scheme can substantially improve the throughput, delay and packet delivery ratio comparing with the previous work.

6.2 Future Work

Spectral resource demand has greatly increased in the last two decades due to emerging wireless services and products. Cognitive radio is a promising technology that enables an unlicensed user to utilize the spectrum hole of the licensed spectrum band and thus, improve the overall spectrum usage. An interesting and important problem to investigate is the cooperative communication technique in the cognitive radio networks. As the future work, we want to consider two research topics: cooperative spectrum sensing and cooperative transmission between primary/secondary users. To devise an accurate and robust spectrum sensing algorithm to detect spectrum holes as accurately as possible, allowing different users to share their sensing results and cooperatively decide on the licensed spectrum occupancy is a promising solution. Moreover, to efficiently exploit the transmission opportunity, cooperation among different terminals may gain large benefits.

Bibliography

[1] I. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless sensor networks: a survey," *Computer Networks*, vol. 38, no. 4, pp. 393 – 422, 2002.

[2] Z. Hasan, H. Boostanimehr, and V. Bhargava, "Green cellular networks: A survey, some research issues and challenges," *Communications Surveys Tutorials, IEEE*, vol. 13, no. 4, pp. 524–540, 2011.

[3] M. Rubinstein, I. Moraes, M. Campista, L. Costa, and O. Duarte, "A survey on wireless ad hoc networks," in *Mobile and Wireless Communication Networks*, ser. IFIP The International Federation for Information Processing, G. Pujolle, Ed. Springer US, 2006, vol. 211, pp. 1–33.

[4] G. L. Stuber, *Principles of Mobile Communication*. Boston: Kluwer Academic Publishers, 1996.

[5] S. Diggavi, N. Al-Dhahir, A. Stamoulis, and A. Calderbank, "Great expectations: the value of spatial diversity in wireless networks," *Proceedings of the IEEE*, vol. 92, no. 2, pp. 219–270, 2004.

[6] D. Gesbert, M. Shafi, D. shan Shiu, P. Smith, and A. Naguib, "From theory to practice: an overview of mimo space-time coded wireless systems," *Selected Areas in Communications, IEEE Journal on*, vol. 21, no. 3, pp. 281–302, 2003.

[7] S. Alamouti, "A simple transmit diversity technique for wireless communications," *Selected Areas in Communications, IEEE Journal on*, vol. 16, no. 8, pp. 1451–1458, 1998.

[8] V. Tarokh, N. Seshadri, and A. Calderbank, "Space-time codes for high data rate wireless communication: performance criterion and code construction," *Information Theory, IEEE Transactions on*, vol. 44, no. 2, pp. 744–765, 1998.

[9] V. Tarokh, H. Jafarkhani, and A. Calderbank, "Space-time block coding for wireless communications: performance results," *Selected Areas in Communications, IEEE Journal on*, vol. 17, no. 3, pp. 451–460, 1999.

[10] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity. part i. system description," *Communications, IEEE Transactions on*, vol. 51, no. 11, pp. 1927–1938, 2003.

[11] X. Wang, J. Li, K. Wu, and H. Liu, "Transmission rate enhancement via adaptive relaying in wireless networks," *International Journal of Parallel, Emergent and Distributed Systems*, vol. 27, no. 3, pp. 235–247, 2012.

[12] X. Wang, J. Li, and K. Wu, "Transmission rate enhancement of cooperative communications in wireless networks," in *Distributed Computing Systems Workshops (ICDCSW), 2011 31st International Conference on*, 2011, pp. 345–349.

[13] X. Wang and J. Li, "Improving the network lifetime of manets through cooperative mac protocol design," *IEEE Transactions on Parallel and Distributed Systems*, vol. 99, no. PrePrints, p. 1, 2013.

[14] X. Wang, J. Li, and F. Tang, "Network coding aware cooperative mac protocol for wireless ad hoc networks," *IEEE Transactions on Parallel and Distributed Systems*, vol. 99, no. PrePrints, p. 1, 2013.

