Design and Performance Analysis of Efficient Cooperative Wireless Communication Systems

by

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I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Cooperative communication has recently become a key technology for modern wireless networks such as 3GPP long-term evolution and WiMAX, because in such networks the transmission rate, the communication reliability, and coverage problems could be improved in a cost-effective manner. This, however, faces many design challenges. First, cooperative transmission typically involves a relaying phase which requires extra resources. This may cause a reduction in the spectral efficiency. Second, extra control signaling increases the complexity of operation, which may limit practical implementation. In addition, a wireless channel is time-varying, mainly due to the multipath propagation. As a result, a careful design of efficient cooperative communication systems is required, not only to enhance the spectral efficiency and maintain the quality-of-service (QoS), but also to be practical.

In this dissertation, we aim to address the challenges imposed by cooperative communication and wireless transmission, and design the efficient and distributed systems which can be practically implemented in existing wireless systems. The research work is divided into two main topics: 1) adaptive cooperative wireless systems with variable-rate transmission, and 2) cooperative wireless systems with a power consumption constraint.

The first topic investigates how the spectral efficiency of cooperative wireless communication systems can be improved while maintaining the QoS in terms of bit error rate and outage probability. The spectral efficiency enhancement is achieved by using three techniques: adaptivity over the relay node (i.e., relay node is active or not), adaptivity over the modulation mode, and relay selection. Based on that, we propose several adaptive cooperative schemes for both the decode-and-forward (DF) and amplify-and-forward (AF) protocols. To evaluate these schemes, we provide performance analysis in terms of average spectral efficiency, average bit error rate (ABER), and outage probability over Rayleigh fading channels.

We start with the single-relay cooperative system using DF protocol, in which two adaptive cooperative schemes with variable-rate transmission are proposed. The first scheme, called the minimum error rate scheme (MERS), aims to exploit the transmit diversity to improve the bit error rate. By trading the multiplexing gain against the diversity gain, we propose the second scheme, called the maximum spectral efficiency scheme (MSES),

in which cooperative transmission is avoided whenever it is not beneficial. The MERS improves the ABER significantly and achieves equal or better average spectral efficiency compared to the fixed (i.e., non-adaptive) relaying scheme. In contrast, the MSES provides the best average spectral efficiency due to its ability to not only adapt to the channel variation but also to switch between cooperative and non-cooperative transmissions. To further increase the spectral efficiency, we then propose the third scheme, called variable-rate based relay selection (VRRS) scheme, in which a relay node is selected from among the available relay nodes, based on a predefined criterion.

Furthermore, we propose two AF adaptive cooperative schemes, mainly to enhance the spectral efficiency. In the first scheme, we introduce a generalized switching policy (GSP) for a single-relay cooperative wireless system that exploits the variable-rate transmission and useful cooperative regions. The second scheme, called the AF efficient relay selection (AFERS) scheme, extends the GSP to also consider the relay selection technique. Analytical and simulation results verify that the AFERS scheme not only outperforms conventional direct transmission in terms of the average spectral efficiency, but also the AF fixed relaying and the outage-based AF adaptive cooperative scheme.

The second topic investigates the fair power consumption of the relay nodes for AF cooperative wireless communication systems. The fairness is defined as to achieve equal power consumption over the relay nodes. We focus on how the relay selection process can be controlled in a distributed manner so that the power consumption of the relay nodes can be included in relay selection. We first introduce a simple closed-form expression for the weight coefficient used in order to achieve the considered fairness that depends only on the local average channel conditions of the relay path. We then derive closed-form expressions of the weighted outage probability and ABER and show that our proposed strategy not only has less complexity than the conventional centralized one but also provides better accuracy in distributing the total consumed power equally among the relay nodes without affecting the performance.

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Dedication

To my parents, my wife, and my children

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List of Abbreviations

3G	Third-generation
4G	Fourth-generation
ABER	Average bit error rate
AF	Amplify-and-forward
AFERS	Amplify-and-forward efficient relay selection scheme
AFFR	Amplify-and-forward fixed relaying
AEGN	Additive white Gaussian noise
BER	Bit error rate
BPSK	binary phase shift keying
CD	Cooperative diversity
CDF	Cumulative distribution function
CF	Compress-and-forward
CSI	Channel state information
CTS	Clear-to-send
DF	Decode-and-forward
DSTC	Distributed space-time coding
EF	Estimate-and-forward
GSP	Generalized switching policy
iid	Independent identically distributed
LTE	Long-term evolution

M-QAM	M-ary quadrature amplitude modulation
MAC	Medium access control
MERS	Minimum error rate scheme
MRC	Maximum ratio combining
MSES	Maximum spectral efficiency scheme
OFDM	Orthogonal frequency division multiplexing
OR	Opportunistic relaying
PDF	Probability density function
QoS	Quality of service
QPSK	quadrature phase shift keying
RF	Radio frequency
RTS	Ready-to-send
SNR	Signal-to-noise ratio
VRRS	Variable-rate based relay selection
WiMAX	Worldwide interoperability for microwave access

Chapter 1

Introduction

In the past few decades, the world has experienced a tremendous growth in wireless communications due to the advances in digital technology. For example, the second-generation (2G) cellular systems brought low-cost, reliable mobile communications. However, the main technical achievements were in increasing system capacity, expanding coverage, and improving quality of service (QoS) for voice services. The success of wireless voice transmission opened the door for new communication systems, such as third-generation (3G), fourth-generation (4G), and worldwide interoperability for microwave access (WiMAX) in support of different services such as multimedia, file retrieval, and Internet browsing. Recently, the ever-increasing demand for these services has forced wireless communication system designers to develop new techniques in order to efficiently utilize the available radio resources.

Among other possible approaches to improve the performance of future wireless communication systems, this dissertation focuses on cooperative communication techniques that can potentially be useful in performance enhancement. This chapter aims to provide the necessary background of the problem. It starts with research motivation, which provides some challenges in wireless communication networks and the potential solutions. This is followed by a general description of the research problem, the main contributions, the thesis structure, and the bibliographic notes.

1.1 Research Motivation

In wireless communications, the characteristics of a channel are usually under continuous change due to multipath fading. Furthermore, the channel suffers from background noise, which is also constantly varying. As a result, the capacity of a wireless link has very high variability. In addition to these challenges, the spectrum over a wireless channel is limited, but the need for that spectrum is increased as a consequence of increasing demand of high data rate services. Therefore, future wireless communication systems should be characterized by quick and effective adaptation at every stage and for every available resource in order to relieve the pressure on the spectrum and meet demand with an acceptable QoS.

Cooperation or relaying has attracted significant attention not only from a physical layer perspective, where the main goal is to achieve spatial diversity [1, 2, 3, 4], but also from an upper layer perspective, such as cooperative design in the application layer, along with the medium access control (MAC) and network layers [5, 6] where the main goal is to determine when and how user cooperation takes place. Cooperative communication has recently become a key technology for modern wireless networks such as 3GPP long-term evolution (LTE) and WiMAX [7, 8], because in such networks, transmission rate and power, communication reliability, and coverage problems could be solved efficiently and in a cost-effective manner. For example, a mobile user at the edge of the cell may perform ping-pong movements which cause frequent handovers between the access points, leading to performance degradation. Instead, another node can act as a relay to keep the mobile user connected to one access point. Another example can be seen in vehicular networks that support multimedia applications where a car may leave the range of the access point before ending the session. One solution is to allow another car to relay the data to the access point, which can decrease the outage probability and improve QoS. All these benefits motivate us to investigate cooperative communication as one of the promising techniques that can be used to combat the above challenges.

