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Efficient Multiuser Cooperative Relay Communications Employing Layered Modulations

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Relay-assisted cooperative communications are promising solutions for error-performance improvement and cell coverage extension. In this thesis, we propose several efficient cooperative relay communication schemes. First, an efficient space-time coded cooperative relay communications scheme that employs linear precoding and transmission-pattern selection is proposed. This is built upon an existing block linear precoding technique for conventional multiple-input multiple-output systems in order to improve the diversity performance of a multihop relay network. Second, we consider several multiuser cooperative relay communication schemes employing layered modulations, such as hierarchical modulation and superposition coding. Conventional cooperative relay communication is effective in mitigating fading effects. However, additional resources, such as time slots or frequency bands are required for the relay, which reduce the overall throughput. Reduction of throughput will become more severe as the number of users increases. In order to overcome this limitation, multiuser cooperative relaying schemes that employ hierarchical modulation and superposition

coding are proposed. These schemes exploit the superimposed message for users in the network and allow the system to transmit two or more independent data streams simultaneously. The proposed schemes do not require additional resources than the conventional schemes, while improving the error performance by flexibly controlling the power division coefficient of superposition coding or the distance parameter of hierarchical modulation.

Efficient Multiuser Cooperative Relay Communications Employing Layered Modulations

by

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Roderick Jaehoon Whang, Author

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DEDICATION

I dedicate this thesis to my lovely wife, Minyoung Lee.

Chapter 1 – Introduction

1.1 Cooperative Communication

Space-time diversity technique, which is widely used to mitigate fading, generally requires more than one antenna at the transmitter and/or receiver. Although transmit diversity is advantageous, when employed at a cellular system base station, it may not be practical for some other scenarios. Specifically, due to size, cost, or hardware limitations, a wireless node may not be able to support multiple transmit antennas. A class of techniques known as cooperative communications allows single-antenna mobiles to exploit some of the benefits of multi-input and multi-output (MIMO) systems. The basic idea is that single-antenna mobiles in a multi-user scenario can share their antenna in a manner that creates a virtual MIMO system. Transmitting independent copies of the signal generates diversity and can effectively combat the deleterious effects of fading. In particular, spatial diversity is generated by transmitting signals from different locations, thus allowing independently faded versions of the signal at the receiver.

1.1.1 Examples of Cooperative Communication

Fig. 1.1 shows several types of cooperative relay communication models with a single destination [32]:

- **Traditional Relay Communication**: Traditional relay communication in Fig. 1.1-(a) is a very simple relaying model. This is realized by means of an arbitrary number of serial and/or parallel relays delivering the information from source towards destination, and gain in path loss and/or diversity gain can be achieved.

- **Supportive Relay Communication**: Supportive relay communication in Fig. 1.1-(b) is the simplest form of cooperation, and this model can exploit the diversity and multiplexing gains.

- **Cooperative Relay Communication**: Supportive relay communication can be extended to cooperative relay communication in Fig. 1.1-(c), where at least two cooperative nodes are each other's respective relays at the same time in order to exploit other's communication link.

- **Distributed Space-Time Relay Communication**: Distributed space-time relay communication in Fig. 1.1-(d) is realized by a number of distributed nodes which are synchronized, and space-time techniques, such as space-time coding are applicable either directly or in a modified form to these architectures.

1.1.2 Cooperative Relaying Protocols

- **Amplify-and-Forward (AF)**: AF relaying is the simplest and most popular method, and the signal received by the relay is amplified and retransmitted. Although it is simple to deploy, noise in the received signal is also amplified and retransmitted from the relay, so that the error performance at the destination would deteriorate.

- **Decode-and-Forward (DF)**: DF relaying decodes the received signal, and re-encodes it prior to retransmission.

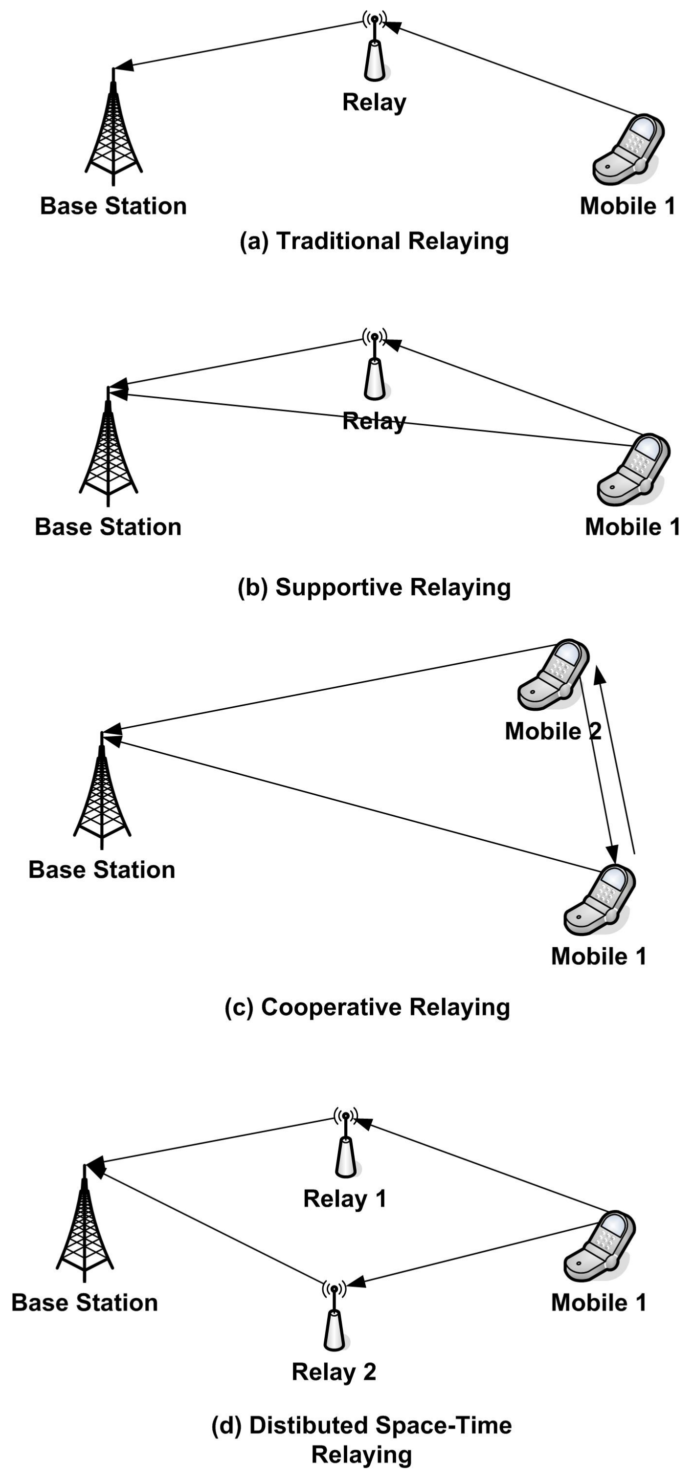

Figure 1.1: Various cooperative communication models.

- **Compress-and-Forward (CF)**: CF relaying relays a compressed version of the detected information stream to destination. This involves some forms of source coding on the sampled signal. Wyner-Ziv coding can be used for optimal compression [28].

1.1.3 Advantages of Cooperative Communication

- **Performance Gains**: System-performance gains can be achieved due to path loss gains, as well as diversity and multiplexing gains. These are resulted from decreased transmission powers, potentially higher capacity, or better cell coverage.
- **Balanced Quality of Service**: In conventional systems users at the cell edge or in shadowed areas suffer from capacity and coverage problems. Cooperative relay communications improve the coverage of all users, so that the equal quality of service (QoS) of all nodes in the network is improved.
- **Reduced Costs**: Compared to a cellular approach to provide a given level of QoS to all users in cell, cooperative relay communication is a more cost effective solution.

1.1.4 Disadvantages of Cooperative Communication

- **Complex Scheduler**: Relaying requires more sophisticated schedulers, since not only the traffic of different users and applications needs to be scheduled, but also the relayed data flows. If not properly handled at the medium access control or network layers, the gains from cooperation at the physical layer will diminish.

- **Increased Overhead**: A full system requires handovers, synchronization, extra security, etc., which increase overhead.

- **Increased End-to-End Latency**: Relaying involves the reception and decoding of the entire data packet before retransmission. If delay-sensitive services are being supported, such as voice or multimedia services, the latency, due to the decoding becomes detrimental. Latency increases with the number of relays and also with the use of interleavers.

- **Extra Relay Traffic**: From a system throughput point of view, the relayed traffic is redundant traffic and hence decreases the effective system throughput, since in most cases, resources in the form of additional time slots or frequency channel are needed.

In this thesis, we focus on techniques that resolve extra relay traffic problems that lead to throughput degradation, and develop several efficient cooperative relaying schemes that employ layered modulations in Chapters 3, 4 and 5.

1.1.5 Error Performance Comparison

The bit error performances of three transmission scenarios are simulated: (1) direct transmission; (2) traditional relaying in Fig. 1.1-(a); and (3) supportive relaying in Fig. 1.1-(b). All systems use BPSK modulation, and a flat Rayleigh fading channel is assumed. For the systems in Fig. 1.1-(a) and (b), decode-and-forward relay is employed.

Fig. 1.2 compares the performances of these three cases. It is observed that supportive relaying scheme outperforms other schemes. Although there is no diversity gain, traditional relaying scheme shows a better performance than the direct transmission scheme, due to path loss gain. Supportive relaying scheme exploits diversity gains and it improves the error performance.

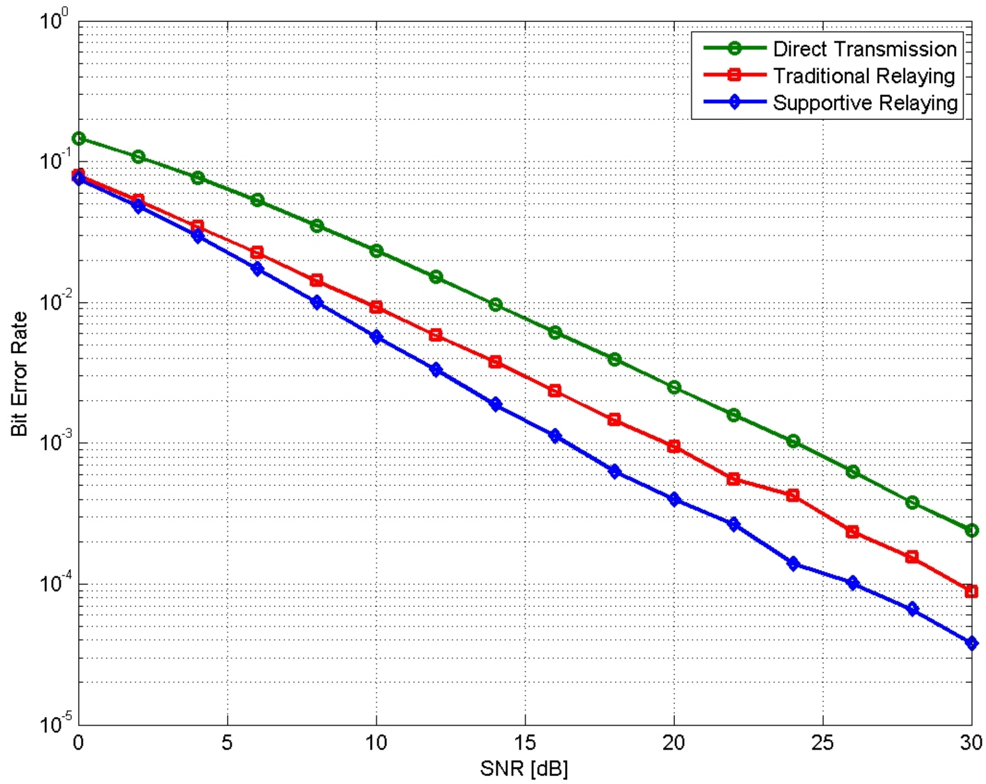

Figure 1.2: Comparison of the BER performances.

1.2 Dissertation Outline

Most existing works on cooperative relay communications have focused on communication scenarios with a single destination. In this thesis, we focus on developing cooperative communication schemes with multiple destinations. We propose new cooperative relay communication schemes that employ layered modulation to resolve problems associated with relay traffic, which induces throughput degradation, while providing a reliable transmission in multiuser cooperative relay communications. We will first briefly review reduced-complexity space-time codes and then propose candidate transmission patterns that are needed for distributed antenna selection in Chapter 2, where, we discuss the proposed pattern-selection scheme for wireless non-regenerative relay networks with block linear precoding. We also derive the expression of the interference level as a function of the number of transmission patterns that the system can select from. We simulate the bit-error-rate performance of the proposed scheme and compare it with that of existing relay schemes. In Chapter 3, throughput loss in the multiuser relay communication is considered, and how layered modulation can mitigate this problem is discussed. In Chapters 4 and 5, we develop multi-user cooperative relay communication schemes which employ layered modulations such as superposition coding and hierarchical modulation to resolve the throughput loss problem which is resulted from the required additional resources for the relay. We propose a scheme that employs superposition coding together with its analysis in Chapter 4. Hierarchical modulation based multiuser cooperative relay communication schemes are proposed and studied in Chapter 5. For the proposed schemes in Chapter 5, we consider two cases of the networks: A symmetric downlink and an asymmetric downlink network. Finally, we draw conclusions in Chapter 6.

Chapter 2 – Transmission Pattern Selection for Relay Communication with Distributed Space-Time Codes

2.1 Introduction

Space-time wireless systems exploit multiple colocated spatial elements at the transmitter and/or receiver to overcome multipath fading or to increase transmission rates. When multiple transmit antennas are available, this is typically combined with an appropriate signal design such as space-time coding [4–8, 10–13] to achieve spatial diversity and/or spatial multiplexing. However, implementing multiple antennas on small-size terminals becomes difficult. Given a fixed transmission power, there exists a fundamental tradeoff between the achievable data rates and transmission distance of a transmitter-receiver pair: a higher data rate will be possible over a shorter communications distance. In networks with a number of distributed terminals that are either mobile or at fixed locations, the network coverage area can be significantly extended by exploiting cooperative diversity. This is achieved by allowing one or multiple terminals to relay the data of an adjacent transmitter toward the more distant destination, forming multihop communications [1, 14, 15]. In order to effectively exploit distributed spatial diversity, cooperative diversity techniques where single-antenna terminals cooperate to exploit virtual multiple-input multiple-output (MIMO) benefits have been studied [1, 2]. One challenge is how to effectively achieve the maximum achievable diversity order with low complexity when the available spatial elements are on terminals at different locations. The Alamouti scheme [5] is a simple and effective orthogonal space-time block code (STBC) of rate one for systems with two transmit antennas. It is well known that complex orthogonal design with transmission rate one does not exist for more than two transmit antennas. The reduced-complexity space-time code, proposed by Nir and Helard [4] applies block linear precoding to the Alamouti code applied on blocks of two antennas. This scheme leads to a diversity order that increases with the size of the precoding matrix at the expense of a linear increase in complexity [4].

In this chapter, we propose a new space-time block coded cooperative relay communications scheme with transmission pattern selection and precoding. We provide a set of candidate distributed transmission patterns. The pattern is selected to maximize the signal-to-noise ratio (SNR) based on the channel conditions. With the proposed patterns, at any time instant, only half of the chosen relays are actively transmitting for a particular source-to-destination pair. Simulation results show that the proposed scheme outperforms the conventional approach using quasi-orthogonal space-time block codes (QO-STBC) introduced in [14]. Since transmission patterns are predetermined and the number of patterns is finite (e.g., 4), the overhead required to feedback the pattern selected is minimal.

In Section 2.2, we briefly review the reduced-complexity space-time code described in [4] and then provide candidate transmission patterns that are needed for distributed antenna selection. In Section 2.3, we discuss the proposed pattern-selection scheme for wireless non-regenerative relay networks with block linear precoding. We also derive the expression of the interference level as a function of the number of transmission patterns that the system can select from. In Section 2.4, we simulate the bit-error-rate performance of the proposed scheme and compare it with that of existing relay schemes. Concluding remarks are given in Section 2.5.

2.2 Precoded STBC and Pattern Selection

For convenience of discussion in the rest of the chapter, this section briefly reviews the reduced-complexity STBC described in [4]. Then, we propose candidate transmission patterns to allow the system to choose the one that results in the highest SNR at the receiver based on the specific channel condition.

2.2.1 Reduced-Complexity STBC

Nir and Helard [4] proposed a space-time block code that applies linear precoding to the extended orthogonal STBC to improve the space-time diversity performance. The diversity of this scheme increases with the size of the precoding matrix. For systems with four transmit antennas, the basic idea of [4] is to apply the 2×2 Alamouti STBC alternatively to transmit antenna pair 1 and 2, and then to transmit antenna pair 3 and 4. The equivalent channel matrix is written as [4]

$$\boldsymbol{\mathcal{H}}_1 = \begin{bmatrix} \boldsymbol{\mathcal{H}}_{12} & 0 \\ 0 & \boldsymbol{\mathcal{H}}_{34} \end{bmatrix}, \tag{2.1}$$

where

$$\boldsymbol{\mathcal{H}}_{ij} = \begin{bmatrix} h_i & h_j \\ -h_j^* & h_i^* \end{bmatrix} \tag{2.2}$$

is the equivalent channel matrix for two successive symbol durations of each pair of antennas. The elements of $\boldsymbol{\mathcal{H}}_{ij}$, h_i and h_j, are the channel responses from transmit antennas i and j to the receiver, respectively. Using the common reception of $\boldsymbol{\mathcal{H}}\boldsymbol{\mathcal{H}}^H$, where $(\cdot)^H$ denotes Hermitian transpose, the diversity order is only two. A precoding matrix can be applied at the transmitter to increase the diversity order. For example, when the number of transmit antenna L equals an integer power of 2, the $L \times L$ linear precoding matrix can be calculated recursively from the 2×2 precoding matrix as

$$\boldsymbol{\Theta}_L = \begin{bmatrix} \boldsymbol{\Theta}_{L/2} & \boldsymbol{\Theta}_{L/2} \\ \boldsymbol{\Theta}_{L/2} & -\boldsymbol{\Theta}_{L/2} \end{bmatrix}, \tag{2.3}$$

where $\boldsymbol{\Theta}_2$ is expressed as

$$\boldsymbol{\Theta}_2 = \begin{bmatrix} e^{j\theta_1}\cos(\eta) & e^{j\theta_2}\sin(\eta) \\ -e^{-j\theta_2}\sin(\eta) & e^{-j\theta_1}\cos(\eta) \end{bmatrix}, \tag{2.4}$$

where η, θ_1, and θ_2 are parameters to be optimized. For $L = 4$, $\boldsymbol{\Theta}_2$ is optimized as

$$\boldsymbol{\Theta}_2 = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ -1 & 1 \end{bmatrix}. \tag{2.5}$$

The overall system is described by matrix

$$\begin{aligned} \boldsymbol{A}_4 &= \boldsymbol{\Theta}_4 \cdot \boldsymbol{\Lambda}_4 \cdot \boldsymbol{\Theta}_4^H \\ &= \frac{1}{2} \begin{bmatrix} \lambda_{12}+\lambda_{34} & 0 & \lambda_{12}-\lambda_{34} & 0 \\ 0 & \lambda_{12}+\lambda_{34} & 0 & \lambda_{12}-\lambda_{34} \\ \lambda_{12}-\lambda_{34} & 0 & \lambda_{12}+\lambda_{34} & 0 \\ 0 & \lambda_{12}-\lambda_{34} & 0 & \lambda_{12}+\lambda_{34} \end{bmatrix}, \end{aligned} \tag{2.6a}$$

where $\lambda_{ij} = |h_i|^2 + |h_j|^2$ and $\boldsymbol{\Lambda}_1 = \boldsymbol{\mathcal{H}}_1 \cdot \boldsymbol{\mathcal{H}}_4^H$. The diagonal elements of $\boldsymbol{A}_4$ are equal to $(1/2)\sum_{l=1}^{L=4} |h_l|^2$. The precoding effectively increases the diversity order from two to four.

This scheme can be applied to other STBCs and several antenna configurations. Moreover, the greater the value of L, the smaller the interference terms [4].

2.2.2 The Proposed Transmission Patterns and Pattern Selection

In designing the possible transmission patterns, we consider a network with one source node, one destination node, and four relay nodes ($L = 4$) between the source and the destination. This represents a typical scenario, and extension to other configurations such as $L = 2$, $L = 6$, or $L = 8$ is straightforward.

There exist quasi-orthogonal STBCs that can be applied in systems with four antennas. These codes provide partial diversity but transmission rate one [12]. There are schemes to achieve full diversity or to improve the performance of quasi-orthogonal codes such as constellation rotation and transmit antenna shuffling [13]. For different sets of fading coefficients, the scheme proposed in [4] does not always result in the highest SNR at the receiver. In the case of four transmit antennas, we propose six alternative transmission matrices that conveniently exploit the basic Alamouti code as ($\boldsymbol{\mathcal{H}}_2$, $\boldsymbol{\mathcal{H}}_3$, $\boldsymbol{\mathcal{H}}_4$,

$\boldsymbol{\mathcal{H}}_5$, and $\boldsymbol{\mathcal{H}}_6$):

$$\boldsymbol{\mathcal{H}}_1 = \begin{bmatrix} h_1 & h_2 & 0 & 0 \\ -h_2^* & h_1^* & 0 & 0 \\ 0 & 0 & h_3 & h_4 \\ 0 & 0 & -h_4^* & h_3^* \end{bmatrix}, \tag{2.7a}$$

$$\boldsymbol{\mathcal{H}}_2 = \begin{bmatrix} h_1 & 0 & h_3 & 0 \\ -h_3^* & 0 & h_1^* & 0 \\ 0 & h_2 & 0 & h_4 \\ 0 & -h_4^* & 0 & h_2^* \end{bmatrix}, \tag{2.7b}$$

$$\boldsymbol{\mathcal{H}}_3 = \begin{bmatrix} h_1 & 0 & 0 & h_4 \\ -h_4^* & 0 & 0 & h_1^* \\ 0 & h_2 & h_3 & 0 \\ 0 & -h_3^* & h_2^* & 0 \end{bmatrix}, \tag{2.7c}$$

$$\boldsymbol{\mathcal{H}}_4 = \begin{bmatrix} 0 & h_2 & h_3 & 0 \\ 0 & -h_3^* & h_2^* & 0 \\ h_1 & 0 & 0 & h_4 \\ -h_4^* & 0 & 0 & h_1^* \end{bmatrix}, \tag{2.7d}$$

$$\boldsymbol{\mathcal{H}}_5 = \begin{bmatrix} 0 & h_2 & 0 & h_4 \\ 0 & -h_4^* & 0 & h_2^* \\ h_1 & 0 & h_3 & 0 \\ -h_3^* & 0 & h_1^* & 0 \end{bmatrix}, \tag{2.7e}$$

$$\boldsymbol{\mathcal{H}}_6 = \begin{bmatrix} 0 & 0 & h_3 & h_4 \\ 0 & 0 & -h_4^* & h_3^* \\ h_1 & h_2 & 0 & 0 \\ -h_2^* & h_1^* & 0 & 0 \end{bmatrix}. \tag{2.7f}$$

Note that $\boldsymbol{\mathcal{H}}_1$, which is the scheme given in [4] without precoding, is also listed above for convenience of description in the sequel. Precoding as described in Section 2.2.1 for the case of $\boldsymbol{\mathcal{H}}_1$ could be applied to the above matrices to achieve full diversity.