[15] X. Wang, J. Li, and M. Guizani, "NCAC-MAC: Network coding aware cooperative medium access control for wireless networks," in *Wireless Communications and Networking Conference (WCNC), 2012 IEEE*, 2012, pp. 1636–1641.

[16] J. G. Proakis, *Digital Communications*. McGraw-Hill Inc., 1994.

[17] D. Tse and P. Viswanath, *Fundamentals of Wireless Communication*. Cambridge University Press, 2005.

[18] E. Telatar, "Capacity of multi-antenna gaussian channels," *European Transactions on Telecommunications*, vol. 10, no. 6, pp. 585–595, 1999.

[19] G. J. Foschini and M. J. Gans, “On limits of wireless communications in a fading environment when usingmultiple antennas,” *Wirel. Pers. Commun.*, vol. 6, no. 3, pp. 311–335, Mar. 1998.

[20] D. Tse, P. Viswanath, and L. Zheng, “Diversity-multiplexing tradeoff in multiple-access channels,” *Information Theory, IEEE Transactions on*, vol. 50, no. 9, pp. 1859–1874, 2004.

[21] A. Sendonaris, E. Erkip, and B. Aazhang, “Increasing uplink capacity via user cooperation diversity,” in *Information Theory, 1998. Proceedings. 1998 IEEE International Symposium on*, 1998, pp. 156.

[22] A. Sendonaris, E. Erkip, and B. Aazhang, “User cooperation diversity. part ii. implementation aspects and performance analysis,” *Communications, IEEE Transactions on*, vol. 51, no. 11, pp. 1939–1948, 2003.

[23] J. Laneman and G. W. Wornell, “Distributed space-time-coded protocols for exploiting cooperative diversity in wireless networks,” *Information Theory, IEEE Transactions on*, vol. 49, no. 10, pp. 2415–2425, 2003.

[24] J. Laneman, D. Tse, and G. W. Wornell, “Cooperative diversity in wireless networks: Efficient protocols and outage behavior,” *Information Theory, IEEE Transactions on*, vol. 50, no. 12, pp. 3062–3080, 2004.

[25] E. C. V. D. Meulen, “Three-terminal communication channels,” *Advances in Applied Probability*, vol. 3, no. 1, pp. pp. 120–154, 1971.

[26] T. Cover and A. Gamal, “Capacity theorems for the relay channel,” *Information Theory, IEEE Transactions on*, vol. 25, no. 5, pp. 572–584, 1979.

[27] G. Kramer, M. Gastpar, and P. Gupta, “Cooperative strategies and capacity theorems for relay networks,” *Information Theory, IEEE Transactions on*, vol. 51, no. 9, pp. 3037–3063, 2005.

[28] R. Nabar, H. Bolcskei, and F. Kneubuhler, “Fading relay channels: performance limits and space-time signal design,” *Selected Areas in Communications, IEEE Journal on*, vol. 22, no. 6, pp. 1099–1109, 2004.

[29] P. Mitran, F. Ono, and V. Tarokh, "Space-time diversity enhancements using collaborative communications," *Information Theory, IEEE Transactions on*, vol. 51, no. 6, pp. 2041–2057, 2005.

[30] A. K. Sadek, W. Yu, and K. J. R. Liu, "On the energy efficiency of cooperative communications in wireless sensor networks," *ACM Trans. Sen. Netw.*, vol. 6, no. 1, pp. 5:1–5:21, Jan. 2010.

[31] K. Vardhe, D. Reynolds, and B. Woerner, "Joint power allocation and relay selection for multiuser cooperative communication," *Wireless Communications, IEEE Transactions on*, vol. 9, no. 4, pp. 1255–1260, 2010.

[32] J. Wu, M. Cardei, F. Dai, and S. Yang, "Extended dominating set and its applications in ad hoc networks using cooperative communication," *Parallel and Distributed Systems, IEEE Transactions on*, vol. 17, no. 8, pp. 851–864, 2006.

