Cooperative Communications in Wireless Networks

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Abstract

This thesis explores the cooperative communications in wireless networks. Working by cooperating with other transmitting nodes, the cooperative communication has a great potential in wireless ad hoc networks, where some nodes act as relays for others. This can provide a new approach of diversity, *cooperative diversity*, to exploit the broadcast nature of the wireless transmission, and can greatly improve the system performance even when other forms of diversity are not available. In this way, cooperation can save the energy, improve the reliability, and increase the pathloss saving for the system.

We first study the single-source multiple-relay decode-and-forward cooperation system. The relays cooperate in a repetition way to help the source node. We apply a simple detector, where no channel state information between the source node and the relay node is available at the destination, and maximal ratio combining is performed without considering whether the forwarded symbol from the relay is incorrect. We analyze the impact of the detection error at the relay node to the system performance. It is demonstrated that the detection errors at the relay node result in an error floor effect. To compensate for such effect, we propose a relay selection protocol, and the analysis and simulation results show that it can lower the error floor and nearly achieve full diversity order.

Next, we extend to the multiple-source multiple-relay cooperation system. In the cooperative transmission protocol we proposed, the relay nodes not only decode and forward the symbols from the source nodes, but also encode the

incoming symbols according to the pre-assigned cooperative code, resulting in higher efficiency and flexibility compared with previous repetition-coded cooperation system. With the general design rules we get, we can make a tradeoff between the achievable diversity order and the data rate. We analyze the impact of the noisy fading interuser channel between the source nodes and the relay nodes on the system performance, and then propose an adaptive symbol selection protocol to compensate for it. The analysis and the simulation results show that the proposed system achieves full diversity order.

Then we study the decode-and-forward cooperative multihop transmission. Different from conventional multihop transmission, each node achieves the spatial diversity by combining all the independently fading symbols from previous nodes on the route line. We consider the possibility for the relay node to forward error-detected symbols, and apply the relay selection protocol to compensate for it. The bit error rate is derived for the cooperation system, and the comparison with the conventional multihop transmission shows that this system can achieve full diversity order. Practical cooperative range and the impact of relay nodes distribution on the system performance are discussed for the practical implementation. Taking 2-hop cooperative transmission for an example, we also show that the equal power allocation and even distance distribution are adequate for practical systems. At the end of this part, we give a discussion on doing cooperation in general ad hoc networks. Cooperative multihop transmission and multipath routing are examples, and general network coding theory is used to design cooperative codes for cooperation.

摘要

本論文研究瞭無綫網絡中的閤作通信。閤作通信是通過不同結點之間的協同工作來實現的，所以它在有很多結點充當中繼的無綫網絡中會有很大的應用。閤作通信可以提供一種新的分集方式—閤作分集，以充分利用無綫傳輸的廣播特性，並且在無法等到其他分集方式的情況下它依然有傚。閤作通信可以節省傳輸能量，提高可靠性，降低繫統的路徑損耗。

我們首先研究瞭單信源、多中繼解碼—傳輸閤作繫統。在這種繫統中，中繼通過一種重復傳輸的方式來幫助信源結點傳輸信息。我們假設在接受耑沒有信源—中繼信道的信道信息，接受耑不管中繼傳輸信息的對錯都採用最大比閤並。我們分析瞭在中繼解碼的錯誤對整個繫統性能的影響，結果顯示這樣的誤碼會使繫統產生誤碼平麵傚應。為瞭消除這種傚應，我們提齣瞭一種中繼選擇協議，分析以及仿真結果證實瞭這種協議可以實現完全分集增益。

接着，我們研究瞭多信源、多中繼閤作繫統。在我們提齣的傳輸協議中，中繼不僅僅解碼並且傳送，而且對不同信源傳來的信息根據事先指定的"閤作碼"進行編碼然后再傳輸，這樣可以提高傚率和靈活性。我們給齣瞭一些基本的設計規則，從而可以在要達到的分集增益和傳輸速率之間實現一個折衷。我們分析瞭信源和中繼之間的衰落信道對繫統性能的影響，並且提齣瞭一個自適應的碼選擇協議來消除這種影響。分析以及仿真結果顯示我們提齣的協議可以實現完全的分集增益。

最后我們研究瞭解碼—傳輸閤作多跳傳輸繫統。和傳統的多跳傳輸不同，在閤作多跳傳輸中，每個結點通過接受路由路徑上在它之前所有結點傳輸的信息來實現一種空間分集傚果。我們攷慮瞭中繼結點傳輸錯誤信息的可

能性，並用中繼選擇協議來消除它的影響。我們給齣瞭閤作繫統的誤碼率，並且和傳統的多跳繫統進行比較，結果顯示我們的閤作繫統可以實現完全分集增益。我們還討論瞭實際中需要攷慮的協作範圍以及中繼結點的分佈對繫統的影響。以一個2跳閤作繫統為例，我們的結果顯示實際繫統中我們隻需要平均功率分配和均勻的中繼距離分佈。在這一部分的最后，我們討論瞭在一般的ad hoc無綫網絡中的閤作。閤作多跳傳輸和閤作多徑路由是可能的閤作方式，網絡編碼理論可以用來為一般的無綫網絡設計閤作碼。

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Chapter 1

Introduction

1.1 Multipath Fading Channels

Compared with the wired communications, wireless communications face greater challenges due to the characteristics of the radio channels. Electromagnetic wave propagation undergoes reflection, diffraction, and scattering. Due to multiple reflecting objects and scatterers in the channel, there will be multiple version of radio waves at the receiver, via different paths of varying length and with different delays. The combination of these waves will give a resultant signal with rapid fluctuation of the amplitudes and phases. Such effect is called *multipath fading*, and it degrades the system performance greatly [1, 2].

There are two important parameters for multipath fading channels:

- Coherence Bandwidth B_c: this is the range of frequencies over which two frequency components have a strong potential for amplitude correlation. If the bandwidth of the transmitted signal, B_s, is smaller than the coherence bandwidth of the channel, this channel is called flat fading channel; otherwise, if $B_s > B_c$, this is the frequency selective fading channel.

- Coherence Time T_c: this is the time duration over which two signals have a strong potential for amplitude correlation. If the symbol period of the transmitted signal, T_s, is smaller than the coherence bandwidth of the channel, this channel is called slow fading channel; otherwise, if $T_s > T_c$, this is the fast fading channel.

To isolate the possible benefits of time and frequency diversity gains in the subsequent studies, we consider frequency flat slow fading channels, which means $B_s < B_c$ and $T_s < T_c$. In such channel, if the transmitted signal is $x(t)$, the complex envelop of the received signal is

$$y(t) = \alpha(t)x(t) + n(t) \tag{1.1}$$

where $\alpha(t)$ is the channel fading coefficient, and $n(t)$ denotes the additive white Gaussian noise, with variance $N_0/2$. In the scattering environment without line-of-sight (LoS) components, the magnitude of the received complex envelop $|\alpha(t)|$ has a Rayleigh distribution at any given time, i.e.,

$$p_\alpha(x) = \frac{x}{\gamma^2}\exp\{-\frac{x^2}{2\gamma^2}\} \tag{1.2}$$

The average envelop power is $E[|\alpha|^2] = 2\gamma^2$.

For binary PSK modulation and optimum receiver, we can easily get the analytical expression of the error probability [3]. The bit error rate for additive white Gaussian noise (AWGN) channel is given by

$$P_e = Q(\sqrt{2\gamma_b}) \tag{1.3}$$

where $\gamma_b = \frac{E_b}{N_0}$ is the signal-to-noise ratio (SNR) at the receiver. And the bit error rate for Rayleigh fading channel is

$$P_e = \frac{1}{2}\Big[1 - \sqrt{\frac{\bar{\gamma_b}}{1+\bar{\gamma_b}}}\Big] \tag{1.4}$$

where $\bar{\gamma_b} = \frac{E_b}{N_0}E[|\alpha|^2]$ is the average SNR.

The performance comparisons of BPSK modulated system in non-fading AWGN channel and Rayleigh fading channel are given in Fig. 1.1. SNR is the signal-to-noise ratio at the receiver, and $E[|\alpha|^2] = 1$ for Rayleigh fading

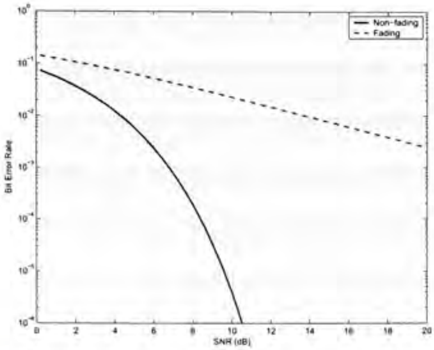

Figure 1.1: Performance comparisons of BPSK systems in AWGN channel and Rayleigh fading channel.

channel. From this figure, we can see that the error rate decreases exponentially with SNR in non-fading channel, but for fading channel it only decreases inversely with SNR. In fact, from (1.4), we can see for $\bar{\gamma}_b \gg 1$, $P_e \approx \frac{1}{4\bar{\gamma}_b}$. Therefore, to get the same performance, we have to transmit much more power in a fading channel.

1.2 Diversity

Diversity has been widely accepted as an important technique to combat the multipath fading channels [2, 3]. It exploits the random nature of radio propagation by finding independent fading paths for transmission. The principle can be explained in this way: if one transmitting path undergoes a deep fade, it is possible that another independently fading channel is in the favorable status, so with more than one path to select from, both the average and instantaneous signal-to-noise ratio can be improved. The number of independently fading channel, L, is called *diversity order*, and it decides the performance improvement of diversity system. For the binary PSK system with L independent channels and applying the optimal combiner, maximal ratio combiner, at the receiver, we can derive the bit error rate as [3]

$$P_e(L) = p^L \sum_{k=0}^{L-1} \binom{L+k-1}{k} (1-p)^k \tag{1.5}$$

where p is the probability of error for the case without diversity, as in (1.4). When $\bar{\gamma}_b \gg 1$, this error probability can be approximated by

$$P_e(L) \approx \left(\frac{1}{4\bar{\gamma}_b}\right)^L \binom{2L-1}{L} \tag{1.6}$$

From this equation, we can see that the error rate decreases inversely with the Lth power of the SNR.

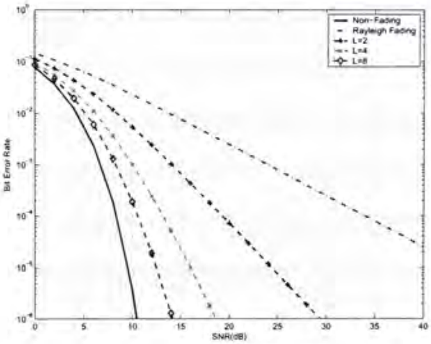

Figure 1.2: Performance comparisons of BPSK systems in Rayleigh fading channel with diversity.

In Fig. 1.2, we get the error probability for diversity system with different diversity order, together with the non-fading system and the system in Rayleigh fading channel without diversity. It clearly demonstrates the benefits of diversity, and as L increases the system performance gets closer to the non-fading case.

The main point to achieve diversity gain is to get several independently fading replicas at the receiver, and there are several ways to achieve this.

- Time Diversity: transmit the same message in L different time slots, where the separation between successive time slots equals or exceeds T_c, the coherence time of the channel.

- Frequency Diversity: transmit the same message on L different carriers, where the separation between successive carriers equals or exceeds B_c, the coherence bandwidth of the channel.

- Spatial Diversity: the signal is transmitted from and/or received by multiple antennas, and the antennas are spaced far apart to make the propagation channels spatially independent.

Recently, a new approach of diversity, *cooperative diversity*, is proposed to combat the multipath fading channels when other forms of diversity are not available [4, 5, 6]. It effectively exploits the broadcast nature of the wireless transmission. In cellular, ad hoc or sensor networks, when one user is transmitting information to a remote terminal, other users nearby can also receive the signal, which, however, is usually not taken into consideration in conventional wireless communication systems. The result is a waste of resource, and cooperative diversity makes use of such kind of resource. In a cooperation system, some surrounding users will act as relays, and forward such information to the destination. This process results in multiple copies from independent fading paths at the destination, and thus brings diversity. This new form of diversity technique is called *cooperative diversity* as it comes from user cooperation.

Take the system in Fig. 1.3 for an example. The circle is the transmission range of node "1", and it intends to transmit to node "7". In the conventional single-hop transmission, node "1" will transmit directly to "7". But node "7" is at the edge of the transmission range of "1", and the channel between these two nodes are frequency-flat slow fading, so the transmission will be highly unreliable. In addition, if we make further constraints on time delay and bandwidth requirement, time and frequency diversities may not be applicable, and multiple antennas will not be feasible if both nodes are mobile terminals. Note that nodes "2", "3", "4", and "5" can also receive the message transmitted by node "1", and if they can help to transmit this message, it is

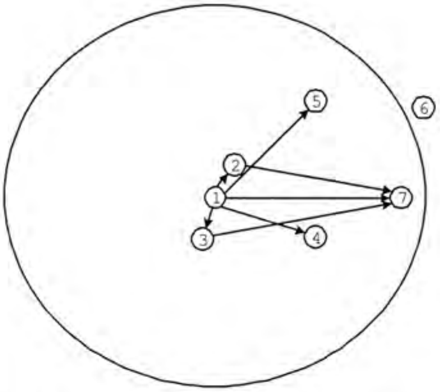

Figure 1.3: An illustration of the cooperation system.

possible to get multiple independently fading copies at the destination node. In this case, we select node "2" and "3" as the cooperative nodes to act as relays for node "1", as they are close to it and can receive the message from "1" reliably. Therefore, as depicted in Fig. 1.3, we have got three independently fading links between "1" and "7", "1" → "7", "1" → "2" → "7", and "1" → "3" → "7", respectively, so it is possible to achieve diversity order 3 with some cooperative protocol. The goal of our study is to design cooperative protocol to achieve this and analyze the system performance of proposed cooperation system.

1.3 Outline of the Thesis

In this thesis, we study cooperative communications in wireless networks, both single-hop and multihop transmission, with emphasis on the achieved cooperative diversity. We will investigate several different systems, designing cooperative protocols and analyzing the corresponding system performance. Chapter 2 is a survey of related work, including former studies on cooperative diversity, and several related areas such as multihop cellular networks, wireless ad hoc networks, and space-time processing. In Chapter 3 and 4, we study the single-hop cooperative communications in wireless systems with n_s source nodes, n_r relay nodes, and single destination node. Chapter 3 deals with single-source multiple-relay cooperation system, $n_s = 1, n_r > 1$, and the nodes cooperate in a repetition way. The impact of the detection error at the relay node on the system performance is analyzed, and then a relay selection protocol is proposed to compensate for such effect. Chapter 4 studies multiple-source multiple-relay cooperation system, $n_s > 1, n_r > 1$. We propose a cooperative coding protocol, in which the relay nodes not only decode and forward the symbols from the source nodes, but also encode the incoming symbols according to the pre-assigned cooperative code. This brings higher efficiency and flexibility compared with the repetition-coded cooperation system with single source node. Cooperative multihop transmission is studied in Chapter 5, where each node achieves the spatial diversity by combining all the independently fading symbols from previous nodes on the route line. We consider the possibility for the relay node to forward error-detected symbols, and propose an adaptive transmission protocol to compensate for it. Practical cooperative range and the impact of relay nodes distribution on the system performance are discussed for the practical implementation. We also give a discussion on how to do user cooperation in general wireless ad hoc networks, and we integrate our results with network coding theory.

Chapter 2

Background and Related Work

Cooperative communication, where mobile users cooperate with each other to improve system performance, is a relatively new area in wireless communications, but it has already attracted so much attention and several milestones have been achieved during the past few years [7]. Although the cooperative schemes and the resulting improvements are new, the theoretic basis about relay channel has long be established [8, 9, 10]. With distributed antennas, cooperation system is also closely related to space-time processing. In addition, with the potential to be extended to multihop transmission, an understanding of wireless networks is necessary. In this chapter, we will give a survey about these backgrounds and related work.

2.1 Cooperative Diversity

As researchers investigated from different aspects, there are several different names for this new technique, such as *User Cooperation* [4, 11, 12], *Cooperative Diversity* [5, 6, 13, 14], and *Coded Cooperation* [15, 16, 17]. As we focus on the achieved diversity order, and our studies are based on the basic decode-and-forward scheme proposed by Laneman, we will use the notation of "Cooperative Diversity", named by Laneman.

2.1.1 User Cooperation

Sendonaris *et. al.* pioneered in this area by proposing "User Cooperation Diversity" to increase the uplink capacity of cellular systems [4]. The capacity gain was achieved by the cooperation of in-cell users, and the robustness to the channel variation was also increased. The idea is that each user in any cell is assigned a partner, and each user not only transmits its own message but also helps to forward the partner's message, resulting in a transmit diversity effect. This is not a simple relay case, and the user acts both as source and relay. It provided a spatial transmit diversity, which would not be feasible for conventional systems as it is impractical to install multiple antennas on the mobile unit. It showed an increased capacity even with the noisy inter-user channel.

The system was then thoroughly investigated in [11, 12]. In [11], the information-theoretic analysis was made: the achievable rate region was derived to demonstrate the capacity gain and the role of interuser channel, which also included pure relay problem as a special case; for the slow-fading system with delay constraints, outage probability was calculated, and it demonstrated that even when it does not significantly increase the capacity, cooperation can be used to reduce the outage probability. A code-division multiple-access (CDMA) implementation was given as an example to explore the benefits of user cooperation. In this 2-user system, the transmission was divided into three period:

- Period 1, each user transmits its first data symbol to the base station.
- Period 2, each user transmits its second data symbol to both the base station and its partner.
- Period 3, each user combines its own data and the symbol received during period 2 to construct a cooperative signal, and transmits it to the base

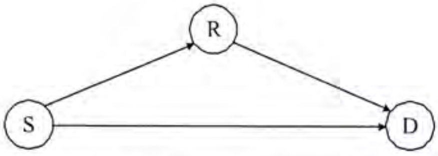

Figure 2.1: A three-node cooperation system.

station.

So Period 2 and 3 are cooperation periods, and their lengths can be adapted to the channel condition to improve the throughput. Practical implementation issues and system performance analysis were considered in [12]. The throughput acted as the performance criterion and was analyzed. Besides the rather complex optimal detector, a suboptimal receiver, called λ-MRC, was developed, where a parameter $\lambda \in [0, 1]$ was used as a measure of the destination's confidence in the bits estimated by the partner. However, the value of λ is determined by the state of the interuser channel, which the destination may not have access to in practical systems.

2.1.2 Cooperative Diversity

Laneman proposed several low-complexity cooperative protocols to achieve spatial diversity, which was called *Cooperative Diversity* [5, 6, 14]. The three-node system as in Fig. 2.1 was studied, and it works in a time-division approach: first, the source transmits to both the relay and destination, and then the relay and source transmit in some cooperative protocol. The proposed cooperative strategies include:

- *Fixed Amplify-and-Forward*: the relay amplifies the message received from the source, and then forwards to the destination.
- *Fixed Decode-and-Forward*: the relay fully decodes the message from the source, re-encodes, and then retransmits the received message.

- *Selection Relaying*: if the source-relay channel is favorable, the relay forwards the received message, either in amplify-and-forward or decode-and-forward scheme; otherwise, the source continues its transmission, doing repetition or applying more powerful channel codes.
- *Incremental Relaying*: it exploits the feedback information from the destination, which tells whether the transmission from the source to the destination is successful or not, and the relay only does the cooperation when the transmission fails.