Now there are six different transmission patterns for the relays. These patterns will have different performances depending on the specific set of channel coefficients. We assume a linear minimum mean-square error (MMSE) receiver. The SNR with each of the transmission patterns given in Eq. (2.7) is expressed as [9]

$$\mathrm{SNR}_j = \frac{1}{\left[(\boldsymbol{I}_4 + \rho \boldsymbol{\mathcal{H}}_k^H \boldsymbol{\mathcal{H}}_k)^{-1}\right]_{j,j}} - 1, \quad j = 1, \cdots, 4 \; and \; k = 1, \cdots, 6, \tag{2.8}$$

where $\boldsymbol{I}_4$ is the 4×4 identity matrix and $\rho = E_b/N_0$ with E_b being the energy per bit and N_0 being the single-sided power spectral density of the additive Gaussian noise. In the case of a zero-forcing (ZF) receiver, the SNR is calculated as [9]

$$\mathrm{SNR}_j = \frac{1}{\left[(\rho \boldsymbol{\mathcal{H}}_k^H \boldsymbol{\mathcal{H}}_k)^{-1}\right]_{j,j}}, \quad j = 1, \cdots, 4 \; and \; k = 1, \cdots, 6, \tag{2.9}$$

For each set of channel coefficients, the six SNR values for the six transmission patterns $\boldsymbol{\mathcal{H}}_k$ $(k = 1, \cdots, 6)$ can be calculated using Eqs. (2.8) or (2.9). In order to achieve the optimum performance, the system chooses the pattern that results in the maximum SNR value.

The receiver needs to send this information to the relays through a feedback channel, which requires 3 feedback bits for the case with 6 patterns. Once a specific transmission pattern is chosen, the same precoding procedure as described in [4] is applied.

2.2.3 Performance Comparison

We simulate the bit error performance of the precoded STBC with proposed transmission pattern selection scheme and compare with three schemes: (a) the sole Alamouti scheme without precoding as described in Eq. (2.1); (b) the Alamouti scheme with precoding in Sec. 2.2.1; and (c) the scheme with quasi-orthogonal STBC (QO-STBC) given in [8]. For all systems, four transmit and one receive antennas are equipped and MMSE receiver is assumed.

Fig. 2.1 compares the error performance. The error performance of the Alamouti scheme with precoding better than the scheme with the sole Alamouti scheme, but worse than the scheme with QO-STBC which uses four transmit antennas. Although the precoded STBC with pattern selection exploits two transmission antennas at any instant time, it outperforms any other schemes. The proposed pattern selection scheme chooses an optimal transmission pattern out of six transmission patterns in Eq. (2.7) and this provides improved performance. The slight expense paid is that it requires feedback information for the alternative patterns.

2.3 The Proposed Cooperative Relay Communication Scheme

In this section, we apply linear precoding, the proposed transmission patterns, and the pattern-selection algorithm described in Section 2.2 for non-regenerative multihop relay communication systems, where each relay is equipped with only one antenna. Multihop relay exploits the intermediate relay stations to communicate with the more distant receiver. This scheme could result in significantly increased network coverage areas.

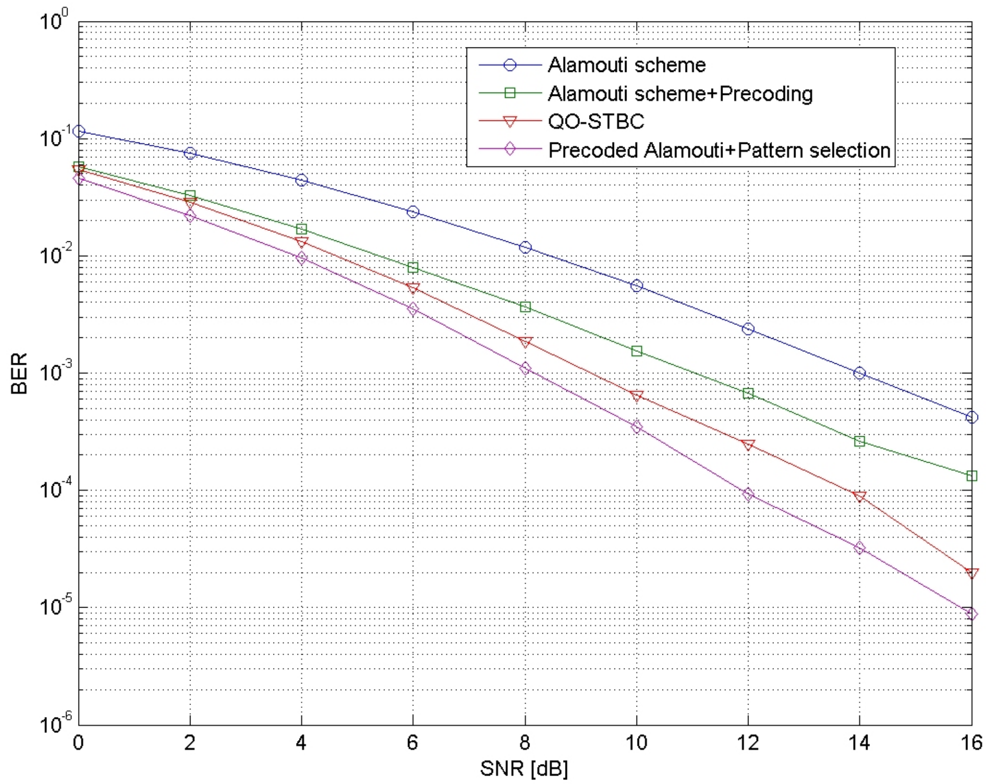

Figure 2.1: Bit error performance of different four-transmit antenna systems

2.3.1 Proposed Distributed Space-Time Encoding for Cooperative Relay Communications

We focus on a single-hop scenario as shown in Fig. 2.2, where the network consists of a source (transmitter), a destination (receiver), and the relay group with L relay notes, either mobile or at a fixed location. The objective is to efficiently use the distributed antennas on the relays to maximize the diversity order for the signal from the source to the destination. We again explain the principle using the specific scenario of $L = 4$. For systems with many relay nodes around the transmitter and the receiver, a group of only four relays nearby will be selected.

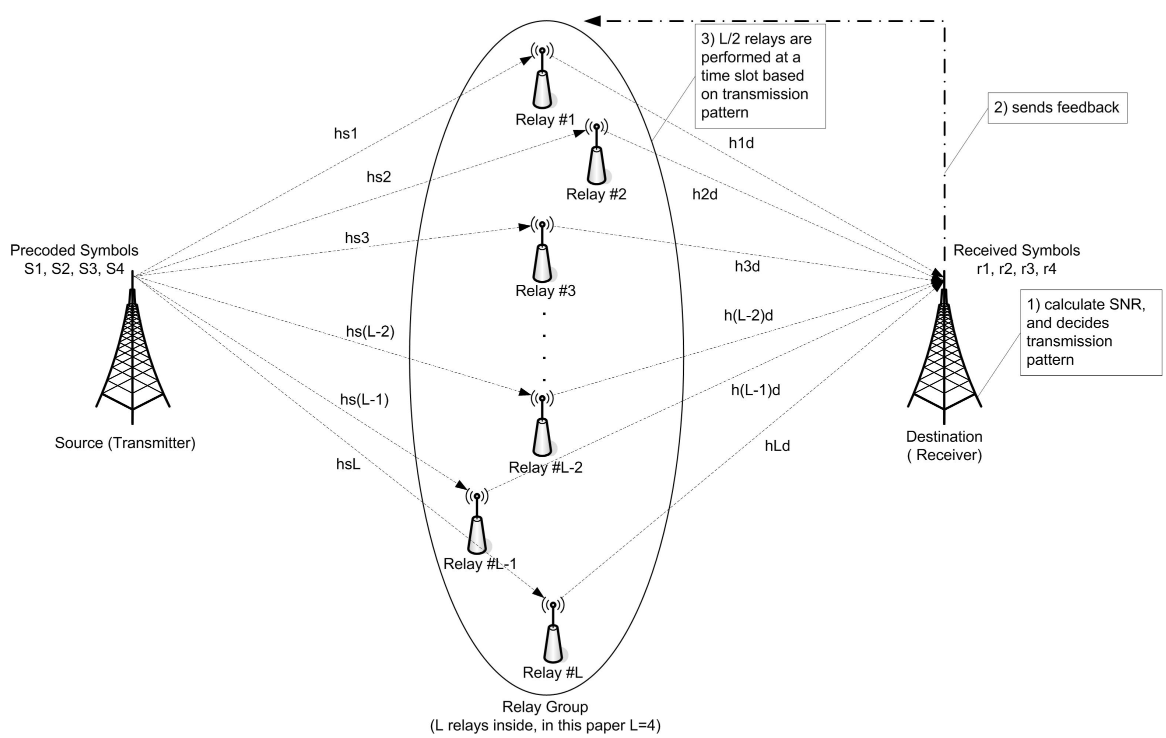

Figure 2.2: Single-hop relay communication system model.

We assume a slowly fading flat Rayleigh channel and the received signal is further distorted by additive white Gaussian noise (AWGN). The transmitter directly precodes complex symbols $s_1, s_2, s_3,$ and s_4 with $\mathbf{\Theta}_4$ as

$$\left[\begin{array}{cccc} S_1 & S_2 & S_3 & S_4 \end{array}\right]^T = \mathbf{\Theta}_4 \left[\begin{array}{cccc} s_1 & s_2 & s_3 & s_4 \end{array}\right]^T, \tag{2.10}$$

where $\mathbf{\Theta}_4$ is calculated from Eq. (2.3) and (2.5), $(\cdot)^T$ denotes transpose, and then sends them to the relays. Each relay group then applies a space-time block code chosen out of the six transmission patterns. The transmitted signals reach the receiver through the relay group.

We are interested in optimizing the signal design, that is, to optimize the signal transmission format of the relay nodes for each time slot. Existing STBCs can be applied for the distributed-antenna scenario by simply viewing each relay as an independent transmit antenna. This requires clock synchronization of the whole network, which is beyond the scope of this paper. Note that the source-to-relay and relay-to-destination distances do not have to be identical as long as the propagation delay caused by the relative distance is insignificant compared with a symbol interval. For example, assume that the maximum relative distance is 5 meters and each node operates at a rate of 1 Mbps. The maximum relative arrival time of the signals from the source to the relays or from the relays to the destination is only 1.65% of a symbol interval. Therefore, if transmissions of all relays are synchronized, the signals from the relays will arrive at the destination approximately at the same time.

The distributed relay transmission can be achieved by having the relay group encode the received symbols with a space-time code, denoted by symbol blocks $\boldsymbol{C}_i$ $(i = 1, \cdots, 6)$.

The corresponding transmission matrices are expressed as

$$\boldsymbol{C}_1 = \begin{bmatrix} c_1 & c_2 & 0 & 0 \\ c_2^* & -c_1^* & 0 & 0 \\ 0 & 0 & c_3 & c_4 \\ 0 & 0 & c_4^* & -c_3^* \end{bmatrix}, \tag{2.11a}$$

$$\boldsymbol{C}_2 = \begin{bmatrix} c_1 & 0 & c_3 & 0 \\ c_3^* & 0 & -c_1^* & 0 \\ 0 & c_2 & 0 & c_4 \\ 0 & c_4^* & 0 & -c_2^* \end{bmatrix}, \tag{2.11b}$$

$$\boldsymbol{C}_3 = \begin{bmatrix} c_1 & 0 & 0 & c_4 \\ c_4^* & 0 & 0 & -c_1^* \\ 0 & c_2 & c_3 & 0 \\ 0 & c_3^* & -c_2^* & 0 \end{bmatrix}, \tag{2.11c}$$

$$\boldsymbol{C}_4 = \begin{bmatrix} 0 & c_2 & c_3 & 0 \\ 0 & c_3^* & -c_2^* & 0 \\ c_1 & 0 & 0 & c_4 \\ c_4^* & 0 & 0 & -c_1^* \end{bmatrix}, \tag{2.11d}$$

$$\boldsymbol{C}_5 = \begin{bmatrix} 0 & c_2 & 0 & c_4 \\ 0 & c_4^* & 0 & -c_2^* \\ c_1 & 0 & c_3 & 0 \\ c_3^* & 0 & -c_1^* & 0 \end{bmatrix}, \tag{2.11e}$$

$$\boldsymbol{C}_6 = \begin{bmatrix} 0 & 0 & c_3 & c_4 \\ 0 & 0 & c_4^* & -c_3^* \\ c_1 & c_2 & 0 & 0 \\ c_2^* & -c_1^* & 0 & 0 \end{bmatrix}. \tag{2.11f}$$

Given the transmitted precoded symbols S_i, $i = 1, \cdots, 4$, to the j-th relay, through the channel with fading coefficient h_{sj}, $j = 1, \cdots, 4$ (see Fig. 2.2), the received signals at the relays are expressed as $r_{ij} = h_{sj}S_i + n_{ij}$, where r_{ij} and n_{ij} are the received symbol and AWGN at the j-th terminal, respectively. The j-th relay encodes a block of four received symbols with the code associated with the j-th row of the symbol block $\boldsymbol{C}_i$ based on the corresponding transmission pattern chosen that yields the maximum SNR value given by Eq. (2.8) for MMSE receiver or Eq. (2.9) for zero-forcing receiver. Of course, it is assumed that this information has already been sent to the relay group from the receiver via feedback for space-time encoding, and receiver knows the channel state information between source and relay, and between relay and destination. After encoding the transmitted symbols, the relays transmit the encoded data to the destination.

For example, when encoding is done with $\boldsymbol{C}_1$, the received signals over four consecutive time slots are expressed as

$$\begin{bmatrix} r_1 \\ r_2 \\ r_3 \\ r_4 \end{bmatrix} = \begin{bmatrix} r_{11} & r_{22} & 0 & 0 \\ r_{21}^* & -r_{12}^* & 0 & 0 \\ 0 & 0 & r_{33} & r_{44} \\ 0 & 0 & r_{43}^* & -r_{34}^* \end{bmatrix} \begin{bmatrix} h_{1d} \\ h_{2d} \\ h_{3d} \\ h_{4d} \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ n_3 \\ n_4 \end{bmatrix}, \tag{2.12}$$

where h_{id}, $i = 1, \cdots, 4$, are channel fading coefficients as shown in Fig. 2.2, and n_i is the AWGN.

Following a similar analysis to the one given in [14], we can derive the expression of the received signals for each of the transmission patterns as

$$\begin{bmatrix} r_1 \\ r_2^* \\ r_3 \\ r_4^* \end{bmatrix} = \boldsymbol{\mathcal{H}}_i \boldsymbol{\Theta}_4 \begin{bmatrix} s_1 \\ s_2^* \\ s_3 \\ s_4^* \end{bmatrix} + \begin{bmatrix} N_1 \\ N_2^* \\ N_3 \\ N_4^* \end{bmatrix}, \tag{2.13}$$

where $\boldsymbol{\mathcal{H}}_i$ $(i = 1, \cdots, 6)$ was given in Section 2.2.2, whose elements are $h_1 = h_{s1}h_{1d}$, $h_2 = h_{s2}^* h_{2d}$, $h_3 = h_{s3}h_{3d}$, and $h_4 = h_{s4}^* h_{4d}$, and

(a) for $\boldsymbol{\mathcal{H}}_1$: $N_1 = n_{11}h_{1d} + n_{22}h_{2d} + n_1$, $N_2 = n_{21}^* h_{1d} - n_{12}^* h_{2d} + n_2$, $N_3 = n_{33}h_{3d} + n_{44}h_{4d} + n_3$, and $N_4 = n_{43}^* h_{3d} - n_{34}^* h_{4d} + n_4$.

(b) for $\boldsymbol{\mathcal{H}}_2$: $N_1 = n_{11}h_{1d} + n_{33}h_{3d} + n_1$, $N_2 = n_{31}^* h_{1d} - n_{13}^* h_{2d} + n_2$, $N_3 = n_{22}h_{3d} + n_{44}h_{4d} + n_3$, and $N_4 = n_{42}^* h_{3d} - n_{24}^* h_{4d} + n_4$.

(c) for $\boldsymbol{\mathcal{H}}_3$: $N_1 = n_{11}h_{1d} + n_{44}h_{2d} + n_1$, $N_2 = n_{41}^* h_{1d} - n_{14}^* h_{2d} + n_2$, $N_3 = n_{22}h_{3d} + n_{33}h_{4d} + n_3$, and $N_4 = n_{32}^* h_{3d} - n_{23}^* h_{4d} + n_4$.

(d) for $\boldsymbol{\mathcal{H}}_4$: $N_1 = n_{22}h_{1d} + n_{33}h_{2d} + n_1$, $N_2 = n_{32}^* h_{1d} - n_{23}^* h_{2d} + n_2$, $N_3 = n_{11}h_{3d} + n_{44}h_{4d} + n_3$, and $N_4 = n_{41}^* h_{3d} - n_{14}^* h_{4d} + n_4$.

(e) for $\boldsymbol{\mathcal{H}}_5$: $N_1 = n_{22}h_{1d} + n_{44}h_{2d} + n_1$, $N_2 = n_{42}^* h_{1d} - n_{24}^* h_{2d} + n_2$, $N_3 = n_{11}h_{3d} + n_{33}h_{4d} + n_3$, and $N_4 = n_{31}^* h_{3d} - n_{13}^* h_{4d} + n_4$.

(f) for $\boldsymbol{\mathcal{H}}_6$: $N_1 = n_{33}h_{1d} + n_{44}h_{2d} + n_1$, $N_2 = n_{43}^* h_{1d} - n_{34}^* h_{2d} + n_2$, $N_3 = n_{11}h_{3d} + n_{22}h_{4d} + n_3$, and $N_4 = n_{21}^* h_{3d} - n_{12}^* h_{4d} + n_4$.

At the receiver, the received symbols from the relay nodes are detected by an MMSE receiver or a ZF receiver. Their performance is analyzed in the next section.

2.3.2 Interference as a Function of the Number of Transmission Patterns

Applying a matched filter at the destination, we can obtain the Grammian matrix [16] for the six cases as

$$\begin{aligned} \boldsymbol{G} &= \boldsymbol{\Theta}_4 \cdot \boldsymbol{\Lambda}_4 \cdot \boldsymbol{\Theta}_4^H \\ &= \frac{1}{2}h^2 \begin{bmatrix} \boldsymbol{I}_2 & 0 \\ 0 & \boldsymbol{I}_2 \end{bmatrix} + \frac{1}{2}h^2 \begin{bmatrix} 0 & W_i\boldsymbol{I}_2 \\ W_i\boldsymbol{I}_2 & 0 \end{bmatrix}, \end{aligned} \tag{2.14}$$

where $\frac{1}{2}h^2 = \frac{1}{2}\sum_{l=1}^{L=4}|h_i|^2$ represents the total channel gain for all transmit antennas, $\boldsymbol{I}_2$ is the 2×2 identical matrix, and W_i can be considered as the channel-dependent interference parameter for the chosen transmission pattern $\boldsymbol{\mathcal{H}}_i$. For the specific case of $L = 4$, $W_i, i = 1, \cdots, 6$, are expressed as

$$W_1 = \left[(|h_1|^2 + |h_2|^2) - (|h_3|^2 + |h_4|^2)\right]/h^2, \tag{2.15a}$$

$$W_2 = \left[(|h_1|^2 + |h_3|^2) - (|h_2|^2 + |h_4|^2)\right]/h^2, \tag{2.15b}$$

$$W_3 = \left[(|h_1|^2 + |h_4|^2) - (|h_2|^2 + |h_3|^2)\right]/h^2, \tag{2.15c}$$

$$W_4 = \left[(|h_2|^2 + |h_3|^2) - (|h_1|^2 + |h_4|^2)\right]/h^2, \tag{2.15d}$$

$$W_5 = \left[(|h_2|^2 + |h_4|^2) - (|h_1|^2 + |h_3|^2)\right]/h^2, \tag{2.15e}$$

$$W_6 = \left[(|h_3|^2 + |h_4|^2) - (|h_1|^2 + |h_2|^2)\right]/h^2. \tag{2.15f}$$

The interference parameters given by Eq. (2.15) change as channel fading coefficients change. Since all channel coefficients are independent and identically distributed, the statistics of $W_1, \cdots, W_6$ are identical. For simplicity of notation, we let $W = W_1$ as

$$W = \left[(|h_1|^2 + |h_2|^2) - (|h_3|^2 + |h_4|^2) \right] / h^2. \tag{2.16}$$

For Rayleigh fading channels, h_{si} and $h_{id}, i = 1, \cdots, 4$, are independent complex Gaussian random variables (r.v.'s). Thus, $h_i = h_{si}h_{id}$ is the product of two independent Rayleigh r.v.'s.

The analytical distribution of W is unfortunately very difficult to obtain. Thus, we plot the simulated probability density function (pdf) of W, $f_W(w)$, and its cumulative density function (cdf), $F_W(w)$, in Fig. 2.3. We find that $f_W(w)$ and $F_W(w)$ can be well approximated by the following functions

$$f_W(w) = \begin{cases} 0.5, & |w| \leq 0.75 \\ \frac{1}{4}[1 + \cos(2\pi(|w| - 0.75))], & 0.75 < |w| \leq 1.25 \\ 0, & \text{otherwise,} \end{cases} \tag{2.17a}$$

$$F_W(w) = \begin{cases} 0, & w \leq -1 \\ \frac{1}{2}w + \frac{1}{2}, & -1 < w < 1 \\ 1, & w \geq 1. \end{cases} \tag{2.17b}$$

Note that $f_W(w)$ in Eq. (2.17a) is a raised-cosine function with a roll-off factor 0.25.

The impact of the channel-dependent interference in Eq. (2.14) can be estimated by calculating the the statistical average of the absolute value of W as a function of the number of transmission patterns n. With the pdf and cdf of W given in Eq. (2.17), and

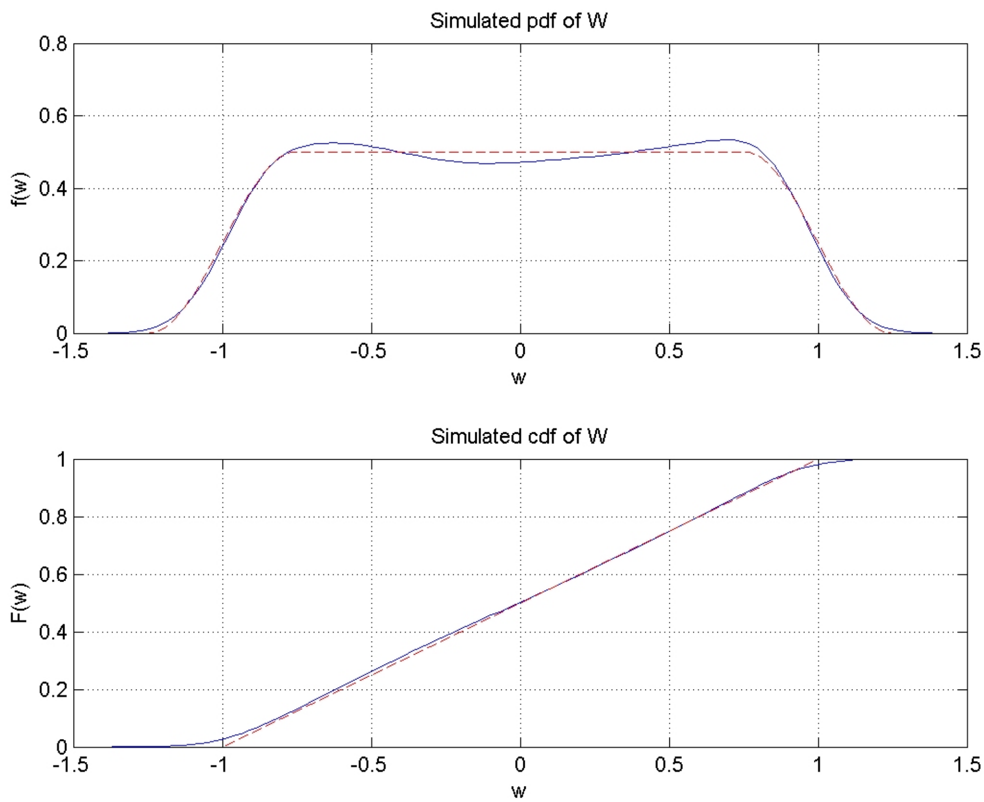

Figure 2.3: The pdf and cdf of W.

following the analysis given in [11, 13], we have

$$E[|W(n)|] = \int_0^{1.25} n[1 - F_W(w)]^{n-1} f_W(w) w dw. \tag{2.18}$$

The values of Eq. (2.18) as a function of n is listed in Table 2.1. As seen from this table, the average interference decreases as n increases. With $n = 2$ patterns, the average interference is reduced by about 51 percent relative to the case with $n = 1$ (only one pattern). Note that for the case of $n = 2$, one feedback bit is needed; for the case of $n = 1$, no feedback is required.