1.2 Problem Description

One powerful tool for mitigating multipath fading in wireless systems is the diversity technique. Diversity provides the destination node with several copies of the transmitted signal, so if one copy undergoes deep fading, the destination can still detect the received signal successfully using the other received copies. Diversity in wireless system can be achieved through time diversity, frequency diversity, and spatial diversity. Time diversity is the use of multiple time slots to send the same information signal to a destination node. To ensure that each time slot will be transmitted over an independent fading channel, the time slots should be well separated; however, this separation will cause a reduction in the transmission rate and an increase in the transmission delay. Frequency diversity is the transmission of the same information signal over different frequency bands. In this case, there will be a reduction in the transmission bandwidth. Spatial diversity can be achieved by using multiple antennas at the transmitter and/or receiver. This type of diversity has been proven to increase capacity without sacrificing the bandwidth or increasing the delay [9, 10, 11, 12].

In wireless applications, it is feasible to have multiple antennas at the base station, but it is difficult to equip a small mobile terminal with multiple antennas because the location of these antennas will be very close to each other, which makes the fading channels non-independent, and hence the achievable diversity gain is reduced. To address this problem, cooperative diversity (CD) is proposed, where several nodes, each with a single antenna, could form a virtual antenna array and cooperate in order to achieve transmit diversity. Fig. 1.1 shows a single-relay cooperative system. Based on the forwarding protocol employed by the relay node, cooperative diversity schemes can be divided into two main types: amplify-and-forward (AF), and decode-and-forward (DF). In the AF protocol, the relay node simply amplifies the received signal from the source node and retransmits it to the destination node. In the DF protocol, the relay node detects, encodes, and retransmits the signal to the destination node. It is obvious that the AF protocol has a simpler operation than the DF protocol. However, the AF protocol may increase the noise level in the system [4]. In addition to the AF and DF protocols, other relaying protocols have been proposed in the literature, such as estimate-and-forward (EF) [13, 14], and compress-and-forward (CF) [15].

In a single-relay CD system, the general operation can be divided into two phases. In the first phase, the source broadcasts the signal to the relay and destination nodes. During the second phase, the relay node forwards the received signal to the destination node, and then the destination node combines the received signals from the source and the relay nodes. The two-phase transmission can achieve the diversity gain; however, the available bandwidth is reduced by half. In this case, we do not know if cooperative transmission outperforms direct transmission or not.

The main factor that affects the performance of CD schemes is the channel characteristic of the transmission links (i.e., the source-destination link, the source-relay link, and the

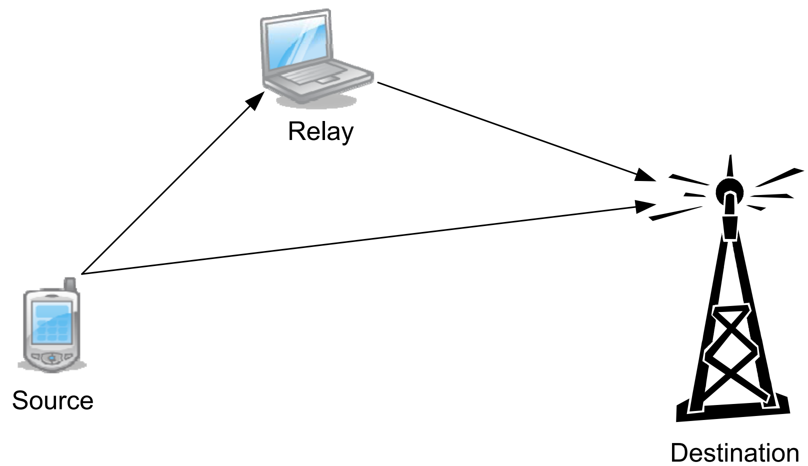

Figure 1.1: Single-relay cooperative system.

relay-destination link). Since these channels are fluctuating all the time due to multipath fading, it is important to make a wireless system adaptive in terms of cooperative and non-cooperative transmissions. This adaptivity can avoid cooperative transmission whenever it is not beneficial. Another important factor that affects the performance of CD system is the number of relay nodes used. Although the diversity order of multiple-relay system is high compared to a single-relay cooperative system, the operation becomes very complicated and the system suffers low spectral efficiency due to the transmission over orthogonal channels. Therefore, relay selection has emerged to solve these problems, in which the best relay among the available relay nodes is selected based on a certain criterion. The advantages of this technique can be summarized as follows:

- Reduces additional resources (e.g. time, frequency or code)
- Simplifies signaling
- Avoids complex synchronization

- Decreases signal processing complexity
- Preserves the diversity order provided by multiple-relay system

The required resources in a multiple-relay system increase by the number of available relay nodes. Thus, there is a massive saving in resources by using relay selection. The complexity of signaling is obvious, since each relay node requires control signals to establish a connection. Synchronization represents one of the important tasks in wireless networks. Due to propagation delay, it is used to adjust the timing between the transmitter and the receiver. When it comes to cooperative transmission, there are two synchronization solutions required: from source to destination, and from relay to destination. Accordingly, it is difficult and sometimes impossible to implement synchronization in multiple-relay environment [16]. Signal processing becomes a complicated task when several signals need to be detected at the destination node. Therefore, the receiver structure needs a special design. Spatial diversity is exploited in cooperative transmission in order to mitigate the impairments of the wireless channels. It has been proven that the diversity order of a relay selection technique (i.e., opportunistic relaying) is similar to the diversity order of the distributed space-time coding (DSTC) system [17].

Another important issue arising in the relay selection technique is fairness among the relay nodes. Usually, the selection criterion depends mainly on the channel condition of the relay path. In this case, the excessive use of the resources of the best relay node may affect its performance. Therefore, an effective relay selection technique should take into account the fairness among the relay nodes. Other issues that also affect the performance of the CD scheme are the type of transmission, whether the rates are fixed or variable, the coding rate, the channel coding, etc.

In conventional direct transmission, the practical design of efficient transmission techniques is fairly well understood. When it comes to systems offering different modes of operation, either cooperative or non-cooperative transmission over highly fluctuated channels, the problem becomes challenging, and requires careful design.

1.3 Main Contributions

The above-mentioned issues and factors encourage us to investigate the cooperative communication systems and propose several solutions. In general, this thesis has two main objectives. Firstly, how the performance of cooperative communication systems can be improved with emphasis on the enhancement of the spectral efficiency. In other words, the main goal is to design spectrally efficient cooperative schemes that have the capability to maintain the QoS in terms of bit error rate (BER) and outage probability. Secondly, if there is a constraint over the resources of the relay nodes such as power consumption, how cooperative communication system can achieve fair relay selection with low operation complexity.

The approach used to achieve the first objective is based on three techniques: adaptive modulation, in which the transmission rate adapts to the channel variation; adaptive relaying, in which the relay node is activated if the system objective is satisfied; and relay selection. Based on that, we propose several adaptive cooperative schemes for both DF and AF protocols which can be implemented in existing wireless communication systems.

For the DF adaptive cooperative system, we first introduce two switching policies, in which adaptive cooperative schemes, the minimum error rate scheme (MERS), and the maximum spectral efficiency scheme (MSES) are proposed, respectively. The MERS aims to achieve acceptable spectral efficiency with a minimum error rate by exploiting the transmit diversity. The MERS aims to maximize spectral efficiency at all times by avoiding cooperative transmission whenever it is not beneficial. Then, to evaluate the performance of these schemes, we start with deriving the cumulative distribution function (CDF) and the probability density function (PDF) of the output signal-to-noise ratio (SNR) of both schemes. By using these results, closed-form expressions of the average spectral efficiency, average bit error rate (ABER), and outage probability are derived under Rayleigh fading channels. Based on the performance metrics, it is shown that the proposed schemes lead to a significant improvement in performance. In addition, it is observed that the performance is degraded when the source-relay link has low channel quality. Therefore, we propose a third DF adaptive cooperative scheme with relay selection in order to further improve performance. It is called the variable-rate based relay selection (VRRS) scheme, in which the best relay node is selected among the available relay nodes based on a predefined criterion. The performance metrics are also derived in closed-form expressions by using the CDF and PDF of the output SNR of the proposed scheme. It is shown that the VRRS scheme outperforms the AF fixed relaying in terms of average spectral efficiency by 10%-100% for a relatively low average SNR.