Outage behavior analysis showed that fixed decode-and-forward does not offer diversity gain for large SNR, because even with optimal detector, requiring the relay to fully decode the source transmissions limits the performance to that of direct transmission between the source and relay. All the other cooperative diversity protocols can achieve full diversity.

The two main schemes are Amplify-and-Forward (AF) and Decode-and-Forward (DF). Without further processing at the relay, AF is simple, but it is impractical to store sufficient information to reproduce the analog signal at the relay, and the noise will be amplified as well. On the other hand, DF will induce error propagation, but this can be relieved by such strategy as selection relaying, and it can do some advanced processing to the digital decoded signal at the relay, so DF is more attractive for practical implementation.

In [13], the authors studied cooperative diversity in single-hop wireless networks with multiple mobile nodes, both in conventional repetition way, extended from [5, 6], and space-time-coded algorithm. They analyzed the outage probabilities and provided some convenient bounds for the decode-and-forward scheme. The results showed that these protocols could achieve full spatial diversity, not just in the number of those decoding relays but the number of total cooperating terminals, and the space-time-coded protocol could achieve higher spectral efficiency than repetition-based one.

2.1.3 Coded Cooperation

The above cooperation schemes have some limitations. First, the cooperation is done by some form of repetition, which is inefficient; second, the schemes either admit forwarding of erroneous estimates of the partner's symbols, or include propagation of the partner's noise, which will diminish the performance; third, for optimal maximum likelihood detection, the knowledge of the interuser channel should be available at the destination. To overcome these limitations, T. E. Hunter and A. Nosratinia proposed a *Coded Cooperation* scheme [15, 16, 17], using existing channel codes, CRC codes for error check and rate-compatible punctured convolutional (RCPC) codes for cooperation.

The users cooperate by dividing the transmission of their N-bit code words into two frames. In the first frame, they each transmit their own first set of N_1 bits, and each user also receives and decodes the partner's transmission. If the partner's data is successfully decoded, the user calculates and transmits the partner's N_2 remaining parity bits in the second frame. Otherwise, it transmits its own parity bits. In this way, two users share their antennas and a part of each user's code words are transmitted from an independent fading channel, so both users will achieve diversity gains.

In [18], this coded cooperation was extended to space-time cooperation, and turbo coded cooperation. In space-time cooperation, in the second frame the users send both their own and the partner's parity bits, which should be sent by two separate channels. The turbo coding can be used with either coded cooperation or space-time cooperation. Space-time cooperation yields gains in fast fading and turbo coded cooperation gains over noncooperative turbo coded systems.

The *distributed turbo codes* for cooperation were proposed by Zhao and Valenti [19, 20]. The source broadcasts a recursive code to both relay and destination. The relay interleaves the decoded message and re-encodes it prior to forwarding it to the destination. Therefore, the destination receives both codes in parallel, and a distributed turbo code is embedded in such relay channel. Such idea can also be extended to the multiple-relay case, with a *multiple turbo code* [21].

2.2 Information-Theoretic Studies

Information-theoretic studies are essential to show the advantages of cooperation, and the achievable capacity. Many early studies pay attention to Shannon capacity of discrete AWGN channels, while some recent studies deal with ergodic fading, and the outage performance with strict delay constraints, or non-ergodic fading.

Cooperative diversity finds its root in relay channels, the study on which dates back to the end of 1960s. In his pioneering studies [8, 9], van der Meulen introduced a model for relay channels with three terminals. Substantial advances in the theory were made by Cover and El Gamal [10], who developed two fundamental coding strategies for the non-fading one-relay systems (Theorems 1 and 6 in [10]), and the capacity of the degraded relay channel was found. [22] used a simpler coding argument to obtain the same achievable rate as in [10]. A combination of these strategies (Theorem 7 in [10]) achieves capacity for several classes of channels, as discussed in [23, 24, 25, 24]. Capacity-achieving codes appeared in [26] for deterministic relay channels, and in [27, 28] for permuting relay channels with states or memory.

Recently, the studies on cooperative diversity in [4, 11, 12, 29] on cellular networks, and in [5, 30, 6, 13, 14] for ad hoc networks spurred much attention on relay channels.

In [31, 32, 33], the authors studied the information-theoretic achievable rate regions and capacity bounds for different cooperation systems. In [31], the capacity bounds of a three-node multiple-input multiple-output (MIMO) relay channel were derived, where the source, relay and destination all have multiple antennas, and the relay node operates in the full-duplex mode. Both the Gaussian and Rayleigh fading channels were investigated. It was shown that, for the Rayleigh fading case, the upper bound could meet the lower bound under certain conditions, which meant that the capacity could be characterized exactly. [32] studied three-node relay channels with transmitter channel state information (CSI) in a Rayleigh-fading environment, and they took into account practical constraints on the transmission/reception duplexing at the relay node and on the synchronization between the source node and the relay node. The results revealed that the optimum relay channel signaling significantly outperformed conventional multihop transmission, and the power allocation played a significant part. [33] gave the upper and lower bounds for the information-theoretic capacity of four-node ad hoc networks, with two transmit nodes and two receive nodes, both receiver cooperation and transmitter cooperation. It was shown that cooperative diversity did not give multiplexing gain, but it gave a high SNR additive gain.

Capacity gains from transmitter and receiver cooperation in a relay channel were also studied and compared in [34, 35], for discrete AWGN channels and fading channels respectively, under different channel state information (CSI) and power allocation assumptions. It was shown that transmitter cooperation is more favorable with CSI at the transmitter (CSIT), while receiver cooperation is superior under optimal power allocation without CSIT. While it was shown that at an asymptotically high signal-to-noise ratio [36] or with a large number of cooperating nodes [37], cooperative systems do not enjoy full multiplexing gain, the authors in [38] considered cooperative capacity gain at moderate SNR with a fixed number of cooperating antennas. They showed that up to a lower bound to an SNR threshold, the cooperative system performs at least as well as a MIMO system with isotropic inputs, and beyond an upper bound to the SNR threshold, the capacity is strictly less than that of a

MIMO channel.

In [39], coding strategies were developed to exploit node cooperation for relay networks. Two basic schemes were studied: the relays decode-and-forward the source message to the destination, or they compress-and-forward their channel outputs to the destination. The results showed that the decode-and-forward strategies are useful for relays that are close to the source, and the compress-and-forward strategies are useful for relays that are close to the destination.

2.3 Multihop Cellular Networks

Related closely to the relay channels, cooperative diversity has a great potential in wireless networks, both cellular networks and wireless ad hoc networks.

A cellular network is a radio network made up of a number of cells each served by a fixed transmitter, known as a base station. These cells are used to cover different areas in order to provide radio coverage over a wider area than the area of one cell. During the past decade, the number of cellular users surged at an exploding speed. To accommodate the great demand on capacity, that is, to support more users in a cell, the coverage area of a single cell shrinks and the number of cells increases. But it requires much more investment to build a larger number of base stations, and the throughput is limited by the total number of cells in an area. Recently, [40, 41, 42] proposed a novel way to deal with such problem, combing the advantages of infrastructure-based cellular networks and the flexibility of multihop transmission. User cooperation can play an important role in such systems.

2.3.1 MCN: Multihop Cellular Network

In [40], the authors presented a novel architecture, Multihop Cellular Network (MCN) as a viable alternative to the conventional Single-hop Cellular Network

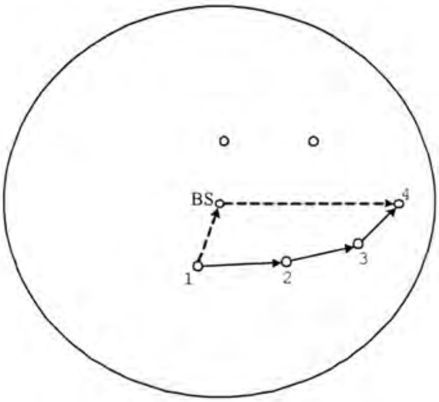

Figure 2.2: Single-hop Cellular system (dashed line) and Multihop Cellular system (solid line).

(SCN), in which the mobile stations can be used as relays for each other, and multihop transmission is implemented. It combines the features of SCN and ad-hoc networks. As in Fig. 2.2, if mobile "1" wants to call mobile "4", in single-hop cellular system, it first sends to the base station and the the base will forward to the destination, while in the multihop cellular system, mobile "1" can connect with "4" via mobile "2" and "3" with multihop transmission. We can see that such system is like the case we studied in Fig. 1.1, so user cooperation can be implemented.

With its inherent characteristics, MCN has the following merits:

1. the number of bases or the transmission ranges of both mobile stations and bases can be reduced.

2. connections are still allowed by multihop transmission without base stations.

3. Multiple packets can be simultaneously transmitted within a cell of the corresponding SCN.

4. paths are less vulnerable than the ones in ad hoc networks because the

bases can help reduce the wireless hop count.

2.3.2 iCAR: Integrated Cellular and Ad Hoc Relaying Systems

Integrated cellular and ad hoc relaying systems (iCAR) [41] is another new wireless system architecture based on the integration of cellular and ad hoc relaying technologies. It deals mainly with the congestion problem due to the unbalanced traffic in a cellular system. The basic idea of iCAR is to place a number of ad hoc relaying stations (ARSs) at some strategic locations, which can be used to relay signals between mobile stations and base stations. With the help of ARSs, it is possible to divert traffic from one, possibly congested, cell to another noncongested cell. This helps to circumvent congestion and makes it possible to maintain calls involving mobiles that are moving into a congested cell, or to accept new call requests involving mobiles that are in a congested cell. It also has other advantages such as extending cellular system' s coverage, providing the interoperability between heterogeneous systems, and enhancing reliability of the system and potential improvement in battery life and transmission rate.

2.3.3 UCAN: Unified Cellular and Ad Hoc Network Architecture

In [42], the authors proposed the Unified Cellular and Ad-Hoc Network (UCAN) architecture to enhance cell throughput for 3G wireless data networks, while maintaining fairness. In UCAN, a mobile terminal is implemented both 3G cellular link and IEEE 802.11-based peer-to-peer links. The 3G base station forwards packets for destination clients with poor channel quality to proxy clients with better channel quality. The proxy clients then use an ad-hoc network composed of other mobile clients and IEEE 802.11 wireless links to forward the packets to the appropriate destinations, thereby improving the cell throughput.

2.4 Wireless Ad Hoc Networks

A wireless ad hoc network [43, 44, 45, 46, 47] is a wireless network comprised of mobile computing devices that use wireless transmission for communication, without fixed infrastructures. Due to the limited coverage of each node and to lower the interference to other nodes, multihop transmission is an inherent characteristic of wireless ad hoc networks. The mobile devices serve as routers for each other due to the limited range of wireless transmission of these devices. In this way, several devices may need to route or help to forward a packet before it reaches its final destination. For conventional multihop transmission, only those relays on the routing line decode the received message and forward it. If we do user cooperation with those relay nodes or take into consideration of other nodes that are not on the routing line, it is possible to improve the throughput and increase the power efficiency.

Wireless ad hoc networks are highly attractive for their advantages and tremendous military and commercial applications, so there has been great interest in this area during last few decades. Wireless ad hoc networks can be deployed quickly anywhere and anytime as they eliminate the complexity of infrastructure setup, and they can easily be reconfigured. They also enjoy high robustness due to their distributed nature, the node redundancy, and the lack of central controller. These networks find applications in several areas, including military communications, collaborative and distributed computing, wireless mesh networks, wireless sensor networks [48], Bluetooth [49], and HomeRF [50].

The information-theoretic study of Shannon capacity region for wireless networks is still an open problem. Even for single-hope multiuser communication systems, the capacity regions are only known for some special channels, such as the general multiple-access channel [51, 52], and a few specific broadcast channels like the AWGN channel and the deterministic channel [53]. Recently, some important results on the scaling law in large scale wireless ad hoc networks were reported [54, 55, 56, 57, 58].

In their landmark paper [54], Gupta and Kumar studied the transport capacity of an ad hoc network, measured by the bit rate multiplied by the distance the bits travel, in bit-meters/sec. They proved that for certain fixed ad hoc networks containing n stationary terminals, even under optimal circumstances, the total throughputs per terminal decay to zero with increasing n in a constant area. The fundamental reason for this constriction is that with a uniform traffic pattern, every node must expend so much effort forwarding its neighboring sources' information that few resources remain to transport its own message. This implies that only small scale ad hoc networks are desirable with current technology. In their following work [55], an achievable rate region in general networks was obtained, with many well-known capacity-defining achievable rate regions as special cases, such as physically degraded and reversely degraded relay channels, and the Gaussian multiple-access channel. It was shown that with more sophisticated multiuser coding, a transport capacity of $\Theta(n)$ bit-meters/sec is achievable, as compared with the best possible transport capacity of $\Theta(\sqrt{n})$ bit-meter/sec in [54], where only point-to-point coding was considered. Next, Xie and Kumar [56, 57] developed new coding schemes, and showed that the achieved rates are higher than those in [54]. In addition, Grossglauser and Tse [58] showed that the mobility can increase the capacity. The strategy is that each source node splits the transmitted packet to as many different nodes as possible, and these "relay" nodes only hand the packets to the destination when they get close to it. Such improvement can be achieved by multiuser diversity, and the scheme is only applicable in those applications that can tolerate large end-to-end delays.

The fundamental questions, "How much information can be transmitted in a general wireless network?", "How should one operate the wireless network?", are still out of reach, and the thorough understanding of cooperation will play an important role in getting the final answers.

2.5 Space-Time Processing

Multiple-Input-Multiple-Output (MIMO) system [59, 60] has recently emerged as one of the most significant technical breakthroughs in wireless communications. In a MIMO system, both the transmitter and the receiver are equipped with multiple antennas. The main idea of MIMO is that the signals at the transmitter and the receiver are processed in such a way to improve the transmission reliability (diversity gain) or/and data rate (multiplexing gain), and this is called space-time (ST) processing, in which time is complemented with spatial dimension.

It was the amazing results on the capacities of MIMO channels [61, 62, 63] that stimulated so many researchers to exploit in this field. For a MIMO system with M_T transmit antennas and M_R receive antennas, it offers a linear (in the number of $\min(M_R, M_T)$) increase in the data rate for the same power and bandwidth. Such effect is called *spatial multiplexing gain*. In [61], Foschini proposed the diagonal BLAST (Bell Laboratories Layered Space-Time) or D-BLAST architecture to approach the promising capacity, which utilized multiple antennas at both the transmitter and receiver and a diagonally-layered coding structure in which code blocks were dispersed across diagonals in space-time. An example with $M_R = M_T = 8$ at 1% outage and $21dB$ average SNR was given, and the achieved rate is 42 $bits/sec/Hz$, which is more than 40 times that of a SISO system with the same total transmitter power and bandwidth. The D-BLAST suffers from implementation complexity, and then a simplified version, V-BLAST (vertical BLAST) [64, 65], was proposed, for which the ordered detection for each substream at the receiver using interference nulling and successive interference cancellation was performed, without any inter-substream coding.

The popularity of the MIMO system also comes from the diversity gain it provides. Different from time/frequency diversity, it is a kind of spatial diversity, and it is attractive because it does not sacrifice time or frequency to achieve diversity gain. The maximum achievable diversity order of a MIMO system with M_T transmit antennas and M_R antennas is $M_T M_R$. An effective and practical way to exploit the diversity gain of MIMO wireless channel is to employ *space-time coding (STC)* [66, 67, 68], where the coding is performed in both spatial and temporal domains to introduce correlation between signals transmitted from various antennas at various time periods. There are generally two different kinds of space-time coding, STTC (Space-Time Trellis Code) [67] and STBC (Space-Time Block Coding) [66, 68], and if designed properly both can achieve full diversity order, $M_T M_R$.

- *STTC* operates on one input symbol at a time, and produce a sequence of vector symbols whose length represents transmit antennas. It can provide both coding gain and diversity gain, and while the diversity gain is determined by the minimum rank among the matrices constructed from pairs of distinct code sequences, the coding gain is quantified by the minimum determinant of these matrices. However, the decoding complexity increases exponentially with transmission rate, and it is difficult to design.

- *STBC* operates on a block of input symbols producing a matrix output whose columns represent time and rows represent antennas. It provides full spatial diversity and enjoy a very simple decoding algorithm based on linear processing at the receiver, but gives no coding gain.

Other than treating diversity gain and multiplexing gain separately, Zheng and Tse [69, 70] studied the fundamental tradeoff between the diversity and multiplexing in point-to-point multiple-antenna channels. Between two extremes, either full diversity gain or full multiplexing gain, the optimal tradeoff curve was studied. Such tradeoff curve can be used as a unified framework to compare the performance of many existing diversity-based and multiplexing-based schemes.

In reality, to be efficient, antennas need to be uncorrelated with each other, which requires them to be spaced at least $\lambda/4$ apart, where λ is the wavelength. This is a stringent requirement for many terminals, so only one or two antennas are practical. In such situation, cooperative diversity gives a solution, as it can achieve spatial diversity with some cooperation schemes, while overcome the limitation of requiring multiple antennas at the transmitter. In fact, it forms a distributed MIMO system. Laneman [13] studied multiple-node distributed space-time-coded cooperative protocols, and it was demonstrated that such protocols achieve full spatial diversity in the number of cooperating terminals, not just the number of decoding relays, and they can achieve higher spectral efficiencies than repetition-based schemes. And the related space-time code design for these protocols was discussed. Nabar [71] studied three different time-division multiple-access-based cooperative protocols in a similar way as for MIMO channels, and it was showed that space-time codes designed for the case of colocated antennas can be used to realize cooperative diversity provided that appropriate power control is employed.

Chapter 3

Single-Source Multiple-Relay Cooperation System

In this chapter, we study the single-source multiple-relay cooperation system, $n_s = 1$ and $n_r > 1$. The relay nodes help to forward the message for the source in a repetition way. We first give the system model, and this model will be used in the subsequent chapters. We apply a simple detector, where no channel state information between the source node and the relay node is available at the destination, and maximal ratio combining is performed without considering whether the forwarded symbol from the relay is incorrect. With such an assumption, we analyze the error performance of the system with multiple relay nodes, and demonstrate the resulting error floor in this system. To compensate for the detection error at the relay node, we then propose a relay selection protocol, which can lower the error floor and nearly achieve full diversity order.

3.1 System Model

We consider ad hoc networks where the mobile nodes are connected by the wireless links. This wireless system includes source, relay, and destination nodes, and a certain node may act as a different type at the different time.

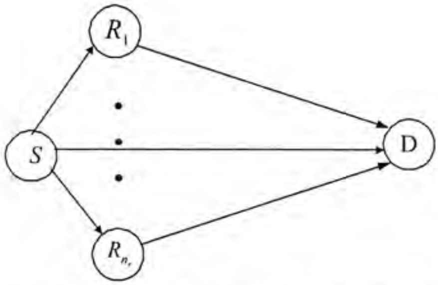

Figure 3.1: Diagram for the single-source multiple-relay cooperation system.

There are n_s source nodes and n_r relay nodes, and we only consider a single destination node here. In this chapter, we consider single-source case, $n_s = 1$, and the system diagram is depicted in Fig. 3.1, where "S" denotes the source node, "R_i" denote the relay nodes, $i = 1, 2, ..., n_r$, and "D" for destination node. Each node transmits and receives with a single omni-directional antenna. Due to RF hardware constraint, simultaneous transmission and reception by any node is not allowed. We consider the single-hop case, where the source and the relay nodes all have direct links with the destination node. The source and the relay nodes work in a cooperative manner to provide diversity at the destination node. All the channels, including source-relay channel, source-destination channel, and relay-destination channel, are assumed to be quasi-static fading, in which the fading coefficient does not change during a symbol period.