Table 2.1: Average Interference as a Function of the Number of Transmission Patterns

n	1	2	3	4	5	6
$E[\|W(n)\|]$	0.5	0.2471	0.1250	0.0625	0.0313	0.0156

2.4 Simulation Results

We simulate the bit-error rate (BER) performance of the proposed scheme and compare four transmission scenarios: (a) transmission using a 4×4 quasi-orthogonal STBC [8, 14]; (b) the proposed scheme with the precoded STBC given in [4] (no feedback is needed); (c) the proposed scheme with precoding where transmission is chosen out of arbitrarily selected two patterns (1-bit feedback); and (d) the proposed scheme with precoding where transmission is chosen out of arbitrarily selected selected four patterns (2-bit feedback).

The system uses QPSK modulation. Since our focus is on non-regenerative relay, no channel encoding/decoding is employed in all simulations. We assume flat fading and the channel coefficients obey a quasi-static model, which is acceptable for slowly fading channels. It is also assumed that the channels from the transmitter to the relays, and from all relays to the receiver are independent, and perfect channel estimates are available at the relays and the receiver. Since fading is assumed to be quasi-static, the delay of the feedback to select the space-time code pattern that yields the largest SNR can be neglected.

Fig. 2.4 compares the performances of four cases assuming an MMSE receiver. It is observed that the relay scheme using the quasi-orthogonal STBC outperforms the scheme using the code given in [4] in the high-SNR region. This is because with the code given in [4], the sum of the noise terms in Eq. (2.13) is smaller than that with the code given in [14]. If we increase the number of transmission patterns, the performance of the proposed scheme with only two relays is found to outperform that of the scheme with quasi-orthogonal STBC at all SNR values. The slight expense paid is that it requires 2 bits of feedback information. At a BER of 10^{-3}, the proposed scheme with 1 bit of feedback (two transmission patterns) achieves about 2 dB gain over the scheme using quasi-orthogonal codes with four relays.

Fig. 2.5 compares the performance when a ZF receiver is employed. A ZF receiver is simpler to implement than an MMSE receiver, but the former performs slightly worse than the latter. For this case, the scheme using the code given in [4] outperforms the scheme with the quasi orthogonal STBC at all SNR values.

As seen from simulation results, no matter if an MMSE or a ZF receiver is employed, the BER performance gap between the cases with two and four patterns is much smaller than that between one and two transmission patterns, that is, the performance gap between 1-bit and 2-bit feedbacks is less than 1 dB. Therefore, the system can achieve a good performance with only one bit of feedback.

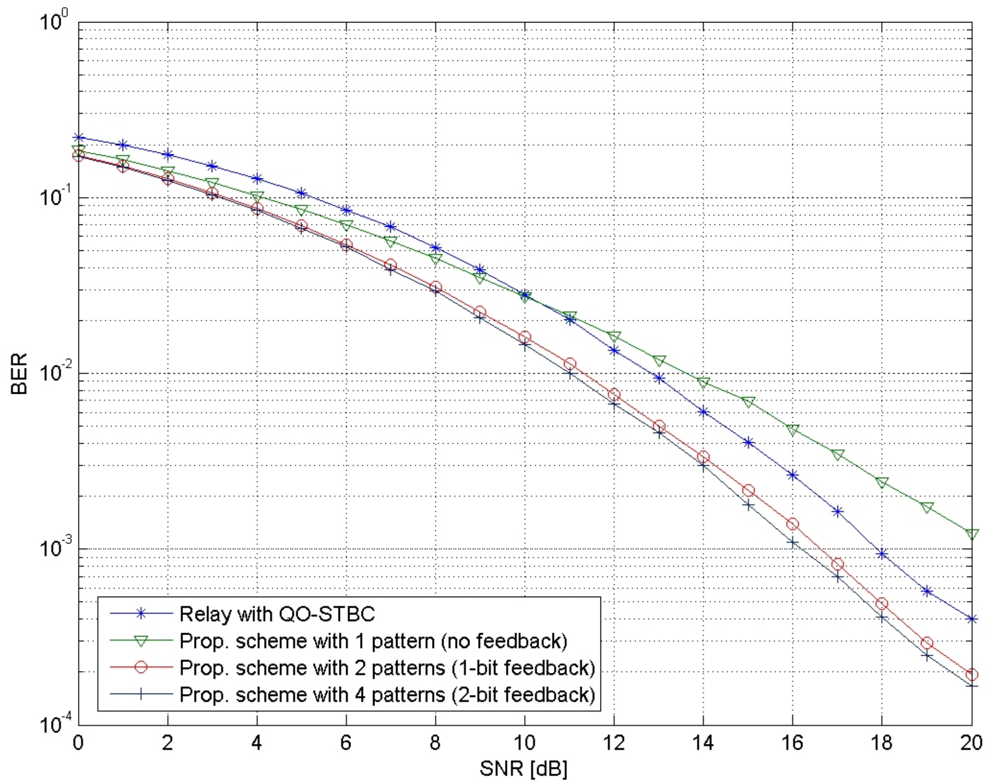

Figure 2.4: BER performance of the proposed system with an MMSE receiver.

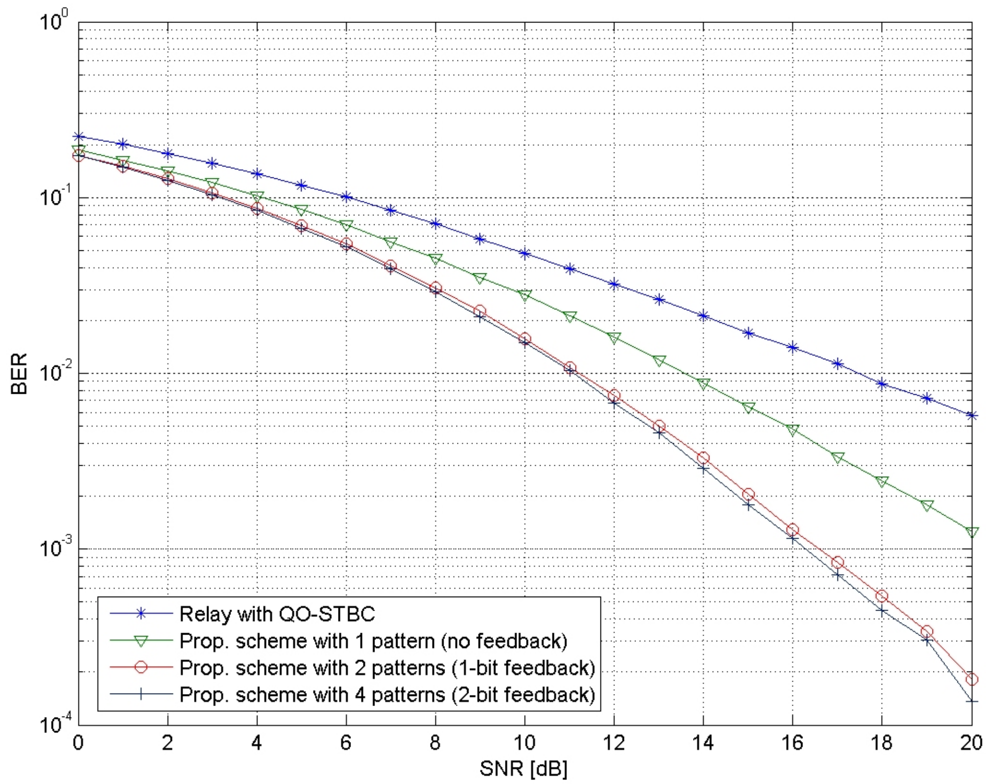

Figure 2.5: BER performance of the proposed system with a ZF receiver.

2.5 Conclusion

We have proposed a new cooperative relay communication scheme with relay-selection that efficiently exploits distributed spatial diversity to improve performance. This scheme maximizes the SNR at the receiver by selecting the transmission pattern out of several possible choices, depending on the channel fading coefficients. We have provided the system model for single-hop communications scenario. Performance comparison is made between the proposed scheme with different number of possible transmission patterns and relay using an existing quasi-orthogonal STBC. Simulation results show that the proposed scheme with only 1 bit of feedback achieves over 2 dB gain at a BER of 10^{-3} over the relay scheme using the quasi-orthogonal STBC. The number of patterns does not need to be high to realize the potential performance gain; with only any two patterns (1-bit feedback) to choose from, the performance already approaches that with four or more patterns (more than 2-bit feedback).

Chapter 3 – Multiuser Relay Communication with Layered Broadcasting

3.1 Introduction

Wireless relay network is emerging as a promising and powerful technique for the high data rate and the reliability requirements of the next generation communication system. By employing a relay node at an intermediate point of a source node and a destination node, the spatial diversity gain could be achieved and the signal to noise ratio is increased, due to the reduced path loss. To extend the coverage area and improve the capacity, extensive research has studied relay protocols and analyzed their performances in terms of the capacity [2, 3, 28, 34], diversity [1, 33], and the diversity-multiplexing tradeoff (DMT) [34] for various environments under several practical constraints and also introduced the relaying protocols using space-time code [19, 20]. In general, a relay node is assumed to operate in the half-duplex mode due to its hardware complexity. For example, in case of the time-division half-duplex relaying, a relay node listens to the information that a source node broadcasts in the first time slot and forwards it to the destination node in the successive second time slot. The substantial loss in capacity due to the half-duplex relaying is unavoidable, and it is a problem in the wireless relay network that has not been completely resolved yet [21]. To mitigate the loss in the capacity due to the half-duplex relaying, more complicated protocols and strategies have been introduced [22–26]. In [22], Host-Madsen and Zhang consider power allocation for the full-duplex relaying, in which a relay node can receive and transmit simultaneously on the same frequency channel. Such full-duplex is, however, usually unrealistic for the physical reasons such as very large interference between transmission and reception signal. In [23], Azarian et. al present an extended non-orthogonal amplify-and-forward (NAF) protocol and a dynamic decode-and-forward (DDF) protocol, which have an optimal DMT for the half-duplex relaying. Also, the results in [23] reveal that more care is necessary in constructing the relay protocols with a half-duplex relay than that without a half-duplex relay. A two-hop relay communication protocol for a bi-directional communication between two or more source/destination nodes using one or multiple half-duplex relays (two-way relaying) was studied in [24]. Successive decoding for a uni-directional communication with two half-duplex relays and a single source/destination node (two-path relaying) is also presented [24]. Both protocols recover a large portion of the capacity loss due to the half-duplex relaying, but no direct link between the source and the destination nodes is considered and two relay nodes need to take turns to transmit the information to a single destination for the two-path relaying. In [25], they propose a successive relaying using repetition coding in two relays wireless network which includes two relay nodes and a single source/destination node, which is the same model as in [24]. Additionally, they consider the direct link between source and destination which is ignored in [24] and hence the cooperative diversity gain is achieved.

In this chapter, to recover the capacity loss and to maximize the network capacity, layered broadcasting known as superposition coding or hierarchical modulation is applied at the source in a partially cooperative relay broadcast channel (RBC). The partially cooperative RBC model is based on a network with four nodes, including a source node, two destination nodes, and a single fixed relay node. The principle of layered broadcasting is that the node with better link quality decodes more layers, and hence it is an applicable technique to the partially cooperative RBC model. Applying layered broadcasting at the source node in the partially cooperative RBC model, total resources required to transmit the information to both of two destination nodes are reduced and the network capacity is increased. We further give the information-theoretic achievable rates of the layered broadcasting protocol and compare this protocol with conventional protocols which do not exploit layered broadcasting at the source node. It is shown that the partially cooperative RBC model with the layered broadcasting protocol recovers the capacity loss of a network with the half-duplex relay and outperforms the conventional protocols.

The remainder of this chapter is organized as follows. Section 3.2 explains the system model for the partially cooperative RBC model and layered modulation based cooperative RBC model. In Section 3.3, we derive the capacity of the partially cooperative RBC with and without layered modulation. Section 3.4 presents the numerical results. Finally, we draw the conclusion in Section 3.5 .

3.2 System Models

In this section, we briefly review the concept of layered broadcasting and introduce the partially cooperative relay broadcast channel (RBC) model and the proposed model.

3.2.1 Partially Cooperative Relay Broadcast Channel (RBC) Model

The partially cooperative RBC model is based on the standard two-user forward link channel model with one base station (BS) and two mobile users, M1 and M2 and described in Fig. 3.1-(a). As shown in Fig. 3.1-(a), we assume that BS-M1 link and BS-M2

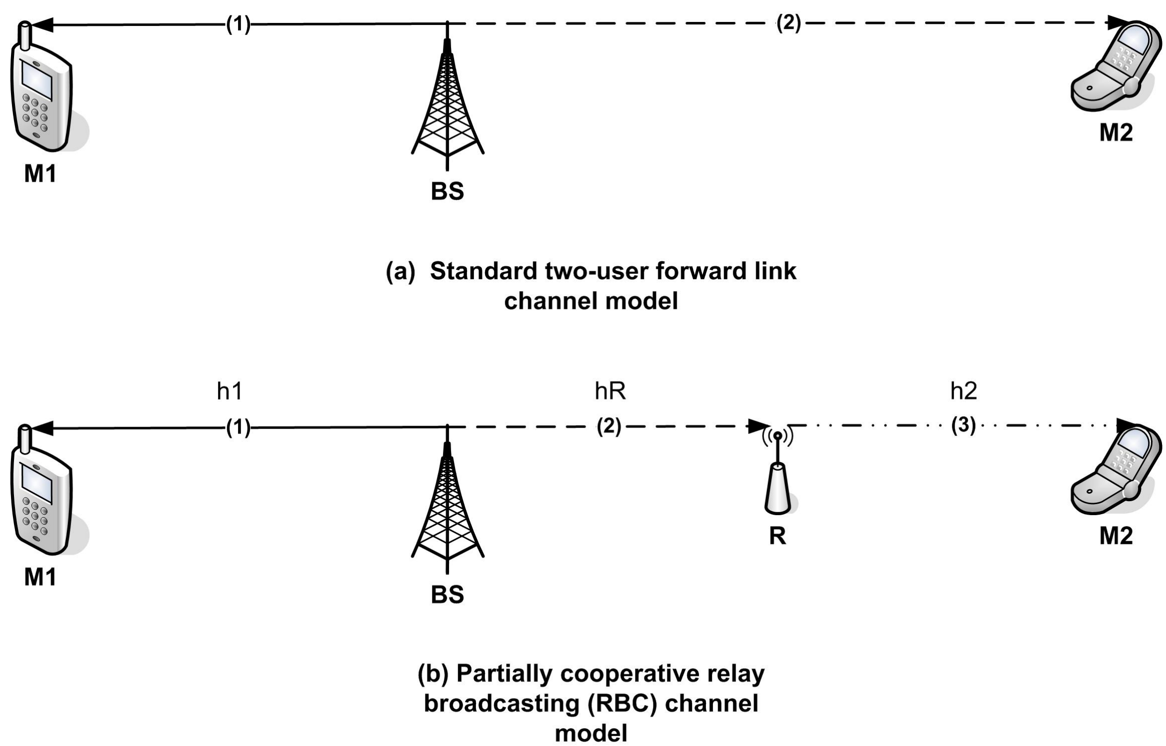

Figure 3.1: Downlink transmission system.

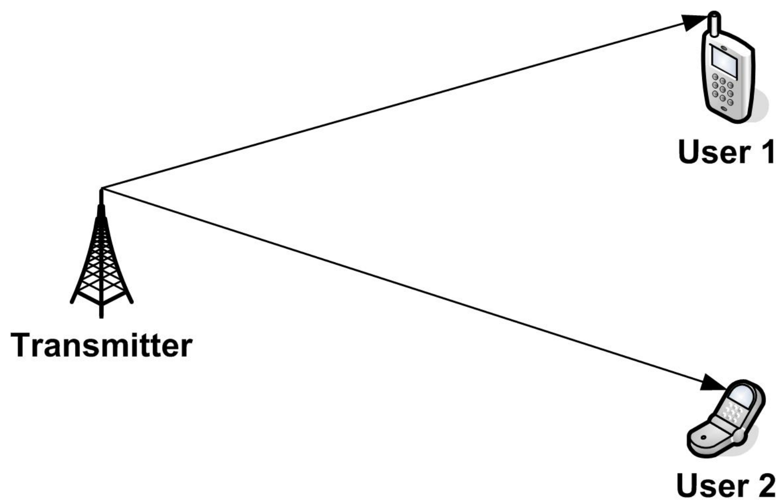

Figure 3.2: 2-user broadcast channel

link are asymmetric and link quality of BS-M2 link is worse than the other one. In order to improve its performance, we deploy the relay (R) between BS and M2. Due to the relay, the partially cooperative RBC model in Fig. 3.1-(b) takes three transmission phases to complete the transmissions, while the standard two-user forward link model in Fig. 3.1-(a) requires two transmission phases. An additional transmission phase for the relay in Fig. 3.1-(b) leads to significant loss of the network capacity $[bits/sec/Hz]$, especially for the high SNR region. In order to overcome this problem, we will propose a partially cooperative RBC, employing layered modulation in the next subsection.

3.2.2 Review of Layered Broadcasting

A broadcast channel has a single transmitter communicating information simultaneously to several receivers (or users). The information communicated to each user may be the same (e.g., TV broadcast) or it may be separate for each user (e.g., base station transmitting user-specific information). We consider the case in which the transmitter is sending independent information to each user. Let us consider a symmetric transmission model where a transmitter with average transmission power P communicating with 2 users in the presence of AWGN as shown in Fig. 3.2. The received real-valued discrete-time baseband signal is

$$y_k[m] = x[m] + n_k[m], \ k = 1, 2, \tag{3.1}$$

where $n_k[m] \sim N(0, \sigma_n^2)$ is the Gaussian noise and $y_k[m]$ is the received signal at user k at time m. The transmited signal $x[m]$ has an average power constraint of P. In the single user case, the capacity of a channel gives the performance limit. Reliable communication can be achieved at any rate $R < C$; reliable communication is impossible at rates $R > C$. In the multiuser case, the performance measure is given by the capacity region C. The capacity region C is the set of all pairs (R_1, R_2), such that simultaneously user 1 and user 2 can reliably communicate at rate R_1 and R_2, respectively. Since the two users share the channel, there is a tradeoff between the reliable communication rates of the users; if one user wants to communicate at a higher rate, the other user needs to lower its rate. From Fig. 3.2 , the single user bounds for R_1 and R_2 are R_k [30, 35]:

$$R_k \leq \frac{1}{2} \log\left(1 + \frac{P}{\sigma_n^2}\right), \ k = 1, 2. \tag{3.2}$$

This upper bound on R_k can be attained by using all the power to communicate with user k (with the other user getting zero rate). Since the situation is symmetric down link channel, the total SNR, P/σ_n^2 is the same for both users. This implies that if user 1 can decode its data, then user 2 should also be able to decode successfully the data of

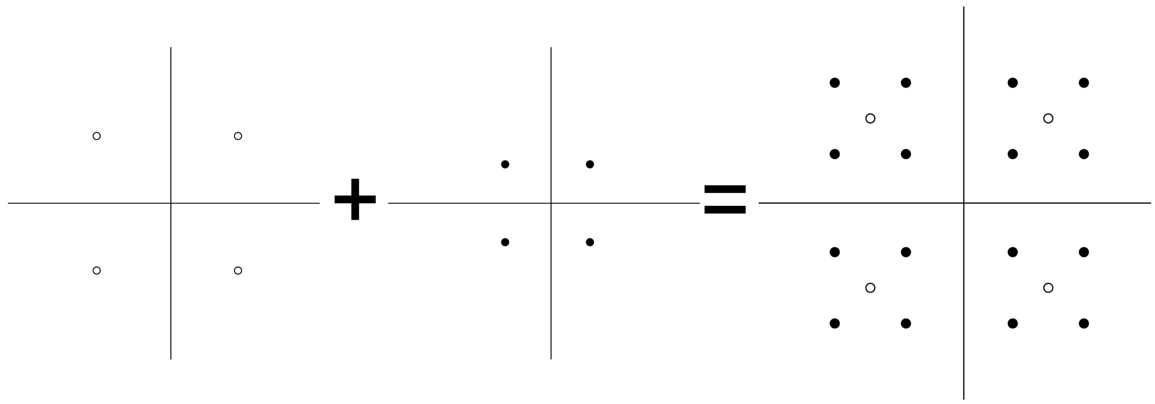

Figure 3.3: Superposition encoding. The power of x_1 is $\sqrt{1-\alpha}$ and the power of x_2 is $\sqrt{\alpha}$.

user 1 and vice versa. Thus the sum information rate can be bounded by the single-user capacity [30]:

$$R_1 + R_2 \leq \frac{1}{2} \log \left(1 + \frac{P}{\sigma_n^2} \right) . \tag{3.3}$$

Thus the capacity region C of the symmetric downlink AWGN channel is given by Eqs. (3.2) and (3.3).

A method to achieve the rate pairs in the capacity region C is to use superposition coding scheme [30,35–37]. Fig. 3.3 shows the superposition coding scheme for two users, each using QPSK constellation. From the figure, it can be seen that the transmitted signal at time k x_k, is the sum of the two user signals and is given by

$$x_k = x_{1k} + x_{2k}. \tag{3.4}$$

Each user decodes its data separately under the constraint $P_1 + P_2 = P$ $(P_1 > P_2)$, where P_1 is used for user 1 and P_2 is used for user 2. The decoding scheme used at the receivers is known as the successive interference cancelation (SIC). The main idea is that if user 1 can decode its data successfully from y_1, then user 2, which has the same total SNR, should be able to decode the data of user 1 from y_2. Then user 2 can subtract the codeword of user 1 from y_2 to better decode its data.

User 1 treats the signal for user 2 as noise and hence can reliably communicate at the rate of [35–37]

$$R_1 = C\left(\frac{P_1}{P_2 + \sigma_n^2}\right) = C\left(\frac{P_1 + P_2}{\sigma_n^2}\right) - C\left(\frac{P_2}{\sigma_n^2}\right). \tag{3.5}$$

User 2 performs the successive interference cancelation; it decodes the data of user 1 first by treating x_2 as noise, subtracts the determined signal of user 1 from y_2, and then extracts its data. Thus the achievable rate for user 2 is [35–37]

$$R_2 = C\left(\frac{P_2}{\sigma_n^2}\right). \tag{3.6}$$

Let $P_1 = (1-\alpha)P$ and $P_2 = \alpha P$, $\alpha \in [0, 0.5]$. Then the achievable rates are

$$R_1 = C\left(\frac{(1-\alpha)P}{\alpha P + \sigma_n^2}\right), \tag{3.7}$$

and

$$R_2 = C\left(\frac{\alpha P}{\sigma_n^2}\right). \tag{3.8}$$

It is also possible to reverse the cancelation order so that instead of user 2, user 1 does interference cancelation.