For the AF adaptive cooperative system, we propose a generalized switching policy (GSP) that gives useful cooperative regions and defines a switching threshold SNR that guarantees that the BER of the cooperative transmission is below the target bit error rate. For simplicity, we show that this switching threshold SNR can be approximated from its original definition without affecting performance. The same methodology of the analysis of the previous schemes is used, in which closed-form expressions of the average spectral efficiency, ABER, and outage probability are derived for Rayleigh fading channels. The GSP is then extended to include the relay selection technique, where an AF efficient relay selection (AFERS) scheme is proposed. After deriving the average spectral efficiency, the

ABER, and the outage probability, the numerical results show that the AFERS scheme has the best average spectral efficiency compared to those of the conventional direct transmission, the outage-based AF adaptive cooperative scheme, and the AF fixed relaying scheme.

Finally, the approach used for the second objective is to design the relay selection process so as to be dependent only on the local information of the channel condition at each relay node. By considering the fair power consumption of the relay nodes for AF cooperative wireless systems, we show how the relay selection process can be controlled in a distributed manner so that the power consumption of the relay nodes can be included in relay selection. The fairness is defined as to achieve equal power consumption over the relay nodes. A distributed relay selection strategy is proposed in order to reduce the complexity of the existing centralized strategy. Our proposed strategy provides a simple closed-form expression for the weight coefficient used to achieve the required fairness that depends only on the local average channel conditions of the relay path. In addition, closed-form expressions of the outage probability and ABER are derived as a function of the weight coefficients and average channel condition of the relay path. It is shown that the proposed strategy not only has less complexity than the conventional centralized one, but also provides better accuracy in distributing the total consumed power equally among the relay nodes without affecting performance.

1.4 Thesis Structure

The remainder of the thesis is organized as follows. In Chapter 2, a brief introduction to background subjects related to our research is presented, which includes classification of cooperative schemes, opportunistic relaying, and adaptive modulation. A literature survey of cooperative communication systems is also provided.

In Chapter 3, we describe the system model and its parameters and present the considered assumptions. After presenting the channel model, we present the signal transmission and reception models for both the DF and AF protocols.

In Chapter 4, we present the DF adaptive cooperative system with variable-rate transmission. We start with the single-relay system, in which two switching policies are introduced. Then, the performance analysis is provided, followed by the evaluation of the proposed schemes. The single-relay system is extended to a multiple-relay environment with relay selection, in which the performance metrics are derived based on the new switching policy. Finally, numerical examples are presented.

In Chapter 5, we present the other adaptive cooperative schemes for AF protocol which also employ adaptive modulation. After introduction of the switching policy for a single-relay system, derivations of the average spectral efficiency, average bit error rate, and outage probability are given. In addition, a relay selection method is considered by assuming a multiple-relay scenario. Then, the performance analysis of the proposed scheme and the numerical examples are presented.

The power consumption constraint of the relay nodes and its effect on the performance of AF cooperative wireless system are studied in Chapter 6. First, we derive the average power consumption of the relay node. Second, we present the conventional centralized strategy that aims to distribute the total consumed power equally among the relay nodes. Third, we introduce our distributed fair relay selection strategy. Fourth, we derive the weighted outage probability and average bit error rate. Finally, we present some numerical examples.

The conclusions of the thesis are summarized in Chapter 7. In addition, future research directions relevant to the work in this thesis are discussed.

1.5 bibliographic notes

Most of the works reported in this thesis can be found in peer reviewed research papers [18, 19, 20, 21, 22, 23, 24, 25]. Chapter 4 is published in [18, 19, 20]. Chapter 5 can be found in [21, 22, 23]. Chapter 6 appeared in [24, 25].

Chapter 2

Background and Literature Review

It has been a decade since user cooperation was introduced by a landmark paper by [1]. Prior to this, the concept of cooperation appeared in the Seventies, with the work of [26]. Recently in the literature, a considerable number of useful design ideas for wireless cooperative communication systems have been proposed. This significant attention is due to the degrees of freedom of design in cooperative communication.

In this chapter, we briefly introduce the background subjects related to our research. These include classification of cooperative communication schemes, opportunistic relaying, and adaptive modulation. Then, we review development in the major issues associated with cooperative communication, specifically in adaptive transmission and relay selection.

2.1 Background

2.1.1 Classification of Cooperative Communication schemes

Cooperative diversity schemes can be classified based on the processing of information at the relay node as either regenerative (e.g., decode-and-forward (DF) protocol) and non-regenerative (e.g., amplify-and-forward (AF) protocol). Further classification can be attained based on the mode of operation at the relay node as either adaptive or non-adaptive relaying schemes. Fixed relaying is a non-adaptive relaying scheme, while selection relaying and incremental relaying are two adaptive relaying schemes. The definitions of these relaying schemes are as follows:

1. Fixed Relaying: This represents the simplest scheme among the available relaying schemes, because the relay node always forwards the amplified received signal in the AF protocol and forwards the decoded and re-encoded received signal from the source node in the DF protocol [27].

2. Selection Relaying: The idea behind this scheme is based on the forwarding of the received signal by the relay node when either the channel quality exceeds a certain limit or no error is detected for the case of DF protocol [5].

3. Incremental Relaying: This scheme outperforms the previous two schemes. The relay node forwards only if a request is made by the destination node. It is characterized by efficient utilization of the resources, and hence it achieves better performance [4].

2.1.2 Opportunistic Relaying

Opportunistic relaying (OR) [17] is an efficient relay selection scheme that achieves the diversity order of the distributed space-time coding (DSTC) system [3]. The success of this scheme is due to the simple process of selection, which can be directly implemented in existing wireless systems. In general, relay selection schemes exploit the channel state information (CSI) of the relay path and/or other performance metrics in order to define the selection criteria. OR considers only the CSI, while other schemes take account of the bit error rate (BER) or outage probability in order to optimize power, spectral efficiency, or delay. Fig. 2.1 illustrates the selection process of OR, its selection criterion, and the overall communication process for one data burst. The selection criterion depends on the estimate of the end-to-end SNR of each relay path, which can be obtained by using ready-to-send (RTS) and clear-to-send (CTS) signaling. The relay node is selected if it has the best end-to-end path quality.