Binary PSK is used, and the coherent detection is performed at the relay and the destination nodes. At the destination, we assume the availability of the state information of the source-destination channel and the relay-destination channel, but not the source-relay channel. This is a more realistic assumption, and the study can then easily be extended to the multihop transmission. At the same time, the λ-MRC [12] and the optimal maximum likelihood detector [5] are not applicable here. We do the maximal ratio combining at the destination. For cooperative protocol, we apply decode-and-forward scheme, where the relay fully decodes the received message from the source and then forwards it.

First, we model the case for a one-source, one-relay, one-destination system. It works in a time division way, and only one node is allowed to transmit at a time to avoid potential interference. In the first time slot, the source node sends a symbol x_1, which is received by both the relay and the destination nodes, as

$$y_R = \alpha_{SR}\sqrt{E_1}x_1 + n_R \tag{3.1}$$

$$y_1 = \alpha_{SD}\sqrt{E_1}x_1 + n_1 \tag{3.2}$$

respectively.

The relay node decodes its received signal as x_1' and sends it during the second time slot, then the destination receives

$$y_2 = \alpha_{RD}\sqrt{E_2}x_1' + n_2 \tag{3.3}$$

Here, α_{SR}, α_{SD}, α_{RD} denote the fading coefficients, which represent the links $S \to R$, $S \to D$, and $R \to D$ respectively. They are modeled as independent zero-mean complex Gaussian random variables. We assume the distributions of α_{SD} and α_{RD} are the same as the source and relay nodes are close to each other. n_i, for $i = 1, 2$ or R, capture the effects of additive receiver noise and other forms of interference, and are modeled as zero-mean, mutually independent, white complex Gaussian random variables with variance $N_0/2$ per dimension.

We define the signal-to-noise (SNR) in each received signal as $\gamma_{i,j} = |\alpha_{i,j}|^2\frac{E_i}{N_0}$, with mean value $\bar{\gamma}_{i,j} = E[\gamma_{i,j}] = E[|\alpha_{i,j}|^2]\frac{E_i}{N_0}$. We assume the symmetric case here, which means $\bar{\gamma}_{SD} = \bar{\gamma}_{RD}$ and $\bar{\gamma}_{SR}$ is the same for every relay node. The total power is constrained as $\sum_{i=1}^{n_s+n_r} P_i = n_s P$, where n_s and n_r are the numbers of the source and the relay nodes respectively, and P is the transmit power from one source node without cooperation. Although not optimal, we assume the power is uniformly assigned, i.e., the transmit power of each node is $n_s P/(n_s + n_r)$. The study of power allocation is beyond the scope of this thesis.

3.2 Fixed Decode-and-Forward Cooperation System

In this section, we will analyze the impact of the noisy fading source-relay channel to the performance of the cooperation system. In such system, the relay node may incorrectly detect the received signal from the source node and forward the error symbol while the destination has no idea of it. We first analyze a simple cooperation system with one source node (node 1), two relay nodes (node 2, 3), and one destination node (node 4).

Transmission Protocol In the first time slot, the source node sends a symbol which is received by the relays and the destination. In the second and third time slots, two relays will forward their detected symbols to the destination respectively. The destination applies MRC to all the symbols from the source and the relay nodes. Although the protocol and the detector are simple, the analysis will give useful hints for further development.

The simulation result of this cooperative system, compared with the one without cooperation and the one with cooperation but without detection error at the relay, is shown in Fig. 3.2. In the simulation, the mean SNR of received signal at the relay node is $\bar{\gamma}_{SR} = 10dB$. From the result, we can see that the performance of this error-relay system degrades greatly from the one without detection error at the relay. It does not provide diversity but has an error floor, which is higher than 10^{-2}.

In the following part of this section, from the analysis of the situation with one and two relays in detection error, we will give the bit error rate for this

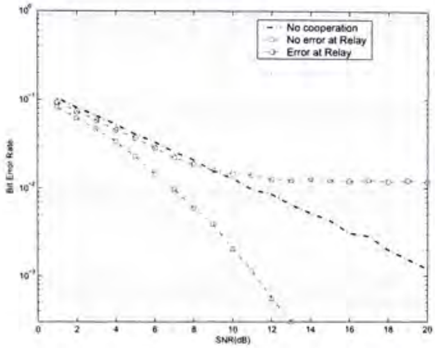

Figure 3.2: The simulation results of the cooperative system with detection error at the relay node, the one without cooperation, and the one with cooperation but without detection error at the relay.

cooperative system and derive some approximations, which will be extended to multiple-relay system.

Proposition 1 If the detection error occurs at one relay, the conditional bit error rate at the destination is

$$P_{e1} = \frac{A^3}{4(A-B)^2(A+B)} - B^3 \frac{9A^2 - 2AB - 3B^2}{4(A+B)^3(A-B)^2} \tag{3.4}$$

where

$$A = \frac{\sqrt{1+\bar{\gamma_c}} + \sqrt{\bar{\gamma_c}}}{\sigma\gamma},\ B = \frac{\sqrt{1+\bar{\gamma_c}} - \sqrt{\bar{\gamma_c}}}{\sigma\gamma}$$

$$E[\alpha_i^2] = 2\gamma^2,\ \bar{\gamma_c} = E[\alpha_i^2]\frac{E_b}{N_0} = \frac{\gamma^2 E_b}{\sigma^2},\ i = 1,2,3$$

The proof is in Appendix A.1.

We consider some high SNR approximation. As $\bar{\gamma_c} \to \infty$, We get

$$\begin{aligned}
\frac{A}{A+B} &= \frac{1}{2}\left[1 + \sqrt{\frac{\bar{\gamma_c}}{1+\bar{\gamma_c}}}\right] \to 1 \\
\frac{A}{A-B} &= \frac{1}{2}\left[1 + \sqrt{1 + \frac{1}{\bar{\gamma_c}}}\right] \to 1 \\
\frac{B}{A+B} &= \frac{1}{2}\left[1 - \sqrt{\frac{\bar{\gamma_c}}{1+\bar{\gamma_c}}}\right] \to \frac{1}{4\bar{\gamma_c}} \\
\frac{B}{A-B} &= \frac{1}{2}\left[-1 + \sqrt{1 + \frac{1}{\bar{\gamma_c}}}\right] \to \frac{1}{4\bar{\gamma_c}}
\end{aligned} \tag{3.5}$$

Applying these into (3.4) results

$$P_{e1} \rightarrow \frac{1}{4}\left[1 - 9(\frac{1}{4\bar{\gamma}_c})^3 + 2(\frac{1}{4\bar{\gamma}_c})^5\right] \rightarrow \frac{1}{4} \tag{3.6}$$

Therefore, if there is one relay node forwarding error symbol, the bit error rate at the destination node will be about 0.25.

Proposition 2 If both relays forward error signals, the conditional bit error rate at the destination is

$$P_{e2} = \frac{B^3}{4(A-B)^2(A+B)} - A^3\frac{9B^2 - 2AB - 3A^2}{4(A+B)^3(A-B)^2} \tag{3.7}$$

The proof is in Appendix A.2.

Using the approximation at the high SNR region as (3.5), we get

$$P_{e2} \rightarrow \frac{1}{4}\left[(\frac{1}{4\bar{\gamma}_c})^3 - 10(\frac{1}{4\bar{\gamma}_c})^2 + 3\right] \rightarrow \frac{3}{4} \tag{3.8}$$

So it means even with high SNR we could not have BER significantly lower than 0.75 if both relay nodes forward error signals.

3.2.1 BER for system with errors at the relay

With *Proposition 1* and *2* we are ready to analyze the system with detection error at the relay node. The overall BER is

$$P_e = \sum_{i=0}^{n_r} P(E|\text{i relays in error})P(\text{i relays in error}) \tag{3.9}$$

The conditional probability $P(E|\text{i relays in error})$, for $i = 1, 2$, are P_{e1} and P_{e2} in (3.4) and (3.7), with the approximations (3.6) and (3.8). $P(E|\text{no relays in error})$ is just the error rate for the 3-branch maximal ratio combining system, $L = 3$ in (1.5).

The probabilities

$$P(\text{i relays in error}) = P_{iR} = \binom{n_r}{i} P_{eR}^i (1 - P_{eR})^{n_r - i} \tag{3.10}$$

where n_r is the number of the relay nodes. In this case, $n_r = 2$. P_{eR} is the error probability at the relay, given by (1.4).

For this two-relay cooperation system, the BER with noisy fading interuser source-relay channel is

$$P_e = P_{e0}P_{0R} + P_{e1}P_{1R} + P_{e2}P_{2R} \tag{3.11}$$

Substitute (3.4), (3.7), and (3.10) into (3.11), we can get the exact value for P_e. If we use (3.6) and (3.8) instead of (3.4) and (3.7), we can get an approximation for P_e.

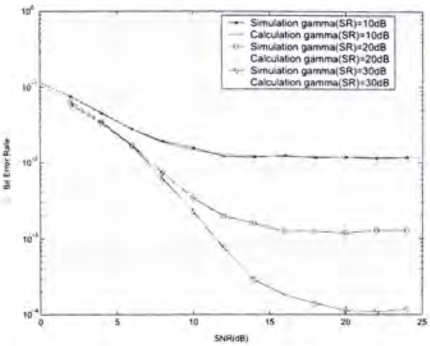

Figure 3.3: Numerical and simulation results of bit error rate for the cooperation systems with different $\bar{\gamma}_{SR}$.

Fig. 3.3 shows BERs from calculation and simulation for $\bar{\gamma}_{SR} = 10dB, 20dB, 30dB$. It can be seen that the results from (3.11) fit the simulation curves very well. In every case, there is an error floor. Even for $\bar{\gamma}_{SR} = 30dB$, the error floor is higher than 10^{-4}, so some advanced protocol is needed for such cooperation system.

Error floor The approximations (3.6) and (3.8) are useful and can be used in the subsequent analysis for simplicity. We use them to calculate the value of error floor. At high SNR, $P_{0R} \ll P_{1R}, P_{2R}$, and applying (3.6) and (3.8) we get

$$P_e \approx P_{e1}P_{1R} + P_{e2}P_{2R} \approx 0.25P_{1R} + 0.75P_{2R} \tag{3.12}$$

This error floor is totally determined by the source-relay channel. For $\bar{\gamma}_{SR} = 10dB$ this approximation gives 0.0118, which agrees very well with the exact formula (3.11).

3.2.2 General BER formula for single-source n_r-relay cooperation system

To analyze the general n_r-relay cooperation system, we give the following proposition:

Proposition 3 For a cooperation system with m_e relay nodes in detection error and m_c nodes (including source node) without detection error, the conditional bit error rate at the high SNR region is approximated by

$$P_{em_cm_e} = 2^{-m_c} \sum_{k=0}^{m_e-1} \binom{m_c + k - 1}{k} 2^{-k} \tag{3.13}$$

The proof is in Appendix A.3.

This proposition is very helpful for further analysis of multiple-relay cooperation system. Notice that (3.13) gives a fixed value for the high SNR region. No matter how high the SNR of the received symbols at the destination is, as long as there are some relay nodes forwarding error symbols, the overall error rate can not be reduced and the system will have an error floor.

Combing (3.13) with (3.9) and (3.10), we can get the BER approximation for cooperation system with n_r relays:

$$P_e = \sum_{i=0}^{n_r} P_{e(n_r+1-i)i}P_{iR} \tag{3.14}$$

The simulation and calculation results for $n_r = 2, 3, 4$ ($\bar{\gamma}_{SR} = 10dB$) are in Fig. 3.4, which show the accuracy of (3.14) at high SNR region. The result

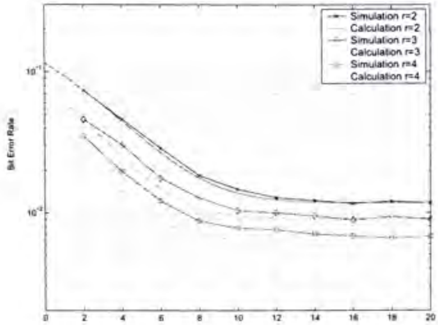

Figure 3.4: Numerical and simulation BERs for the systems with different n_r.

also demonstrates that it is of little advantage to increase the number of relays if the source-relay channel is noisy and fading.

3.2.3 Discussion of Interuser Channels

AWGN Channel

If the channel between the source and the relay nodes is AWGN channel, which means the channel is not fading, $|\alpha_{SR}|^2 = 1$. Then in (3.10), P_{eR} will become

$$P_{eR} = Q(\sqrt{2\gamma_{SR}}) \tag{3.15}$$

where $\gamma_{SR} = \frac{E_b}{N_0}$.

With AWGN interuser channel, it is expected that the probabilities P_{iR} in (3.10) will be smaller, and thus the error floor will be lowered. Fig. 3.5 shows the calculated SNRs for $\gamma_{SR} = 5dB, 10dB, 15dB$, compared with the one without cooperation and the one with ideal interuser channel. The values for different γ_{SR} are calculated by (3.11), and the other two are calculated by (1.5), with $L = 1, L = 3$ respectively. As γ_{SR} increases the performance gets closer to the one with ideal interuser channel. For $\gamma_{SR} = 10dB$ the error floor is near 10^{-6}, and $\gamma_{SR} = 15dB$ does not show error floor in the calculation

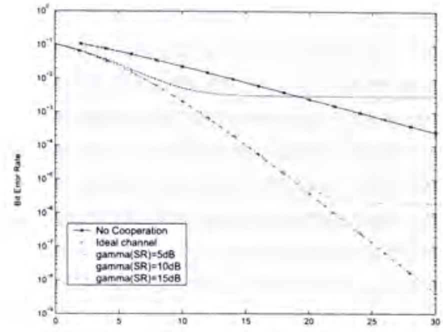

Figure 3.5: Numerical results of BERs for $\gamma_{SR} = 5dB, 10dB, 15dB$, compared with the one without cooperation and the one with cooperation but without detection error at the relay.

range, which otherwise can be calculated to be 10^{-16} by (3.12). So for AWGN interuser channel, $\gamma_{SR} = 10dB$ is good enough for practical application.

Path-Loss model

In the above analysis, we assume a unity gain fading channel, $E[|\alpha_i|^2] = 1$, and fix the average SNR at the relays. If we use the path-loss model based on the network geometry, and assign the fading coefficients according to $E[|\alpha_i|^2] \propto G/d_{i,j}^{\nu}$, where $d_{i,j}$ is the distance between node i and node j, G captures the effects of antenna gain and carrier wavelength, and ν is the path loss exponent depending on the specific propagation environment, and we assign $\nu = 4$ here for urban environment.

In this model, with the same noise variance at the relay and destination node, denote $c = \bar{\gamma}_{SR} - \bar{\gamma}_{SD} = 10\lg(\frac{d_{SD}}{d_{SR}})^4(dB)$, and we still assume $\bar{\gamma}_{RD} = \bar{\gamma}_{SD}$ here. Fig. 3.6 shows the comparison of BERs for different values of c, the one without cooperation, and the one with ideal interuser channel achieving diversity order 3. The BERs for different c are calculated by (3.11), and the other two are calculated by (1.5), with $L = 1, L = 3$ respectively. From the

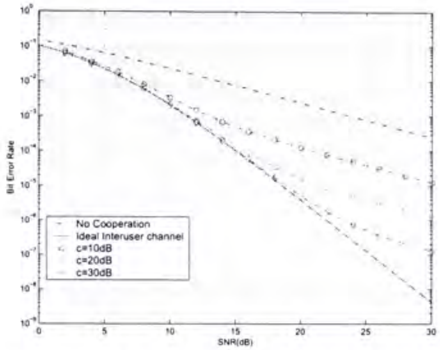

Figure 3.6: Simulation results of different c for path-loss model, compared with the one without cooperation, and the one with ideal interuser channel which achieves diversity order 3.

figure, we can see that full diversity is achieved at low SNR at the destination, but when SNR is higher than some threshold, there will be no diversity gain, the larger the value of c, the higher the threshold. For such a simple detector, $c = 30dB$ is good enough for practical implementation even with fading channel between source and relay node, corresponding to $\frac{d_{SD}}{d_{SR}} = 5.6$, which is not difficult to get.

3.3 Relay Selection Protocol

From the results in last section, we can see that the detection errors at the relays result in the error floor, which determines the overall performance of the decode-and-forward cooperation system. To compensate for such effect, a more efficient cooperative protocol should be developed. There are already some adaptive protocols considering the detection error at the relays [14, 29]. In this paper, we propose a relay selection protocol. The protocol is simple, and the performance analysis will show its efficiency.

3.3.1 Transmission Protocol

The main idea of our protocol is to prevent the relay node from forwarding the error signals. This is similar to the selection relaying scheme in [14], where an SNR threshold was used to decide the corresponding cooperative strategies. In our protocol, we use an error detection scheme at the relay node to detect if there is any error occurred during the demodulation/decoding process. If no error is detected, the relay will send a control signal to other nodes to announce that it will join the cooperation and forward the detected signal. Otherwise, it will send a control signal to inform other nodes that it will quit the cooperation and will send nothing. Consequently, the destination node will adjust the number of its maximal ratio combiner to the number of the active nodes. Where the study in [14] only dealt with the single-relay situation, we try to analyze the multiple-relay systems.

For simplicity, we would use a linear block code as the error-detection code. It may also bring extra temporal diversity under fast fading channel. The system we are going to analyze is the same as in last section, with one source, two relays, and one destination. We use an (n_d, k_d) BCH code as the error-detecting code. The result can easily be extended to multiple-relay systems with (3.13).

3.3.2 BER Analysis for Relay Selection Protocol

As the error-detecting code does not provide a great coding gain in slow fading channel, we will calculate the bit error rate P_e before decoding the code at the destination. We concentrate on analyzing the performance improvement with the relay selection protocol.

At every relay node, there are three possible states ($i = 1$ or 2, is the index of relay node):

- $S_i(1)$: The relay forwards the correct bit.

- $S_i(2)$: The relay forwards an error bit.
- $S_i(3)$: The relay declares an error, and quits the cooperation.

Denote $P(S_i(1)) = P_c$, $P(S_i(2)) = P_u$, $P(S_i(3)) = P_d$. These statuses are independent of each other, i.e., $P(S_1(i), S_2(j)) = P(S_1(i))P(S_2(j))$.

We first calculate the conditional probability, and then get the expected value on fading coefficients. The conditional probability that the codeword will be detected correctly at the relay is

$$P_{wc|\alpha} = (1 - p_{eR|\alpha})^{n_d} \tag{3.16}$$

where $p_{eR|\alpha}$ is the conditional bit error rate between the source and the relay nodes, given by

$$p_{eR|\alpha} = Q(\sqrt{2 \mid \alpha \mid^2 \gamma_{SR}}) \tag{3.17}$$

and $\gamma_{SR} = \frac{E_c}{N_0}$ is the SNR of the received symbol at the relay.

For Rayleigh fading, $|\alpha|^2$ is an exponentially distributed r.v., and we assume $E[|\alpha|^2] = 1$. The pdf is given by $f_{|\alpha|^2}(u) = e^{-u}, u \geq 0$. Therefore, the unconditional probability is given by

$$P_{wc} = E_\alpha[P_{wc|\alpha}] = \int_0^\infty (1 - p_{eR|\alpha})^{n_d} e^{-u} du \tag{3.18}$$

For an (n_d, k_d) error detecting code, the conditional probability of an undetected error is

$$P_{wu|\alpha}(E) = \sum_{i=d_{min}}^{n_d} A_i p_{eR|\alpha}^i (1 - p_{eR|\alpha})^{n_d - i} \tag{3.19}$$

where A_i is the weight distribution of the code, and d_{min} is the minimum Hamming distance of the code.