[33] A. Sadek, Z. Han, and K. Liu, "Distributed relay-assignment protocols for coverage expansion in cooperative wireless networks," *Mobile Computing, IEEE Transactions on*, vol. 9, no. 4, pp. 505–515, 2010.

[34] Y. Zhu, M. Huang, S. Chen, and Y. Wang, "Energy-efficient topology control in cooperative ad hoc networks," *Parallel and Distributed Systems, IEEE Transactions on*, vol. 23, no. 8, pp. 1480–1491, 2012.

[35] T. Himsoon, W. Siriwongpairat, Z. Han, and K. Liu, "Lifetime maximization via cooperative nodes and relay deployment in wireless networks," *Selected Areas in Communications, IEEE Journal on*, vol. 25, no. 2, pp. 306–317, 2007.

[36] S. Kadloor and R. Adve, "Relay selection and power allocation in cooperative cellular networks," *Wireless Communications, IEEE Transactions on*, vol. 9, no. 5, pp. 1676–1685, 2010.

[37] E. Beres and R. Adve, "Optimal relay-subset selection and time-allocation in decode-and-forward cooperative networks," *Wireless Communications, IEEE Transactions on*, vol. 9, no. 7, pp. 2145–2155, 2010.

[38] L. Chen, L. Libman, and J. Leneutre, "Conflicts and incentives in wireless cooperative relaying: A distributed market pricing framework," *Parallel and Distributed Systems, IEEE Transactions on*, vol. 22, no. 5, pp. 758–772, 2011.

[39] J. Laneman, G. W. Wornell, and D. Tse, "An efficient protocol for realizing cooperative diversity in wireless networks," in *Information Theory, 2001. Proceedings. 2001 IEEE International Symposium on*, 2001, pp. 294.

[40] J. Laneman and G. Wornell, "Energy-efficient antenna sharing and relaying for wireless networks," in *Wireless Communications and Networking Confernce, 2000. WCNC. 2000 IEEE*, vol. 1, 2000, pp. 7–12 vol.1.

[41] H. Ochiai, P. Mitran, H. Poor, and V. Tarokh, "Collaborative beamforming for distributed wireless ad hoc sensor networks," *Signal Processing, IEEE Transactions on*, vol. 53, no. 11, pp. 4110–4124, 2005.

[42] R. Mudumbai, J. Hespanha, U. Madhow, and G. Barriac, "Scalable feedback control for distributed beamforming in sensor networks," in *Information Theory, 2005. ISIT 2005. Proceedings. International Symposium on*, 2005, pp. 137–141.

[43] Z. Ding, W. H. Chin, and K. Leung, "Distributed beamforming and power allocation for cooperative networks," *Wireless Communications, IEEE Transactions on*, vol. 7, no. 5, pp. 1817–1822, 2008.

[44] D. Benevides da Costa and S. Aissa, "Performance of cooperative diversity networks: Analysis of amplify-and-forward relaying under equal-gain and maximal-ratio combining," in *Communications, 2009. ICC '09. IEEE International Conference on*, 2009, pp. 1–5.

[45] P. Liu, Z. Tao, S. Narayanan, T. Korakis, and S. Panwar, "Coopmac: A cooperative mac for wireless lans," *Selected Areas in Communications, IEEE Journal on*, vol. 25, no. 2, pp. 340–354, 2007.

[46] H. Zhu and G. Cao, "rdcf: A relay-enabled medium access control protocol for wireless ad hoc networks," *Mobile Computing, IEEE Transactions on*, vol. 5, no. 9, pp. 1201–1214, 2006.

[47] S. Moh and C. Yu, "A cooperative diversity-based robust mac protocol in wireless ad hoc networks," *Parallel and Distributed Systems, IEEE Transactions on*, vol. 22, no. 3, pp. 353–363, 2011.