2.1.3 Adaptive Modulation

In adaptive modulation, the destination node needs to estimate the received SNR and feed this information back to the source node. The modulation mode selection is based on predesigned target performance. This predesigned target performance, which can be represented by the target BER, partitions the range of SNR into regions $[\gamma_n,\gamma_{n+1})$, where each region has a spectral efficiency n which corresponds to one of the modulation modes used (e.g., M-ary quadrature amplitude modulation (M-QAM) with $n = 2, 3..., N$ b/s/Hz where N is the maximum spectral efficiency). If SNR $< \gamma_2$, no transmission takes place, and the system is declared to be under an outage condition, and for this reason $n = 0$. In M-QAM with coherent detection and Gray coding, BER can be approximated as [28]

$$\texttt{BER}(n,\gamma) = \frac{2(\sqrt{2^n}-1)}{n\sqrt{2^n}} Q\left(\sqrt{\frac{3\gamma}{2^n-1}}\right), \quad n \geq 2 \tag{2.1}$$

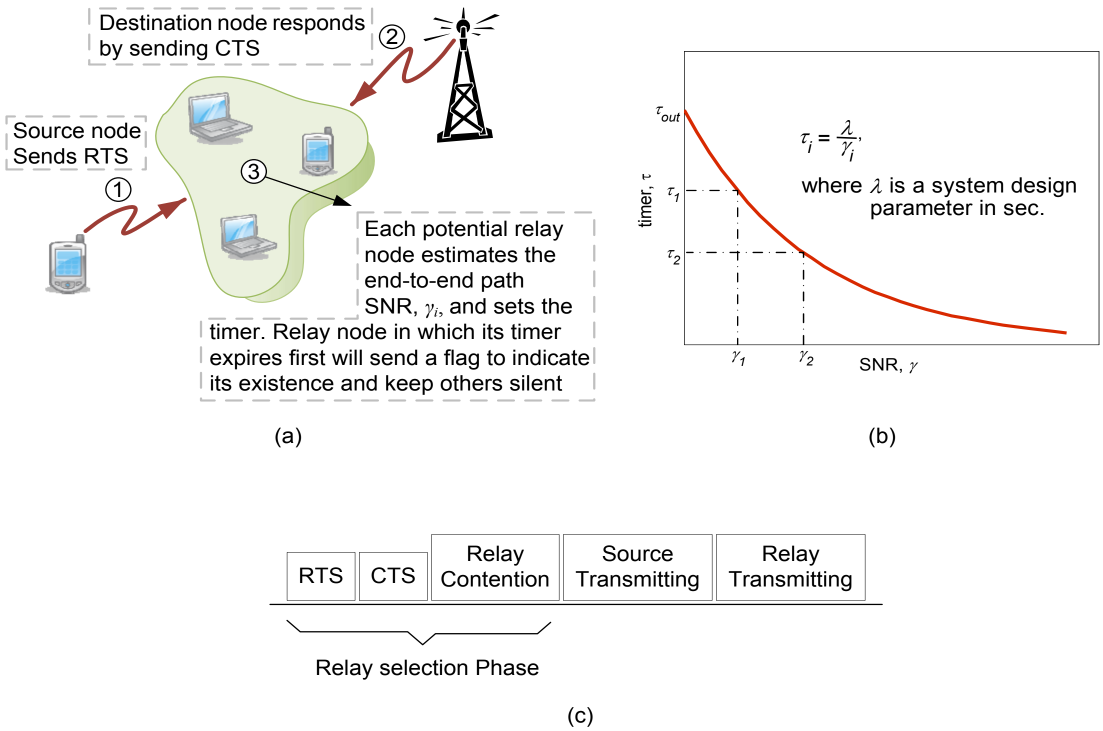

Figure 2.1: a) Selection process of opportunistic relaying; b) Selection criteria; and c) The overall communication process for one data burst.

where $Q(\cdot)$ is the Gaussian Q-function defined as $Q(x) = \int_x^\infty \frac{1}{\sqrt{2\pi}} e^{-y^2/2} dy$. Then the switching thresholds are given by

$$\gamma_n = \frac{2^n - 1}{3}\left(Q^{-1}\left(\frac{n\sqrt{2^n}\text{BER}_T}{2(\sqrt{2^n} - 1)}\right)\right)^2, \quad 2 \leq n \leq N \tag{2.2}$$

and $\gamma_{N+1} = \infty$.

2.2 Literature Review

2.2.1 Adaptive Transmission in Cooperative Communication Systems

Adaptive transmission has been investigated extensively in the past without considering cooperative communications (e.g., [29, 30, 31, 32, 33, 34, 35]), whereas only a few works have been done on the joint design of cooperative diversity with adaptive transmission. In [36], single-relay coded cooperative schemes with adaptive modulation are studied under large-scale fading only. Simulation results show improvement in the throughput compared to that of direct transmission. In [37], an adaptive cooperative technique is introduced in order to optimize energy consumption. In this study, the performance improvement comes from incorporating a user's location to determine a useful cooperation area, but the case when cooperation is not useful is not included. This problem is considered in [38], where cooperation is used only when direct link quality is not good enough to achieve the target spectral efficiency. The switching criterion used in this work depends on the mutual information of the direct link. In [39], the main objective of the work is to increase the reliability of the conventional direct transmission with adaptive modulation by using the cooperative transmission mode only when the direct link is under an outage condition. In [40], the channel capacity of DF and AF schemes with adaptive modulation is evaluated. This evaluation considers the optimal power and rate adaptation scenario, and the optimal rate adaptation and constant transmit power scenario which were adopted from [41]. Results show that the DF scheme outperforms the AF scheme when both power and rate values are optimized; however, comparing the two scenarios together under the DF scheme shows no effect in optimizing power at a high average SNR. In [42], a modulation-adaptive DF scheme is introduced. Three conditions are defined based on the resulting BER, and thus there are three modes of operation: direct transmission, cooperative, and direct with retransmission. The drawback of this scheme is the complexity of detection, since the destination may receive different modulations from the source and relay nodes during cooperative transmission mode. In [43] and [27], the performance of cooperative communication system with adaptive modulation is studied. The former investigates the throughput for single relay, while the latter considers a multiple-relay system in which an upper bound for the SNR of the relay path is used to derive the outage probability, average spectral efficiency, and average error rate of the AF fixed relaying scheme under Rayleigh fading channels. Results show a reduction in the spectral efficiency as the number of relay nodes increases, since orthogonal transmissions are required.

Adaptive transmission under an orthogonal frequency division multiplexing (OFDM) system has shown some interest. In [44], a link adaptation and link selection method is proposed for a single user in a wireless relay network. This work aims to allow the overall throughput to be always larger than or equal to that of transmission without relaying and non-adaptive transmission, but it does not show how the BER of this adaptive method performs. In [45] and [46], the bit loading in OFDM cooperative system is studied. Both approaches aim to minimize the transmit power consumption subject to the target throughput. In [45], the resource allocation problem for a cooperative OFDM system is investigated. It is shown that energy can be minimized by selecting either the direct or cooperative mode that has the better channel gain. The switching policy is based only on the channel gain of the direct link and the effective channel gain of the relay path. In [46], a single-relay OFDM cooperative system is considered, in which power allocation policies are proposed to improve transmit power efficiency and link performance. However, by considering maximizing the spectral efficiency, these power allocation policies may allocate zero power to the relay node, which means that cooperation is useless in some cases.