When the weight distribution is hard to get, we will use the upper bound for undetected probability

$$P_{wu|\alpha} \leq 2^{-(n_d - k_d)}[1 - (1 - p_{eR|\alpha})^{n_d}] \tag{3.20}$$

with the unconditional undetected error probability upper bounded by

$$P_{wu} \leq 2^{-(n_d-k_d)}(1-P_{wc}) \tag{3.21}$$

The probability of the codeword to be declared as error at the relay is

$$P_{wd} = 1 - P_{wc} - P_{wu} \tag{3.22}$$

Therefore, with probability P_{wd}, the codeword will be declared in error at the relay and this relay will quit the cooperation; with probability P_{wc}, the relay will forward the correct codeword to the destination node; with probability P_{wu}, the forwarded codeword is incorrect.

The corresponding bit error probabilities are given by

$$\begin{aligned} P_u &= \frac{2^{k_d-1}-1}{2^{k_d}-1}P_{wu} \\ P_c &= P_{wc} + \frac{2^{k_d-1}}{2^{k_d}-1}P_{wu} \\ P_d &= 1 - P_c - P_d \end{aligned} \tag{3.23}$$

The error probabilities at the destination node is

$$P_e = \sum_{i=1}^{3}\sum_{j=1}^{3} P(E \mid S_1(i), S_2(j))P(S_1(i), S_2(j)) \tag{3.24}$$

with

$$\begin{aligned} P\Big(E \mid S_1(1), S_2(1)\Big) &= P_{eMRC}(L=3) \\ P\Big(E \mid S_i(1), S_j(2), i \neq j\Big) &= P_{e1} \\ P\Big(E \mid S_1(2), S_2(2)\Big) &= P_{e2} \\ P\Big(E \mid S_i(1), S_j(3), i \neq j\Big) &= P_{eMRC}(L=2) \\ P\Big(E \mid S_i(2), S_j(3), i \neq j\Big) &= P'_{e1} \\ P\Big(E \mid S_1(3), S_2(3)\Big) &= P_{eMRC}(L=1) \end{aligned}$$

For P_{e1} and P_{e2}, we will use the approximations in (3.6) and (3.8). P'_{e1} is the BER of a one-source one-relay system with the relay in error, and it can be easily found as $P'_{e1} = 1/2$. $P_{eMRC}(L)$ is the BER for L-branch maximal ratio combining receiver [3].

Next we will use high SNR approximation to analyze the error floor. In high SNR region, $P_{e1} = 0.25, P_{e2} = 0.75, P'_{e1} = 0.5, P_{eMRC}(L) \ll P_{e1}, P_{e2}, P'_{e1}$. Therefore, (3.24) can be approximated by

$$\begin{aligned} P_e &\approx 2P_{e1}P_cP_u + P_{e2}P_u^2 + 2P'_{e1}P_dP_u \\ &= 0.5P_cP_u + 0.75P_u^2 + P_dP_u \end{aligned} \tag{3.25}$$

From this expression, we can see that the approximation of P_e is decided totally by the relay nodes. For the $(7,4)$ Hamming code, the error floor is 9.16×10^{-4} for $\bar{\gamma}_{SR} = 10dB$. For the (63,45) BCH code, the value is 2.9×10^{-7} for $\bar{\gamma}_{SR} = 20dB$ with the upper bound in (3.21).

To verify (3.24), we use the $(7,4)$ Hamming code as an example. Its weight distribution A_i in (3.19) is

$$A_0 = 1, A_1 = A_2 = 1, A_3 = A_4 = 7, A_5 = A_6 = 0, A_7 = 1$$

We can get the exact P_e. The simulation results and the theoretical results calculated by (3.24) are compared in Fig. 3.7 with $\bar{\gamma}_{SR} = 10dB$. We can see that the results agree very well. The error floor is about 10^{-3}. Notice that the error floor for the system without relay selection is about 10^{-2}.

However, compared with the one without cooperation in Fig. 3.2, this cooperation system provides little diversity gain, which results from small number of relay nodes performing cooperation due to the relatively low P_c. To improve the achieved diversity order, P_c should be kept high, while the error-detecting code should be powerful enough to lower P_u to reduce the error floor. For $\bar{\gamma}_{SR} = 20dB$, we use the $(63,45)$ BCH code as the error-detecting code. The simulation result for the overall BER at the destination node is shown in Fig. 3.8, together with the one without cooperation and the one without detection error at the relay. We can see that it does not show an error floor in the

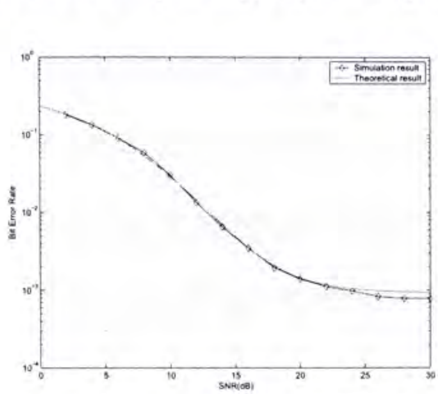

Figure 3.7: Numerical and simulation results of BERs for relay selection protocol with (7,4) Hamming code as error-detecting code.

simulation range and a diversity order of nearly 3 is achieved, compared with an error floor of 10^{-3} without relay selection in Fig. 3.3.

Furthermore, if the source-relay channel is fast fading, we can use an error-correction codes as the outer code, resulting in a system similar to the hybrid ARQ in [72]. As shown in [72], as long as the minimum distance of the error-correction code is greater than twice that of the error-detection code, it will have higher correct detection probability and lower undetected error probability at the relay node, which will keep the diversity gain and lower the error floor.

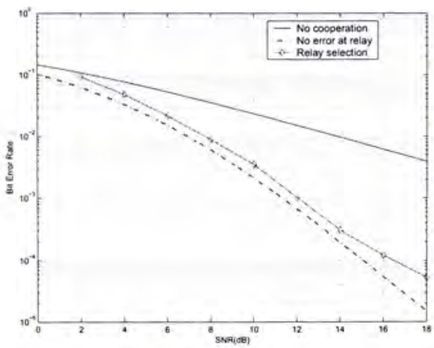

Figure 3.8: Simulation result for the relay selection protocol with (63, 45) BCH code as error-detecting code, compared with the one without cooperation, and the one with cooperation but without detection error at the relay node.

Chapter 4

Multiple-Source Multiple-Relay Cooperation System

The single-source multiple-relay cooperation system in last chapter is a repetition coded system. Each relay node only forwards the message for a certain source node by repetition. If there are several source nodes which have symbols to send to a common destination, a relay node nearby may receive all these symbols. It will be a waste of resource if the relay only forwards for a single source node at a time. In this chapter we try to design an efficient protocol for the multiple-source multiple-relay system. To improve the efficiency, some processing should be applied to the incoming symbols at the relay node, and we do some linear block coding, which we call "*cooperative coding*".

For the studied multiple-source multiple-relay cooperation system, there are n_s source nodes and n_r relay nodes, $n_s, n_r \geq 1$, as depicted in Fig. 4.1, where "S_i" denote the source nodes, $i = 1, 2, ..., n_s$, "R_j" denote the relay nodes, $j = 1, 2, ..., n_r$, and "D" for the destination node. The channel model and the receiver structure are as stated in Chapter 3. All the source nodes want to transmit to the destination, and the relays will cooperate to help these transmissions. The source nodes and the relay nodes are close to each other, so this is a symmetry case, where the fading coefficients of the source/relay-destination channels are i.i.d. (independent identically distributed). We also

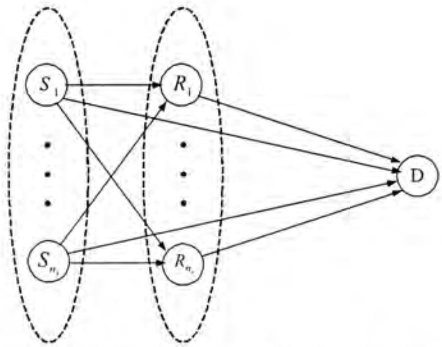

Figure 4.1: Diagram for the multiple-source multiple-relay cooperation system.

assume equal power allocation, and it is the single-hop transmission.

4.1 Transmission Protocol

Cooperative Coding For the system with n_s source nodes, n_r relay nodes, and a single destination node, the *cooperative code* is a (n_s+n_r, n_s) linear code, of which n_s information bits are sent from the source nodes and n_r parity bits are generated at the relay nodes by encoding the incoming symbols from the source nodes. Every transmission period consists of $n_s + n_r$ time slots. In the first n_s time slots, the source nodes take turns to send out their own symbols, while the relay nodes receive and detect them; then the relay nodes encode the received symbols according to the pre-assigned cooperative code to generate the parity bits; in the next n_r time slots, the relay nodes send the parity bits one by one; finally, the destination node performs soft-decision decoding on the messages received from the source and relay nodes.

This system is similar to the coding system in the fading channel which provides temporal diversity [3]. However, the coded bits are from different nodes, so the achieved diversity is spatial diversity rather than temporal diversity. Similar to the temporal counterpart, the achieved diversity order is decided by the minimum distance of the cooperative code. According to the *Singleton bound* [73], the greatest minimum distance for a $(n_s + n_r, n_s)$ code is $n_r + 1$. Therefore, the achievable diversity order for this cooperative coding system is $n_r + 1$, when a Maximum Distance Separable (MDS) code is used as the cooperative code, and we will show that it can be achieved with the adaptive cooperative coding protocol.

With the Singleton bound, it is straightforward to get some general results for this cooperation system with $n_s + n_r$ nodes:

a) The maximum diversity order is $n_s + n_r$, but the data rate becomes $1/(n_s + n_r)$. It is a repetition code system, as we discussed in last chapter. In the ith period of time (divided into $n_s + n_r$ time slots), all the nodes help to forward the message for ith source node: ith node transmits in the 1st time slot, and then all the other nodes take turns to forward the received message from ith node in the following $n_s + n_r - 1$ time slots.

b) The maximum achievable data rate for required diversity order, L, is $n_{s'}/(n_{s'} + L - 1)$. MDS code should be used. In every time period, $L - 1$ nodes should be assigned as relay nodes, and if $n_r < L - 1$, some source nodes should take turn to act as relay nodes for each other. So $n_{s'} = n_s$ if $n_r \geq L - 1$; $n_{s'} = n_s + n_r + 1 - L$ if $n_r < L - 1$, and an $(n_{s'} + L - 1, L - 1)$ MDS code should be used.

c) The maximum diversity order under required data rate: If the data rate $R = \frac{m}{m+n}, m + n = n_s + n_r$ and $m \leq n_s$, the maximum diversity order will be $n + 1$, and an $(n + m, m)$ MSD code should be used.

According to these rules, we can make a tradeoff between the achieved diversity order and the data rate under different requirements.

The above discussion is mainly based on the comparison with the temporal diversity system, but there is a major difference for the cooperative coding system: the information bits at the relay nodes are obtained from the source nodes. Such information may not be reliable as the channel between the source node and the relay node is a fading channel. The consequence is that the coded bits from some relay nodes may be incorrectly encoded, which may greatly degrade the system performance. In the following sections, we will analyze the impact of such noisy interuser channel between the source and the relay nodes on the system performance, and an adaptive cooperative coding protocol is proposed to compensate for it.

4.2 Fixed Cooperative Coding System

We first analyze the fixed cooperative coding system, where the relays decode the received messages from the source nodes and then encode them according to the assigned cooperative code, which is a linear block (n_c, k_c) code. We will analyze the impact of detection errors at the relay nodes.

4.2.1 Performance Analysis

To analyze the impact of the error at the relay node to the system performance, we take a simple $(6, 3)$ cooperative code for example. The generator matrix is

$$G = \begin{bmatrix} 1 & 0 & 0 & 0 & 1 & 1 \\ 0 & 1 & 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 & 1 & 0 \end{bmatrix}$$

As the parity checks for relay nodes are symmetry, it will make the analysis simple. From G, we can see that the minimum Hamming distance of this cooperative code is 3, so the achievable diversity order is 3. However, if a relay node detects the symbol from some source nodes incorrectly, it will forward error-encoded symbol, and thus degrade the performance of the cooperation system. The comparison between the system without cooperation, the system with cooperation but without detection error at the relay, and the system with detection error at the relay is in Fig. 4.2. From the result, we can see that

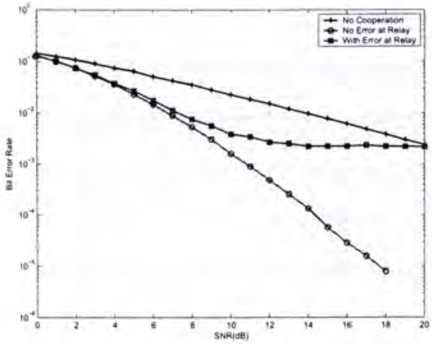

Figure 4.2: The simulation results of cooperative coding system with detection error at the relay node, the one without cooperation, and the one with cooperation but without detection error at the relay, $\bar{\gamma}_{SR} = 20dB$.

the achieved diversity order is 3 without detection error at the relay node. However, if the source-relay channel is fading and there is detection error at the relay node, the system will have an error floor.

As it is difficult to derive the exact BER formula for such cooperative coding system, we try to give an upper bound and a lower bound to analyze the system performance. The bit error rate is averaged on all the source nodes.

Upper Bound We use the union bound to get the upper bound for the word error probability

$$P_w \leq \sum_{m=2}^{M} P_2(m) \tag{4.1}$$

where M is the size of the codebook, and for an (n_c, k_c) cooperative code $M = 2^{k_c}$.

We assume that all the source nodes send zero, so the all-zero codeword C_1 is transmitted in the cooperation system. $P_2(m)$ is the probability of decoding the transmitting codeword C_1 to codeword C_m at the destination node, given by

$$P_2(m) = \sum_{R_e \subseteq \mathcal{R}} P(E^m|R_e)P(R_e) \tag{4.2}$$

where $\mathcal{R}$ is the set of all three relay nodes, i.e., $\mathcal{R} = \{R_1, R_2, R_3\}$, and R_e is the set of those relay nodes which send the wrong code bits. $P(R_e)$ denotes the probability that the relay nodes in R_e forward error messages.

The corresponding bit error probability is given by

$$P_b = \frac{2^{k_c-1}}{2^{k_c}-1} P_w \tag{4.3}$$

Lower Bound The error probability will be no less than $P(d_{min})$, the probability of wrongly decoding the codeword to the one with the minimum distance to C_1:

$$P_w \geq P(d_{min}) \tag{4.4}$$

d_{min} is the minimum Hamming distance of the cooperative code.

For the simple cooperative code, we can analyze every $P_2(m)$ for accuracy. Otherwise, we can get a loose upper bound with

$$P_w \leq (M-1)P(d_{min}) \tag{4.5}$$

Analysis of $P(R_e)$

Denote $P_{eR,k}$ as the probability that the kth relay forwards erroneous message. It is given by

$$\begin{aligned} P_{eR,k} &= \sum_{i=1}^{3} g_{ik} P_{e,S\to R}(1-P_{e,S\to R})^2 \\ &+ \sum_{i=1}^{3}(\sum_{i\neq k} g_{ik} \bmod 2) P_{e,S\to R}^2 (1-P_{e,S\to R}) \\ &+ (\sum_{i=1}^{3} g_{ik} \bmod 2) P_{e,S\to R}^3 \end{aligned} \tag{4.6}$$

where g_{ik} is the element at ith row and kth column of the generator matrix G, and $P_{e,S\to R}$ is the bit error rate of the transmission from the source node to the relay node in the fading channel, given by (1.4).

C_1	[0 0 0 0 0 0]
C_2	[0 0 1 1 1 0]
C_3	[0 1 0 1 0 1]
C_4	[0 1 1 0 1 1]
C_5	[1 0 0 0 1 1]
C_6	[1 0 1 1 0 1]
C_7	[1 1 0 1 1 0]
C_8	[1 1 1 0 0 0]

Table 4.1: The codebook for the (6,3) cooperative code

For this $(6, 3)$ cooperative code, $P_{eR,k}$ is the same for every relay node due to the symmetry, which will simplify some of the following analysis. Therefore,

$$P(R_e) = \prod_{R_i \in R_e} P_{eR,i} \prod_{R_j \in \bar{R}_e} (1 - P_{eR,j}) \tag{4.7}$$

Analysis of $P(E^m|R_e)$

This probability may be different for different codeword C_m. Fortunately, from Table 4.1, we can see that some of the different codewords have the same distance distribution, which will reduce our work. Denote w_m as the weight of mth codeword C_m. $w_2 = w_3 = w_5$, and $w_4 = w_6 = w_7$. Therefore, $P_2(2) = P_2(3) = P_2(5)$ and $P_2(4) = P_2(6) = P_2(7)$, so we only have to get $P_2(2)$, $P_2(4)$ and $P_2(8)$.

The correlation metrics of the cooperative code is

$$CM_i = C(\mathbf{r}, \mathbf{C}_i) = \sum_{j=1}^{n_c} (2c_{ij} - 1) r_j \tag{4.8}$$

where c_{ij} denotes the bit in the jth position of the ith codeword. For the all-zero symbol, we get the received signal $r_j = \mathrm{Re}[\alpha_j^*(-\alpha_j\sqrt{\varepsilon_c} + n_j)]$, where maximal ratio combining is performed. $P_2(m)$ is the probability of $CM_1 < CM_m$, which is $\mathrm{Prob}(\mathrm{Re}[\sum_{i=1}^{w_m} \alpha_i^*(\alpha_i\sqrt{\varepsilon_c} - n_i)] < 0)$ if no detection error occurs at the relay node, given by [3]

$$P_2(m) = P(w_m) = p^{w_m} \sum_{k=0}^{w_m - 1} \binom{w_m + k - 1}{k} (1-p)^k \tag{4.9}$$

where p is the probability of error for the case without diversity, given by (1.4).

If there is an detection error at some relay, r_j will be $\text{Re}[\alpha_j^*(\alpha_j\sqrt{\varepsilon_c}+n_j)]$ for some parity bits. We denote such correlation metrics CM_{m,R_e} if the relays in set R_e are in detection error. So

$$P(E^m|R_e) = \text{Prob}(CM_{1,R_e} - CM_{m,R_e} < 0|R_e) \tag{4.10}$$

and

$$\begin{aligned} &CM_{1,R_e} - CM_{m,R_e} \\ &= 2Re\Big[\sum_{i=1}^{w_m-k_e} \alpha_{k_i}^*(\alpha_{k_i}\sqrt{\varepsilon_c} - n_{k_i}) + \sum_{j=1}^{k_e} \alpha_{k_j}^*(-\alpha_{k_j}\sqrt{\varepsilon_c} - n_{k_j})\Big] \end{aligned} \tag{4.11}$$

where k_e is determined by codeword C_m and the position of error bit, $0 \le k_e \le |R_e|$, and k_i, k_j are the index of incoming path at the destination, which can be decided accordingly.

From *Proposition 3*, the approximation of the probability in (4.10) is given by $P_{em_cm_e}$ in (3.13), where $m_c = w_m - k_e$, $m_e = k_e$.