3.2.3 Cooperative Relay Broadcast Channel Model with Layered Broadcasting

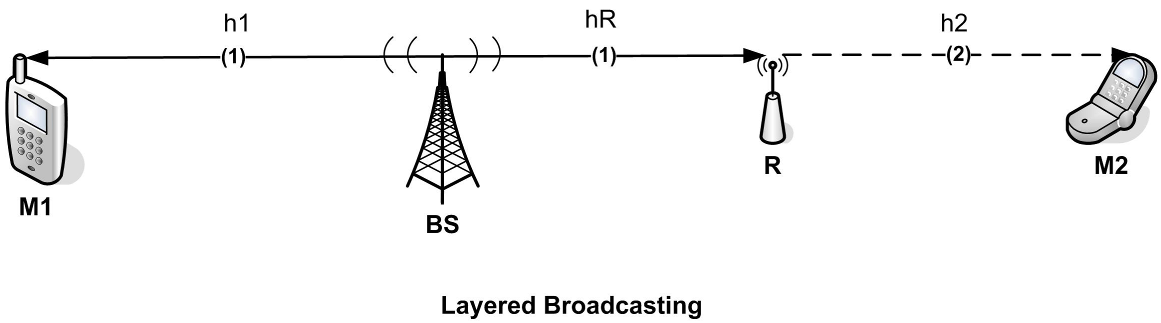

Figure 3.4: Proposed Downlink transmission system.

In Sec. 3.2.3, we introduced the partially cooperative RBC model and its problems. Now, we propose the new partially cooperative RBC with layered modulation. In the partially cooperative RBC model, BS-M1 link and BS-R link fall into the class of two-node broadcast channel model. Fig. 3.4 describes the proposed partially cooperative RBC model with layered modulation. The link from BS to R has a better quality of link than the link from BS to M1. In addition, it is more reasonable for the relay node to execute the successive interference cancelation than for the mobile node to execute it, due to hardware complexity. Therefore, the information for M2, which is forwarded to M2 through the relay (R), is superimposed on the information for M1. The transmission structure of the proposed model is described as follows,

Step 1: BS broadcasts $\sqrt{\alpha}x_1 + \sqrt{1-\alpha}x_2$, where x_1 is the information for M1 and x_2 is the information for M2, then M1 and R receives that information. The received signals at M1 and R are

$$y_{M1} = \left(\sqrt{1-\alpha}x_1 + \sqrt{\alpha}x_2\right) h_1 + n_1, \tag{3.9}$$

and

$$y_R = \left(\sqrt{1-\alpha}x_1 + \sqrt{\alpha}x_2\right) h_R + n_R, \tag{3.10}$$

where each h_i and n_i, $i \in \{1, 2, R\}$ denote a complex channel coefficient and additive Gaussian noise $N(0, N_0)$, respectively. M1 does not execute the successive interference cancelation, but treats x_2 as an additional noise and decodes its information, while R first decodes x_1 and subtracts it from the received signal and decodes x_2 to forward to M2.

Step 2: In the second transmission phase, R forwards the re-encoded information x_2 to M2. The received signal at M2 is

$$y_R = x_2 h_2 + n_2. \tag{3.11}$$

In a later section, we will derive the capacity region of the partially cooperative RBC model with layered broadcasting (LBC) and compare the conventional models.

3.3 Achievable Capacity Region

We assume a block Rayleigh fading channel environment and all the channel information are known at BS, hence the adaptive modulation and coding (AMC) can be applied at BS to achieve the capacity region. The path loss due to the distance of the link and the channel model is considered. We consider the following SNRs,

$$\gamma = \frac{|h|^2}{N_0}. \tag{3.12}$$

A link with SNR of γ can reliably transfer up to

$$C(\gamma) = \log_2(1+\gamma)\ [bits/s/Hz], \tag{3.13}$$

where the bandwidth is normalized, and we will ignore the "Hz" from the units and always use the measure $[bit/s]$. Thus we can use 'rate' and 'spectral efficiency' interchangeably.

3.3.1 Conventional RBC Model

For the partially cooperative RBC model in Fig. 3.1-(b), it is assumed that γ_0, γ_1 and γ_2 are the received SNRs at M1 (BS-M1 link), the relay (BS-R link) and M2 (R-M2 link), respectively. This model takes three transmission phases to transmit the information to M1 and M2. In this system model, M2 receives the information only from R at the third transmission phase, hence the resource-efficiency is decreased. The overall spectral efficiency of the partially cooperative RBC model can be expressed as a combination of the direct transmission and the multi-hop transmission [28].

$$C_{RBC} \quad = \quad \frac{1}{3}\left\{C(\gamma_0) + \min\{C(\gamma_1), C(\gamma_2)\}\right\}. \tag{3.14}$$

3.3.2 RBC with Layered Broadcasting

In Sec. 3.2.3, we proposed the partially cooperative RBC with layered modulation and described how it works. We assume that all channel conditions of each link are the same as the case in Sec. 3.3.1. BS broadcasts $\sqrt{\alpha}x_1 + \sqrt{1-\alpha}x_2$, where x_1 is the information for M1 and x_2 is the information for M2, and both M1 and R receive the information. The successive interference cancelation is executed after receiving the information from BS. After the first transmission phase, the capacities of M1 and R, employing layered broadcasting at BS, are given by the following rates:

$$C_{M1} \leq \log_2\left(1 + \frac{\alpha\gamma_0}{(1-\alpha)\gamma_0 + 1}\right), \tag{3.15}$$

$$C_{R_1} \leq \log_2\left(1 + \frac{\alpha\gamma_1}{(1-\alpha)\gamma_1 + 1}\right), \tag{3.16}$$

and

$$C_{R_2} \leq \log_2(1 + (1-\alpha)\gamma_1). \tag{3.17}$$

where C_{M1} is achievable rate of x_1 at M1, C_{R_1} and C_{R_2} are achievable rates of x_1 and x_2 at R, respectively.

The achievable rate of x_2 at M2 after the second transmission phase is

$$C_{M_2} = \log_2(1 + \gamma_2). \tag{3.18}$$

The proposed model takes two transmission phases to complete the transmissions. By the max-flow min-cut theorem, the capacity of relay network is determined by its bottleneck, and the capacity of M1 is decided by the minimum link of BS-R link and R-M1 link. Overall spectral efficiency of the proposed scheme employing layered broadcasting is derived as

$$C_{LBC} = \frac{1}{2}\left\{C\left(\min\left(\frac{\alpha\gamma_0}{(1-\alpha)\gamma_0+1}, (1-\alpha)\gamma_1\right)\right) + C(\gamma_2)\right\}. \quad (3.19)$$

The value of α is a critical parameter which should be set not to cut down again the effect of increased resource-efficiency, due to the increased signal to interference and noise ratio or the effect of the bottleneck.

3.4 Numerical Results

In this section, we evaluate the spectral efficiency of the partially cooperative RBC with layered modulation in Fig. 3.4 and compare the conventional models. It is assumed that received SNRs at M1, R and M2 are $\gamma_0 = \frac{|h_1|^2}{N_0}\frac{1}{(d_{BS-M1})^l}$, $\gamma_1 = \frac{1}{(d_{BS-R})^l}\gamma_0$ and $\gamma_2 = \frac{1}{(d_{R-M2})^l}\gamma_0$, respectively. d_{BS-M1}, d_{BS-R} and d_{R-M2} are link distances of BS-M1 link, BS-R link and R-M2 link, respectively and l is the path loss coefficient. For all system models, we assumed that $l = 3$, $d_{BS-M1} = 1$, and $d_{BS-R} + d_{R-M2} = 1.5$. BS-M2 link as more distant than BS-M1 link and the relay is exploited in BS-M2 link.

Fig. 3.5 compares the total spectral efficiencies of three models, the proposed model, conventional RBC model in Fig. 3.1-(b) and the direct transmission model in Fig. 3.1-(a). At the expense of the relay and layered modulation, the proposed model outperforms any other system models. We set $\alpha = 0.8$ and link distance of BS-R is 0.6 in this simulation. Generally, a destination node which receives information from a source with aid of a relay node requires a dedicated orthogonal resource for relaying, and it leads to a significant network capacity $[bits/sec/Hz]$ loss, especially in the high SNR region. And this simulation shows that the spectral efficiency of the conventional RBC model in Fig. 3.1-(b) becomes worse than that of the direct transmission model in Fig. 3.1-(a) in high SNR range.

We also investigate how the capacity of the proposed model changes according to the value of α which controls the power level of superposition. In this simulation, we fix $\gamma = 20dB$. Fig. 3.6 shows three different cases, where d_r is a link distance of BS-R link. As the relay moves away from BS; d_r increases, and the maximum achievable rate is shown at the lower value of α. When $d_r = 0.6$, the maximum achievable rate is shown at $\alpha = 0.9$, but when $d_r = 1.0$, the maximum achievable rate is shown at $\alpha = 0.75$.

As shown in numerical results, in order to maximize the capacity, we need to consider several factors which are the value of α, and the relay location etc.

3.5 Conclusion

In this chapter, we have studied the capacity of network with a source node BS, two destination nodes M1, M2 and a single relay node R. Due to the complexity issue of mobile relaying, we define the partially cooperative RBC model where a fixed relay node is employed between the nodes. Under the constraints that the relay node R operates in the half-duplex mode, due to its hardware complexity, exploiting a layered broadcasting protocol at BS is considered to improve the network capacity. It is shown that the layered broadcasting protocol in the partially cooperative RBC with a specific value of α, efficiently recovers the loss of a network capacity in the half-duplex relay and

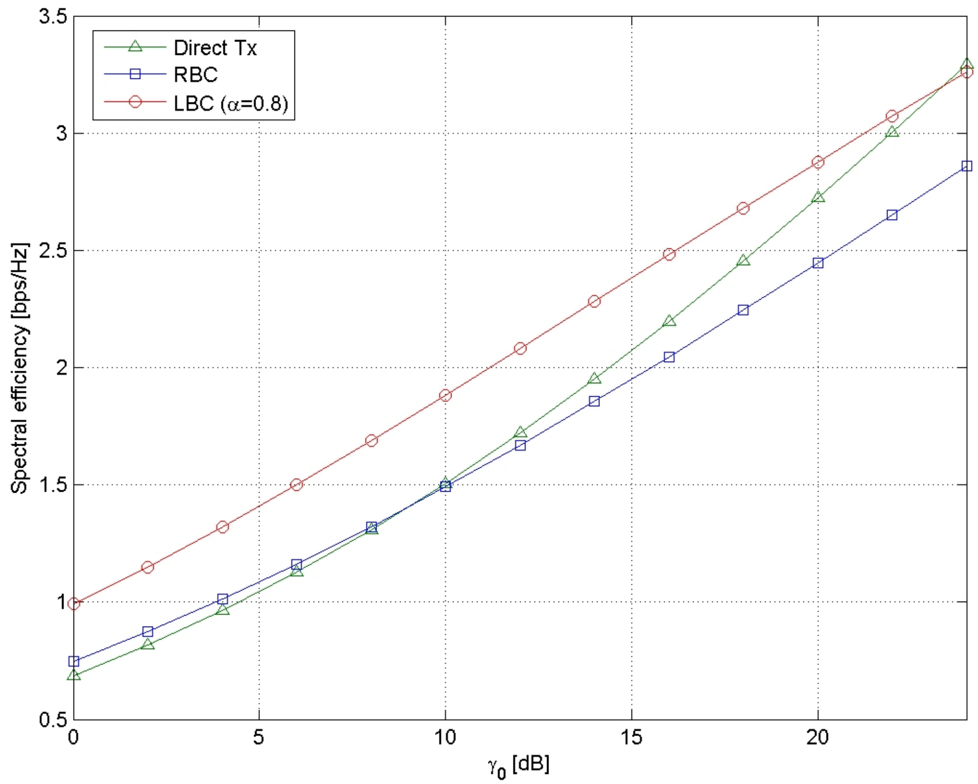

Figure 3.5: The spectral efficiency of the partially cooperative RBC with layered modulation.

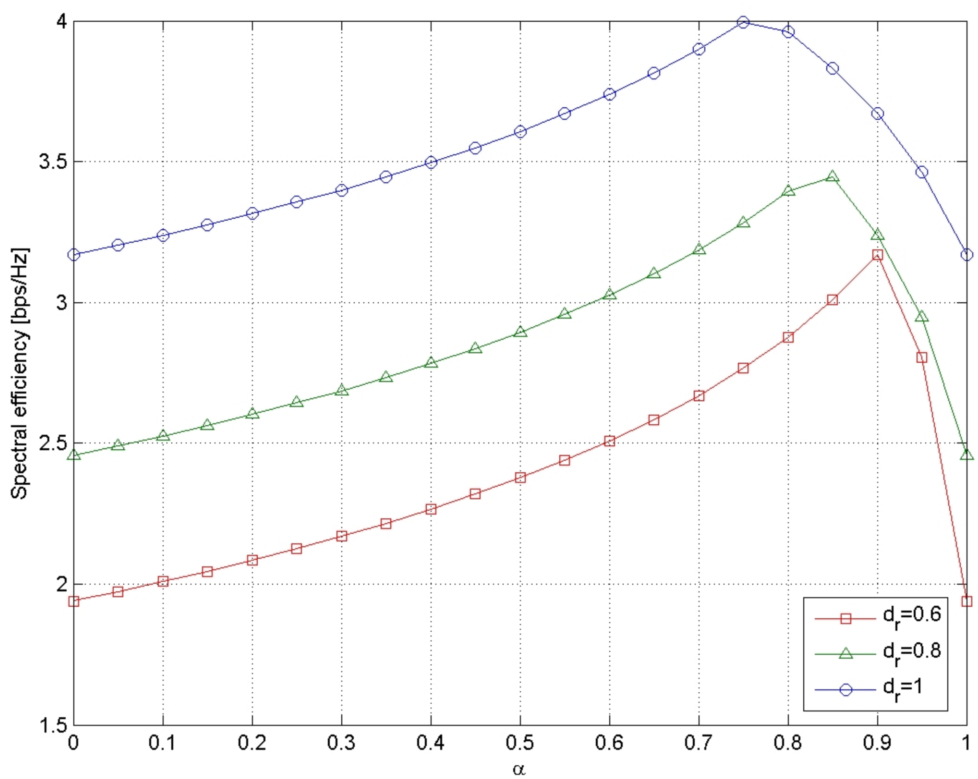

Figure 3.6: The spectral efficiency according to the value of α ($\gamma_0 = 20dB$).

outperforms the conventional protocols.

Chapter 4 – Cooperative Multiuser Relay Communication with Superposition Coding

4.1 Introduction

A widely used technique to mitigate fading for wireless communications is spatial diversity. Spatial diversity requires more than one antenna at one or both ends of the communications link. Recently, cooperative communication schemes have been proposed to provide spatial diversity through virtual antennas [1, 2, 33, 34]. However, additional resources must be allocated for cooperation or a relay, which degrades the overall data throughput of the network, as mentioned in Chapter 3. Reduction of throughput will become more severe as the number of users increases. In order to overcome this problem, many cooperative schemes have been proposed.

In Chapter 3, we showed how layered modulation effectively resolves the throughput reduction problem in cooperative relay communication. In [39–41, 47–50, 53], layered modulation methods such as hierarchical modulation and superposition coding are applied for cooperative communications. Hierarchical modulation, which has been used in the digital video broadcast (DVB) standard, offers another degree of freedom in protecting the transmitted messages according to their relative importance [44, 46]. Superposition coding has been introduced for performing efficient broadcasting [35–37]. With superposition coding, the source creates two independent messages, which are basic and superposed messages, and superimposes these two messages in one modulation domain. Then, superposition signal is broadcasted to destination. The receiver with a good channel is able to decode both messages, while the one with a poor channel is able to decode only the basic message. By employing layered modulation, multiple data streams can be transmitted simultaneously without additional resources, but the BER is increased. Although there are some existing efforts on applying layered modulation for cooperative relay communications, most these efforts have focused on communication scenarios with a single destination. [39, 40] introduced a superposition coding based two-step relaying scheme that consists of one source, one relay and a single destination. This scheme focused on spectral efficiency aspects and employs superposition coding in order to increase the transmission rate. In [53], we proposed and considered a multiuser cooperative relay communication with hierarchical modulation in symmetric downlink transmission model. The proposed scheme resolves the throughput reduction problem and also provides reliable transmission.

In this chapter, we consider a single source, multi-destination model based on superposition coding that employs adaptive relay. We develop an efficient transmission scheme that provides improved overall network throughput and reliable transmission quality. We define network throughput as the sum of the data rates that are delivered to all terminals in a network. For clarity of description, we consider the system assuming one base station, one relay, and two users (mobiles or destinations) operating in a half-duplex mode; extension to a general network configuration is straightforward. We develop a scheme for the following scenario: One of the mobiles is in the cell coverage area of the base station and the other is not, where a relay must be employed for the mobile which is out of cell coverage.

The proposed system does not require additional transmission phases for the cooperation and provides a more reliable transmission than conventional scheme. Upon the decoding results at the mobile in cell coverage area, this mobile is also able to relay the message to the other node. We show that with an appropriate power-division coefficient α of superposition coding, the proposed scheme provides more reliable transmission than conventional communication systems, while both schemes require the same number of transmission phases.

4.2 System Description

4.2.1 Conventional Communication Schemes

Consider the downlink wireless transmission model as shown in Fig. 4.1, which consists of one base station (BS), one relay (R), and two mobiles (M1 and M2) operating in half-duplex mode. Transmission of the signals for M1 and M2 requires three transmission phases. We call this downlink transmission model an asymmetric communications model, because one of the mobiles is in the cell coverage area of the base station and the other one is out of cell coverage of the network. For this scenario, a relay must be employed for M2 as shown in Fig. 4.1 and there is no diversity gain. It is assumed that every node is interested in a message that includes the information for it and does not listen to the messages intended for others. The BS generates and delivers messages s_1 and s_2 to M1 and M2, respectively. It is assumed that the channels between different pairs of terminals experience independent, flat Rayleigh fading, and all the terminals are equipped with a single antenna.

The conventional scheme in Fig. 4.1 employs a relay (R) between the BS and M2, where decode-and-forward operation is assumed, and M1 does not benefit from the relay. If M1 receives a retransmission from R to improve the transmission quality, this requires

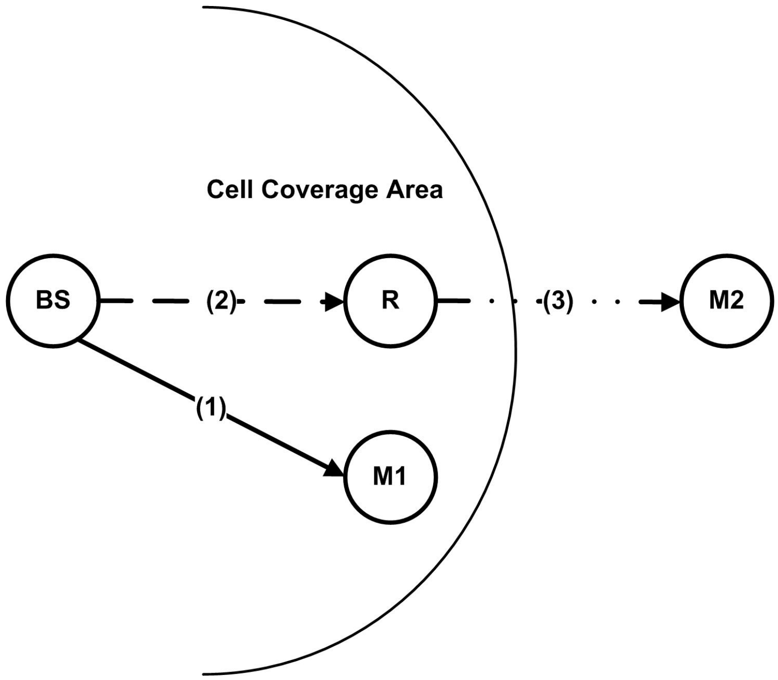

Figure 4.1: Conventional Downlink Transmission System: Direct Transmission + Relay Transmission (3-transmission phase)

additional resources such as time slots or frequency bands, which will reduce the overall throughput of the network; in this case, four transmission phases will be required to complete the transmissions. In order to overcome this limitation, we develop a scheme that employs superposition coding described next.

4.2.2 Superposition Coding

In general, a layered modulation could be the superposition of any two modulation schemes. For broadcast and multicast services, a QPSK enhancement layer may be superposed on a base QPSK or 16-QAM layer to obtain the resultant signal constellation.

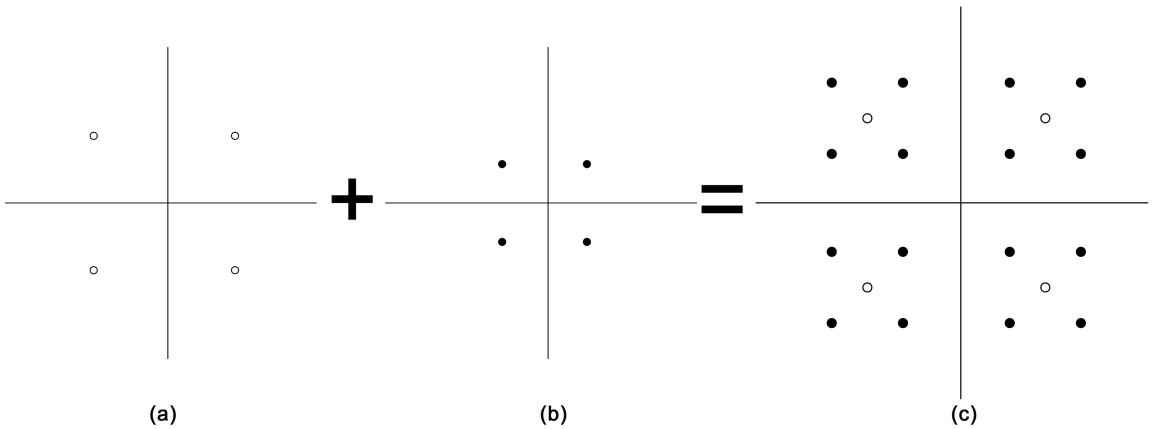

Figure 4.2: Constellation for superimposed QPSK. The circles and black symbols denote the constellations of s_1 and s_2 respectively. The power of s_1 is $\sqrt{E(1-\alpha^2)}$ and the power of s_2 is $\sqrt{E\alpha^2}$.

In a two-node broadcast channel, one link of the broadcast channels may have the capability to transmit at a higher rate than the other link and it is well known that the capacity region of a two-node broadcast channel is achieved by layered (superimposed) broadcasting. Fig. 4.2 shows an example of superposition coding scheme for two users using QPSK constellation. In layered broadcasting, the information for two nodes (node M1 and node M2) are superimposed and the BS transmits the following signal:

$$x_{SC} = \sqrt{E(1-\alpha^2)}s_1 + \sqrt{E\alpha^2}s_2, \tag{4.1}$$

where E is the transmission energy and α $(0 < \alpha^2 < 1)$ is a power division coefficient. s_1 is the information message for node M1, and s_2 is the information message for node M2. If node M2 has a better link quality, node M2 decodes the information for node M1 first, then subtracts it from the received signal and decodes the information for node M2 by using the successive interference cancelation (SIC) method. Node M1 decodes only the information for node M1 first, and then it treats the information for node M2 as an additional noise.