2.2.2 Relay Selection

This section emphasizes the related works in the literature regarding relay selection. OR is proposed in [17], in which the best relay is selected based on a quality policy among the available relay nodes. This opportunistic relaying is adopted in [47] in order to study the performance of an AF cooperative system with relay selection and adaptive modulation. The aim of [47] is to increase spectral efficiency by exploiting cooperative transmission when the direct link experiences an outage. This mode of operation is not optimal in terms of maximizing spectral efficiency; however, it reduces the complexity of the system. In [17], a diversity order of opportunistic relaying scheme is derived and proven to be similar to that of DSTC system without synchronization requirement, but the scheme requires the CSI of each relay channel. This channel state information is studied by [48], in which the same diversity order can be achieved with less information exchange. In [49], an extension of [17] is presented under an aggregate power constraint. In [50], the relay selection rule based on the location of the node is demonstrated. However, distance is not the only factor for representing a quality of channel, especially for the multipath fading scenario. In [51], a selection cooperation (SC) scheme is proposed. This scheme outperforms DSTC system in terms of outage probability under high SNR assumption. The work in [52] was the first research to consider hybrid-ARQ in cooperative relaying. The results provide second-order diversity but not full diversity. There are also several research works on the performance analysis of relay selection schemes using either AF or DF protocols [53, 54, 55, 56]. In [53], closed-form expressions for tight lower bounds of the symbol error probability and outage probability are derived for AF multiple-relay CD system with OR. In [54], a diversity order analysis of the DF cooperative system is introduced with OR. The analysis combines the cooperative maximum ratio with the relay selection. The work by [55] provides comparisons between OR and SC schemes in terms of outage and bit error probability (BEP) for the DF protocol. Numerical results show that SC has a slightly lower outage probability. However, for BEP, both schemes may outperform one another. In [56], a closed-form of the outage probability is derived for AF relaying scheme with OR. This work does not include the direct link from source to destination. Furthermore, the control signaling is reduced by considering only relays that have end-to-end channel qualities larger than the target threshold. However, the end-to-end channel qualities should be reported by all these relays, which requires more control signaling. In [57] and [58], outage probability is derived for AF OR under a high SNR scenario and DF OR, respectively. The same cooperative system as in [58] is considered in [59] to study the effect of the CSI on the average symbol error probability. In [60], an adaptive selection cooperative scheme is proposed for ad hoc networks. The objective of this scheme is to increase throughput, reduce transmission power, and increase the lifetime of the network. It is a modification of the SC scheme [51]. In this study, power saving is accomplished first by letting a relay node not transmit if the received data is incorrect, and second by reducing the overall outage probability. Also, the lifetime of the network is increased by selecting a relay node that has maximum residual energy. Similar objectives are investigated in cooperative wireless sensor network [61], but with the OR scheme. It basically incorporates power control at the physical layer. In [62], a new relay selection method is introduced based on a threshold value. This threshold value is exploited to decide whether to use a direct link or to let the best relay cooperate with the source node. The disadvantage of this method is the difficulty in optimizing the threshold value, which makes it unrealistic to implement. In [63], a new selection protocol called ”switch and examine node selection” is proposed, which was adopted from the switching diversity method proposed in [64]. This protocol is a suboptimal relay selection scheme; however, it is characterized by low complexity, and power saving.

Other research works investigate relay selection from different perspectives [65, 66, 67, 68] by including factors such as constraint on the resources of the relay node in the relay selection criterion. In [65], a new fair relay selection strategy is proposed which considered power consumption of the relay nodes. The fairness is basically defined as to achieve equal average power consumption over all available relay nodes when the AF scheme is used. The approach used to achieve the required fairness requires the knowledge of the average SNRs of the relay path for all available relay nodes, a central controller to numerically calculate a weight coefficient for each relay node, and control channels to exchange the average SNRs and the weight coefficients. The fairness strategy is adopted in [66] and [67], but with the DF protocol. In [68], a selection method is proposed to consider how much power a node should consume for helping other nodes and how much power other nodes should contribute to a node.

Chapter 3

System Description

The previous chapter provided the necessary general background for the research problem described in Chapter 1. In this chapter, in order to avoid redundant information about the system model, we describe the general model and its parameters with emphasis on the required setting in each chapter. Also, we state the assumptions used throughout the thesis and describe the channel model in terms of the cumulative distribution function (CDF) and the probability density function (PDF) of the signal-to-noise ratio (SNR) of each link. Finally, we present the signal transmission and reception models for both decode-and-forward (DF) and amplify-and-forward (AF) protocols.

3.1 System Model

We consider a cooperative wireless communication system consisting of L relay nodes (R_i, i = 1,2, ..., L), where only one relay is selected to cooperate with source node S to transfer the information signal to destination node D, as shown in Fig. 3.1. Before we further

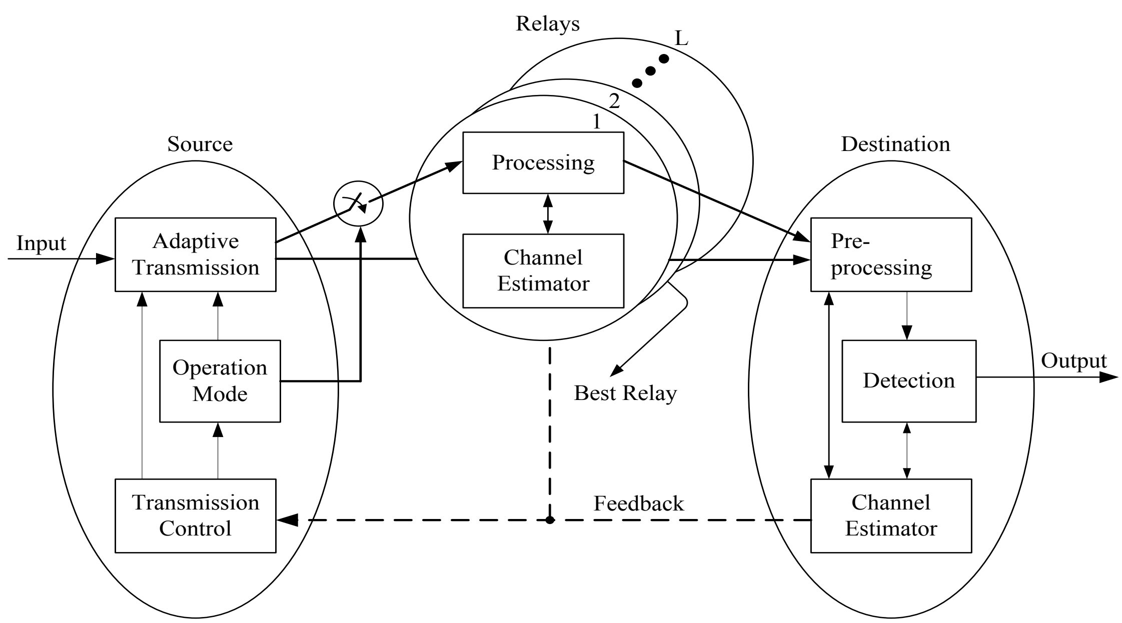

Figure 3.1: Wireless cooperative system with adaptive transmission capability.

describe the system, the following assumptions are made:

A1) The links between nodes are modeled as independent block Rayleigh fading channels; i.e., the channel gain does not change during the transmission of one frame

A2) The channel is assumed to be reciprocal [61, 69]; i.e., the uplink and downlink gains are the same

A3) The transmit power from the source and relay nodes are constant. Although varying the power in conjunction with varying the rate can be done, a minimal gain is expected [29]

A4) For the DF protocols, the relay node is equipped with an error detection technique such as cyclic redundancy; therefore, the relay node is kept silent in the second phase of transmission if an error is detected [46, 70]

For cooperative transmission mode, a two-phase transmission protocol is required. In the first phase, the source node broadcasts, and the relay and destination nodes listen, so it can be called a listening phase. In the second phase, the relay node forwards the received signal to the destination node where the two signals from the source and relay nodes are combined using maximum ratio combining (MRC). The following settings are required by the proposed schemes in the upcoming chapters:

- For single-relay system in Sections 4.1 and 5.1, since $L = 1$, the best relay node becomes the primary one
- For Chapters 4 and 5, since adaptive transmission technique is used, the feedback channel is required
- For Section 4.2 and Chapter 6, the cooperative transmission is used all the time, in this case the switch in Fig. 3.1 is "ON" at all times