[48] H. Shan, H. T. Cheng, and W. Zhuang, "Cross-layer cooperative mac protocol in distributed wireless networks," *Wireless Communications, IEEE Transactions on*, vol. 10, no. 8, pp. 2603–2615, 2011.

[49] J. Wang, H. Zhai, Y. Fang, J. Shea, and D. Wu, "Omar: Utilizing multiuser diversity in wireless ad hoc networks," *Mobile Computing, IEEE Transactions on*, vol. 5, no. 12, pp. 1764–1779, 2006.

[50] J. Zhang, Q. Zhang, and W. Jia, "Vc-mac: A cooperative mac protocol in vehicular networks," *Vehicular Technology, IEEE Transactions on*, vol. 58, no. 3, pp. 1561–1571, 2009.

[51] J. Alonso-Zarate, E. Kartsakli, C. V. Verikoukis, and L. Alonso, "Persistent rcsma: A mac protocol for a distributed cooperative arq scheme in wireless networks," *EURASIP J. Adv. Sig. Proc.*, 2008.

[52] H. Adam, W. Elmenreich, C. Bettstetter, and S. Senouci, "Core-mac: A mac-protocol for cooperative relaying in wireless networks," in *Global Telecommunications Conference, 2009. GLOBECOM 2009. IEEE*, 2009, pp. 1–6.

[53] I. F. Akyildiz, X. Wang, and W. Wang, "Wireless mesh networks: a survey," *Comput. Netw. ISDN Syst.*, vol. 47, no. 4, pp. 445–487, Mar. 2005.

[54] I. Akyildiz, T. Melodia, and K. Chowdury, "Wireless multimedia sensor networks: A survey," *Wireless Communications, IEEE*, vol. 14, no. 6, pp. 32–39, 2007.

[55] P. Almers, E. Bonek, A. Burr, N. Czink, M. Debbah, V. Degli-esposti, H. Hofstetter, P. Kysti, D. Laurenson, G. Matz, A. F. Molisch, C. Oestges, and H. zcelik, "Survey of channel and radio propagation models for wireless mimo systems," *EURASIP Journal on Wireless Communications and Networking*.

[56] A. Ibrahim, A. Sadek, W. Su, and K. Liu, "Cooperative communications with relay-selection: when to cooperate and whom to cooperate with?" *Wireless Communications, IEEE Transactions on*, vol. 7, no. 7, pp. 2814–2827, 2008.

[57] A. Sadek, Z. Han, and K. Liu, “A distributed relay-assignment algorithm for cooperative communications in wireless networks,” in *Communications, 2006. ICC ’06. IEEE International Conference on*, vol. 4, 2006, pp. 1592–1597.

[58] S. Sharma, Y. Shi, Y. Hou, H. Sherali, and S. Kompella, “Cooperative communications in multi-hop wireless networks: Joint flow routing and relay node assignment,” in *INFOCOM, 2010 Proceedings IEEE*, 2010, pp. 1–9.

[59] A. Sadek, W. Su, and K. Liu, “Multinode cooperative communications in wireless networks,” *Signal Processing, IEEE Transactions on*, vol. 55, no. 1, pp. 341–355, 2007.

[60] A. Ibrahim, Z. Han, and K. Liu, “Distributed energy-efficient cooperative routing in wireless networks,” *Wireless Communications, IEEE Transactions on*, vol. 7, no. 10, pp. 3930–3941, 2008.

[61] X. Huang, H. Zhai, and Y. Fang, “Robust cooperative routing protocol in mobile wireless sensor networks,” *Wireless Communications, IEEE Transactions on*, vol. 7, no. 12, pp. 5278–5285, 2008.

[62] R. Huang, C. Zhang, H. Zhao, and Y. Fang, “Improving handoff performance by utilizing ad hoc links in multi-hop cellular systems,” *Wirel. Netw.*, vol. 17, no. 4, pp. 893–906, May 2011.