4.3 Superposition Coding Based Cooperative Relay Communication

Superposition coding described above can be employed for cooperative relay communication to improve transmission reliability. Fig. 4.3 shows a network that consists of a BS, a relay, and two users, M1 and M2. The relay adaptively selects the amplify-and-forward (AF) or the decode-and-forward (DF) protocol upon the decoding result at the relay. In order to determine whether the relay and M1 have decoded the received symbols correctly or not, cyclic redundancy check (CRC) codes are employed. This also prevents error propagation to next node. The overall process of this scheme is described as follows.

1) BS generates two messages s_1 and s_2 for M1 and M2, respectively, and broadcasts the superimposed signal, s_{SC}, expressed as

$$s_{SC} = \sqrt{E_{BS}}\left(\sqrt{1-\alpha^2}s_1 + \sqrt{\alpha^2}s_2\right), \tag{4.2}$$

where s_1 and s_2 are arbitrarily assigned as the basic message and superposed message, respectively, E_{BS} is the transmission energy at BS and α is a power-division coefficient, typically chosen in the range $0 < \alpha^2 < 0.5$.

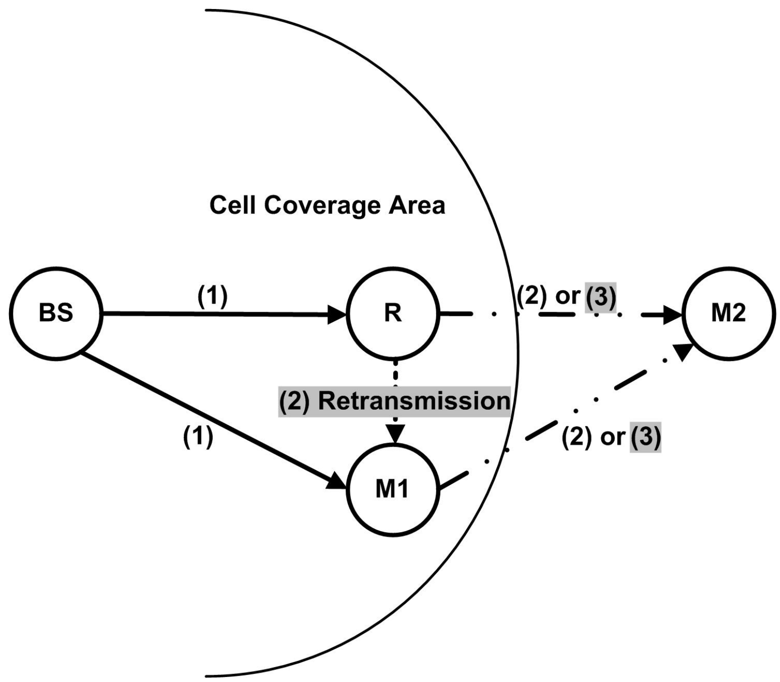

Figure 4.3: Proposed Scheme: Superposition coding plus relay transmission (2-transmission phases without retransmission or 3-transmission phases with retransmission)

- The signal received by the relay is expressed as

$$Y_R = \sqrt{E_{BS}} h_{BS-R} \left(\sqrt{1-\alpha^2} s_1 + \sqrt{\alpha^2} s_2 \right) + n_R, \tag{4.3}$$

where h_{BS-R} is the channel coefficient of the BS-R link, and n_R is additive white Gaussian noise at the relay. The relay decodes s_1 first and then s_2 by using SIC.

- The signal received by M1 is expressed as

$$Y_{M1} = \sqrt{E_{BS}} h_{BS-M1} \left(\sqrt{1-\alpha^2} s_1 + \sqrt{\alpha^2} s_2 \right) + n_{M1}, \tag{4.4}$$

where h_{BS-M1} is the channel coefficient of the BS-M1 link, and n_{M1} is additive white Gaussian noise at M1. M1 decodes s_1 first and then s_2.

Since CRC codes are employed in the transmitted signal from the BS, R and M1 are able to determine whether the received symbols from BS are correct or not.

2) Upon the decoding results of s_1 at M1 and R, we have to consider the following three cases:

(i) If M1 fails to decode s_1, and R succeeds in decoding s_1 correctly: R retransmits symbol s_1 to M1; an additional transmission phase is required. The received signal at M1 is

$$Y_{M1}^{case1} = \sqrt{E_R} h_{R-M1} s_1 + n'_{M1}, \tag{4.5}$$

where h_{R-M1} is the channel coefficient of the R-M1 link, and n'_{M1} is additive white Gaussian noise at M1.

(ii) If both M1 and R fail to decode s_1 correctly: transmission from R will not proceed.

(iii) If M1 succeeds in decoding s_1 correctly: no transmission from R is needed.

3) Upon the decoding results of s_2 at M1 and R, the following four cases are considered to determine which node should deliver s_2 to M2:

(i) Both R and M1 have decoded symbol s_2 correctly: in this case both R and M1 retransmit s_2 to M2, and M1 also works as a relay. The system provides diversity gain in this case.

The received signal at M2 after the two-step process is expressed as

$$Y_{M2}^{case1} = \left(\sqrt{E_R}h_{R-M2} + \sqrt{E_{M1}}h_{M1-M2}\right) s_2 + n_{M2}, \tag{4.6}$$

where h_{R-M2} and h_{M1-M2} are the channel coefficients of the R-M2 link and M1-M2 link, respectively and n_{M2} is additive white Gaussian noise at M2. M2 then decodes the received symbol by using maximum ratio combining (MRC).

(ii) Only R successfully decodes s_2: in this case R retransmits s_2 to M2. The signal received by M2 is written as

$$Y_{M2}^{case2} = \sqrt{E_R}h_{R-M2}s_2 + n_{M2}. \tag{4.7}$$

(iii) Only M1 successfully decodes s_2: in this case M1 retransmits s_2 to M2, and M1 works as a relay. The signal received by M2 is written as

$$Y_{M2}^{case3} = \sqrt{E_{M1}}h_{M1-M2}s_2 + n_{M2}. \tag{4.8}$$

(iv) Both R and M1 fail in decoding s_2: in this case only R performs amplify-and-forward relaying with its received signal from the BS. M2 receives the amplified signal from R as

$$\begin{aligned} Y_{M2}^{case4} &= \sqrt{E_R} h_{R-M2} Y_R + n_{M2} \\ &= \sqrt{E_R}\sqrt{E_{BS}} h_{R-M2} h_{BS-R} s_{SC} + \sqrt{E_R} h_{R-M2} n_R + n_{M2} \\ &= \sqrt{\boldsymbol{E}'} \boldsymbol{H} s_{SC} + \boldsymbol{N}, \end{aligned} \tag{4.9}$$

where $\boldsymbol{E}' = E_R E_{BS}$, $\boldsymbol{H} = h_{R-M2} h_{BS-R}$, and $\boldsymbol{N} = \sqrt{E_R} h_{R-M2} n_R + n_{M2}$.

M2 decodes s_1 first, then s_2 by using SIC.

In the proposed scheme, R performs retransmission to M1, and M1 also relays the message to M2 upon successful decoding. To complete the transmission, the proposed scheme requires two transmission phases (without a retransmission to M1) or three transmission phases (with a retransmission to M1); this is at most the same number of transmission phases as required by the conventional scheme in shown in Fig. 4.1, which requires three transmission phases.

4.4 Performance Analysis

In this section we analyze the symbol-error rate (SER) performance of the system that employs superimposed QPSK modulation as shown in Fig. 4.2.

4.4.1 SER Analysis

We start from the bit-error rate (BER) expression of superimposed BPSK modulation. Fig. 4.4 shows the superimposed BPSK constellation, where the solid dots represent the

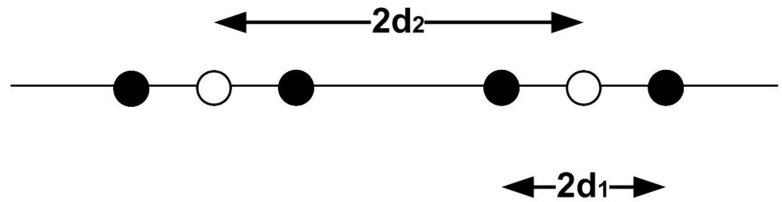

Figure 4.4: Superimposed BPSK constellation. $2d_1$ is the distance between s_1 and $2d_2$ is the distance between s_2.

actual transmitted symbols, and the circles represent fictitious symbols. With superimposed BPSK modulation, the received signal over an AWGN channel can be expressed as

$$Y_{BPSK,AWGN} = \sqrt{E}\left(\sqrt{1-\alpha^2}s_1 + \sqrt{\alpha^2}s_2\right) + n, \tag{4.10}$$

where n is the noise term and the noise power equals N_0. SNR is written as $\gamma = E/N_0$. Without loss of generality, s_1 is assigned as the basic message and s_2 the superposed message.

4.4.1.1 Over an AWGN channel

As derived in [44], the average bit error probabilities for s_1 and s_2 over an AWGN channel are

$$\begin{aligned} P_{\mathrm{BER},AWGN}(s_1) &= \frac{1}{4}\left[P_b(s_1|00_{sent}) + P_b(s_1|01_{sent}) + P_b(s_1|10_{sent}) + P_b(s_1|11_{sent})\right] \\ &= \frac{1}{2}\left[\frac{1}{2}erfc\left(\frac{d_1+d_2}{\sqrt{N_0}}\right) + \frac{1}{2}erfc\left(\frac{d_2-d_1}{\sqrt{N_0}}\right)\right] \\ &= \frac{1}{2}Q\left(\sqrt{2\gamma}\left(\sqrt{1-\alpha^2}+\sqrt{\alpha^2}\right)\right) + \frac{1}{2}Q\left(\sqrt{2\gamma}\left(\sqrt{1-\alpha^2}-\sqrt{\alpha^2}\right)\right), \end{aligned} \tag{4.11}$$

and

$$\begin{aligned} P_{\mathrm{BER},AWGN}(s_2) &= \frac{1}{4}\left[P_b(s_2|00_{sent}) + P_b(s_2|01_{sent}) + P_b(s_2|10_{sent}) + P_b(s_2|11_{sent})\right] \\ &= \frac{1}{4}erfc\left(\frac{d_1}{\sqrt{N_0}}\right) - \frac{1}{4}erfc\left(\frac{d_1+d_2}{\sqrt{N_0}}\right) + \frac{1}{4}erfc\left(\frac{d_1+2d_2}{\sqrt{N_0}}\right) \\ &\quad + \frac{1}{4}erfc\left(\frac{d_1}{\sqrt{N_0}}\right) + \frac{1}{4}erfc\left(\frac{d_2-d_1}{\sqrt{N_0}}\right) - \frac{1}{4}erfc\left(\frac{2d_2-d_1}{\sqrt{N_0}}\right) \\ &= -\frac{1}{2}Q\left(\sqrt{2\gamma}\left(\sqrt{1-\alpha^2}+\sqrt{\alpha^2}\right)\right) + \frac{1}{2}Q\left(\sqrt{2\gamma}\left(2\sqrt{1-\alpha^2}+\sqrt{\alpha^2}\right)\right) \\ &\quad + \frac{1}{2}Q\left(\sqrt{2\gamma}\left(\sqrt{1-\alpha^2}-\sqrt{\alpha^2}\right)\right) - \frac{1}{2}Q\left(\sqrt{2\gamma}\left(2\sqrt{1-\alpha^2}-\sqrt{\alpha^2}\right)\right). \\ &\quad + Q\left(\sqrt{2\gamma\alpha^2}\right) \end{aligned} \tag{4.12}$$

From Eqs. (4.11) and (4.12), the SER of superimposed QPSK modulation over an AWGN channel is obtained as

$$P_{SER,AWGN}(s_1) = 1 - \left[1 - \frac{1}{2}Q\left(\sqrt{\gamma}J_2\right) + \frac{1}{2}Q\left(\sqrt{\gamma}J_3\right)\right]^2, \tag{4.13}$$

and

$$P_{\text{SER},AWGN}(s_2) =$$
$$1 - \left[1 - Q\left(\sqrt{\gamma}J_1\right) + \frac{1}{2}Q\left(\sqrt{\gamma}J_2\right) - \frac{1}{2}Q\left(\sqrt{\gamma}J_3\right) - \frac{1}{2}Q\left(\sqrt{\gamma}J_4\right) + \frac{1}{2}Q\left(\sqrt{\gamma}J_5\right)\right]^2, \quad (4.14)$$

where $J_1 = \alpha,\ J_2 = \sqrt{1-\alpha^2} + \sqrt{\alpha^2},\ J_3 = \sqrt{1-\alpha^2} - \sqrt{\alpha^2},\ J_4 = 2\sqrt{1-\alpha^2} + \sqrt{\alpha^2}$, and $J_5 = 2\sqrt{1-\alpha^2} - \sqrt{\alpha^2}$.

4.4.1.2 Over a flat Rayleigh fading channel

In a flat Rayleigh fading environment, the superimposed QPSK signal can be written as

$$Y_{QPSK,fading} = \sqrt{E}h\left(\sqrt{1-\alpha^2}s_1 + \sqrt{\alpha^2}s_2\right) + n, \quad (4.15)$$

where h denotes the channel coefficient with variance σ^2.

The probability density function of the SNR, $\widehat{\gamma} = \left(\sqrt{E}|h|\right)^2/N_0$ is written as [29]

$$P_{\widehat{\gamma}}(\widehat{\gamma}) = \frac{1}{\gamma\sigma^2}\exp\left(-\frac{\widehat{\gamma}}{\gamma\sigma^2}\right). \quad (4.16)$$

By averaging the SER for AWGN over the probability density of the SNR, the symbol error probabilities over a Rayleigh fading channel is obtained as

$$P_{\text{SER},fading}(s_1) = \int_0^\infty P_{\text{SER},AWGN}(s_1)P_{\widehat{\gamma}}(\widehat{\gamma})d\widehat{\gamma}, \quad (4.17)$$

and

$$P_{SER,fading}(s_2) = \int_0^\infty P_{SER,AWGN}(s_2) P_{\widehat{\gamma}}(\widehat{\gamma}) d\widehat{\gamma}. \tag{4.18}$$

From the results given in [27], Eqs. (4.17) and (4.18) can be expressed as

$$P_{SER,fading}(s_1) = K_1(J_2) + K_1(J_3) - \frac{1}{4}K_2(J_2) - \frac{1}{4}K_2(J_3) - \frac{1}{2}K_3(J_2, J_3), \tag{4.19}$$

and

$$\begin{aligned} P_{SER,fading}(s_2) = \; & 2K_1(J_1) - K_1(J_2) + K_1(J_3) + K_1(J_4) - K_1(J_5) - K_2(J_1) - \frac{1}{4}K_2(J_2) \\ & -\frac{1}{4}K_2(J_3) - \frac{1}{4}K_2(J_4) - \frac{1}{4}K_2(J_5) + K_3(J_1, J_2) - K_3(J_1, J_3) - K_3(J_1, J_4) \\ & +K_3(J_1, J_5) + \frac{1}{2}K_3(J_2, J_3) + \frac{1}{2}K_3(J_2, J_4) - \frac{1}{2}K_3(J_2, J_5) - \frac{1}{2}K_3(J_3, J_4) \\ & +\frac{1}{2}K_3(J_3, J_5) + \frac{1}{2}K_3(J_4, J_5), \end{aligned} \tag{4.20}$$

where

$$K_1(x) = \frac{1}{2}\left(1 - \sqrt{\frac{x^2\gamma\sigma^2}{2 + x^2\gamma\sigma^2}}\right), \tag{4.21}$$

$$K_2(x) = \frac{1}{4} - \frac{1}{\pi}\left(1 - \sqrt{\frac{x^2\gamma\sigma^2}{2 + x^2\gamma\sigma^2}}\right) \arctan\left(\sqrt{\frac{2 + x^2\gamma\sigma^2}{x^2\gamma\sigma^2}}\right), \tag{4.22}$$

and

$$K_3(x_1, x_2) = \frac{1}{4} - \frac{1}{2\pi}\sqrt{\frac{x_1^2\gamma\sigma^2}{2 + x_1^2\gamma\sigma^2}} \arctan\left(\frac{x_1}{x_2}\sqrt{\frac{2 + x_1^2\gamma\sigma^2}{x_1^2\gamma\sigma^2}}\right) + \frac{1}{2\pi}\sqrt{\frac{x_2^2\gamma\sigma^2}{2 + x_2^2\gamma\sigma^2}} \arctan\left(\frac{x_2}{x_1}\sqrt{\frac{2 + x_2^2\gamma\sigma^2}{x_2^2\gamma\sigma^2}}\right). \quad (4.23)$$

With the two SER expressions, (4.19) and (4.20), we can determine the two-bit symbol error rates at M1, M2, and R.

1) **Symbol error rates of s_1 and s_2 at R**: The SER expressions at R can be directly derived from Eqs. (4.19) and (4.20) by substituting σ^2 with σ^2_{BS-R}, which is the variance of the channel in the BS-R link. Let these error expressions be denoted as $\mathbf{P^R_{SER}(s_1)}$ and $\mathbf{P^R_{SER}(s_2)}$.

2) **The symbol error rates of s_1 and s_2 at M1**: For the SER of s_1 at M1, we need to consider retransmission from the relay, as described in Sec. 4.3. The SER is derived as

$$\mathbf{P^{M1}_{SER}(s_1)} = P^{M1'}_{SER}(s_1)\left\{P^R_{SER}(s_1) + \left(1 - P^R_{SER}(s_1)\right) SER^{R-M1}_{QPSK}(s_1)\right\}. \quad (4.24)$$

where $P^{M1'}_{SER}(s_1)$ is the SER of s_1 at M1 after the first transmission phase, which is calculated from Eq. (4.20) by substituting σ^2 with σ^2_{BS-M1}. $SER^{R-M1}_{QPSK}(s_1)$ is the QPSK symbol error rate of s_1, which is transmitted from R to M1. It can be derived from [29].

The SER of s_2 at M1 is calculated from Eq. (4.20) by substituting σ^2 with σ^2_{BS-M1}, which is the variance of the channel in the BS-M1 link. Let this SER be denoted as $\mathbf{P_{SER}^{M1}(s_2)}$.

3) **Symbol error rate of s_2 at M2**: The four cases mentioned in Sec. 4.3 must be considered in deriving the SER expressions at M2.

   (i) Both R and M1 successfully decode symbol s_2: The received signal at M2 is Y_{M2}^{case1}, and the SER of s_2 at M2 can be written as

$$P_{SER}^{M2-case1}(s_2) \quad = \quad \left(1 - P_{SER}^{R}(s_2)\right)\left(1 - P_{SER}^{M1}(s_2)\right) SER_{QPSK}^{MRC}(s_2), \tag{4.25}$$

   where $SER_{QPSK}^{MRC}(s_2)$ is the QPSK symbol error rate of s_2 at M2 with MRC, which can be obtained directly from the results in [29].

   (ii) Only R succeeds in decoding s_2: The received signal at M2 is Y_{M2}^{case2}, and the SER of s_2 at M2 is

$$P_{SER}^{M2-case2}(s_2) \quad = \quad \left(1 - P_{SER}^{R}(s_2)\right) P_{SER}^{M1}(s_2) SER_{QPSK}^{R-M2}(s_2), \tag{4.26}$$

   where $SER_{QPSK}^{R-M2}(s_2)$ is the QPSK symbol error rate of s_2, which is transmitted from R to M2.

   (iii) Only M1 succeeds in decoding s_2: The received signal at M2 is Y_{M2}^{case3}, and the SER of s_2 at M2 is

$$P_{SER}^{M2-case3}(s_2) \quad = \quad P_{SER}^{R}(s_2)\left(1 - P_{SER}^{M1}(s_2)\right) SER_{QPSK}^{M1-M2}(s_2), \tag{4.27}$$

   where $SER_{QPSK}^{M1-M2}(s_2)$ is the QPSK symbol error rate of s_2, which is transmitted from M1 to M2.

(iv) Both R and M1 fail in decoding s_2: R retransmits amplified Y_R and the received signal at M2 is Y_{M2}^{case4}. The SER calculated as

$$P_{SER}^{M2-case4}(s_2) = P_{SER}^{R}(s_2)P_{SER}^{M1}(s_2)SER_{SC}^{A\&F}(s_2), \tag{4.28}$$

where M2 decodes the amplified superposition message Y_R from R, and the symbol error rate of s_2 at M2 is denoted as $SER_{SC}^{A\&F}(s_2)$, which is calculated from Eq. (4.20) and [32].

The final SER expression of s_2 at M2 cis written as

$$\mathbf{P_{SER}^{M2}(s_2)} = P_{SER}^{M2-case1}(s_2) + P_{SER}^{M2-case2}(s_2) + P_{SER}^{M2-case3}(s_2) + P_{SER}^{M2-case4}(s_2). \tag{4.29}$$

4.4.2 Simulation Results

In this subsection, we evaluate the SER performance of the proposed scheme employing superposition coding in Fig. 4.3. We plot the performances of M1 and M2, which are derived in Eqs. (4.24) and (4.29), and compare the cases for different values of power division coefficient α and the conventional scheme in Fig. 4.1. As we assumed in Sec. 4.3, basic message s_1 is assigned for M1 and superposed message s_2 is assigned for M2. Also CRC code is employed at BS to determine decoding results. In simulations, we assume that only QPSK modulation is employed in the conventional scheme in Fig. 4.1 and superimposed QPSK is employed in the proposed scheme.

In addition to the performance of the proposed scheme, we also examine the performance of the proposed scheme without a retransmission from R to M1. As shown in Fig. 4.5, the SER of s_2 at M2 outperforms conventional schemes, but the SER of s_1 at M1 is worse than conventional schemes. This is the reason why we need to employ a retransmission from R to M1.

Fig. 4.6 shows the SER performances of the proposed system with α =0.2 and 0.35 and compares the conventional scheme. The SER performance of the proposed scheme outperforms conventional schemes when α =0.2 and 0.35. When α increases from 0.2 to 0.35, there is a tradeoff between the performances of each user. The SER of M2 improves, whereas the SER of M1 deteriorates. We also provide the average SERs of the proposed scheme from the Monte Carlo simulations when $\alpha = 0.2$. Different from the conventional scheme, the relay in the proposed scheme performs a retransmission to M1, and M1 also performs as a relay upon decoding results at each node. It is obvious that these improvements come at the expense of increased complexity because of employing the CRC and superposition coding.

We have investigated the case that s_1 is assigned as basic message and s_2 is assigned as superposed message. Now, we consider the opposite case where s_2 is assigned as basic message and s_1 is assigned as superposed message. The SER expressions for this case can be derived straightforwardly from Sec. 4.4.1. Simulation conditions are the same as the previous case, and Fig. 4.7 shows error performances at M1 and M2. Although we alternate the assigning messages, the proposed scheme still outperforms conventional scheme when α =0.25 and 0.4. As shown in Fig. 4.6 and 4.7, regardless of how we assign basic message and superposed message, the proposed scheme provides improved performance with a specific value of α.