3.2 Channel Model

For the independent Rayleigh fading channels, the CDF of the output SNR for each link from node i to node j is given by

$$F_{\gamma_{ij}}(x) = 1 - e^{-x/\bar{\gamma}_{ij}}, \tag{3.1}$$

where $\bar{\gamma}_{ij} = \mathrm{E}[\gamma_{ij}]$, and $\mathrm{E}(.)$ is the expectation operator. The PDF is given by

$$f_{\gamma_{ij}}(x) = \frac{1}{\bar{\gamma}_{ij}} e^{-x/\bar{\gamma}_{ij}}. \tag{3.2}$$

3.3 Signal Transmission and Reception

3.3.1 Decode-and-Forward Protocol

In the DF protocol, the transmission starts with broadcasting source information $x(t)$ to the selected relay and destination nodes in the first phase. The received signals at the selected relay and destination nodes are

$$y_{SR_b}(t) = h_{SR_b}x(t) + n_{SR_b}(t), \qquad t = 1, 2, ...\tfrac{T}{2}, \tag{3.3}$$

$$y_{SD}(t) = h_{SD}x(t) + n_{SD}(t), \qquad t = 1, 2, ...\tfrac{T}{2}, \tag{3.4}$$

respectively, where h_{SR_b} and h_{SD} are the fading coefficients between the source and the selected relay nodes and the source and destination nodes, respectively, $n_{SR_b}(t)$ and $n_{SD}(t)$ are the additive white Gaussian noise (AWGN) terms at the selected relay and destination nodes, respectively, with a variance of N_o for all links, and T is a time-slot duration. In the second phase, the selected relay node detects, encodes, and retransmits the received signal to the destination node. Then the received signal at the destination node can be written as

$$y_{R_bD}(t) = h_{R_bD}\hat{x}(t) + n_{R_bD}(t), \qquad t = \tfrac{T}{2} + 1, ..., T, \tag{3.5}$$

where h_{R_bD} is the fading coefficient between the selected relay and destination nodes, n_{R_bD} is the AWGN term at the destination node, and $\hat{x}(t)$ is the transmitted signal from the selected relay node to the destination node, which is the original source signal *x(t)* if there is no error detected. With MRC, the instantaneous DF received SNR becomes

$$\gamma_{DF}^{b} = \gamma_{SD} + \gamma_{R_b D}, \tag{3.6}$$

where γ_{SD} and $\gamma_{R_b D}$ are the instantaneous SNRs between the source and destination nodes, and the selected relay and destination nodes, respectively. If the cooperative transmission is not activated, the received signal at the destination node is

$$y_{SD}(t) = h_{SD}x(t) + n_{SD}(t), \qquad t = 1, 2, ..., T. \tag{3.7}$$

3.3.2 Amplify-and-Forward Protocol

In the AF protocol, the first phase is similar to DF protocol. So (3.3) and (3.4) can be used to represent the received signals at the selected relay and destination nodes. In the second phase, the selected relay node amplifies the received signal, $y_{SR_b}(t)$, and transmits it to the destination node. The received signal at the destination node is

$$y_{R_b D}(t) = G_{R_b} h_{R_b D} y_{SR_b}(t) + n_{R_b D}(t), \qquad t = \tfrac{T}{2} + 1, ., T, \tag{3.8}$$

where G_{R_b} is the amplifying gain which can be defined as

$$G_{R_b}^2 = \frac{P_S}{P_S |h_{SR_b}|^2 + N_o}, \tag{3.9}$$

where P_S is the average symbol power. Similarly, after the completion of the two phases, destination node detects the two received signals from the source and the selected relay nodes. With MRC, the instantaneous AF received SNR becomes

$$\gamma_{AF}^{b} = \gamma_{SD} + \gamma_{R_b}, \tag{3.10}$$

where γ_{R_b} is the end-to-end SNR of the selected relay path which can be written as

$$\gamma_{R_b} = \frac{\gamma_{SR_b}\gamma_{R_bD}}{\gamma_{SR_b} + \gamma_{R_bD} + 1}, \tag{3.11}$$

where γ_{SR_b} is the instantaneous SNR between the source and selected relay nodes. For derivation tractability, (3.11) can be approximated by its upper bound [71, 53]

$$\gamma_{R_b} \leq \gamma_{SR_bD} = \min(\gamma_{SR_b}, \gamma_{R_bD}), \tag{3.12}$$

where γ_{SR_bD} is the upper bound end-to-end SNR of the selected relay path.

If the cooperative transmission is not activated, the source node transmits the information signals using the full time-slot duration, T, and then the received signal at the destination node is given by (3.7).

Chapter 4

DF Adaptive Cooperative System with Variable-Rate Transmission

Adaptivity in wireless communication systems is very important in order to meet the demand for higher data rates in the time-varying channel and carefully exploit the limited available resources. Adaptivity could take different forms: channel adaptation and/or quality of service (QoS) adaptation. Channel adaptation is the ability of the system to adapt to variations in channel propagation and network topologies. QoS adaptation is the ability of the system to respond to different and varying QoS requirements. During the last two decades, several factors have contributed to the interest in adaptive methods: the growing demand for spectrally efficient communication, the availability of fast and powerful hardware devices, and improvement in prediction techniques.

Adaptivity is accomplished in two ways. In the first method, the system adapts to channel variations by selecting a higher modulation level if the channel is in good condition, and vice versa. In the second method, it is achieved by using the adaptive cooperative schemes, in which the relay node cooperates with the source node if the target performance can be achieved. The chapter is divided into two main sections. In Section 4.1, we start with a single-relay system where two decode-and-forward (DF) adaptive cooperative schemes are introduced. The first scheme is characterized by minimizing the average bit error rate (ABER), which is called the minimum error rate scheme (MERS), and the second scheme is characterized by maximizing the average spectral efficiency, which is called the maximum spectral efficiency scheme (MSES). Then, we derive the average spectral efficiency, the ABER, and the outage probability for both proposed schemes. This leads us to the evaluation of the performance of these two schemes by presenting some numerical examples supported by computer simulation in order to verify our analytical results. In Section 4.2, we move to a multiple-relay scenario where the relay selection technique is used to further enhance the performance of the previously proposed schemes. A variable-rate based relay selection (VRRS) scheme is first introduced by defining the selection strategy, and then the mode of operation is described. In addition, we analyze the performance in terms of the average spectral efficiency and ABER. In addition, the system is evaluated by presenting some numerical examples. Finally, we summarize the chapter by providing some comments in Section 4.3.

4.1 Single-Relay System

4.1.1 Minimum Error Rate Scheme

In wireless cooperative systems, the system design parameters can be traded against one another based on the target objective; for example, rate versus outage, diversity versus multiplexing gains, capacity versus coverage, or any balance between them. Also, the tradeoff can be between the complexity of the design and the achievable performance. The fixed relaying scheme can achieve full diversity [27], but the system suffers low spectral efficiency due to orthogonality problem. The adaptive DF cooperative scheme proposed in

[42, 72] achieves good performance, but increases the operation complexity by allowing two modulation modes to be received by the destination node. Furthermore, in the DF scheme that employs variable-rate transmission, it is not feasible to select the best transmission rate based only on the received effective signal-to-noise ratio (SNR) at the destination node γ_{DF}, because this transmission rate may not also be supported by the source-relay link. Therefore, the objective of the minimum error rate scheme is to improve the performance of the cooperative wireless system under the DF protocol that considers a feasible design of variable-rate transmission and less complexity. Then, we can define the following strategy:

1) If $\gamma_{SR} < \gamma_{th}$, do not cooperate,

where γ_{SR} is the SNR of the source-relay link, and γ_{th} is the minimum switching threshold SNR in which the link can support the transmission (i.e., for the case of M-ary quadrature amplitude modulation (M-QAM), $\gamma_{th} = \gamma_2$)

2) If $\gamma_{SR} \geq \gamma_{th}$, cooperate.