[63] C. Patterson, R. Muntz, and C. Pancake, “Challenges in location-aware computing,” *Pervasive Computing, IEEE*, vol. 2, no. 2, pp. 80–89, 2003.

[64] H. Shan, P. Wang, W. Zhuang, and Z. Wang, “Cross-layer cooperative triple busy tone multiple access for wireless networks,” in *Global Telecommunications Conference, 2008. IEEE GLOBECOM 2008. IEEE*, 2008, pp. 1–5.

[65] C. Zhai, J. Liu, L. Zheng, and H. Xu, “Lifetime maximization via a new cooperative mac protocol in wireless sensor networks,” in *Global Telecommunications Conference, 2009. GLOBECOM 2009. IEEE*, 2009, pp. 1–6.

[66] C. Perkins and E. Royer, “Ad-hoc on-demand distance vector routing,” in *Mobile Computing Systems and Applications, 1999. Proceedings. WMCSA ’99. Second IEEE Workshop on*, 1999, pp. 90–100.

[67] M. Gokturk and O. Gurbuz, "Cooperation in wireless sensor networks: Design and performance analysis of a mac protocol," in *Communications, 2008. ICC '08. IEEE International Conference on*, 2008, pp. 4284–4289.

[68] "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," IEEE Standard 802.11, Jun. 1999.

[69] S. Cui, A. Goldsmith, and A. Bahai, "Energy-efficiency of mimo and cooperative mimo techniques in sensor networks," *Selected Areas in Communications, IEEE Journal on*, vol. 22, no. 6, pp. 1089–1098, 2004.

[70] A. Goldsmith, *Wireless Communications*. New York, NY, USA: Cambridge University Press, 2005.

[71] C. Savarese, J. Rabaey, and J. Beutel, "Location in distributed ad-hoc wireless sensor networks," in *Acoustics, Speech, and Signal Processing, 2001. Proceedings. (ICASSP '01). 2001 IEEE International Conference on*, vol. 4, 2001, pp. 2037–2040 vol.4.

[72] X. Qin and R. Berry, "Opportunistic splitting algorithms for wireless networks," in *INFOCOM 2004. Twenty-third AnnualJoint Conference of the IEEE Computer and Communications Societies*, vol. 3, 2004, pp. 1662–1672 vol.3.

[73] QualNet, http://web.scalable-networks.com/content/qualnet.

[74] J. Broch, D. A. Maltz, D. B. Johnson, Y.-C. Hu, and J. Jetcheva, "A performance comparison of multi-hop wireless ad hoc network routing protocols," in *Proceedings of the 4th annual ACM/IEEE international conference on Mobile computing and networking*, ser. MobiCom '98. New York, NY, USA: ACM, 1998, pp. 85–97.

[75] R. Ahlswede, N. Cai, S.-Y. Li, and R. Yeung, "Network information flow," *Information Theory, IEEE Transactions on*, vol. 46, no. 4, pp. 1204–1216, 2000.

[76] S.-Y. Li, R. Yeung, and N. Cai, "Linear network coding," *Information Theory, IEEE Transactions on*, vol. 49, no. 2, pp. 371–381, 2003.

[77] L. Xiao, T. Fuja, J. Kliewer, and D. Costello, "A network coding approach to cooperative diversity," *Information Theory, IEEE Transactions on*, vol. 53, no. 10, pp. 3714–3722, 2007.

[78] X. Bao and J. Li, "Adaptive network coded cooperation (ancc) for wireless relay networks: matching code-on-graph with network-on-graph," *Wireless Communications, IEEE Transactions on*, vol. 7, no. 2, pp. 574–583, 2008.

[79] B. Nazer and M. Gastpar, "Computation over multiple-access channels," *Information Theory, IEEE Transactions on*, vol. 53, no. 10, pp. 3498–3516, 2007.