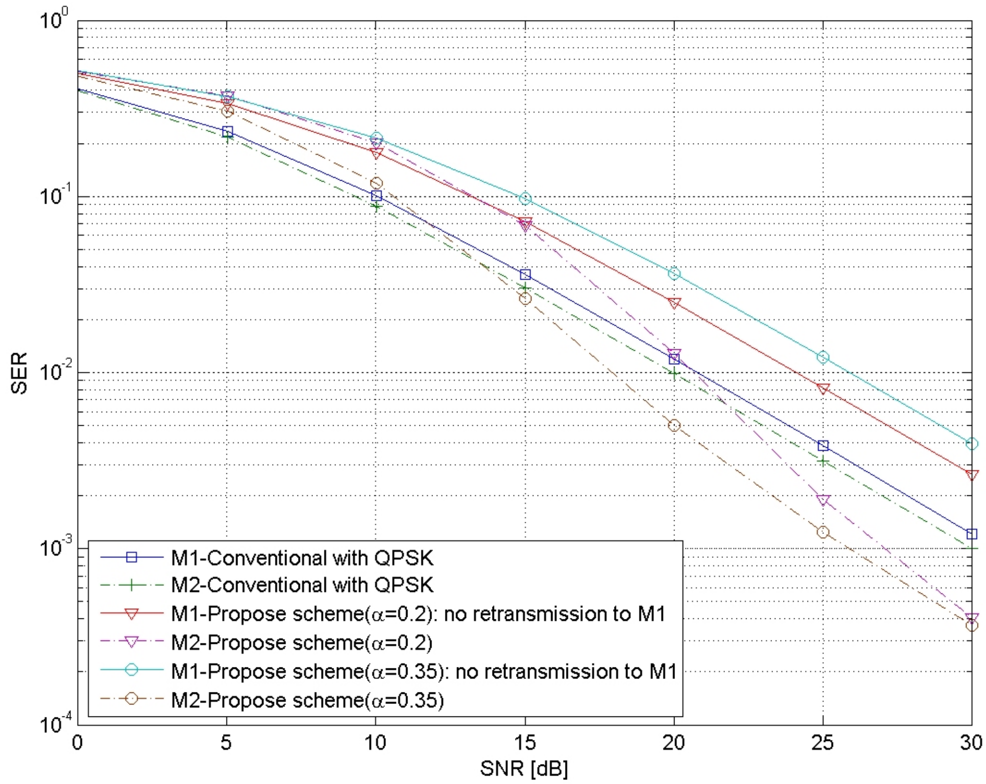

Figure 4.5: The SER performance of the proposed system with no retransmission from R to M1: s_1 is assigned as basic message and s_2 is assigned as superposed message.

4.5 Conclusion

A multiuser asymmetric downlink transmission scheme that exploits the superposition coding to improve the performance without additional resources (time slots or frequency bands) for the relay is proposed and studied in this chapter. Error-rate expressions of the proposed scheme are derived, and the SER performances of this scheme for various power-division coefficients α are compared. With the same number of transmission phases,

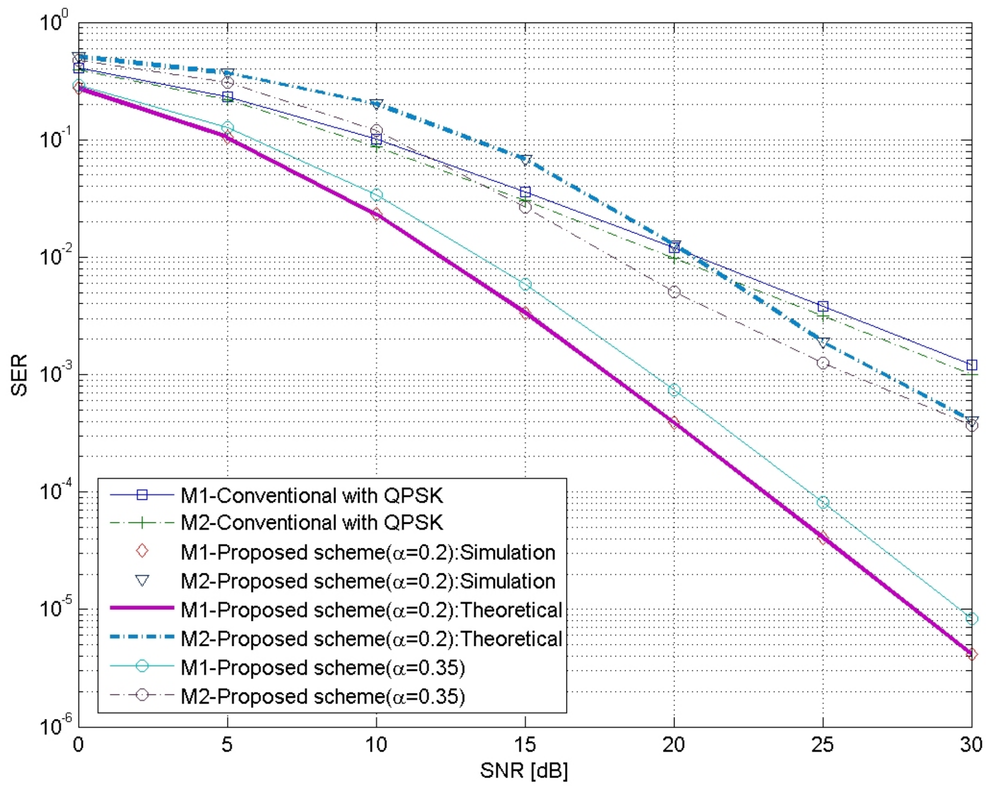

Figure 4.6: The SER performance of the proposed system: s_1 is assigned as basic message and s_2 is assigned as superposed message.

the performance of the proposed scheme is significantly improved over the conventional scheme. As shown in the simulation results of the proposed scheme, message assignment as the basic message or the superposed message can be arbitrarily assigned and the proposed scheme still performs better than the traditional scheme with some specific values of α.

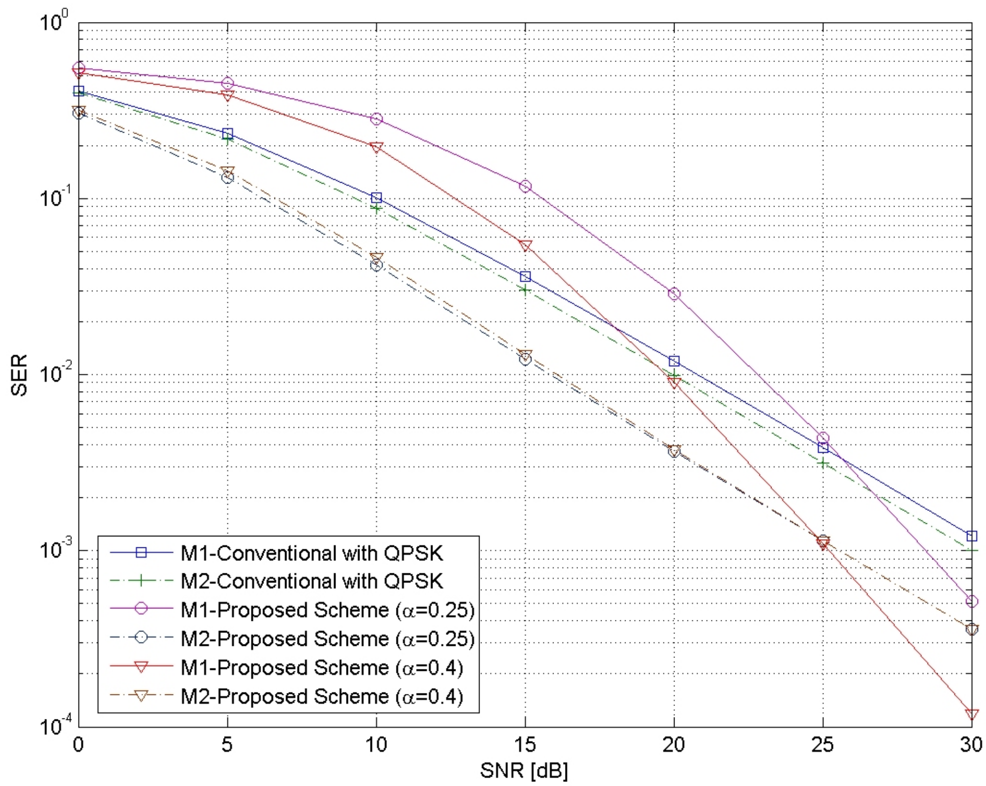

Figure 4.7: The SER performance of the proposed system: s_2 is assigned as basic message and s_1 is assigned as superposed message.

Chapter 5 – Multiuser Cooperative Relay Communications Employing Hierarchical Modulation

5.1 Introduction

We proposed multi-user cooperative relaying scheme employing superposition coding in Chapter 4 and this proposed scheme efficiently improves the error performance without any additional resource for the relay. However the proposed scheme in Chapter 4 should employ the CRC codes, in addition to superposition coding scheme. In this chapter, we develop new multi-user transmission schemes that use only hierarchical modulation to minimize throughput degradation in a multiuser network, due to additional resources for the relay. The proposed schemes do not require additional transmission phases for the relay and also provide more reliable transmission than conventional cooperative relay communication schemes. The base station must deliver its message to multiple users. We develop a system that requires the same number of transmission phases as the conventional communication schemes which has no diversity gains. For clarity of description, we develop the model assuming two users (mobiles) and one base station operating in a half-duplex mode; extension a general network configuration is straightforward. We develop schemes for two different scenarios: in the first scenario, both mobiles are in the cell coverage area of the base station; in the second scenario, one of the mobiles is in cell coverage area of the base station and the other is not. We show that with an appropriate distance parameter of hierarchical modulation, the proposed scheme provides more reliable transmission than conventional communication systems while both schemes require the same number of transmission phases.

5.2 System Description

5.2.1 Conventional Communication Schemes

Let us consider the downlink of a wireless transmission system as shown in Fig. 5.1-(A), which consists of a base station (BS), and two mobile stations. Transmission of data from the BS to the two users requires two phases. In order to improve reception reliability, especially for mobiles at the cell edge, cooperative communications could be exploited by employing a relay as illustrated in Fig. 5.1-(B). The improved coverage area through cooperative communications comes at the expense of more transmission phases, which reduce the throughput of the network since additional resources (e.g., time slots or frequency bands) are required for the relay. For example, the multiuser cooperative communications scenario shown in Fig. 5.1-(B) requires twice of the transmission phases of Fig. 5.1-(A), even though both systems have the same number of end users.

5.2.2 Hierarchical Modulation

In the DVB standard for digital terrestrial television (DVB-T), hierarchical modulation, a kind of layered modulation, is designated as an alternative to the conventional modulation methods, such as QPSK, 16-QAM and 64-QAM. With hierarchical modulation, two autonomous DVB-T multiplexes can be transmitted on a single TV frequency channel, with different transmission qualities. The total data rate of QPSK in 64-QAM; combi-

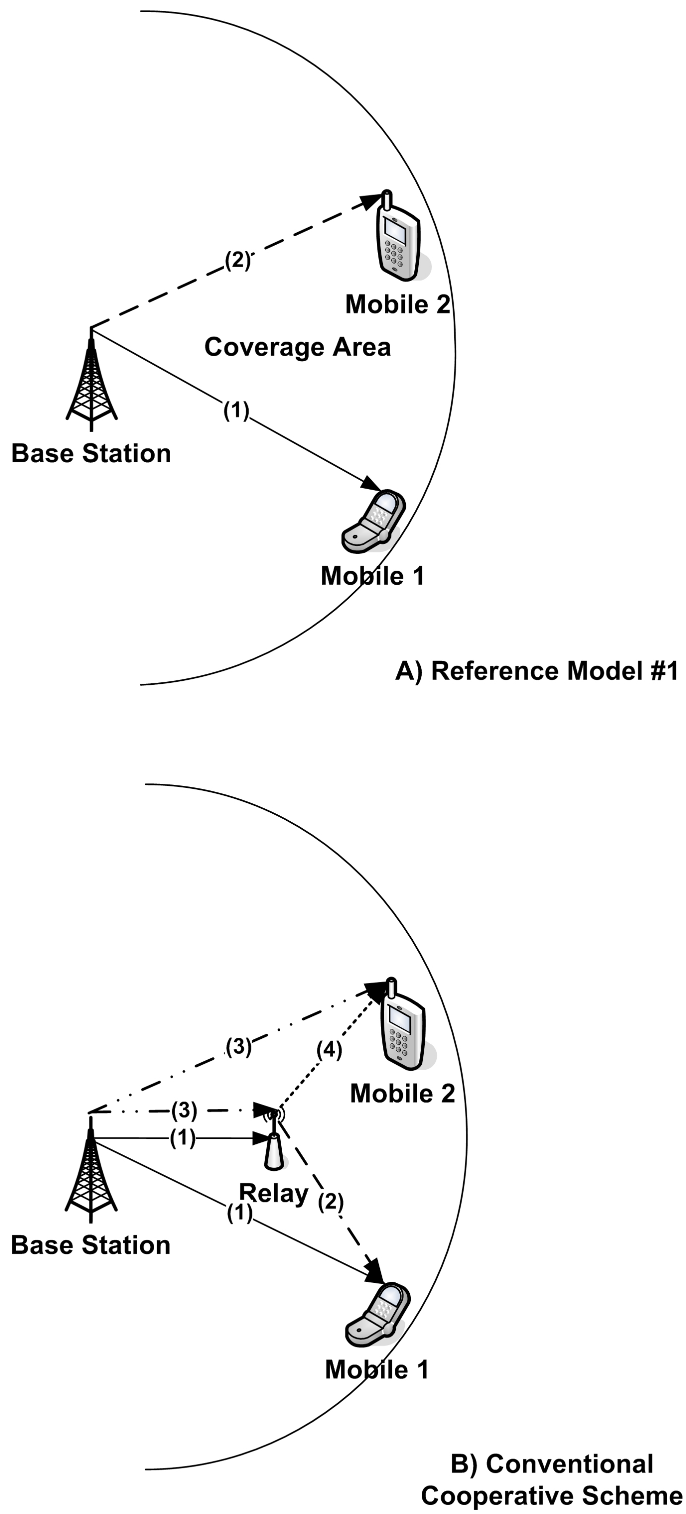

Figure 5.1: Conventional communications schemes: All mobiles are in cell coverage area.

nation of QPSK and 16-QAM is higher than in the case of non-hierarchical modulation using 16-QAM. A portion of high priority symbol can be used in particular for portable indoor and mobile reception. With this arrangement, flexible service coverage can be provided [43].

Hierarchical modulation is a signal processing techniques for multiplexing and modulating multiple data streams into one single symbol stream, where base-layer symbols and enhancement-layer symbols are synchronously overplayed before transmission. Hierarchical modulation is also taken as one of the practical implementations of superposition precoding, which can improve the achievable maximum sum rate of broadcast channels. However, traditional hierarchical modulation suffers from serious inter-layer interference (ILI) with impact on the achievable symbol rate. Furthermore, ILI and the imperfect demodulation of base-layer symbols increase the demodulation error rate of enhancement-layer symbols.

For the proposed scheme, we consider the 4/16-QAM hierarchical modulation [44,45] with Gray code mapping as shown in Fig. 5.2. It can be viewed as the combination of two quadrature phase-shift keying (QPSK) modulations with two levels of hierarchy: common bits, or high-priority bits, which are to be assigned to the bit stream that requires a higher level of protection (poor link), and enhancement bits, or low-priority bits, which are to be assigned to the bit stream for which a low level of protection (good link) is acceptable.

In Fig. 5.2, the symbols marked by a circle represent the high priority bits and the symbols marked black dots represent the actual transmitted symbols. In this constellation, the distance between two fictitious symbols of the high-priority bits is $2d_1$, and the distance between two neighboring symbols within the same quadrant is $2d_2$. The

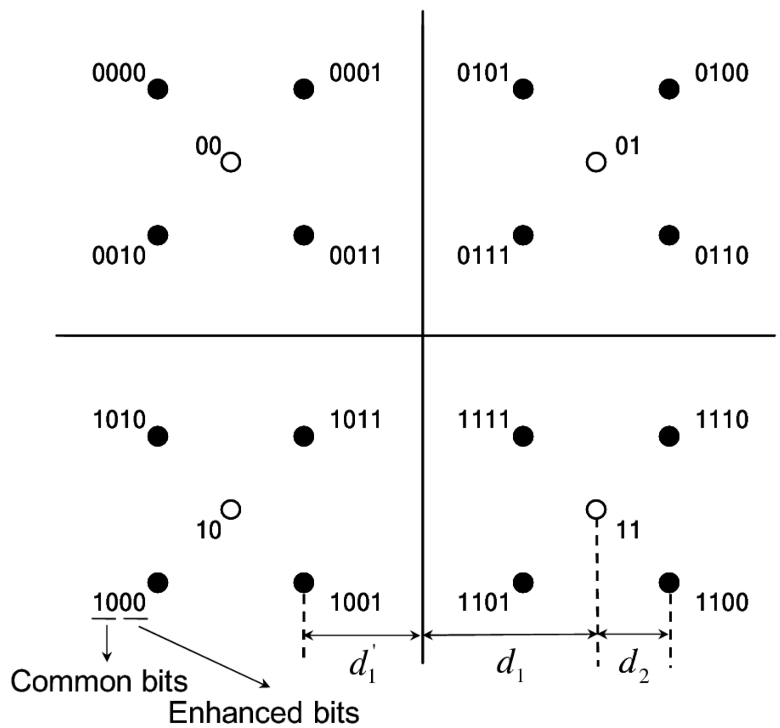

Figure 5.2: Constellation of 4/16-QAM hierarchical modulation.

relationship between d_1, d_2, and the average energy per symbol is given by [50]

$$E_a = 2(d_1^2 + d_2^2). \tag{5.1}$$

The distance parameter $d_1^{'}$ is related to d_1 and d_2 as

$$d_1^{'} = d_1 - d_2. \tag{5.2}$$

Thus,

$$d_2 = \frac{1}{2}\sqrt{E_a - d_1^{'2}} - \frac{d_1^{'}}{2}. \tag{5.3}$$

5.3 Multiuser Relay Communications Employing Hierarchical Modulation: Symmetric Model

5.3.1 Proposed System Model

The proposed network model for cooperative multiuser communications that employs 4/16-QAM hierarchical modulation with gray mapping is shown in Fig. 5.3. The channel is assumed to be frequency-flat Rayleigh and the relay performs decode-and-forward.

Let us assume that data streams m_1 = AB and m_2 = CD, where $A, B, C, D \in \{0, 1\}$, are to be delivered to mobile 1 and mobile 2, respectively. Without loss of generality, we arbitrarily assign m_1 as the enhancement bits and m_2 as the common bits, before transmission employing 4/16-QAM hierarchical modulation begins. This requires two transmission phases, whereas the conventional cooperative scheme in Fig. 5.1-(B) requires four transmission phases.

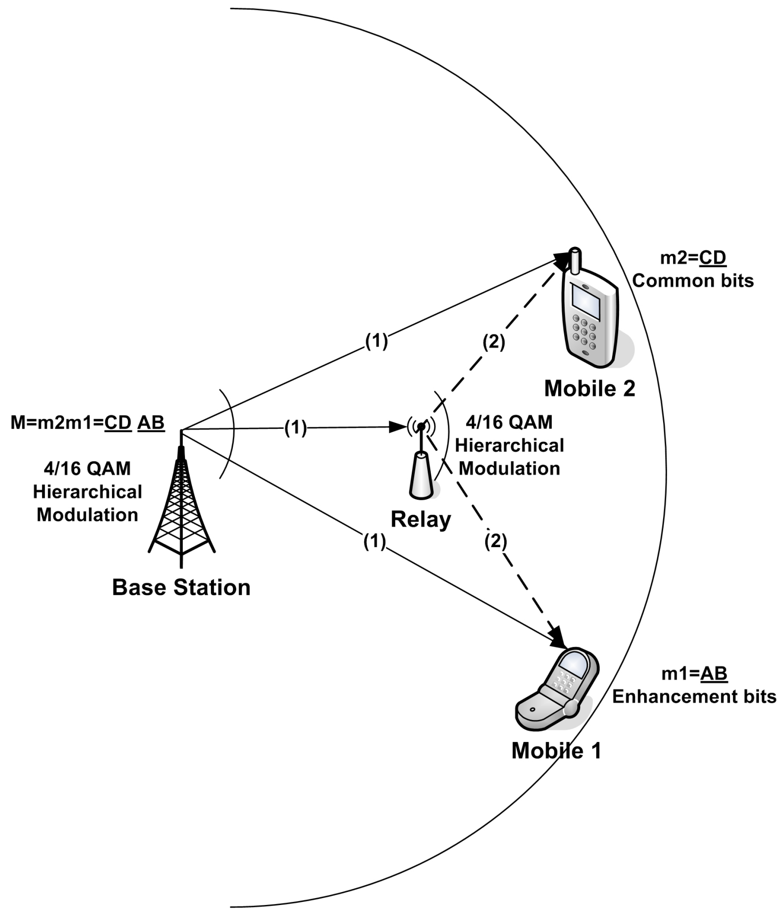

Figure 5.3: Hierarchical modulation based cooperative multiuser communication: Symmetric model.

The two phases of the proposed scheme are described as follows.

1) In first phase, m_1 and m_2 are concatenated to form one symbol $M =$ CDAB, which is broadcast to the relay and two mobiles with energy per symbol E_a^b. The received signals at the relay, mobile 1 and mobile 2 during the first phase are represented, respectively, by

$$r_{b,r} = \alpha_{b,r} \times h_{b,r} \times \sqrt{E_a^b} \times M + n_{b,r}, \tag{5.4a}$$

$$r_{b,m1} = \alpha_{b,m1} \times h_{b,m1} \times \sqrt{E_a^b} \times M + n_{b,m1}, \tag{5.4b}$$

$$r_{b,m2} = \alpha_{b,m2} \times h_{b,m2} \times \sqrt{E_a^b}, \times M + n_{b,m2}, \tag{5.4c}$$

where subscripts b, r, $m1$, and $m2$ represent the base station, the relay, mobile 1, and mobile 2, respectively; $h_{b,r}$, $h_{b,m1}$, and $h_{b,m2}$ are the Rayleigh fading channel coefficients (block fading assumed); $n_{b,r}$, $n_{b,m1}$, and $n_{b,m2}$ are additive white Gaussian noise components; and $\alpha_{b,r}$, $\alpha_{b,m1}$ and $\alpha_{b,m2}$ are power scaling factors.

2) In the second phase, the relay demodulates the received symbol from the base station and re-broadcasts decoded symbol to the two mobiles. The received signals in this phase at mobile 1 and mobile 2 are expressed as

$$r_{r,m1} = \alpha_{r,m1} \times h_{r,m1} \times \sqrt{E_a^r} \times M^{'} + n_{r,m1}, \tag{5.5a}$$

$$r_{r,m2} = \alpha_{r,m2} \times h_{r,m2} \times \sqrt{E_a^r} \times M^{'} + n_{r,m2}, \tag{5.5b}$$

where E_a^r is the transmitted average symbol energy of the relay and $M^{'}$ is the transmitted symbol from the relay. With the received signals from the base station and the relay, each mobile combines its received signals using the maximal ratio combining (MRC). The combined signals at mobile 1 and mobile 2 are given by

$$r_{m1} = \alpha_{b,m1} \times h^*_{b,m1} \times r_{b,m1} + \alpha_{r,m1} \times h^*_{r,m1} \times r_{r,m1}, \tag{5.6a}$$

$$r_{m2} = \alpha_{b,m2} \times h^*_{b,m2} \times r_{b,m2} + \alpha_{r,m2} \times h^*_{r,m2} \times r_{r,m2}. \tag{5.6b}$$

After demodulation at each mobile, mobile 1 gets the last two bits of the symbol (enhancement bits), $m_1 = \text{AB}$, and mobile 2 gets the first two bits of the symbol (common bits), $m_2 = \text{CD}$, from the demodulated symbol.