The output SNR of this scheme can be defined as

$$\gamma_{MERS} = \begin{cases} \gamma_{SD}, & \gamma_{SR} < \gamma_{th}, \\ \gamma_{\min}, & \gamma_{SR} \geq \gamma_{th}, \end{cases} \tag{4.1}$$

where $\gamma_{\min} = \min(\gamma_{SR}, \gamma_{DF})$, and $\gamma_{DF} = \gamma_{SD} + \gamma_{RD}$.

4.1.2 Derivation of Performance Metrics of MERS

4.1.2.1 Average Spectral Efficiency

The average spectral efficiency of the MERS can be expressed as

$$\eta^{MERS} = \Pr(\gamma_{SR} < \gamma_{th}) \sum_{n=2}^{N} n\, a(n) + (1 - \Pr(\gamma_{SR} < \gamma_{th})) \sum_{m=2}^{N} \frac{m}{2} b(m), \tag{4.2}$$

where m is the spectral efficiency of the cooperative transmission and divided by two due to the half duplex constraint. $a(n)$ and $b(m)$ are the probability that γ_{SD} and $\gamma_{\min}$ fall in region n and m, respectively. Then $a(n)$ can be represented as

$$a(n) = \int_{\gamma_n}^{\gamma_{n+1}} f_{\gamma_{SD}}(x)\, dx = F_{\gamma_{SD}}(\gamma_{n+1}) - F_{\gamma_{SD}}(\gamma_n), \tag{4.3}$$

where $f_{\gamma_{SD}}(x)$ is the probability density function (PDF) of γ_{SD}, and $F_{\gamma_{SD}}(x)$ is its cumulative distribution function (CDF). Similarly, $b(m)$ can be represented as

$$\begin{aligned} b(m) &= \int_{\gamma_m}^{\gamma_{m+1}} f_{\gamma_{\min}}(z|\gamma_{SR} > \gamma_{th})\, dz \\ &= F_{\gamma_{\min}}(\gamma_{m+1}|\gamma_{SR} > \gamma_{th}) - F_{\gamma_{\min}}(\gamma_m|\gamma_{SR} > \gamma_{th}), \end{aligned} \tag{4.4}$$

where $f_{\gamma_{\min}}(z|\gamma_{SR} > \gamma_{th})$ is the conditional PDF of $\gamma_{\min}$ given that γ_{SR} is greater than the minimum switching threshold, γ_{th}, and $F_{\gamma_{\min}}(z|\gamma_{SR} > \gamma_{th})$ is its conditional CDF. From Appendix A, the conditional CDF of γ_{min} and its corresponding conditional PDF can be given by

$$F_{\gamma_{\min}}(z|\gamma_{SR} > \gamma_{th}) = \begin{cases} 1 - \frac{e^{-z/\bar{\gamma}_{SR}}}{e^{-\gamma_{th}/\bar{\gamma}_{SR}}} \left[e^{-z/\bar{\gamma}_{SD}} + \frac{\bar{\gamma}_{RD}}{\bar{\gamma}_{RD}-\bar{\gamma}_{SD}} \left(e^{-z/\bar{\gamma}_{RD}} - e^{-z/\bar{\gamma}_{SD}} \right) \right], & z > \gamma_{th}, \\ 1 - e^{-z/\bar{\gamma}_{SD}} - \frac{\bar{\gamma}_{RD}}{\bar{\gamma}_{RD}-\bar{\gamma}_{SD}} \left(e^{-z/\bar{\gamma}_{RD}} - e^{-z/\bar{\gamma}_{SD}} \right), & z \le \gamma_{th}, \end{cases} \tag{4.5}$$

and

$$f_{\gamma_{\min}}(z|\gamma_{SR} > \gamma_{th}) = \begin{cases} \frac{1}{e^{-\gamma_{th}/\bar{\gamma}_{SR}}} \left[\frac{(\bar{\gamma}_{SR}+\bar{\gamma}_{RD})}{\bar{\gamma}_{SR}(\bar{\gamma}_{RD}-\bar{\gamma}_{SD})} e^{-z\left(\frac{1}{\bar{\gamma}_{SR}}+\frac{1}{\bar{\gamma}_{RD}}\right)} - \frac{(\bar{\gamma}_{SR}+\bar{\gamma}_{SD})}{\bar{\gamma}_{SR}(\bar{\gamma}_{RD}-\bar{\gamma}_{SD})} e^{-z\left(\frac{1}{\bar{\gamma}_{SR}}+\frac{1}{\bar{\gamma}_{SD}}\right)} \right], & z > \gamma_{th}, \\ \frac{1}{\bar{\gamma}_{RD}-\bar{\gamma}_{SD}} \left(e^{-z/\bar{\gamma}_{RD}} - e^{-\gamma_{th}/\bar{\gamma}_{SD}} \right), & z \le \gamma_{th}, \end{cases} \tag{4.6}$$

respectively. Substituting (4.5) into (4.4) and then substituting (4.3) into (4.2), the average spectral efficiency of the MERS can be given by

$$\begin{aligned}\eta^{MERS} &= (1 - e^{-\gamma_{th}/\bar{\gamma}_{SR}}) \sum_{n=2}^{N} n\,\psi(n, 1/\bar{\gamma}_{SD}) \\ &+ \tfrac{1}{\bar{\gamma}_{SD}-\bar{\gamma}_{RD}} \sum_{m=2}^{N} \tfrac{m}{2} \left[\bar{\gamma}_{SD}\psi(m, \tfrac{1}{\bar{\gamma}_{SR}} + \tfrac{1}{\bar{\gamma}_{SD}}) - \bar{\gamma}_{RD}\psi(m, \tfrac{1}{\bar{\gamma}_{SR}} + \tfrac{1}{\bar{\gamma}_{RD}})\right],\end{aligned} \tag{4.7}$$

where $\psi(\alpha, \beta) = e^{-\gamma_\alpha \beta} - e^{-\gamma_{\alpha+1}\beta}$.

4.1.2.2 Average Bit Error Rate

In general, the ABER can be defined as the average number of bits in error divided by the total average number of transmitted bits. Therefore, the ABER of the MERS can be expressed as

$$\text{ABER}^{MERS} = \tfrac{1}{\eta^{MERS}} \left[\Pr(\gamma_{sr} < \gamma_{th}) \cdot \sum_{n=2}^{N} n\ \text{ABER}_{a(n)} + \sum_{m=2}^{N} \tfrac{m}{2}\ \text{ABER}_{b(m)}\right], \tag{4.8}$$

where $\text{ABER}_{a(n)}$ and $\text{ABER}_{b(m)}$ are the ABER of the direct and cooperative transmissions, respectively. Then $\text{ABER}_{a(n)}$ can be written as

$$\text{ABER}_{\text{a(n)}} = \int_{\gamma_\text{n}}^{\gamma_{\text{n}+1}} \text{BER}(\text{n}, x) f_{\gamma_{\text{SD}}}(x)dx, \tag{4.9}$$

where BER(.,.) is the BER of the M-QAM which can be approximated as [28]

$$\text{BER}(n, \gamma) = \frac{2(\sqrt{2^n} - 1)}{n\sqrt{2^n}} Q\left(\sqrt{\frac{3\gamma}{2^n - 1}}\right), \quad n \geq 2, \tag{4.10}$$

where $Q(\cdot)$ is the Gaussian Q-function defined as $Q(x) = \int_x^\infty \frac{1}{\sqrt{2\pi}} e^{-y^2/2} dy$. To solve the ABER, it is necessary to define a common finite integral as

$$\Phi(\gamma_{s1}, \gamma_{s2}, \bar{\gamma}, B) = \int_{\gamma_{s1}}^{\gamma_{s2}} Q\left(\sqrt{Bx}\right) \frac{e^{-\frac{x}{\bar{\gamma}}}}{\bar{\gamma}} dx. \tag{4.11}$$