For example, if no error at the relays, $C_1 = [0\ 0\ 0\ 0\ 0\ 0]$, $C_2 = [0\ 0\ 1\ 1\ 1\ 0]$, $r_j = \text{Re}[\alpha_j^*(-\alpha_j\sqrt{\varepsilon_c}+n_j)]$. Assume the first relay node R_1 sends error code bit, then $r_4 = \text{Re}[\alpha_4^*(\alpha_4\sqrt{\varepsilon_c}+n_4)]$, and $r_{i,i\neq 4} = \text{Re}[\alpha_i^*(-\alpha_i\sqrt{\varepsilon_c}+n_i)]$. Accordingly,

$$\begin{aligned} &CM_{1,\{R_1\}} - CM_{2,\{R_1\}} \\ &= 2Re[\alpha_4^*(-\alpha_4\sqrt{\varepsilon_c} - n_i)] + 2Re\Big[\sum_{i=3,5} \alpha_i^*(\alpha_i\sqrt{\varepsilon_c} - n_i)\Big] \end{aligned} \tag{4.12}$$

Then from *Proposition 3*, $P(E^2|R_e = \{R_1\}) = P_{e21}$.

Following the same way, comparing the codeword C_1 with C_m and based on (4.10) (4.11), we can get the following probabilities:

For $P_2(2)$

$$\begin{aligned} &P\big(E^2|R_e = \{R_i\}, i = 1,2,3\big) = \frac{1}{3}P(w_m = 3) + \frac{2}{3}P_{e21} \\ &P\big(E^2|R_e = \{R_i, R_j\}, i,j = 1,2,3, i \neq j\big) = \frac{1}{3}P_{e12} + \frac{2}{3}P_{e21} \\ &P\big(E^2|R_e = \{R_1, R_2, R_3\}\big) = P_{e12} \end{aligned} \tag{4.13}$$

For $P_2(4)$

$$\begin{aligned}
&P\big(E^4|R_e=\{R_i\},i=1,2,3\big)=\frac{1}{3}P(w_m=4)+\frac{2}{3}P_{e31}\\
&P\big(E^4|R_e=\{R_i,R_j\},i,j=1,2,3,i\neq j\big)=\frac{1}{3}P_{e22}+\frac{2}{3}P_{e31}\\
&P\big(E^4|R_e=\{R_1,R_2,R_3\}\big)=P_{e22}
\end{aligned}\tag{4.14}$$

For $P_2(8)$

$$P(E)=P(w_m=3)\tag{4.15}$$

A loose upper bound If the code is more complicated, we can use a loose upper bound. In fact, from (4.11) we can see that the probability (4.10) is greatest when $k_e=|R_e|$. Denote $k_0=|R_e|$, we can get an upper bound for probability (4.10)

$$P(E^m|R_e)\leq P_{e(w_m-k_0)k_0}=2^{-(w_m-k_0)}\sum_{k=0}^{k_0-1}\binom{(w_m-k_0)+k-1}{k}2^{-k}\tag{4.16}$$

4.2.2 Numerical Results and Discussion

Up to now, we have got the values of $P(R_e)$ and $P(E^m|R_e)$. Thus we can get the upper bound and the lower bound for error probability. The comparisons between the simulation result and the calculated bounds by (4.2) and (4.4) are in Fig. 4.3.

From the figure, we can see that the bounds are not very tight. This is due to the union bound we use, but they follow the change of the BER curve, and at the high SNR region the simulation result is very close to the lower bound. In addition, from (4.13) (4.14) we can see the error floor is caused by those $P_{em_cm_e}$ terms, which is constant at the high SNR region. In the complete BER formula, the terms in $P(E^m|R_e)$ are weighted by $P(R_e)$ terms, so if we can reduce the value of $P(R_e)$ the error floor will be reduced subsequently. In other words, if we want to have lower error floor, we have to reduce the probability that the relay nodes send error code bits.

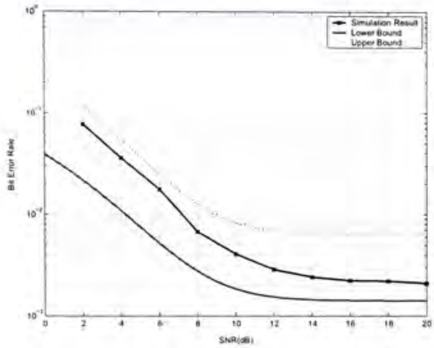

Figure 4.3: Simulation result and calculated bounds of bit error rate for $\bar{\gamma}_{SR} = 20dB$, for fixed cooperative coding system.

4.3 Adaptive Cooperative Coding

From the discussion in last section, to lower down the error floor, we should reduce the probability of relay nodes sending error code bits, for which we propose an *adaptive cooperative coding protocol* in this section. This protocol does some error-detecting processing at the relay nodes, and encodes the incoming symbols according to the check results. The performance analysis in the following part of this section, together with the simulation result, will show the effectivity of this protocol.

Adaptive Cooperative Coding Protocol First, the source nodes take turns to send their data messages, which are received by both the relay and the destination. At the relay node, error detection is performed on the symbol from each source node. If some symbol is detected in error, it will be omitted from the encoding process at the relay node, by changing the corresponding element in the generator matrix to zero. For example, if at the 1st relay node the symbol from the 2nd source node is in detection error, g_{24} is set to "0". Then the relay will inform the destination which symbol has been omitted and the destination node will change the detecting scheme accordingly. In fact, it can be explained intuitively that the relay node only helps the source node whose transmission to that relay node is reliable.

This adaptive protocol is somehow similar to the "relay selection protocol" in Chapter 3, but there is a major difference, which makes this adaptive candidate more attractive. For the relay selection protocol, as long as the symbol from one source node is in detection error, the relay will quit the cooperation. However, there is the chance that even when some symbols are detected incorrectly the encoded symbol sending from the relay node is still correct, which depends on the generator matrix. The adaptive cooperative coding protocol takes this into consideration, and when some error occurs at the relay it adapts by changing the generator matrix of cooperative code rather than totally quits the cooperation. Compared with relay selection protocol, this adaptive protocol can be called as *Symbol Selection Protocol.* The performance comparison of the relay selection protocol and symbol selection protocol for this 3-source 3-relay system is in Fig. 4.4, together with the non-cooperative case and the cooperation system without detection error at the relay. We can see that the relay selection protocol in this situation does not achieve full diversity order, while the symbol selection protocol can provide full diversity order, and approaches the performance of the ideal cooperation system without detection error at the relay.

4.3.1 Performance Analysis of Adaptive Cooperative Coding System

As in Chapter 3, we use linear block (n_d, k_d) codes as error-detecting codes. We will analyze the bit error rate before decoding the error-correcting code at the destination, as the error-detecting code does not provide much coding gain in slow fading channel.

The analysis of the status of the relay node is the same as in Chapter 3.

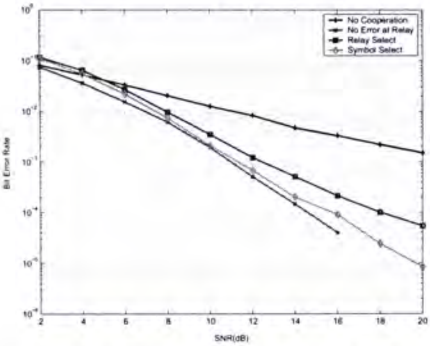

Figure 4.4: Comparison of relay selection protocol and symbol selection protocol.

The correct detection probability, P_c, the undetected probability, P_u, and the probability of detecting error at the relay node, P_d, are given by (3.23).

The analysis for adaptive cooperative coding system is somehow similar to the one in last section, but it is more complicated. For this system, if the symbol from a source node is detected as error at the relay node, the relay will omit this symbol, by changing the generator matrix of the cooperative code. Therefore, the detecting error at different relay nodes and the error symbols from different source nodes result in different generator matrices, which complicates our analysis.

Denote the set of parity elements of generator matrix $\{g_{ij}, i = 1, 2, 3, j = 4, 5, 6\}$ by $\mathcal{G}$. If a symbol from a certain source node is in error at the relay node, a subset of $\mathcal{G}$ will be changed, denoted by g, $g \subseteq \mathcal{G}$. So the probability $P_2(m)$ can be given as

$$P_2(m) = \sum_{g \subseteq \mathcal{G}} P_2(m|g)P(g) \tag{4.17}$$

where $P(g)$ denotes the probability that the subset g have changed. Similar to (4.2), the conditional probability $P_2(m|g)$ is given by

$$P_2(m|g) = \sum_{R_e \subseteq \mathcal{R}} P(E^m|R_e, g)P(R_e|g) \tag{4.18}$$

$P(R_e|g)$ is given by (4.7), where $P_{eR,i}$ are calculated according to the change of the generator matrix.

To simplify our analysis, we will only calculate $P_2(2)$, and then get the upper bound and the lower bound according to (4.5) and (4.4).

4.3.2 Analysis of $P_2(2)$

As the information bits are [0 0 1] for C_2, only the changes of g_{34}, g_{35}, g_{36} have impacts on $P_2(2)$. In addition, $g_{36} = 0$, so we only have to analyze the change of g_{34} and g_{35}.

Only one of g_{34} and g_{35} is changed Here we assume g_{34} is changed. $P(g)$ is given by

$$P(g) = P_d(1 - P_d) \tag{4.19}$$

For $P(E^2|R_e, g)$, we can do the general way as (4.13), but now the codeword C_2 becomes [0 0 1 0 1 0], which is different from C_1 only at the 5th bit in the parity part, so we only have to analyze the 2nd relay node:

$$P_{eR,2|g} = P'_u(1 - P_u) + P_u(1 - P'_u) \tag{4.20}$$

where P'_u is the undetected error probability at the 2nd relay node for the symbol from the 3rd source node, conditioned on the event that g_{35} does not change, given by $P'_u = \frac{P_u}{P_u+P_c}$.

Now $P(E^2|R_e, g)$ is given by

$$\begin{aligned} &P(E^2|R_2 \,\text{is correct}, g) = P(w_m = 2) \\ &P(E^2|R_e = \{R_2\}, g) = P_{e11} \end{aligned} \tag{4.21}$$

Both g_{34} and g_{35} are changed $P(g)$ is given by

$$P(g) = P_d^2 \tag{4.22}$$

C_2 is [0 0 1 0 0 0], and no relay node plays a part in the system, so

$$P(E^2|g) = P(w_m = 1) \tag{4.23}$$

Neither g_{34} nor g_{35} is changed $P(g)$ is given by

$$P(g) = (1 - P_d)^2 \tag{4.24}$$

C_2 becomes [0 0 1 1 1 0], so we have to analyze the 1st and 2nd relay nodes. $P_{eR,1|g}$ and $P_{eR,2|g}$ are the same as (4.20).

Now $P(E^2|R_e, g)$ is given by

$$\begin{aligned} &P(E|R_1 \,\text{and}\, R_2 \,\text{are correct}, g) = P(w_m = 3) \\ &P(E|R_e = \{R_1, R_2\}, g) = P_{e12} \\ &P(E|R_e = \{R_i\}, i = 1, 2, g) = P_{e21} \end{aligned} \tag{4.25}$$

4.3.3 Numerical Results and Discussion

Substituting the formulas in last section into (4.17) (4.18), we can get the value of $P_2(2)$, and then get the bounds through (4.4) and (4.5). For example, we take BCH $(7,4)$ code as error-detecting code, whose distance distribution is easy to follow. The comparison of the simulation result and calculated bounds is shown in Fig. 4.5. The bounds show the achievable diversity order, and the lower bound is very close to the simulation result at high SNR region. Compared with Fig. 4.3, the error floor is reduced by an order even with such simple code.

There are two types of codes used in the system, cooperative code and error-detecting code, and they play different roles. From the formulas in last section, we can see those $P_{em_cm_e}$ terms are weighted by the terms with P_u, P_c, and P_d, which are determined by the error-detecting code. So if we use more powerful error-detecting code, the error floor will be reduced further. On the other hand, the achievable diversity order is decided by the minimum distance

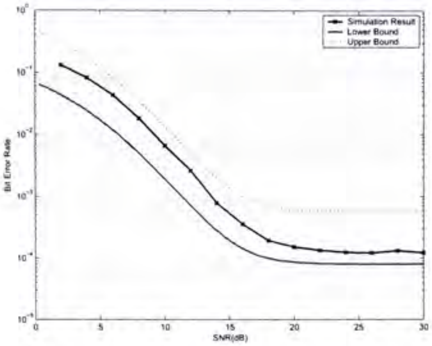

Figure 4.5: Simulation result and calculated bounds of bit error rate for adaptive cooperative coding system with BCH (7,4) code as error-detecting code.

of the cooperative code. If we use MDS code instead of the simple linear $(6, 3)$ cooperative code, for this 3-source 3-relay cooperation system, the achievable diversity order will be 4.

The simulation results for the improved systems are in Fig. 4.6. The error-detecting code is BCH $(63, 45)$ code, and both cooperation systems apply adaptive cooperative coding, one using linear $(6, 3)$ code and the other using MDS code. The generator matrix for MDS code is [73]

$$G = \begin{bmatrix} 1 & 0 & 0 & 1 & 1 & 1 \\ 0 & 1 & 0 & 1 & t & t^2 \\ 0 & 0 & 1 & 1 & t^2 & t \end{bmatrix}$$

where the coding is performed in $GF(4)$, and t is the root of the primitive polynomial $t^2 + t + 1 = 0$.

From Fig. 4.6, we can see that the linear $(6, 3)$ cooperative coding system achieves diversity order 3, while MDS cooperative coding system can achieve diversity order 4. Neither of them shows the error floor in the simulation range. So with the adaptive cooperative coding protocol, we can achieve full diversity order.

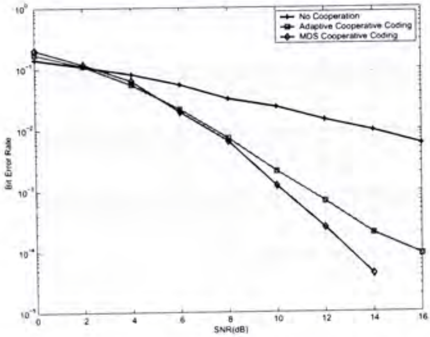

Figure 4.6: Simulated results of adaptive cooperative coding systems with MDS code and the linear (6,3) code as cooperative codes.

Chapter 5

Cooperative Multihop Transmission

Working by cooperating with other transmitting nodes, cooperation transmission has a great potential in wireless ad hoc networks, where some nodes act as relays for others. It can save the transmission energy, improve the reliability, and increase the pathloss saving for the system. Ad hoc networks are characterized by multihop relaying, but former studies on cooperation systems mainly focused on single-hop transmission, so they should be extended to the multihop case.

In [74], the authors introduced the concept of *multihop diversity*, a cooperation system with multihop transmission, where the diversity is achieved by receiving signals that have been transmitted by multiple previous nodes along a single primary route. It is shown that multihop diversity schemes, both decoded and amplified relaying, outperform the traditional multihop transmission. As it is assumed that a decoding error at any intermediate node will result in a detection error at the destination node, the decoded relaying scheme does not achieve diversity, while the amplified relaying provides full diversity order. Although such assumption makes it easier to analyze, it is too simple and greatly degrades the system performance. It is possible to improve the performance with more advanced detection schemes, such as the λ-MRC detector [12] and the optimal maximum likelihood detector [5]. However, the state information of previous source-relay and relay-relay channels is required.

In this chapter, we study the decode-and-forward cooperative multihop transmission. We take into consideration the possibility of the relay node forwarding error signals, and apply the relay selection protocol in Chapter 3 to compensate for it. What is available at every node is the channel state information of those incoming channels from which it receives symbols, and at the destination the maximal ratio combining is applied for all the received symbols.

5.1 System Model

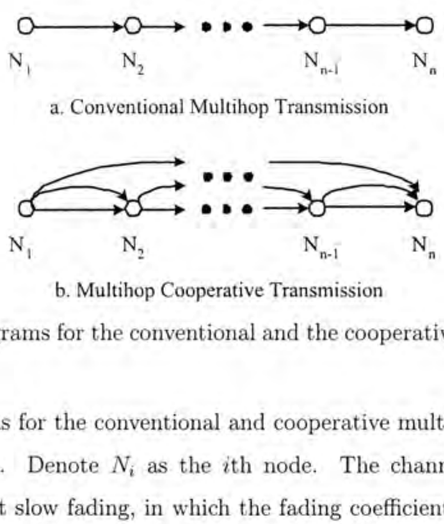

Figure 5.1: Diagrams for the conventional and the cooperative multihop transmission.

The diagrams for the conventional and cooperative multihop transmission are in Fig. 5.1. Denote N_i as the ith node. The channel is assumed to be frequency-flat slow fading, in which the fading coefficient does not change during a symbol period. We use the path-loss model based on the network geometry, and assign the fading coefficients according to $E[|\alpha|^2] \propto d_{i,j}^{-\nu}$, where $d_{i,j}$ is the distance between the node N_i and the node N_j, and ν is the path loss exponent depending on the specific propagation environment. We assign $\nu = 4$ here for urban environment.

The routing and medium access control are out of the scope of our study, and we assume the route is set and there is no contention. The focus is on the achieved diversity order at the destination node. The relay nodes are first assumed to be uniformly distributed on the route line, and the impact of the node distribution will be discussed later. It works in a time-division way, i.e., only one node is allowed to transmit during a time slot. Each node transmits and receives with a single omni-directional antenna. Simultaneous transmission and reception by any node is not allowed.

5.1.1 Conventional Multihop Transmission

For the conventional multihop transmission, each relay node on the route line receives the symbol only from last node. In the ith time slot of a transmit cycle, the node N_i sends the detected symbol to the node N_{i+1}. N_{i+1} receives it as

$$y_{i+1} = \alpha_{i,i+1}\sqrt{E_i}x_i + z_{i,i+1} \tag{5.1}$$

where the random variables $\alpha_{i,j}$, $i, j = 1, 2, ..., n, (i < j)$, denote the fading coefficients, which represent the links $N_i \to N_j$, and $E[|\alpha_{i,j}|^2] = \sigma^2_{i\to j}$. They are modeled as independent zero-mean complex Gaussian random variables. At the ith node, $\alpha_{k,i}$, $k = 1, 2, ..., i-1$, are available but no other channel state information. $z_{i,j}$, $i, j = 1, 2, ..., n$, capture the effects of additive receiver noise and other forms of interference, and are modeled as zero-mean, mutually independent, white complex Gaussian random variables with variance $\sigma_n^2 = N_0/2$ per dimension. The total power is constrained as $\sum_{i=1}^{n} P_i = P$. P is the power of signal for the equivalent single-hop transmission. We assume the power is uniformly assigned, i.e., every node has transmit power P/n.

The node N_{i+1} demodulates and detects y_{i+1} as x_{i+1} and forwards to the next node, N_{i+2}. It goes on until the symbol reaches the destination node, and one transmit cycle ends.

5.1.2 Cooperative Multihop Transmission

The cooperative multihop transmission works as follows: When one node transmits, all the nodes after it receive the transmitted symbol and store this information for the following detection. After all the former nodes transmit, the current node will combine all the received symbols and do the detection. Before forwarding the detected symbol, each node will do error-check: if it checks no error, it will send a control signal to indicate that it will join the cooperation and forwards the detected symbol; otherwise, it will send a control signal to inform other nodes that it will quit the cooperation and does not forward the symbol.