5.3.2 Performance Analysis

In this section, we analyze the error performance of the proposed system over a Rayleigh fading channel. Without loss of generality, we assume that the enhancement bits are always assigned to mobile 1 and the common bits are always assigned to mobile 2 during the transmission. we determine the bit-error rate (BER) at mobile 1 and mobile 2.

The in-phase and quadrature-phase channels are assumed to be completely separable. Thus, the analysis of the two-dimensional data can be reduced to the analysis of a single dimensional data.

An analysis approach similar to the one described in [50] can be developed here. We evaluate all transmission possibilities and derive the error performance as a function of the constellation parameters. Fig. 5.4 illustrates all possible cases that the base station broadcasts a symbol, $0x1x$ or $0x0x$. The first bit and the third bit of $0x1x$ and $0x0x$ represent, respectively, the common bit and the enhancement bit carried by the in-phase channel. In order to complete the analysis, there are four steps in the procedure as shown in Fig. 5.4.

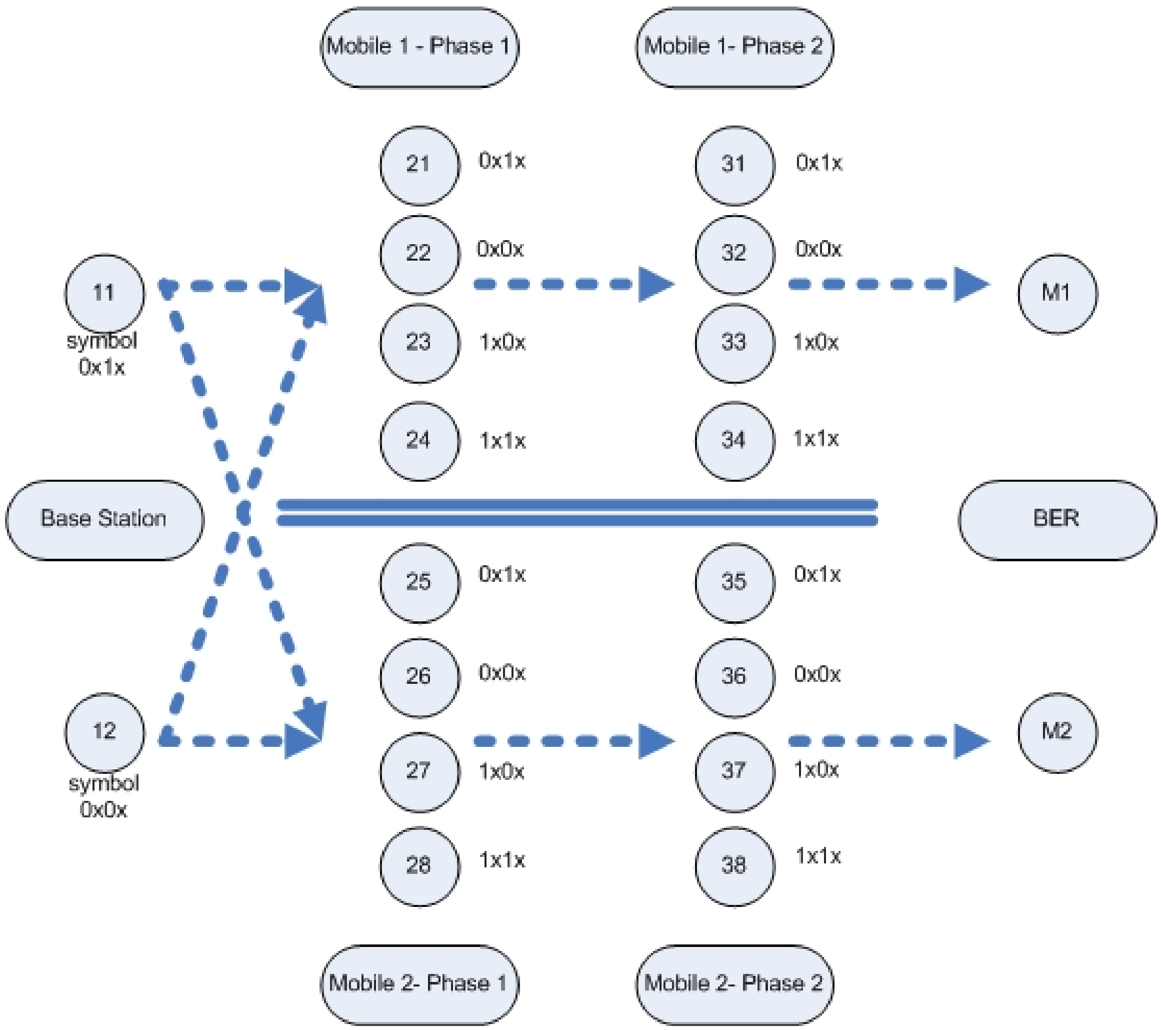

Figure 5.4: Model for performance analysis.

In Step 1, the base station broadcasts symbol $0x1x$ or $0x0x$, which is defined as State 11 or State 12. In Steps 2 and 3, the states are partitioned into two cases to analyze individually for mobile 1 and mobile 2. Due to the symmetry, the analysis for the case of $1x0x$ and $1x1x$ is the same as the case of $0x1x$ and $0x0x$. In Step 2, there are four possible symbol candidates $0x1x$, $0x0x$, $1x0x$, and $1x1x$ in the first phase of mobile 1 and mobile 2, according to the received symbol from Step 1, which depend on the demodulation results. The corresponding State 21 to State 24 are for mobile 1 and State 25 to State 28 are for mobile 2, as shown in Fig. 5.4. According to the symbols from the base station and the relay, there also exist four possible symbols for the second phase of mobile 1 and mobile 2 in Step 3 as in Step 2. Finally in Step 4, State $M1$ and State $M2$ represent, respectively, the enhancement bit error and the common bit error of the demodulated symbol.

The traversed path from Step 1 to Step 4 can be evaluated by using the transition probability. The transition probability from Step 1 to Step 2 is expressed as $P_{1i\to 2j|1i}$; for mobile 1, $i = 1, 2$ and $j = 1, \cdots, 4$; for mobile 2, $i = 1, 2$ and $j = 5, \cdots, 8$. The transition probability from Step 2 to Step 3 is expressed as $P_{2j\to 3k|1i\to 2j}$; for mobile 1, $k = 1, 2, 3, 4$; for mobile 2, $k = 5, 6, 7, 8$.

The conditional BER of the enhancement bits of mobile 1 and the common bits of mobile 2 with history of the traversed path can be expressed as

$$\begin{aligned} P_{e,M1|1i\to 2j\to 3k} &= Pr\{\text{bit error at Mobile } 1|1i \to 2j \to 3k\} \\ &= \delta_{i1}\delta_{k2} + \delta_{i1}\delta_{k3} + \delta_{i2}\delta_{k1} + \delta_{i2}\delta_{k4}, \end{aligned} \tag{5.7}$$

$$\begin{aligned} P_{e,M2|1i\to 2j\to 3k} &= Pr\{\text{bit error at Mobile } 2|1i \to 2j \to 3k\} \\ &= \delta_{k7} + \delta_{k8}, \end{aligned} \tag{5.8}$$

where δ_{xy} equals 1 when $x = y$ and equals 0 otherwise. Note that $P_{e,M1|1i\to 2j\to 3k}$ and $P_{e,M2|1i\to 2j\to 3k}$ are either 1 or 0, depending on the traversed path. A bit error occurs for paths that satisfy $P_{e,M1|1i\to 2j\to 3k} = 1$ or $P_{e,M2|1i\to 2j\to 3k} = 1$.

Based on this analysis model and the conditional BER, we can obtain the average BER for the enhancement bits of mobile 1 and the common bits of mobile 2. The average BER for the enhancement bits of mobile 1 is expressed as

$$\begin{aligned} P_{e_b,M1} &= 2\sum_{i=1}^{2}\sum_{j=1}^{4}\sum_{k=1}^{4} P_{e,M1|1i\to 2j\to 3k} \times P_{2j\to 3k|1i\to 2j} \times P_{1i\to 2j|1i} \times \pi_{1i} \\ &= 2\sum_{j=1}^{4}\left[\sum_{k=2}^{3} P_{2j\to 3k|11\to 2j} \times P_{11\to 2j|11} \times \pi_{11} + \right. \\ &\quad \left. \sum_{k=1,4} P_{2j\to 3k|12\to 2j} \times P_{12\to 2j|12} \times \pi_{12}\right], \end{aligned} \tag{5.9}$$

where π_{11} and π_{12} are the probability of State 11 and State 12, respectively.

The average BER for the the common bits of mobile 2 is expressed as

$$\begin{aligned} P_{e_b,M2} &= 2\sum_{i=1}^{2}\sum_{j=5}^{8}\sum_{k=5}^{8} P_{e,M2|1i\to 2j\to 3k} P_{2j\to 3k|1i\to 2j} \times P_{1i\to 2j|1i} \times \pi_{1i} \\ &= 2\sum_{i=1}^{2}\sum_{j=5}^{8}\sum_{k=7}^{8} P_{2j\to 3k|1i\to 2j} \times P_{1i\to 2j|1i} \times \pi_{1i}, \end{aligned} \tag{5.10}$$

where the expressions of the state transition probabilities, $P_{1i\to 2j|1i}$ and $P_{2j\to 3k|1i\to 2j}$ can be derived from the Appendix of [50] and [44, 45].

In order to simplify Eqs. (5.9) and (5.10), we define the following variables: $x_1 = -(d_1 + d_2)$, $x_2 = -d_1'$, $x_3 = d_1'$, $x_4 = d_1 + d_2$, $x_5 = -(d_1 + d_2)$, $x_6 = -d_1'$, $x_7 = d_1'$, $x_8 = d_1 + d_2$, $y_0 = -\infty$, $y_1 = -d_1$, $y_2 = 0$, $y_3 = d_1$, $y_4 = \infty$ for mobile 1 or $y_4 = -\infty$ for mobile 2, $y_5 = -d_1$, $y_6 = 0$, $y_7 = d_1$, $y_8 = \infty$, σ^2 is the variance of channel coefficients, and N_0 is the variance of noise. With these variables, we have

$$P_{1i\to 2j|1i} = \boldsymbol{\mathcal{H}}\left(1 + \frac{(y_{j-1} - x_i)^2\sigma_{b,r}^2}{N_0 \sin^2\theta}\right) - \boldsymbol{\mathcal{H}}\left(1 + \frac{(y_j - x_i)^2\sigma_{b,r}^2}{N_0 \sin^2\theta}\right), \tag{5.11}$$

where

$$\boldsymbol{\mathcal{H}}(x) = \begin{cases} \frac{1}{\pi}\int_0^{\pi/2}\left(1 + \frac{x^2\sigma_{b,r}^2}{N_0 \sin^2\theta}\right)^{-1} d\theta, & x \geq 0 \\ 1 - \frac{1}{\pi}\int_0^{\pi/2}\left(1 + \frac{x^2\sigma_{b,r}^2}{N_0 \sin^2\theta}\right)^{-1} d\theta, & x < 0, \end{cases} \tag{5.12}$$

and

$$\begin{aligned} P_{2j\to 3k|1i\to 2j} = {} & E\left\{Q\left(\frac{|h_{b,l}|^2(y_{k-1} - x_i) + |h_{r,l}|^2(y_{k-1} - x_j)}{\sqrt{\frac{(|h_{s,l}|^2 + |h_{r,l}|^2)N_0}{2}}}\right)\right\} \\ & - E\left\{Q\left(\frac{|h_{b,l}|^2(y_k - x_i) + |h_{r,l}|^2(y_k - x_j)}{\sqrt{\frac{(|h_{s,l}|^2 + |h_{r,l}|^2)N_0}{2}}}\right)\right\}, \end{aligned} \tag{5.13}$$

where $l = m1, m2$.

Since the analysis for the case of $1x0x$ and $1x1x$ is the same as the case of $0x1x$ and $0x0x$, a scaling factor of 2 is included in $P_{e_b,M1}$ and $P_{e_b,M2}$. The symbol-error rate (SER) of the symbols that carry the enhancement bits for mobile 1 and that carry the common bits for mobile 2 as a function of the BER expressions derived above are written as

$$P_{e_s,M1} = 1 - (1 - P_{e_b,M1})^2, \tag{5.14a}$$

$$P_{e_s,M2} = 1 - (1 - P_{e_b,M2})^2. \tag{5.14b}$$

5.3.3 Simulation Results

In this subsection, we evaluate the SER performance of the proposed scheme shown in Fig. 5.3 and compare the cases with different values of the distance parameter $d_1^{'}$. In this simulation, we arbitrarily assign symbols for mobile 1 as enhancement bits and symbols for mobile 2 as common bits; results will not change if enhancement bits are assigned to mobile 2 and common bits to mobile 1.

Fig. 5.5 and Fig. 5.6 show, respectively, the SER results of mobile 1 and mobile 2 with the proposed scheme with $d_1^{'}$ =0.8, 1.0, 1.2 and 1.5 and $E_a^b = E_a^r = 10$ in a Rayleigh fading environment. It is assumed that the base station and the relay use the same constellation of hierarchical modulation. It is observed from Figs. 5.5 and 5.6 that $d_1^{'}$ increases, the SER performance of mobile 2 improves whereas the performance of mobile 1 deteriorates. Although mobile 2 has the best performance when $d_1^{'} = 1.5$, simulation results show that the performance of mobile 1 is the worst. The performance of mobile 1 gets better as $d_1^{'}$ decreases and mobile 1 has the best performance when $d_1^{'} = 0.8$. The analytical SER curves obtained by using Eq. (5.9) and Eq. (5.10) are provided in Fig. 5.5 and 5.6 for comparison.

We also compare the proposed scheme and the conventional scheme shown in Fig. 5.1-(A), which has no relay and no hierarchical modulation, but requires two transmission phases, the same as required by the proposed scheme. To make a fair comparison, for the conventional scheme, 4-QAM modulation is assumed, so that each mobile receives 2 bits symbol. The proposed system outperforms the conventional scheme; as observed from Fig. 5.5 and Fig. 5.6, with $d_1^{'} = 0.8$, the proposed scheme performs about 3 dB better than the conventional scheme at an SER of 10^{-3} for both mobile 1 and mobile 2. The improvement in error performance with the proposed scheme comes at the expense of an increased complexity because of the needs of a relay and hierarchical modulation.

Another scenario is to employ conventional cooperative communications as shown in Fig. 5.1-(B) with 16-QAM; this results in the same transmission efficiency as the proposed scheme - 4 bits per mobile after 4-transmission phase. The BER performances for mobile 1 and mobile 2 are shown in Fig. 5.7, together with the BER curve of direct transmission. Performance of both mobile 1 and mobile 2 with the proposed scheme when $d_1^{'} = 1$ is better than this scenario. Note that another advantage of the proposed scheme is that the performance of different mobile stations can be flexibly controlled by varying the value of the distance parameter $d_1^{'}$ according to specific fading conditions (e.g., distance to the base station and shadowing).

5.4 Alternative Cooperative Relay Communication Employing Hierarchical Modulation: Asymmetric Model

Sec. 5.3 dealt with the case that all mobiles are in the cell coverage area, and a relay is employed in order to improve the performance. We call this the symmetric communications model, because the network structure for two mobiles is the bilateral symmetry.

In this section, we consider the scenario that one mobile is in cell coverage area and the other one is out of coverage area as in Fig. 5.8-(A), where mobile 1 is able to directly

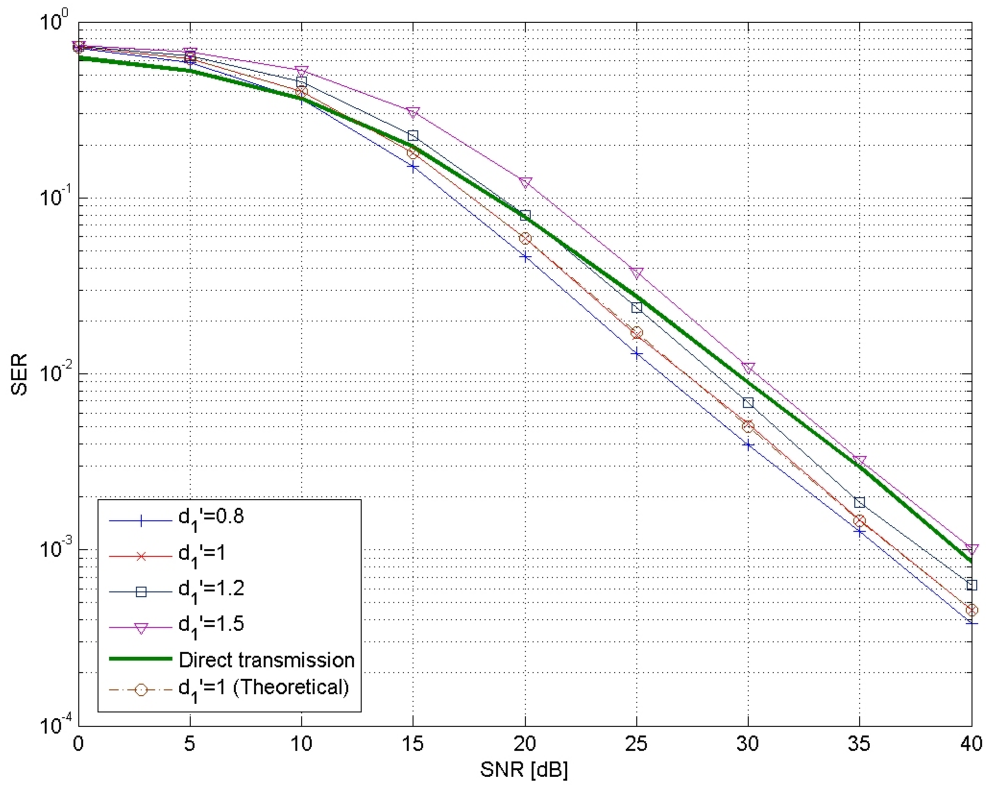

Figure 5.5: The SER performance of mobile 1 (enhancement bits are assigned to mobile 1 and common bits are assigned to mobile 2): Symmetric model.

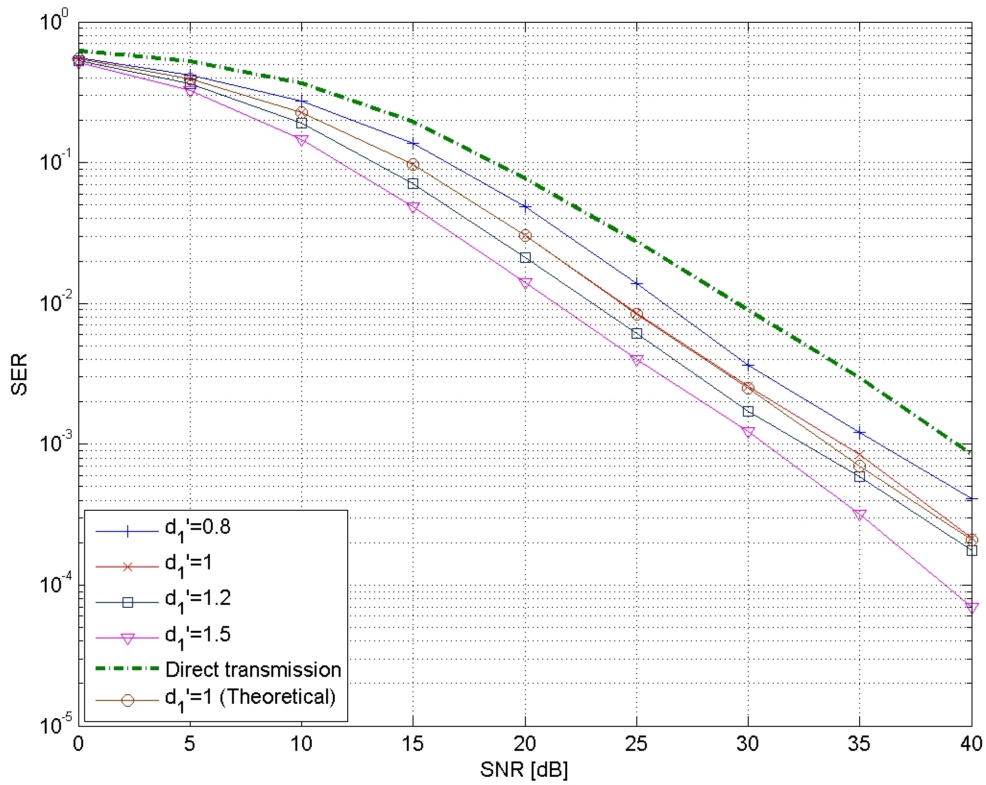

Figure 5.6: The SER performance of mobile 2 (enhancement bits are assigned to mobile 1 and common bits are assigned to mobile 2): Symmetric model.