[80] C. Peng, Q. Zhang, M. Zhao, Y. Yao, and W. Jia, "On the performance analysis of network-coded cooperation in wireless networks," *Wireless Communications, IEEE Transactions on*, vol. 7, no. 8, pp. 3090–3097, 2008.

[81] A. Munari, F. Rossetto, and M. Zorzi, "Phoenix: making cooperation more efficient through network coding in wireless networks," *Wireless Communications, IEEE Transactions on*, vol. 8, no. 10, pp. 5248–5258, 2009.

[82] E. Fasolo, F. Rossetto, and M. Zorzi, "Network coding meets mimo," in *Network Coding, Theory and Applications, 2008. NetCod 2008. Fourth Workshop on*, 2008, pp. 1–6.

[83] Y. Wang, S. Cui, R. Sankar, and S. Morgera, "Delay-throughput trade-off with opportunistic relaying in wireless networks," in *Global Telecommunications Conference (GLOBECOM 2011), 2011 IEEE*, 2011, pp. 1–5.

[84] S.-T. Sheu, Y. Tsai, and J. Chen, "Mr2rp: the multi-rate and multi-range routing protocol for ieee 802.11 ad hoc wireless networks," *Wirel. Netw.*, vol. 9, no. 2, pp. 165–177, Mar. 2003.

[85] M. Khalid, Y. Wang, I. ho Ra, and R. Sankar, "Two-relay-based cooperative mac protocol for wireless ad hoc networks," *Vehicular Technology, IEEE Transactions on*, vol. 60, no. 7, pp. 3361–3373, 2011.

[86] G. Bianchi, "Performance analysis of the ieee 802.11 distributed coordination function," *Selected Areas in Communications, IEEE Journal on*, vol. 18, no. 3, pp. 535–547, 2000.

[87] OMNeT++, http://www.omnetpp.org/.

List of Publications

1. Xiaoyan Wang, Jie Li and Feilong Tang, "Network Coding Aware Cooperative MAC Protocol for Wireless Ad Hoc Networks", *IEEE Transactions on Parallel and Distributed Systems (TPDS)*, 2013, accepted.

2. Xiaoyan Wang and Jie Li, "Improving the Network Lifetime of MANETs through Cooperative MAC Protocol Design", *IEEE Transactions on Parallel and Distributed Systems (TPDS)*, 2013, accepted.

3. Xiaoyan Wang, Jie Li and Kui Wu, and Huaibei Liu, "Transmission Rate Enhancement via Adaptive Relaying in Wireless Networks", *International Journal of Parallel, Emergent and Distributed Systems*, Volume 27, Issue 3, pp. 235-247, 2012.

4. Xiaoyan Wang, Jie Li and Mohsen Guizani, "NCAC-MAC: Network Coding Aware Cooperative Medium Access Control for Wireless Networks", *Proc. of the IEEE Wireless Communications and Networking Conference (IEEE WCNC 2012)*, 1-4, Apr. 2012, Paris, France, pp. 1636-1641.

5. Xiaoyan Wang, Jie Li and Kui Wu, "Transmission Rate Enhancement of Cooperative Communications in Wireless Networks", *Proc. of the IEEE International Conference on Distributed Computing Systems (IEEE ICDCS 2011) Workshop on Wireless Ad hoc and Sensor Networks*, 21-24, June 2011, Minneapolis, USA, pp. 345-349.

6. Xiaoyan Wang, Jie Li, Xiaoning Peng and Beiji Zou, "Secure and Efficient Data Aggregation for Wireless Sensor Networks", *Proc. of the IEEE Vehicular Technology Conference (IEEE VTC 2010-Fall)*, 6-9, Sep. 2010, Ottawa, Canada, pp. 1-5.

7. Xiaoyan Wang and Jie Li, "Precision Constraint Data Aggregation for Dynamic Cluster-based Wireless Sensor Networks", *Proc. of the International Conference on Mobile Ad-hoc and Sensor Networks (MSN 2009)*, 14-16, Dec. 2009, Wuyi Mountain, China, pp. 172-179.