In the first time slot, the source node sends the signal x_1. At the ith node $(i = 2, 3, ..., n)$, the received signal is

$$y_i = \alpha_{1,i}\sqrt{E_1}x_1 + z_{1,i} \tag{5.2}$$

After j time slots, the node N_{j+1} has received all the symbols from previous nodes. It does the maximal ratio combining and get the decision variable as

$$U = Re\big[\sum_{k\in\mathcal{D}} \alpha^*_{k,j+1}(\alpha_{k,j+1}x_k + z_{k,j+1})\big] \tag{5.3}$$

where $\mathcal{D}$ is the set of those nodes joining the cooperation. This signal is detected as x_{i+1}. Then the node does the error check. If no error is detected, it will forward x_{i+1} to the following nodes; otherwise it will inform other nodes that it will not join the cooperation and send nothing.

5.2 Performance Evaluation

In this section, we will analyze the bit error rate for conventional and cooperative multihop transmission.

5.2.1 Conventional Multihop Transmission

Assuming that an error at an intermediate node will cause an error at the destination node, we can get an upper bound for the overall bit error rate for L-hop transmission

$$P_e \leq 1 - \prod_{i=1}^{L} (1 - P_{e,i \to i+1}) \tag{5.4}$$

where $P_{e,i \to i+1}$ is the error probability of the transmission from the node N_i to the node N_{i+1}, given by (1.4).

5.2.2 Cooperative Multihop Transmission

First, we give the following proposition to assist our analysis.

Proposition 4 For a network with $n_c + n_e + 1$ nodes, among which n_c nodes (including the source node) forward correct symbols and n_e nodes forward wrong symbol due to undetected error, and there is one destination node. Denote $\mathcal{S}_c$ as the set of the nodes sending correct symbols, and $\mathcal{S}_e$ as the set of the nodes sending error symbols, and $|\mathcal{S}_c| = n_c$ and $|\mathcal{S}_e| = n_e$. The conditional error probability at the destination node for this system is given by

$$\begin{aligned} P_{en_cn_e}(\mathcal{S}_c, \mathcal{S}_e) &= Prob(U < 0) \\ &= (-1)^{n_c+n_e-1} \cdot \sum_{i \in \mathcal{S}_c} \frac{B_i}{A_i + B_i} \prod_{j \in \mathcal{S}_c, j \neq i} \frac{A_j B_j}{(A_i - A_j)(A_i + B_j)} \prod_{k \in \mathcal{S}_e} \frac{A_k B_k}{(A_i + A_k)(A_i - B_k)} \\ &+ (-1)^{n_c+n_e-1} \cdot \sum_{i \in \mathcal{S}_e} \frac{A_i}{A_i + B_i} \prod_{j \in \mathcal{S}_e, j \neq i} \frac{A_j B_j}{(B_i + A_j)(B_i - B_j)} \prod_{k \in \mathcal{S}_c} \frac{A_k B_k}{(B_i - A_k)(B_i + B_k)} \end{aligned} \tag{5.5}$$

The proof of this proposition is in Appendix A.4.

This formula is useful for the analysis of cooperative multihop transmission, and can give helpful hints for the system design. First, we use it to show the achieved diversity order without detection error at the relay nodes. Setting $n_c = 1, 2, 3, 4, 5$ respectively, and $n_e = 0$, we calculate the bit error rate using

(5.5) and the results are plotted in Fig. 5.2. Here we fix the distance between the source node and the destination node, and assume $E[|\alpha_{S,D}|^2] = 1$. It clearly demonstrates that the system achieves full diversity order.

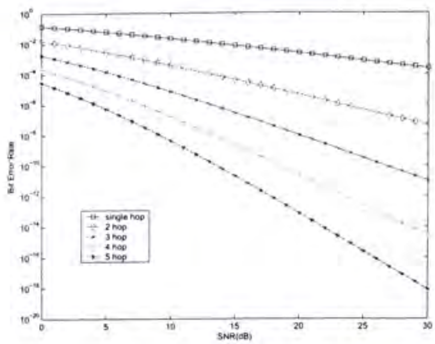

Figure 5.2: Numerical results of bit error rate for cooperative multihop transmission with no error at intermediate relay node.

In Fig. 5.3, we get the bit error rate for a 5-hop system, and one of the relay nodes forwards error symbol. From the results we can see that the forwarding error symbol brings the error floor effect. The nearer the relay node to the destination, the more impact it has on the system performance. Although the performance is degraded, it may still be acceptable if the neighbor nodes of the destination forward correct symbols, which is possible as the diversity order increases as the node gets closer to the destination. Therefore, it is unrealistic to assume error propagation that error detection at the intermediate node causes error at the destination as in [74]. In the proposed multihop cooperative transmission, we use an adaptive protocol and the probability for relay node to forward error symbol is greatly reduced.

BER Analysis for Multihop Cooperative Transmission

We use linear block code as error-detection scheme, and as in last two chapters we use an (n_d, k_d) BCH code.

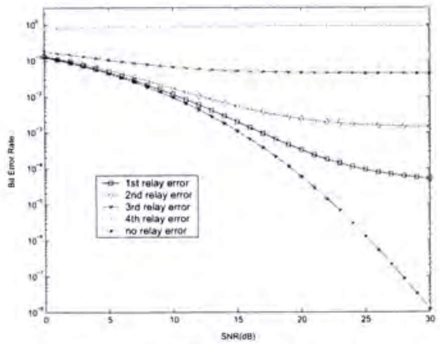

Figure 5.3: Numerical results of BERs for 5-hop cooperative transmission, with one relay node in error

Denote the probabilities:

- $P(S_i = 1) = Prob(\text{Node } N_i \text{ forwards the correct signal})$.
- $P(S_i = 2) = Prob(\text{Node } N_i \text{ forwards an error signal})$.
- $P(S_i = 3) = Prob(\text{Node } N_i \text{ declares an error, and quit the cooperation})$.

where S_i, $i = 2, 3, ..., n-1$, are the statuses of all the relay nodes, and the statuses of different relay nodes are independent, i.e., $P(S_i, S_j) = P(S_i)P(S_j)$. For simplicity, we denote $P_{ci} = P(S_i = 1)$, $P_{ei} = P(S_i = 2)$, and $P_{di} = P(S_i = 3)$.

Therefore, the bit error rate of the system can be written as

$$P_e = \sum_{S_i, i=2,3,...,n-1} P_{en_cn_e}(\mathcal{S}_c, \mathcal{S}_e | S_2, ..., S_{n-1}) P(S_2, ..., S_{n-1}) \qquad (5.6)$$

This BER is before decoding at the destination. In slow fading channel, this BER is close to that of the overall system.

We take 2-hop and 3-hop as examples to give the bit error rate for cooperative transmission.

2-hop cooperative transmission

This is a special case for single-source multiple-relay cooperation system we studied in Chapter 3, for $n_s = 1, n_r = 1$. The probabilities of relay statuses, P_{c2}, P_{e2}, P_{d2}, are given by (3.23).

Based on (5.6), the bit error rate for this 2-hop cooperative transmission system is

$$\begin{aligned} P_e &= P_{c2}P_{e20}(\{N_1, N_2\}, \{\ \phi\}) \\ &+ P_{d2}P_{e10}(\{N_1\}, \{\ \phi\}) \\ &+ P_{e2}P_{e11}(\{N_1\}, \{\ N_2\}) \end{aligned} \tag{5.7}$$

3-hop cooperative transmission

P_{sw3} is give by

$$P_{sw3} = E_{\alpha_{1,3},\alpha_{2,3}}[(1 - P_3(E|\alpha_{1,3}, \alpha_{2,3}))^{n_c}] \tag{5.8}$$

where

$$\begin{aligned} P_3(E|\alpha_{1,3}, \alpha_{2,3}) &= P_{c2}Q\left(\sqrt{2(|\alpha_{1,3}|^2 + |\alpha_{2,3}|^2)\gamma_3}\right) \\ &+ P_{d2}Q\left(\sqrt{2|\alpha_{1,3}|^2\gamma_3}\right) + P_{e2}Q\left(\sqrt{2\frac{(|\alpha_{1,3}|^2 - |\alpha_{2,3}|^2)^2}{|\alpha_{1,3}|^2 + |\alpha_{2,3}|^2}\gamma_3}\right) \end{aligned} \tag{5.9}$$

Then with (3.19) and (3.23), we can get P_{c3}, P_{d3}, and P_{e3}.

The bit error rate for 3-hop cooperative transmission is

$$\begin{aligned}P_e = {} & P_{c2}P_{c3}P_{e30}(\{N_1, N_2, N_3\}, \{\phi\}) \\ & + P_{c2}P_{d3}P_{e20}(\{N_1, N_2\}, \{\phi\}) \\ & + P_{d2}P_{c3}P_{e20}(\{N_1, N_3\}, \{\phi\}) \\ & + P_{d2}P_{d3}P_{e10}(\{N_1\}, \{\phi\}) \\ & + P_{c2}P_{e3}P_{e21}(\{N_1, N_2\}, \{N_3\}) \\ & + P_{d2}P_{e3}P_{e11}(\{N_1\}, \{N_3\}) \\ & + P_{e2}P_{c3}P_{e21}(\{N_1, N_3\}, \{N_2\}) \\ & + P_{e2}P_{d3}P_{e11}(\{N_1\}, \{N_2\}) \\ & + P_{e2}P_{e3}P_{e12}(\{N_1\}, \{N_2, N_3\})\end{aligned} \tag{5.10}$$

5.2.3 Numerical Results

We use the BCH (63,45) code as the error-detecting code. The distance between the source node and the destination node is normalized, and the fading coefficient $E[|\alpha_{1,n}|^2] = 1$. The simulated and calculated results for 2-hop and 3-hop multihop transmission, both conventional and cooperative, are in Fig. 5.4 and Fig. 5.5. (5.4) is used to calculate the theoretical BER for conventional multihop transmission. From the results, we can see that both 2-hop and 3-hop cooperative transmissions achieve full diversity order, and the calculated results fit the simulated curves well. At low SNR region, the conventional system outperforms the cooperative system due to the error-detecting code.

5.3 Discussion

5.3.1 Cooperative Range

To derive the error rate for the cooperation system, we have to make an expectation to get P_{sw} as in (5.8), which is difficult for a large L. However, for

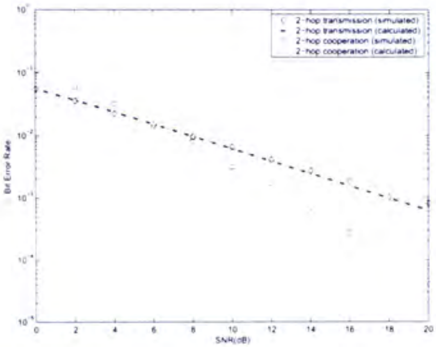

Figure 5.4: Numerical and simulation results of BERs of 2-hop conventional and cooperate transmission.

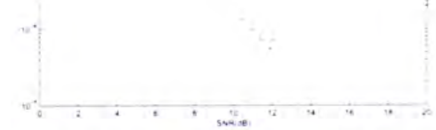

Figure 5.5: Numerical and simulation results of BERs of 3-hop conventional and cooperate transmission.

the cooperative multihop transmission, do we need to consider large L? The farther the relay nodes to the current node, the less it contributes to the detection at this node. In addition, if we consider to receive from all the former nodes, all the remaining nodes on the routing line have to keep active and receive the signal every time slot, which is a waste of energy. If we only detect based on the symbols from several nodes immediately before the considering node, it will be more efficient and energy-saving.

We use (5.5) to analyze the system performance with different L. Here L means the number of previous nodes taken into consideration at the current node. Applying (5.5) as the performance criterion for the system, we assume that the transmission between former relay nodes are reliable, so this is the best we can do. We assume each node has transmit power P and the distance between neighboring nodes are the same, $E[|\alpha_{i,i+1}|^2] = 1$. In Fig. 5.6, we calculate the BER for $L = 1, 2, 3, 4, 10$. We can see that before $20dB$, for $L \geq 3$, the performance does not improve much with the increase of L. So it is sufficient to consider the symbols from 3 former nodes. The simulated results for a 5-hop cooperative transmission, $L = 3, 5$, are in Fig. 5.7. The curves for $L = 3$ and $L = 5$ are close to each other, with the difference less than $1dB$. So we can apply $L = 3$ in practical system.

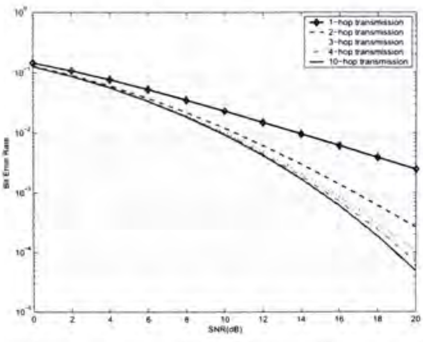

Figure 5.6: Comparison of cooperative transmissions for different L, $L = 1, 2, 3, 4, 10$.

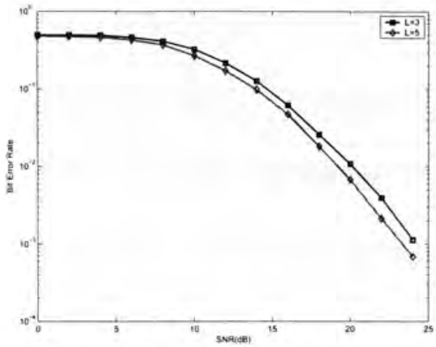

Figure 5.7: Simulation results of 5-hop cooperative transmission for $L = 3, 5$

5.3.2 Relay Node Distribution

During the discussion in last section, we assume that the relay nodes are evenly distributed on the route line. But this is not the usual case, and next we will discuss the impact of the relay distribution on the system performance.

Denote D as the distribution matrix of the distances between the source and relay nodes, $D = \{d_1, d_2, ..., d_{n-1}\}$, where d_i is the distance between the ith node and the destination node. We analyze different relay distribution for a 3-hop cooperative transmission and use (5.10) to calculate the bit error rate. The distance from source to the destination is normalized to 3. The distance distributions we consider include

- $D = \{3, 2, 1\}$: the uniform distribution
- $D = \{3, 2.9, 2.8\}$: 2 relays are near the source
- $D = \{3, 1.5, 1.4\}$: 2 relays are in the middle of the source and the destination
- $D = \{3, 0.2, 0.1\}$: 2 relays are near the destination

- $D = \{3, 2.9, 0.1\}$: 1 relay is near the source and the other is near the destination

The results are in Fig. 5.8. Compared with the conventional 3-hop transmission in Fig. 5.5, all 5 cooperative transmissions achieve diversity order near 3 and only shift from each other with several dB. The evenly distributed one performs the best, and the one with both relay nodes near the destination has the largest BER. Therefore, it is better to assign those evenly distributed nodes as the relays for cooperative multihop transmission.

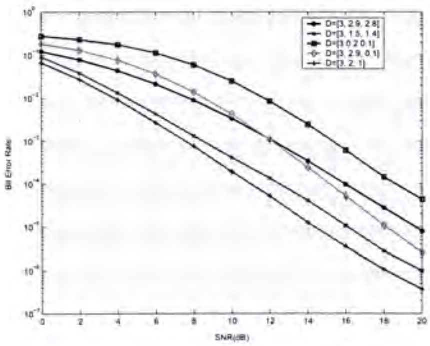

Figure 5.8: Simulated results of BERs for different distance distributions.

5.3.3 Power Allocation and Distance Distribution (2-hop Case)

For 2-hop cooperative transmission, with (5.7) and (3.23), we can do optimal power allocation or choose optimal distance distribution. The scenario for 2-hop transmission is as Fig. 5.9. The total power is P, and we assign aP to the

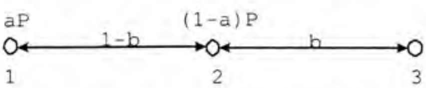

Figure 5.9: Diagram of 2-hop cooperative transmission.

source node and $(1-a)P$ to the relay node, $0 < a < 1$. The distance between the source and the destination is normalized to one, and the distance between the relay and the destination is b, $0 < b < 1$.

By setting $\frac{\partial P_e}{\partial a} = 0$, we can get the optimal value of a for a fixed b. Similarly, by setting $\frac{\partial P_e}{\partial b} = 0$, we can get the optimal distance distribution for a given power allocation. There is no closed form solution, but we can get the numerical result.

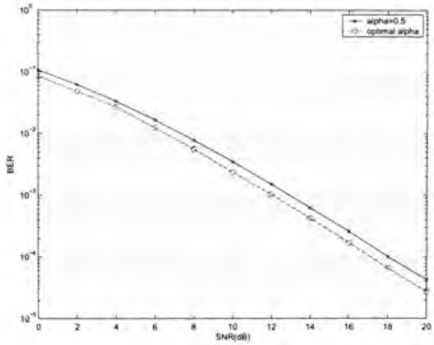

Figure 5.10: Simulation results of BERs with even power allocation and optimal power allocation.

In Fig. 5.10, we compare the BER for the system with even power allocation and the one with optimal power allocation, with $b = 0.5$. We can see that with optimal power allocation, we can get $1dB$ SNR gain. However, to do power allocation, channel state information (CSI) is required at the transmitter, which in our assumption is unavailable, and generally it is difficulty to get. Therefore, it is practical for us to do equal power allocation in cooperative multihop transmission.

In Fig. 5.11, we compare the BER for the system with even distance distribution and the one with optimal distance distribution, with equal power allocation. We can see that with optimal distance distribution, we can only get $0.5dB$ gain. This confirms our conclusion in last section that we should try

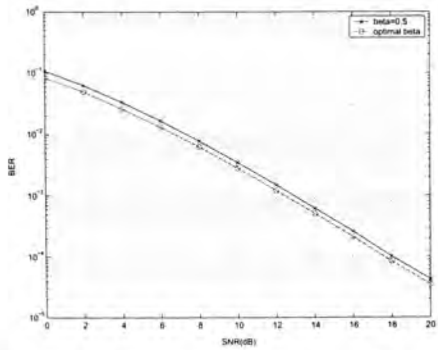

Figure 5.11: Simulation results of BERs with even distance distribution and optimal distance distribution.

to assign those evenly distributed nodes as relay nodes in practical systems.

5.4 Cooperation in General Wireless Ad Hoc Networks

So far, we have studied single-hop single/mutiple-source multiple-relay cooperation system and multihop cooperative transmission. In this section, we discuss the possible ways to extend it to the general wireless ad hoc network settings.

A wireless ad hoc network comprises mobile devices that use wireless transmission for communication, and the mobile devices also serve as relays for each other due to the limited range of wireless transmission of these devices, resulting in multihop transmission. To do user cooperation in wireless ad hoc networks, cooperative multihop transmission is one way to achieve cooperative diversity. Another way of exploiting cooperation is to apply multipath routing into wireless ad hoc networks. In [75], the authors utilized a mesh structure which yielded no extra overhead to provide multiple alternate routes, which were used only when the primary route was disconnected. A multipath extension of dynamic source routing (DSR) was proposed in [76], in which alternate routes were maintained and used when the primary one failed. These two schemes can be regarded as selective diversity for multihop transmission. Based on DSR, in [77] the authors proposed the Multipath Source Routing (MSR), in which the load were distributed between multiple routing paths, so it improved the throughput. On the other hand, [78] applied the diversity coding [79] into multipath routing, adding some overhead to each packet, which was then fragmented into small blocks and distributed over the available paths, so it provided extra protection against routing failures.

But all these schemes only do repetition or do coding at the source node. As demonstrated in the adaptive cooperative coding system, additional processing at the relay nodes will improve the efficiency. Naturally, it will remind us of network coding. In fact, all the mentioned schemes fall in the domain of network coding theory [80, 81, 82, 83]. In the paradigm of network coding, intermediate nodes can encode incoming information received from the input links before it is transmitted on the output links, and thus improve the throughput.