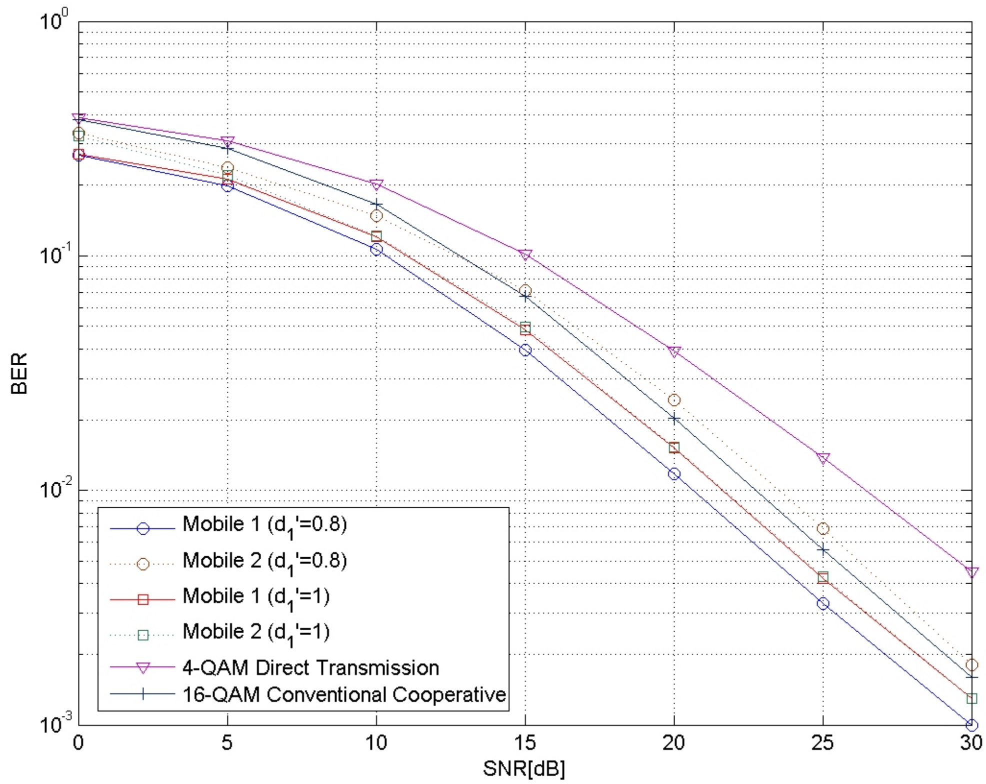

Figure 5.7: The BER performances of mobile 1 and mobile 2

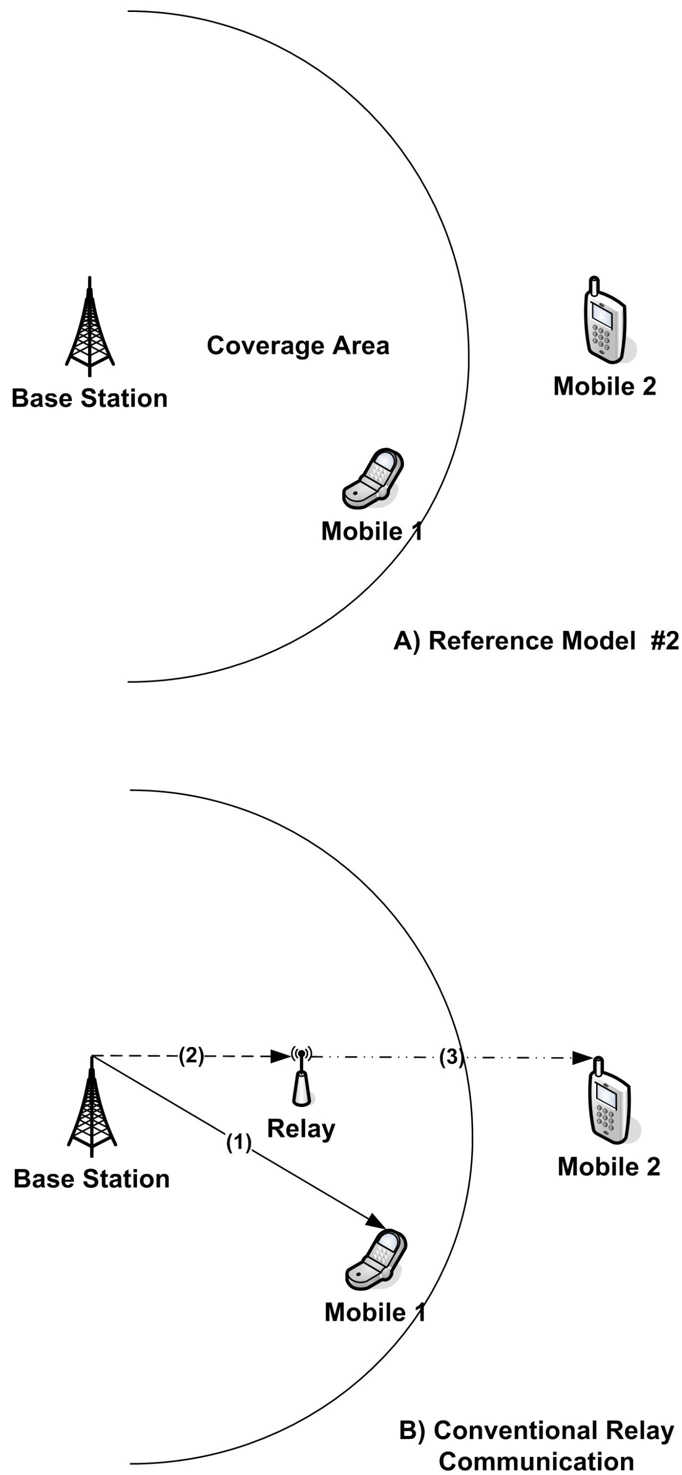

Figure 5.8: Conventional communications schemes: one mobile is out of cell coverage area.

receive the signal from the base station but mobile 2 cannot. For this scenario, a relay must be employed, as shown in Fig. 5.8-(B), and there will be no diversity gain. We call this an asymmetric communications case, and three transmission phases are required to complete the transmissions.

5.4.1 Proposed System Model

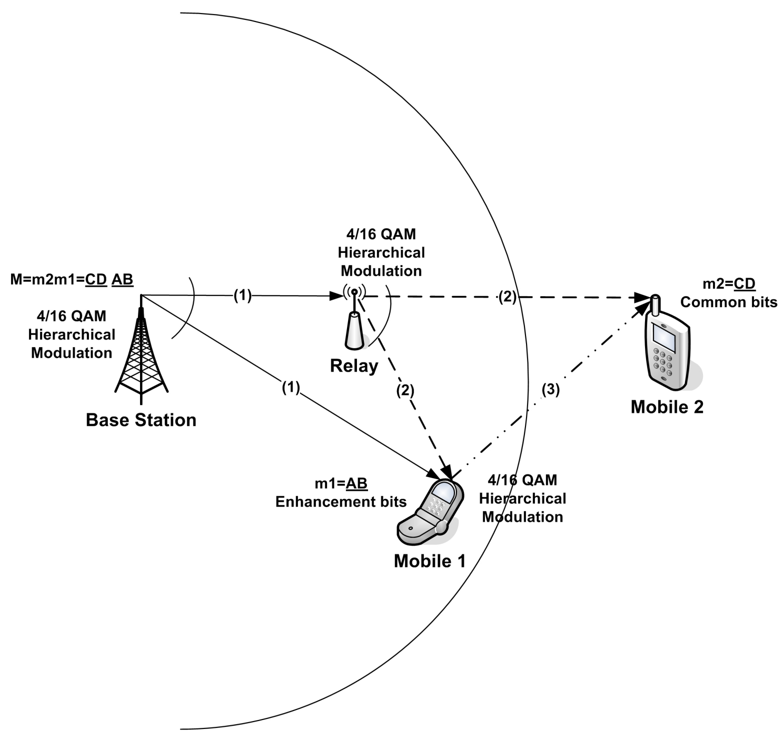

Figure 5.9: Hierarchical modulation based cooperative multiuser communication: Asymmetric model.

The proposed scheme that employs hierarchical modulation for the asymmetric communications scenario is shown in Fig. 5.9. We again analyze this scheme using a simple network with one base station, one relay, and two mobile users, all operating in a half-duplex mode.

In alternative proposed scheme, data streams $m_1 = \text{AB}$ and $m_2 = \text{CD}$ generated at base station, where $A, B, C, D \in \{0, 1\}$, are to be delivered to mobile 1 and mobile 2, respectively. We arbitrarily assign m_1 as the enhancement bits and m_2 as the common bits, before transmission begins.

The three steps of transmission process in the proposed scheme are described as follows.

1) In the first phase, m_1 and m_2 are concatenated to form a 4/16 QAM hierarchical modulation symbol $M = \text{CDAB}$, which is broadcast to the relay and mobile 1 with energy per symbol E_a^b. The received signals at the relay and mobile 1 during the first phase are represented, respectively, by

$$r_{b,r} = \alpha_{b,r} \times h_{b,r} \times \sqrt{E_a^b} \times M + n_{b,r}, \tag{5.15a}$$

$$r_{b,m1} = \alpha_{b,m1} \times h_{b,m1} \times \sqrt{E_a^b} \times M + n_{b,m1}. \tag{5.15b}$$

2) In the second phase, the relay demodulates the received symbol from the base station and re-broadcasts it to the two mobiles. During the second transmission phase, the received signals at mobile 1 and mobile 2 are expressed as

$$r_{r,m1} = \alpha_{r,m1} \times h_{r,m1} \times \sqrt{E_a^r} \times M^{'} + n_{r,m1}, \tag{5.16a}$$

$$r_{r,m2} = \alpha_{r,m2} \times h_{r,m2} \times \sqrt{E_a^r} \times M^{'} + n_{r,m2}. \tag{5.16b}$$

where E_a^r is the transmitted average symbol energy of the relay and $M^{'}$ is the transmitted symbol from the relay. Upon receiving the signals from the base station and the relay, mobile 1 combines both received signals using the MRC method. The combined signals at mobile 1 is given by

$$r_{m1} \quad = \quad \alpha_{b,m1} \times h^*_{b,m1} \times r_{b,m1} + \alpha_{r,m1} \times h^*_{r,m1} \times r_{r,m1}. \tag{5.17}$$

After demodulation, mobile 1 gets the last two bits of the symbol (enhancement bits), $m_1 = \text{AB}$, and ignores the first two bits of the symbol (common bits), $m_2 = \text{CD}$.

3) In the third phase, the demodulated 4/16-QAM symbol at mobile 1 is re-transmitted to mobile 2; mobile 1 works as a relay and thus provides spatial diversity. During this phase, the received signals at mobile 2 is expressed as

$$r_{m1,m2} = \alpha_{m1,m2} h_{m1,m2} \sqrt{E_a^{m1}} M'' + n_{m1,m2}, \tag{5.18}$$

where E_a^{m1} is the transmitted energy of the relay and M'' is the transmitted symbol from mobile 1. Upon receiving the signals from the relay and mobile 1, mobile 2 combines both received signals using the MRC method. The combined signals at mobile 2 is given by

$$r_{m2} \quad = \quad \alpha_{r,m2} \times h^*_{r,m2} \times r_{r,m2} + \alpha_{m1,m2} \times h^*_{m1,m2} \times r_{m1,m2}. \tag{5.19}$$

After demodulation, mobile 2 gets the first two bits of the symbol (common bits), $m_2 = \text{CD}$, from the demodulated 4/16-QAM symbol.

5.4.2 Simulation Results

The SER performance of the proposed scheme in Fig. 5.9 is simulated in this section. In this simulation, we arbitrarily assign enhancement bits to mobile 1 and common bits to mobile 2. Fig. 5.10 and Fig. 5.11 show, respectively, the error performance curves of mobile 1 and mobile 2 with the proposed scheme over a Rayleigh fading channel. Other parameters are: $d_1^{'}$ =0.8, 1.0, 1.2 and 1.5 and $E_a^b = E_a^r = E_a^{m1} = 10$. Also, the base station, the relay, and mobile 1 all use the same constellation of hierarchical modulation.

Similar to the observation in Sec. 5.3.3, Fig. 5.10 and 5.11 show that as $d_1^{'}$ increases, the SER performance of mobile 2 improves and the SER performance mobile 1 deteriorates, as expected. The difference of the proposed scheme in Fig. 5.9 from the conventional scheme in Fig. 5.8-(B) is that mobile 1 acts as a relay, since it also has the message intended for mobile 2. This enables the system to exploit diversity gains and to improve the error performance.

We also compare the case shown in Fig. 5.8-(B), which employs 4-QAM and requires three transmission phases to complete the transmission. The proposed scheme performs better than the conventional scheme with specific values of the distant parameter $d_1^{'}$, even though they use the same number of transmission phases.

We have investigated the case that enhancement bits are assigned to mobile 1 and common bits are assigned to mobile 2. Now, we consider the opposite case that common bits are assigned to mobile 1 and enhancement bits are assigned to mobile 2. Other simulation conditions are the same as the previous case. Fig. 5.12 and Fig. 5.13 show the SER performances of mobile 1 and mobile 2, respectively. For this case, the proposed scheme still outperforms the conventional relay scheme.

As shown in Figs. 5.10, 5.11, 5.12, and 5.13, regardless of how we assign the bits

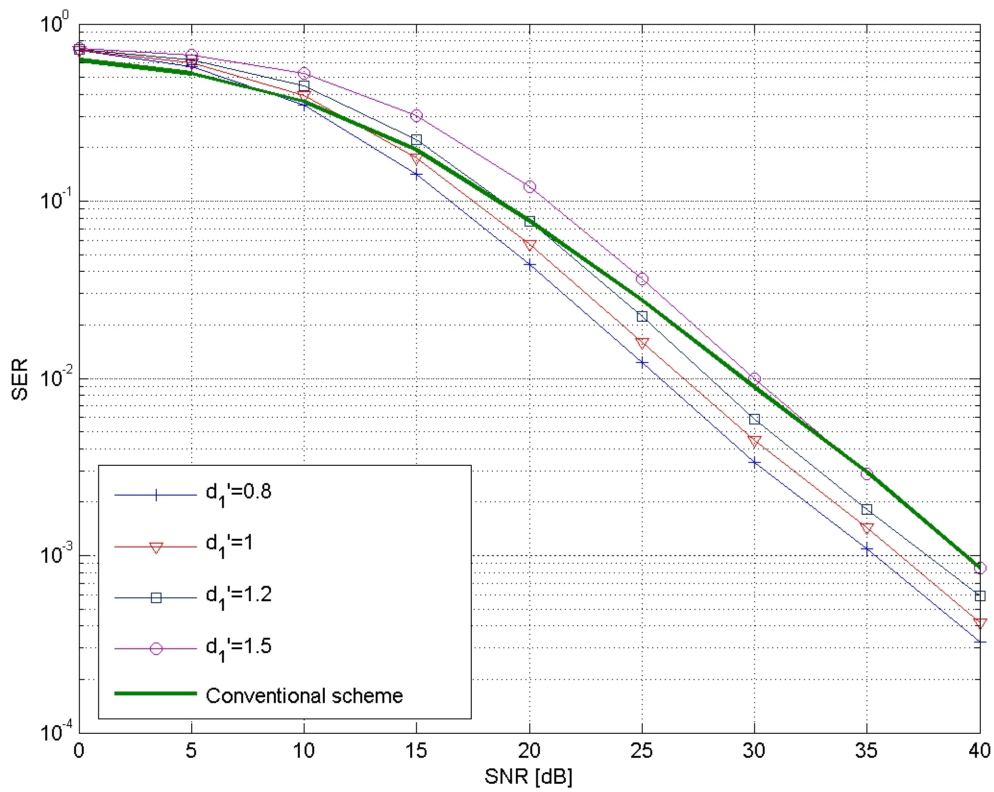

Figure 5.10: The SER performance of mobile 1 (enhancement bits are assigned to mobile 1 and common bits are assigned to mobile 2): Asymmetric model.

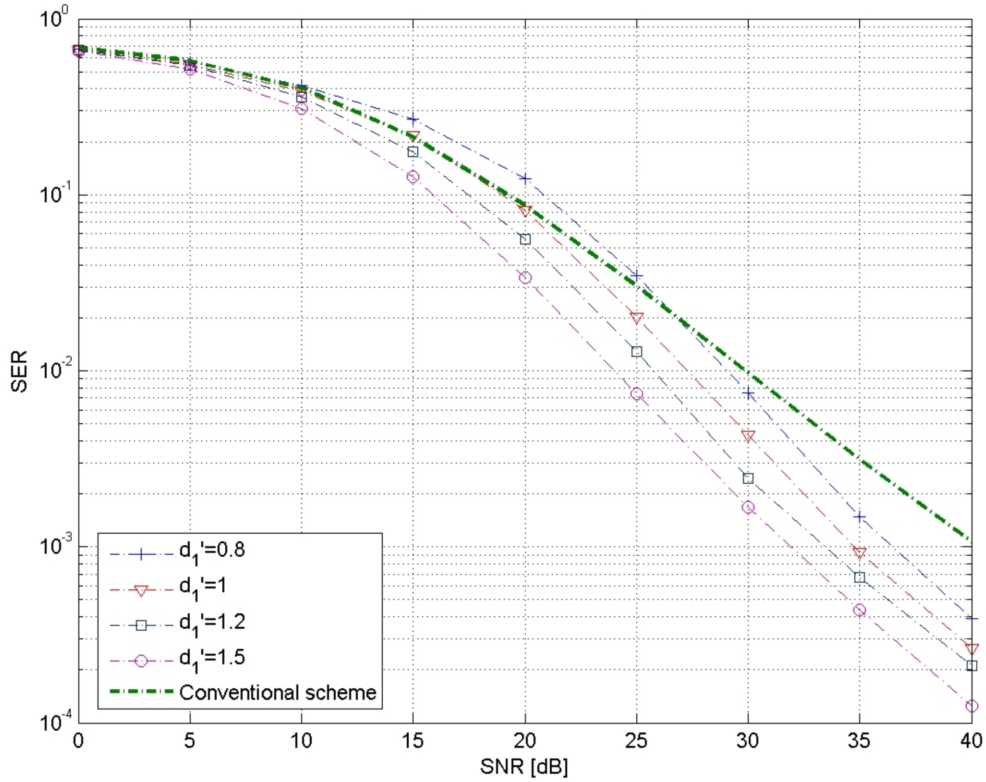

Figure 5.11: The SER performance of mobile 2 (enhancement bits are assigned to mobile 1 and common bits are assigned to mobile 2): Asymmetric model.

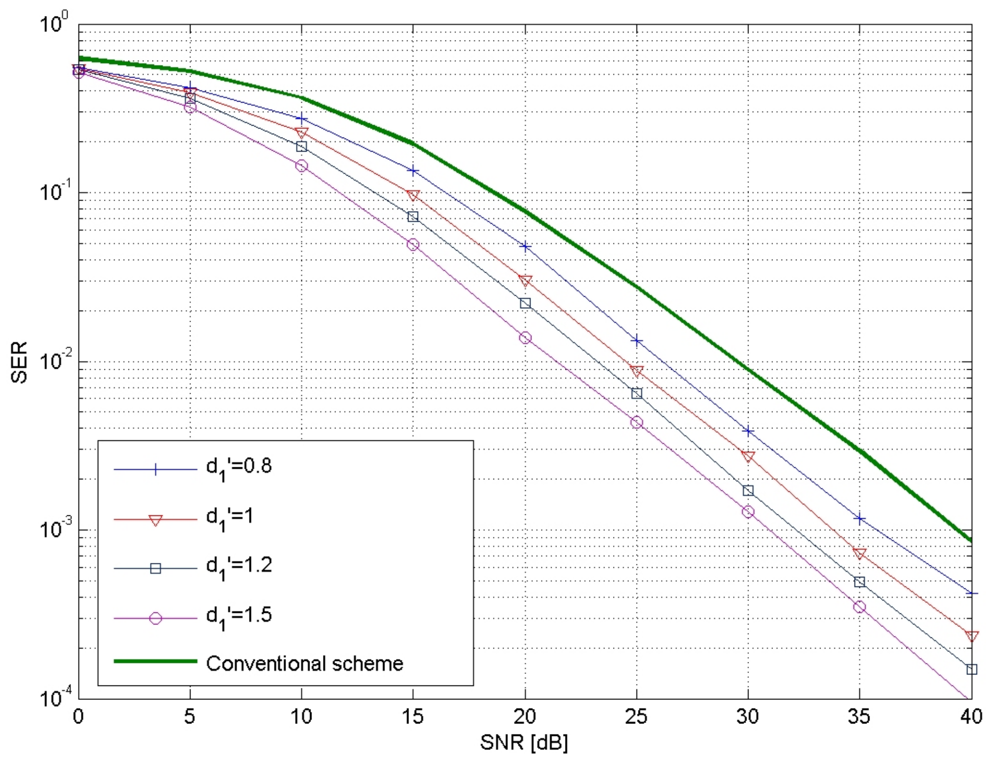

Figure 5.12: The SER performance of mobile 1 (common bits are assigned to mobile 1 and enhancement bits are assigned to mobile 2): Asymmetric model.

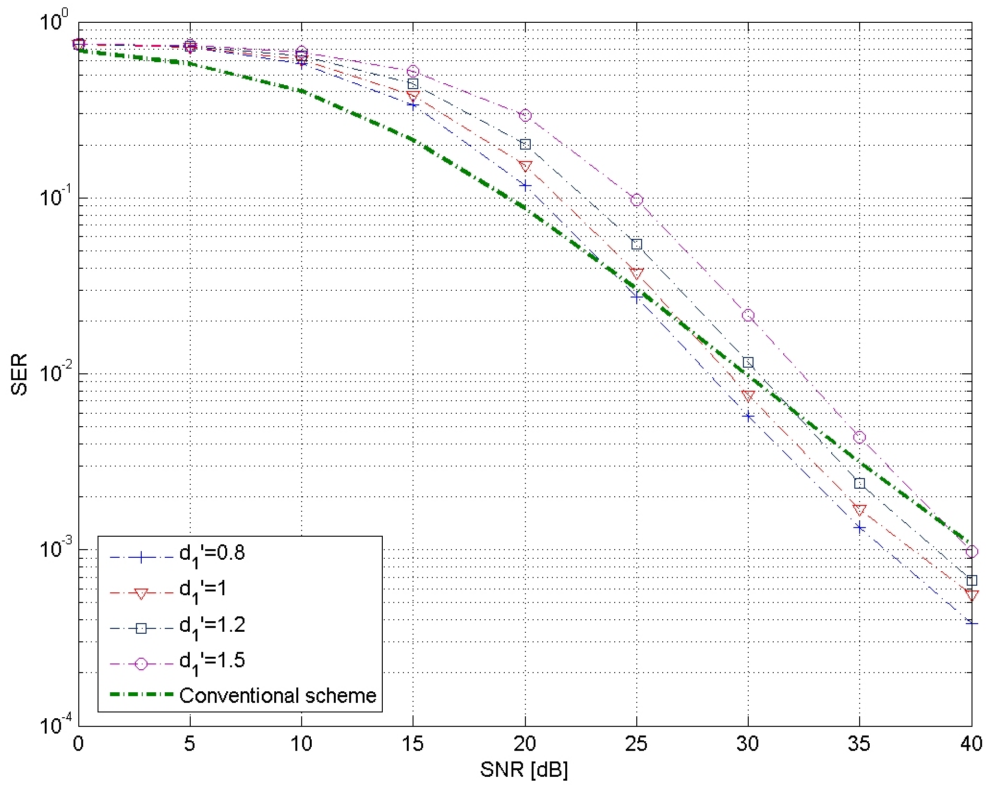

Figure 5.13: The SER performance of mobile 2 (common bits are assigned to mobile 1 and enhancement bits are assigned to mobile 2): Asymmetric model.

to mobile 1 and mobile 2, the performance of the proposed scheme outperforms the convention relay scheme in Fig. 5.8-(B). Thus, we can randomly assign the enhancement bits and common bits to mobile 1 and mobile 2 with a specific distance parameter.

5.5 Conclusions

In this chapter, we considered the downlink of symmetric and asymmetric multiuser cooperative communications models and proposed two types of transmission schemes that employ hierarchical modulation to resolve the problem of reduced data throughput due to additional resources required by the relay. These schemes effectively reduce the number of transmission phases to the same as the conventional schemes while achieving a better error performance. Regardless how enhancement bits and common bits are assigned to different users, the proposed schemes with some specific values of the distance parameter of hierarchical modulation provide better performance than conventional schemes.

Chapter 6 – Conclusions

We have proposed the space-time cooperative relay communication scheme with relay-selection that efficiently exploits distributed spatial diversity to improve performance in Chapter 2. This scheme maximizes the SNR at the receiver by selecting the transmission pattern out of several possible transmission patterns upon the criterion of the SNR with each transmission pattern. Simulation results show that the proposed scheme with only two transmission patterns already approaches that with four or more patterns (more than 2-bit feedback) and achieves over 2 dB gain at a BER of 10^{-3} over the relay scheme using the quasi-orthogonal STBC.

In Chapter 3, we have studied the spectral efficiency of network with one base station, two users M1, M2 and a single relay in half-duplex mode. In a relay transmission network, additional resources such as transmission phase should be allowed to the relay and it leads to a significant loss of the network capacity. In order to overcome this problem, the partially cooperative RBC model employing a layered broadcasting protocol at BS is considered. Numerical results showed that the layered broadcasting protocol in the partially cooperative RBC model with a specific value of α, recovers the loss of a network capacity, due to the half-duplex relay and outperforms the conventional protocols.

New multi-user cooperative relaying schemes that employ superposition coding and hierarchical modulation are proposed in Chapter 4 and Chapter 5, respectively, to improve the error performance. The proposed schemes require no additional transmission phase for the relay, while providing reliable transmissions. As shown from simulation results of the proposed scheme employing superposition coding, the system can freely assign the message as basic message or superposed message with a specific value of α and this provides improved performance. For the hierarchical modulation based scheme, we considered symmetric and asymmetric downlink multiuser cooperative communications models and proposed two types of transmission schemes. These schemes also effectively reduce the number of transmission phases to the same as the conventional schemes, while achieving a better error performance. Regardless how enhancement bits and common bits are assigned to different users, the proposed schemes with some specific values of the distance parameter of hierarchical modulation provide better performance than conventional schemes. The derivations of the optimal power division coefficient of superposition coding and distance parameter of hierarchical modulation to achieve a certain target error rate are left as future works.

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