5.4.1 Cooperation Using Linear Network Codes

In wireless communications, the transmission between two nodes suffers from the fading channel, the transceiver noise and other interference, so the information transmission on such link is not free of noise. Therefore, the assumption of the noise-free channel made in [80, 81] is not applicable here. But the principles are similar, as our interest is the number of independently fading links between the source and the destination, which can be measured by the minimum cut between the source node and the destination node. To apply network coding in a wireless cooperation system, we should first clarify some characteristics in the wireless networks.

1. For transmission, the nodes in the cooperation system can only broadcast to other nodes, which means in a transmission cycle the messages on the output channels from any node T are the same.

2. The node can not transmit and receive at the same time.

3. To avoid interference, only one node is allowed to transmit in a certain transmission range.

4. Due to the fading channel, the transmission to the intermediate nodes is not reliable, so every node should check the incoming symbol or monitor the input channel to decide whether to send the encoded symbol or not.

5. Due to last point and the possible mobility of the node, the network topology will change from time to time.

Such networks are represented by the directed acyclic graphs.

Notation: we denote the source node and the destination node by S and D, and the value of max flow between S and any non-source node T is $maxflow(T)$. Let F be a finite field, and the information source generates a vector $x = (x_1\ x_2 \dots\ x_\omega)$ in F^ω. In(T) denotes the set of edges incoming at T, and Out(T) denotes the set of edges outgoing from T. Assume that there are ω *imaginary channels* ending at the source node. The network code can be described either by local encoding kernel $\{k_{de}\}$ or global encoding kernel $\{f_e\}$, which are defined below.

Local description of a linear network code on an acyclic network (Definition 2.4 in [84]) Let F be a finite field and ω a positive integer. An ω-dimensional F-valued linear network code on an acyclic communication network consists of a scalar $k_{d,e}$, called *the local encoding kernel*, for every adjacent pair (d,e). Meanwhile, this local encoding kernel at the node T means the $| In(T) | \times | Out(T) |$ matrix $K_T = [k_{d,e}]_{d \in In(T), e \in Out(T)}$.

Global description of a linear network code on an acyclic network (Definition 2.5 in [84]) Let F be a finite field and ω a positive integer. An ω-dimensional F-valued linear network code on an acyclic communication network consists of a scaler $k_{d,e}$ for every adjacent pair (d,e) in the network as well as an ω-dimensional column vector f_e for every channel e such that:

1. $f_e = \sum_{d \in In(T)} k_{d,e} f_d$, where $e \in Out(T)$.

2. The vector f_e for the ω imaginary channels $e \in In(S)$ form the natural basis of the vector space F^ω.

The vector f_e is called *the global encoding kernel* for the channel e.

Design Criterion

Assume that there are M edge-disjoint links between S and D. We say that a transmission system can achieve diversity order L if any $L-1$ links between the source and the destination fail, the transmitted message $[x(s_1), x(s_2), ..., x(s_\omega)]$ can still be decoded from the information on the remaining $M - L + 1$ links, which requires that the dimension of the global encoding kernels on these links is greater than or equals ω. The maximum diversity order is achieved when $M - L + 1 = \omega$, and the symbols on every set of $M - L + 1$ links are independent, corresponding to that every $M - L + 1$ global encoding kernels on different links are linearly independent. This maximum achievable diversity order is $M + 1 - \omega$.

A cross layer thinking will be helpful for the system design here. For example, we can use the algorithms in multipath routing to get the routing information on different path, and then can get the graph for coding design, which will be sent to the intermediate nodes and the destination before transmitting data packets. From the network coding theory, we also can do the random coding if the field size is sufficiently large, as did in [85] for Avalanche.

5.4.2 Single-Source Single-Destination Systems

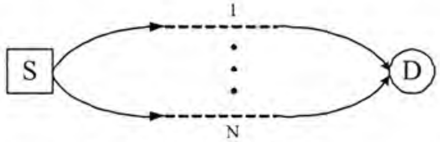

Figure 5.12: The equivalent graph for the single-source single-destination network.

If $maxflow(D) = N_l$, we can find N_l edge-disjoint paths from S to D. The graph for this system is in Fig. 5.12. There are two encoding schemes as follows:

1. To achieve the maximum diversity order, $L = N_l$, we can set the local encoding kernels of the intermediate nodes on those disjoint paths to be "1".

2. To increase the throughput and get diversity order $L, L < N_l$, we can use an $(N_l, N_l - L + 1)$ MDS code, applying the linear processing on the information data, and send code bits on N_l disjoint paths. Again, the local encoding kernels for those intermediate nodes are set to be "1".

This is in fact a special form of multipath routing. Scheme 1 is the same to [77], and scheme 2 is the same to [78]. There is a tradeoff between the robustness and the throughput. The schemes in [75, 76] can be viewed as a selective combining, where only one path is used. Our study of single-source multiple-relay in Chapter 3 is a single-hop case for scheme 1.

It is also possible to further increase the robustness, by applying the same scheme on some intermediate node on a certain path, whose link to the next node is not so reliable. This can be done in a cross-layer way, using the knowledge of physical layer when routing.

5.4.3 Multiple-Source Single-Destination Systems

If there are some nodes near each other intending to transmit packets to the same destination, more advanced network codes can be applied to increase the efficiency. Assume there are k source node, $S_1, S_2, ..., S_k$, one destination node D, and other intermediate node T_i, as in Fig. 5.13.

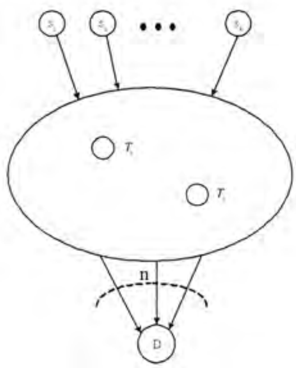

Figure 5.13: The diagram for the multiple-source single-destination network.

Maximum Diversity Order If there are N_{in} input channels into the destination node, then the maximum achievable diversity order is $N_{in} - k + 1$, which can be achieved if the minimum cut between every source node S_i and the destination node D is $N_{in} - k + 1$.

To get the equivalent graph of this system, we first do some pre-processing:

- Add a node S_0, which has links to all the source node. The input channel of every source is one of the imaginary channels. This transforms the problem into a single-source one, which is studied thoroughly [80, 81].

- Broadcast: add an extra node T_i' to every non-source non-destination node T_i, where there is a link between the added node and the existing node, and the output channels for the added node is those for the original node, which means the global encoding codes for these channels are the same, indicating broadcast.

- Split the N_{in} input channels to the destination into $\binom{N_{in}}{k}$ sets, and the channels in each set are linked to an imaginary node $D_i, i = 1, 2, \ldots, m, m = \binom{n}{k}$.

The resulting equivalent graph is in Fig. 5.14. If the global encoding kernels for the input channels to every imaginary destination node D_i are linearly independent, we will be able to decode the data from k source nodes at every D_i, which means for the real destination node D we can do the decoding if we get any k channels, and this subsequently means that we get a diversity order of $N_{in} - k + 1$. The network code can give such linearly independence, if $maxflow(D_i) = k$ on this equivalent graph, and the algorithm for the linear multicast network code [86] can be applied. The linear multicast network code for this equivalent graph is the cooperative code we need for the original graph.

If for some D_i, $maxflow(D_i) < k$, the maximum achievable diversity will be lower than $N_{in} - k + 1$ for some source nodes. But for those nodes the minimum cuts between which and the destination D are $N_{in} - k + 1$, can they achieve full diversity order? For $m = 2$, it is true as suggested in [87]; but for $m > 2$, it becomes rather complicated.

The multiple-source multiple-relay cooperation system we studied in Chapter 4 is a special case of single-hop transmission. The equivalent graph for this example is in Fig. 5.15, where nodes 1, 2, 3 denote the source nodes and node 4, 5, 6 are the relay nodes, and S is the imaginary source node.

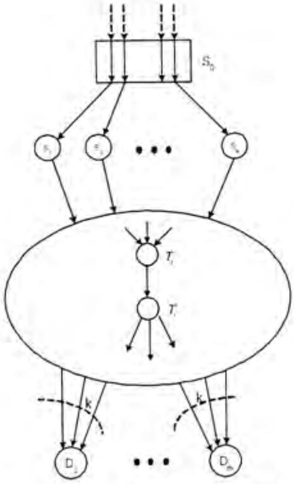

Figure 5.14: The equivalent graph for the multiple-source single-destination network.

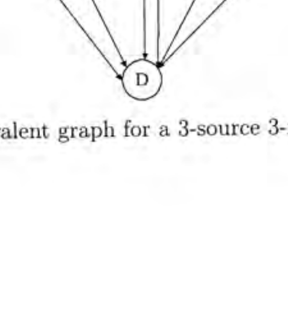

Figure 5.15: The equivalent graph for a 3-source 3-relay cooperation system.

The generator matrix for the linear (6, 3) code is

$$G = \begin{bmatrix} 1 & 0 & 0 & 0 & 1 & 1 \\ 0 & 1 & 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 & 1 & 0 \end{bmatrix}$$

Denote f_{ei} as the global encoding kernel for the output channel from node i. Then for this code

$$f_{e1} = [1 \quad 0 \quad 0]^T$$

$$f_{e2} = [0 \quad 1 \quad 0]^T$$

$$f_{e3} = [0 \quad 0 \quad 1]^T$$

$$f_{e4} = [0 \quad 1 \quad 1]^T$$

$$f_{e5} = [1 \quad 0 \quad 1]^T$$

$$f_{e6} = [1 \quad 1 \quad 0]^T$$

In Chapter 4, we decided the achievable diversity order by minimum Hamming distance of the code, and here we can use network coding theory to analyze it. f_{e4}, f_{e5}, and f_{e6} are linearly dependent, so this code could not achieve full diversity order. For example, if the channels $(1, D)$, $(2, D)$ and $(3, D)$ fail, the transmitted symbols x_1, x_2 and x_3 could not be decoded from the information on the three remaining channels. In fact, the dimension of each set of four global encoding kernel is 3, so we can decode 3 messages from the messages on every four channels, which means the achievable diversity order is 3, as we demonstrated in Chapter 4.

We also analyzed the system which used Maximum Distance Separable (MDS) code as cooperative code, and showed that all three source nodes achieved full diversity order. The generator matrix for this MDS code is

$$G = \begin{bmatrix} 1 & 0 & 0 & 1 & 1 & 1 \\ 0 & 1 & 0 & 1 & t & t^2 \\ 0 & 0 & 1 & 1 & t^2 & t \end{bmatrix}$$

where the coding is performed in $GF(4)$, and t is the root of the primitive polynomial $t^2 + t + 1 = 0$.

For this code, the global encoding kernels are

$$f_{e1} = [1 \quad 0 \quad 0]^T$$

$$f_{e2} = [0 \quad 1 \quad 0]^T$$

$$f_{e3} = [0 \quad 0 \quad 1]^T$$

$$f_{e4} = [1 \quad 1 \quad 1]^T$$

$$f_{e5} = [1 \quad t \quad t^2]^T$$

$$f_{e6} = [1 \quad t^2 \quad t]^T$$

For this code, every 3 encoding kernel are linearly independent, so this code can achieve full diversity order. This is just as we demonstrated in Chapter 4. As stated in [84], MDS code is a special case of generic linear network code.

Chapter 6

Conclusion

In this thesis, we investigate the cooperative communications in wireless networks. The systems we studied include the single-source multiple-relay cooperation systems, the multiple-source multiple-relay cooperation system, and the cooperative multihop transmission systems. We investigate the protocol designs and general coding strategies, which shows great prospect of further effort in this area. As we make a realistic assumption of the channel state information, we pay special attention on the analysis of the impact of error detection at the intermediate relay nodes. To compensate for the error at the relay, we propose adaptive protocols: the relay selection protocol for the single-source multiple-relay cooperation systems, the symbol selection protocol for the multiple-source multiple-relay cooperation systems, and the adaptive transmission protocol for the cooperative multihop transmission systems. One of the major contributions of this thesis is the derivations and the theoretical results on the performance of these cooperative communication systems, which is of great value for the further study. All these proposed schemes, together with many current studies on the cooperative communications, fall in the domain of the network coding theory, which we state in Chapter 5 and apply this to design cooperative protocol for general wireless ad hoc networks.

There are still many open problems in this area. From the fundamental information-theoretic study to the practical implementation into current wireless systems. The capacity-related study of the wireless network with user cooperation is just at its beginning. Cooperative communications have demonstrated their advantages, but in the practical systems there will always be some tradeoffs, such as the tradeoff between the complexity involving in cooperation system, the corresponding power consumption, and the throughput improvement. Such study will be interesting and useful. Resource allocation, such as power allocation and channel assignment, is another important topic, and also the cross-layer design issue to improve the performance. In a word, to get full benefit from the cooperation in wireless networks, there is still a long way to go, and it requires us researchers to keep on exploring.

Bibliography

[1] E. Biglieri, J. Proakis, , and S. S. (Shitz), "Fading channels: Information theoretic and communications aspects," *IEEE Transactions on Information Theory*, vol. 44, pp. 2619–2692, Oct 1998.

[2] T. S. Rappaport, *Wireless Communications: Principles and Practice*, 2nd ed. Upper Saddle River, NJ: Prentice Hall PTR, 2002.

[3] J. G. Proakis, *Digital Communications*, 4th ed. New York: McGraw-Hill, 2001.

[4] A. Sendonaris, E. Erkip, and B. Aazhang, "Increasing uplink capacity via user cooperation diversity," in *Proceeding of IEEE International Symposium on Information Theory*, Cambirdge, MA, USA, Aug. 1998, p. 156.

[5] J. N. Laneman and G. W. Wornell, "Energy-efficient antenna sharing and relaying for wireless networks," in *Proceeding of IEEE Wireless Communications and Networking Conference*, vol. 1, Chicago, IL, USA, Sept. 2000, pp. 7–12.

[6] J. N. Laneman, G. W. Wornell, and D. N. C. Tse, "An efficient protocol for realizing cooperative diversity in wireless networks," in *Proceeding of IEEE International Symposium on Information Theory*, Washington, DC, USA, June 2001, p. 220.

[7] A. Nosratinia, T. E. Hunter, and A. Hedayat, "Cooperative communication in wireless networks," *IEEE Communications Magazine*, vol. 42, no. 10, pp. 74–80, Oct. 2004.

[8] E. C. van der Meulen, "Transmission of information in a t-terminal discrete memoryless channel," PhD Dissertation, Univ. California, Berkeley, CA, USA, June 1968.

[9] ——, "Three-terminal communication channels," *Adv. Appl. Probab.*, vol. 3, pp. 120–154, 1971.

[10] T. M. Cover and A. A. E. Gamal, "Capacity theorems for the relay channel," *IEEE Transactions on Information Theory*, vol. 25, pp. 572–584, Sept. 1979.

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

[12] ——, "User cooperation diversity-part ii: Implementation aspects and performance analysis," *IEEE Transactions on Communications*, vol. 51, no. 11, pp. 1939–1948, Nov. 2003.

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

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

[15] T. E. Hunter and A. Nosratinia, "Cooperation diversity through coding," in *Proceeding of IEEE International Symposium on Information Theory*, Lausanne, Switzerland, June 2002, p. 220.

[16] ——, "Coded cooperation under slow fading, fast fading, and power control," in *Proc. Asilomar Conf. Signals, Syst., Comput.*, Pacific Grove, California, USA, Nov. 2002.

[17] ——, "Performance analysis of coded cooperation diversity," in *Proceeding of IEEE International Conference on Communications*, vol. 4, Anchorage, Alaska, USA, May 2003, pp. 2688–2692.

[18] M. Janani, A. Hedayat, T. E. Hunter, and A. Nosratinia, "Coded cooperation in wireless communications: Space-time transmission and iterative decoding," *IEEE Transactions on Signal Processing*, vol. 52, no. 2, pp. 362–371, Feb. 2004.

[19] B. Zhao and M. Valenti, "Distributed turbo coded diversity for the relay channel," *IEE Electronics Letters*, vol. 39, no. 10, pp. 786–787, May 2003.

[20] M. Valenti and B. Zhao, "Distributed turbo codes: Towards the capacity of the relay channel," in *Proceeding of IEEE Vehicular Technology Conference*, Orlando, FL, USA, Oct. 2003, pp. 322–326.

[21] D. Divsalar and F. Pollara, "Multiple turbo codes," in *Proc. IEEE MILCOM*, Nov. 1995, pp. 279–285.

[22] C. Zeng, F. Kuhlmann, and A. Buzo, "Achievability proof of some multiuser channel coding theorems using backward decoding," *IEEE Transactions on Information Theory*, vol. 35, no. 6, pp. 1160–1165, Nov. 1989.

[23] A. A. E. Gamal, "Results in multiple user channel capacity," PhD Dissertation, Stanford Univ., Stanford, CA, USA, May 1978.

[24] M. R. Aref, "Information flow in relay networks," PhD Dissertation, Stanford Univ., Stanford, CA, USA, Oct. 1980.

[25] A. A. E. Gamal, "On information flow in relay networks," in *Proc. IEEE National Telecommunications Conf.*, vol. 2, Miami, FL, USA, Nov. 1981, p. D4.1.1 - D4.1.4.

[26] P. Vanroose and E. C. van der Meulen, "Uniquely decodable codes for deterministic relay channels," *IEEE Transactions on Information Theory*, vol. 38, no. 4, pp. 1203–1212, July 1992.

[27] R. Ahlswede and A. H. Kaspi, "Optimal coding strategies for certain permuting channels," *IEEE Transactions on Information Theory*, vol. 33, no. 3, pp. 310–314, May 1987.

[28] K. Kobayashi, "Combinatorial structure and capacity of the permuting relay channel," *IEEE Transactions on Information Theory*, vol. 33, no. 6, pp. 813–826, Nov. 1987.

[29] A. Stefanov and E. Erkip, "Cooperative information transmission in wireless networks," in *Proceedings of Asian-European Information Theory Workshop*, Breisach, Germany, June 2002.

[30] J. N. Laneman and G. W. Wornell, "Exploiting distributed spatial diversity in wireless networks," in *Proc. 38th Allerton Conf. Communication, Control, and Computing*, Monticello, IL, USA, Oct. 2000.

[31] B. Wang, J. Zhang, and A. Høst-Madsen, "On the capacity of mimo relay channels," *IEEE Transactions on Information Theory*, vol. 51, no. 1, pp. 29–43, Jan. 2005.

[32] A. Høst-Madsen and J. Zhang, "Capacity bounds and power allocation in wireless relay channel," *IEEE Transactions on Information Theory*, vol. 51, no. 6, pp. 2020–2040, June 2005.

[33] A. Høst-Madsen, "Capacity bounds for cooperative diversity," *IEEE Transactions on Information Theory*, vol. 52, no. 4, pp. 1522–1544, Apr. 2006.

[34] C. T. K. Ng and A. J. Goldsmith, "Capacity gain from transmitter and receiver cooperation," in *Proceeding of IEEE International Symposium on Information Theory*, 2005, pp. 397–401.

[35] ——, "Capacity and power allocation for transmitter and receiver cooperation in fading channels," in *Proceeding of IEEE International Conference on Communications*, Istanbul, Turkey, Jun 2006.

[36] A. Høst-Madsen, "The multiplexing gain of wireless networks," in *ISIT*, 2005, pp. 2065–2069.

[37] M. Gastpar and M. Vetterli, "On the capacity of large gaussian relay networks," *IEEE Transactions on Information Theory*, vol. 51, no. 3, pp. 765–779, Mar. 2005.

[38] C. T. K. Ng, J. N. Laneman, and A. J. Goldsmith, "The role of snr in achieving mimo rates in cooperative systems," in *IEEE Information Theory Workshop (ITW)*, 2006.

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

[40] Y.-D. Lin and Y.-C. Hsu, "Multihop cellular: a new architecture for wireless communications," in *INFOCOM 2000*, vol. 3, Mar. 2000, pp. 1273–1282.

[41] H. Wu, C. Qiao, S. De, and O. Tonguz, "Integrated cellular and ad hoc relaying systems: icar," *IEEE Journal on Selected Areas in Communications*, vol. 19, no. 10, pp. 2105–2115, Oct 2001.

[42] H. Luo, R. Ramjee, P. Sinha, L. Li, and S. Lu, "Multihop cellular: a new architecture for wireless communications," in *Proc. ACM MOBICOM*, Sept. 2003, pp. 353–367.

[43] J. Jubin and J. D. Tornow, "The darpa packet radio network protocol," in *IEEE Proc.*, vol. 75, 1, Jan 1987, pp. 21–32.

[44] F. A. Tobagi, "Modeling and performance analysis of multihop packet radio networks," in *IEEE Proc.*, vol. 75, 1, Jan 1987, pp. 135–155.

[45] M. B. Pursley, "The role of spread spectrum in packet radio networks," in *IEEE Proc.*, vol. 75, 1, Jan 1987.

[46] L. Kleinrock and J. Silvester, "Spatial reuse in multihop packet radio networks," in *IEEE Proc.*, vol. 75, 1, Jan 1987.

[47] C. S. R. Murthy and B. Manoj, *Ad Hoc wireless networks : architectures and protocols.* Upper Saddle River, NJ: Prentice Hall PTR, 2004.

[48] I. A. Akyildiz, W. S. amd Y. Sankarasubramaniam, and E. Cayirci, "A survey of sensor networks," *IEEE Commun. Mag.*, vol. 40, pp. 102–115, Aug 2002.

[49] J. C. Haartsen, "The bluetooth radio system," *IEEE Personal Commun.,*, vol. 7, pp. 28–36, Feb 2000.

[50] K. J. Negus, A. P. Stephens, and J. Lansford, "Homerf: Wireless networking for the connected home," *IEEE Personal Commun.,*, vol. 7, pp. 20–27, Feb 2000.

[51] R. Ahlswede, "Multi-way communication channels," in *Proc. 2nd Int. Symp. Information Theory (Tsahkadsor, Armenian S.S.R.)*, Budapest, Hungary, 1971, pp. 23–52.

[52] H. Liao, "Multiple access channels," PhD Dissertation, Univ. Hawaii, Dept. Elec. Eng., Honolulu, HI, 1972.

[53] T. M. Cover, "Comments on broadcast channels," *IEEE Personal Commun.,*, vol. 44, pp. 2524–2530, Oct 1998.

[54] P. Gupta and P. R. Kumar, "The capacity of wireless networks," *IEEE Transactions on Information Theory*, vol. 46, pp. 388–404, Mar 2000.

[55] ——, "Toward an information theory of large networks: An achievable rate region," *IEEE Transactions on Information Theory*, vol. 49, pp. 1877–1894, Aug 2003.

[56] L.-L. Xie and P. R. Kumar, "A network information theory for wireless communication: Scaling laws and optimal operation," *IEEE Transactions on Information Theory*, vol. 50, no. 5, pp. 748–767, May 2004.

[57] ——, "An achievable rate for the multiple-level relay channel," *IEEE Transactions on Information Theory*, vol. 51, no. 4, pp. 1348–1358, Apr 2005.

[58] M. Grossglauser and D. N. C. Tse, "Mobility increases the capacity of adhoc wireless networks," *IEEE/ACM Trans. Netw*, vol. 10, pp. 477–486, Aug 2002.

[59] A. Paulraj, R. Nabar, and D. Gore, *Introduction to space-time wireless communications*. Cambridge: Cambridge University Press, 2003.

[60] 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," *JSAC*, vol. 21, pp. 281–302, Apr. 2003.

[61] G. J. Foschini, "Layered space-time architecture for wireless communication in a fading environment when using multi-element antennas," *Bell Lab. Tech. J.*, vol. 1, no. 2, pp. 41–59, July 1996.

[62] G. J. Foschini and M. J. Gans, "On limits of wireless communications in a fading environment when using multiple antennas," *Wireless Personal Commun.*, vol. 6, no. 3, p. 311, Mar. 1998.

[63] I. E. Telatar, "Capacity of mulit-antenna gaussian channels," *Europ. Trans. Telecommun.,*, vol. 10, pp. 585–595, Nov. 1999.

[64] P. W. Wolniansky, G. J. Foschini, G. D. Golden, and R. A. Valenzuela, "V-blast: an architecture for realizing very high data rates over rich-scattering wireless channel," in *Proceedings on URSI International Symposium on Signals, Systems, and Electronics*, Sept. 1998, pp. 295–300.

[65] G. D. Golden, G. J. Foschini, R. A. Valenzuela, and P. W. Wolniansky, "Detection algorithm and initial laboratory results using v-blast space-time communication architecture," *Electronics Letters*, vol. 35, no. 1, pp. 14–15, Jan. 1999.

[66] S. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE Journal on Selected Areas in Communications*, vol. 16, pp. 1451–1458, Oct. 1998.

[67] V. Tarokh, N. Seshadri, and A. R.Calderbank, "Space-time codes for high data rate wireless communication: Performance criterion and code construction," *IEEE Transactions on Information Theory*, vol. 44, pp. 744–765, Mar. 1998.

[68] V. Tarokh, H. Jafarkhani, and A. R. Calderbank, "Space ⊢time block codes from orthogonal designs," *IEEE Transactions on Information Theory*, vol. 45, pp. 1456–1467, July 1999.

[69] L. Zheng and D. N. C. Tse, "Diversity and freedom: A fundamental tradeoff in multiple antenna channels," in *ISIT*, Lausanne, Switzerland, July 2002, p. 476.

[70] ——, "Diversity and multiplexing: A fundamental tradeoff in multiple antenna channels," *IEEE Transactions on Information Theory*, vol. 49, pp. 1073–1096, May 2003.

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

[72] T. Klove and M. Miller, "The detection of errors after error-correction decoding," *IEEE Transactions on Communications*, vol. 32, pp. 51–517, May 1984.

[73] R. C. Singleton, "Maximum distance q-nary codes," *IEEE Transactions on Information Theory*, vol. 10, pp. 116–118, 1964.

[74] J. Boyer, D. Falconer, , and H. Yanikomeroglu, "Multihop diversity in wireless relaying channels," *IEEE Transactions on Communications*, vol. 52, no. 10, pp. 1820–1830, Oct. 2004.

[75] S. Lse and M. Gerla, "Aodv-br: Backup routinp in ad hoc network," in *WCNC*, Sep 2000, pp. 1311–1316.

[76] A. Nasipuri and S. R. Das, "On-demand multipath routing for mobile ad hoc networks," in *IEEE ICCCN*, 1999, pp. 64–70.

[77] L. Wang, L. Zhang, Y. Shu, and M. Dong, "Multipath source routing in wireless ad hoc nelworks," in *Canadian Conf. Elec. Comp. Eng.*, vol. 1, 2000, pp. 479–483.

[78] A. Tsiriocs and Z. J. Haas, "Multipath routing in the presence of frequent topological changes," *IEEE Communications Magazine,*, vol. 39, no. 11, pp. 132–138, Nov 2001.

[79] E. A. et al., "Diversity coding for transparent self-healing and fault-tolerant communication networks," *IEEE Transactions on Communications*, vol. 41, no. 11, pp. 1677–1686, Nov 1993.

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

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

[82] R. Koetter and M. Médard, "Beyond routing: An algebraic approach to network coding," in *INFOCOM*, vol. 1, July 2002, pp. 122–130.

[83] ——, "An algebraic approach to network coding," *IEEE/ACM Transactions on Networking*, vol. 11, no. 5, pp. 782–795, Oct. 2003.

[84] R. W. Yeung, S.-Y. R. Li, N. Cai, and Z. Zhang, *Theory of network coding*. submitted to Foundation and Trends in Communications and Information Theory.

[85] C. Gkantsidis and P. R. Rodriguez, "Network coding for large scale content distribution," in *INFOCOM*, Mar. 2005, pp. 2235–2245.

[86] S. Jaggi, P. Sanders, P. A. Chou, M. Effros, S. Egner, K. Jain, and L. Tolhuizen, "Polynomial time algorithms for multicast network code construction," *IEEE Transactions on Information Theory*, vol. 51, pp. 1973–1982, June 2005.

[87] C. K. Ngai and R. W. Yeung, "Multisource network coding with two sinks," in *2004 International Conference on Communications, Circuits and Systems*, vol. 1, 2004, pp. 34–37.

Appendix A

Proof of Proposition 1-4

A.1 Proof of Proposition 1

"1" is assumed to be sent from the source node. In this situation, one of the relays, assuming node 3, detects incorrectly and forwards the error symbol to the destination node. At the receiver, the decision variable becomes

$$Z_1 = Re\left[\alpha_1^*(\alpha_1\sqrt{E_b} + n_1) + \alpha_2^*(\alpha_2\sqrt{E_b} + n_2) + \alpha_3^*(-\alpha_3\sqrt{E_b} + n_3)\right] \quad (A.1)$$

The characteristic function of Z_1 conditioned on the fading coefficients is

$$E[e^{juz_1} \mid \alpha_i, i = 1,2,3] = \exp[ju|\alpha_1|^2\sqrt{E_b} - \frac{u^2}{2}|\alpha_1|^2\sigma^2] \cdot \exp[ju|\alpha_2|^2\sqrt{E_b} - \frac{u^2}{2}|\alpha_2|^2\sigma^2] \cdot \exp[-ju|\alpha_3|^2\sqrt{E_b} - \frac{u^2}{2}|\alpha_3|^2\sigma^2] \quad (A.2)$$

where α_i is the fading coefficient of the channel between node i and the destination node, σ^2 is the variance of the noise.

Making the expectation on fading coefficients α_i, we can get the unconditional characteristic function

$$\phi_{Z_1}(u) = E[e^{juz_1}] = \left[\frac{AB}{(u - jA)(u + jB)}\right]^2 \frac{AB}{(u + jA)(u - jB)} \quad (A.3)$$

where

$$A = \frac{\sqrt{1 + \overline{\gamma}_c} + \sqrt{\overline{\gamma}_c}}{\sigma\gamma}, \ B = \frac{\sqrt{1 + \overline{\gamma}_c} - \sqrt{\overline{\gamma}_c}}{\sigma\gamma}$$

$$E[\alpha_i^2] = 2\gamma^2,\ \bar{\gamma_c} = E[\alpha_i^2]\frac{E_b}{N_0} = \frac{\gamma^2 E_b}{\sigma^2},\ i = 1, 2, 3$$

As "1" is assumed to be sent, the error occurs when the decision variable $Z_1 < 0$. As the characteristic function is defined as

$$\phi_{Z_1}(u) = E[e^{juz_1}] = \int_{-\infty}^{\infty} p_{Z_1}(z_1)e^{juz_1}dz_1 \tag{A.4}$$

the pdf of Z_1 is given by the inverse Fourier integral

$$p_{Z_1}(z_1) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \phi_{Z_1}(u)e^{-juz_1}du \tag{A.5}$$

So $Prob(Z_1 < 0)$ is given by

$$\begin{aligned} Prob(Z_1 < 0) &= \int_{-\infty}^{0} p_{Z_1}(z_1)dz_1 \\ &= \int_{-\infty}^{0}\Big[\frac{1}{2\pi}\int_{-\infty}^{\infty}\phi_{Z_1}(u)e^{-juz_1}du\Big]dz_1 \\ &= \frac{1}{2\pi}\int_{-\infty}^{\infty}\phi_{Z_1}(u)\Big[\int_{-\infty}^{0}e^{-juz_1}dz_1\Big]du \\ &= -\frac{1}{2\pi j}\int_{-\infty+j\epsilon}^{\infty+j\epsilon}\frac{\phi_{Z_1}(u)}{u}du \end{aligned} \tag{A.6}$$

The bit error rate

$$P_{e1} = Prob(Z_1 < 0) = -\frac{1}{2\pi j}\int_{-\infty+j\epsilon}^{\infty+j\epsilon}\frac{\phi_{Z_1}(u)}{u}du \tag{A.7}$$

can be evaluated by closing the contour in the upper half plane and using the Cauchy's residue theorem: The integral of $g(z)$ over a closed contour is equal to $2\pi j$ times the sum of the residues at the poles of $g(z)$. The residue at a pole of order m at $z = a$ is given by

$$r_a = \frac{1}{(m-1)!}\frac{d^{m-1}}{dz^{m-1}}(z-a)^m g(z)|_{z=a} \tag{A.8}$$

The residues of $\phi_{Z_1}(u)/u$ at $u = Aj$ and $u = Bj$ are

$$r_1 = B^3\frac{9A^2 - 2AB - 4B^2}{4(A+B)^3(A-B)^2}$$

$$r_2 = -\frac{A^3}{4(A-B)^2(A+B)}$$

So, we can get the BER at the receiver when one relay forwards the error symbol as

$$P_{e1} = -\frac{1}{2\pi j}[2\pi j(r_1 + r_2)] = \frac{A^3}{4(A-B)^2(A+B)} - B^3\frac{9A^2 - 2AB - 3B^2}{4(A+B)^3(A-B)^2} \tag{A.9}$$

A.2 Proof of Proposition 2

In this situation, both relays detect incorrectly and forward the error symbol to the destination node. At the receiver, the decision variable becomes

$$Z_2 = Re\big[\alpha_1^*(\alpha_1\sqrt{E_b} + n_1) + \alpha_2^*(-\alpha_2\sqrt{E_b} + n_2) + \alpha_3^*(-\alpha_3\sqrt{E_b} + n_3)\big] \tag{A.10}$$

The corresponding characteristic function is

$$E[e^{juz_2}] = \frac{AB}{(u-jA)(u+jB)}\left[\frac{AB}{(u+jA)(u-jB)}\right]^2 \tag{A.11}$$

The error occurs when the decision variable $Z_2 < 0$. As (A.7), the bit error rate is

$$P_{e2} = Prob(Z_2 < 0) = -\frac{1}{2\pi j}\int_{-\infty+j\epsilon}^{\infty+j\epsilon}\frac{\phi_{Z_2}(u)}{u}du \tag{A.12}$$

Applying Cauchy's residue theorem, we can get the BER at the receiver when one relay forwards the error symbol

$$P_{e2} = \frac{B^3}{4(A-B)^2(A+B)} - A^3\frac{9B^2 - 2AB - 3A^2}{4(A+B)^3(A-B)^2} \tag{A.13}$$

A.3 Proof of Proposition 3

At the high SNR region, the decision variable Z_3 is mainly decided by the fading coefficients, and the additive Gaussian noise does not play a significant role. For a cooperation system with m_e relays in detection error and m_c

nodes (including source node) correctly detected, we approximate the decision variable at the destination as

$$Z_3 = \Big(\sum_{i=1}^{m_c} |\alpha|_i^2 - \sum_{j=1}^{m_e} |\alpha|_j^2\Big)\sqrt{E_b} \tag{A.14}$$

All the fading coefficients α_i are i.i.d. Denote $\beta_i = |\alpha_i|^2$. β_i is exponentially distributed with pdf $f_{\beta_i}(u) = \frac{1}{2\gamma^2}e^{-u/(2\gamma^2)}$, for $u \geq 0$, where $E[|\alpha_i|^2] = 2\gamma^2$.

We can get the characteristic function of Z_3 as

$$E[e^{juz_3}] = \frac{1}{(-1)^{m_c}(2\gamma^2 j)^{m_c+m_e}(u+\frac{j}{2\gamma^2})^{m_c}(u-\frac{j}{2\gamma^2})^{m_e}} \tag{A.15}$$

As (A.7), the error bit rate is

$$\begin{aligned} P_{em_cm_e} &= Prob[Z_3 < 0] \\ &= -\frac{1}{2\pi j}\int_{-\infty+j\epsilon}^{\infty+j\epsilon} \frac{1}{(-1)^{m_c}(2\gamma^2 j)^{m_c+m_c}} \frac{1}{(u+\frac{j}{2\gamma^2})^{m_c}(u-\frac{j}{2\gamma^2})^{m_e}} \frac{du}{u} \end{aligned} \tag{A.16}$$

Closing the contour around the upper half plane and applying the residue theorem, we have

$$P_{em_cm_e} = -\frac{1}{(-1)^{m_e}(2\gamma^2 j)^{m_c+m_e}} \frac{1}{(n-1)!} \frac{d^{m_e-1}}{du^{m_e-1}} (u^{-1}(u+\frac{j}{2\gamma^2})^{-m_c}) \mid_{u=\frac{j}{2\gamma^2}} \tag{A.17}$$

Differentiating it results

$$P_{em_cm_e} = 2^{-m_c}\sum_{k=0}^{m_e-1}\binom{m_c+k-1}{k}2^{-k} \tag{A.18}$$

A.4 Proof of Proposition 4

"1" is assumed to be sent from the source node. At the destination node N_n ($n = n_c + n_e + 1$), the decision variable is

$$Z_4 = Re\big[\sum_{i \in \mathcal{S}_c} \alpha_{i,n}^*(\alpha_{i,n} + z_{i,n}) + \sum_{j \in \mathcal{S}_e} \alpha_{j,n}^*(-\alpha_{j,n} + z_{j,n})\big] \tag{A.19}$$

where $\alpha_{i,j}$ are mutually independent complex Gaussian random variables, and $z_{i,j}$ are additive Gaussian noise. $|\mathcal{S}_c| = n_c$ and $|\mathcal{S}_e| = n_e$.

The unconditional characteristic function of U_4 is

$$\phi_{Z_4}(u) = E[e^{juz_4}]$$
$$= \prod_{i\in\mathcal{S}_c} \frac{A_iB_i}{(u - jA_i)(u + jB_i)} \prod_{j\in\mathcal{S}_e} \frac{A_jB_j}{(u + jA_j)(u - jB_j)} \tag{A.20}$$

where

$$A_i = \frac{\sqrt{2}}{\sigma_{i\to n}\sigma_n}\left[\sqrt{1+\bar{\gamma}_{i\to n}} + \sqrt{\bar{\gamma}_{i\to n}}\right]$$
$$B_i = \frac{\sqrt{2}}{\sigma_{i\to n}\sigma_n}\left[\sqrt{1+\bar{\gamma}_{i\to n}} - \sqrt{\bar{\gamma}_{i\to n}}\right]$$
$$E[|\alpha_{i,n}|^2] = \sigma^2_{i\to n},\ \bar{\gamma}_{i\to n} = E[|\alpha_{i,n}|^2]\frac{E_b}{N_0} = \frac{\sigma^2_{i\to n}E_b}{2\sigma^2_n}$$

As (A.7), the bit error rate is

$$Prob(Z_4 < 0) = -\frac{1}{2\pi j}\int_{-\infty+j\epsilon}^{\infty+j\epsilon} \phi_{Z_4}(u)\frac{du}{u} \tag{A.21}$$

Applying Cauchy's residue theorem, we can get the BER at the destination node for this system as (5.5).