(4.11) can be solved using integration by parts as shown in Appendix C, which equals to

$$\begin{aligned} \Phi(\gamma_{s1}, \gamma_{s2}, \bar{\gamma}, B) = {} & Q\left(\sqrt{B\gamma_{s1}}\right) e^{-\gamma_{s1}/\bar{\gamma}} - \sqrt{\frac{B}{\frac{2}{\bar{\gamma}}+B}} Q\left(\sqrt{2\gamma_{s1}\left(\frac{1}{\bar{\gamma}} + \frac{B}{2}\right)}\right) \\ & - Q\left(\sqrt{B\gamma_{s2}}\right) e^{-\gamma_{s2}/\bar{\gamma}} + \sqrt{\frac{B}{\frac{2}{\bar{\gamma}}+B}} Q\left(\sqrt{2\gamma_{s2}\left(\frac{1}{\bar{\gamma}} + \frac{B}{2}\right)}\right), \end{aligned} \tag{4.12}$$

then, the ABER of the direct transmission can be given by

$$\mathrm{ABER}_{\mathrm{a(n)}} = \mathrm{A}_n \Phi(\gamma_n, \gamma_{n+1}, \bar{\gamma}_{SD}, B_n), \tag{4.13}$$

where $A_n = 2(\sqrt{2^n} - 1)/(n\sqrt{2^n})$ and $B_n = 3/(2^n - 1)$.

For the DF protocol, to have error free transmission, there must be a successful transmission from source-relay link, then a successful transmission after combining the two links from the source and relay nodes. Hence, the ABER at the destination node can be expressed as [46]

$$\mathrm{ABER}_{b(m)} = \mathrm{ABER}_{b(m)}^{SR} \cdot \mathrm{ABER}_{b(m)}^{SD} + (1 - \mathrm{ABER}_{b(m)}^{SR}) \cdot \mathrm{ABER}_{b(m)}^{DF}. \tag{4.14}$$

The ABER at the relay node, $\mathrm{ABER}_{b(m)}^{SR}$, should be calculated based on whether γ_{SR}

is the minimum or not, therefore $\text{ABER}_{b(m)}^{SR}$ can be written as

$$\begin{aligned}\text{ABER}_{b(m)}^{SR} = &\int_{\gamma_m}^{\gamma_{m+1}} \text{BER}(m,z)(1-F_{\gamma_{DF}}(z))f_{\gamma_{SR}}(z)\,dz \\ &+ \int_{\gamma_m}^{\gamma_{m+1}}\int_{z}^{\infty} \text{BER}(m,y)f_{\gamma_{SR}}(y)f_{\gamma_{DF}}(z)\,dydz.\end{aligned} \tag{4.15}$$

Similarly,

$$\begin{aligned}\text{ABER}_{b(m)}^{DF} = &\int_{\gamma_m}^{\gamma_{m+1}} \text{BER}(m,z)(1-F_{\gamma_{SR}}(z))f_{\gamma_{DF}}(z)\,dz \\ &+ \int_{\gamma_m}^{\gamma_{m+1}}\int_{z}^{\infty} \text{BER}(m,y)f_{\gamma_{DF}}(y)f_{\gamma_{SR}}(z)\,dydz,\end{aligned} \tag{4.16}$$

and

$$\text{ABER}_{b(m)}^{SD} = \int_{0}^{\infty} \text{BER}(m,x)f_{\gamma_{\text{SD}}}(x)dx. \tag{4.17}$$

(4.15), (4.16), and (4.17) are solved and simplified as

$$\begin{aligned}&\text{ABER}_{b(m)}^{SR} \\ &= \frac{A_m}{\bar{\gamma}_{SD}-\bar{\gamma}_{RD}}\Bigg[\bar{\gamma}_{SD}\Phi(\gamma_m,\gamma_{m+1},\bar{\gamma}_S,B_m) - \bar{\gamma}_{SD}\sqrt{\frac{B_m}{\frac{2}{\bar{\gamma}_{SR}}+B_m}}\Phi(\gamma_m,\gamma_{m+1},\bar{\gamma}_{SD},C_m) \\ &+\bar{\gamma}_{RD}\sqrt{\frac{B_m}{\frac{2}{\bar{\gamma}_{SR}}+B_m}}\Phi(\gamma_m,\gamma_{m+1},\bar{\gamma}_{RD},C_m) - \bar{\gamma}_{RD}\Phi(\gamma_m,\gamma_{m+1},\bar{\gamma}_S RD,B_m)\Bigg],\end{aligned} \tag{4.18}$$

$$\begin{aligned}&\text{ABER}_{b(m)}^{DF} \\ &= \frac{A_m}{\bar{\gamma}_{SD}-\bar{\gamma}_{RD}}\Bigg[\bar{\gamma}_{SD}\Phi(\gamma_m,\gamma_{m+1},\bar{\gamma}_S,B_m) - \bar{\gamma}_{SD}\sqrt{\frac{B_m}{\frac{2}{\bar{\gamma}_{SD}}+B_m}}\Phi(\gamma_m,\gamma_{m+1},\bar{\gamma}_{SR},D_m) \\ &+\bar{\gamma}_{RD}\sqrt{\frac{B_m}{\frac{2}{\bar{\gamma}_{RD}}+B_m}}\Phi(\gamma_m,\gamma_{m+1},\bar{\gamma}_{SR},E_m) - \bar{\gamma}_{RD}\Phi(\gamma_m,\gamma_{m+1},\bar{\gamma}_S RD,B_m)\Bigg],\end{aligned} \tag{4.19}$$

and

$$\text{ABER}_{b(m)}^{SD} = A_m \left(1 - \sqrt{\frac{B_m}{\frac{2}{\bar{\gamma}_{SD}} + B_m}}\right), \tag{4.20}$$

respectively, where

$$\begin{aligned}
&\bar{\gamma}_S = \bar{\gamma}_{SD}\bar{\gamma}_{SR}/(\bar{\gamma}_{SD} + \bar{\gamma}_{SR}),\\
&\bar{\gamma}_{SRD} = \bar{\gamma}_{SR}\bar{\gamma}_{RD}/(\bar{\gamma}_{SR} + \bar{\gamma}_{RD}),\\
&C_m = 2(1/\bar{\gamma}_{SR} + B_m/2),\\
&D_m = 2(1/\bar{\gamma}_{SD} + B_m/2), \text{ and}\\
&E_m = 2(1/\bar{\gamma}_{RD} + B_m/2).
\end{aligned}$$

Substituting (4.18), (4.19), and (4.20) into (4.14) and then substituting (4.13) into (4.8), a closed-form expression for the ABER of the MERS can be obtained.

4.1.2.3 Outage Probability

In general, the outage probability under adaptive modulation transmission can be defined as the probability when the output SNR is below the minimum switching threshold. In the MERS, the outage probability depends on the output SNR from source-relay link, γ_{SR} and the combined output SNR from source-destination and relay-destination links, γ_{DF}. Hence, the outage probability of the MERS can be obtained as

$$\begin{aligned}
P_{out}^{MERS} &= \Pr[\gamma_{SD} < \gamma_{th} | \gamma_{SR} < \gamma_{th}] \cdot \Pr(\gamma_{sr} < \gamma_{th})\\
&+ \Pr[\gamma_{\min} < \gamma_{th} | \gamma_{SR} \geq \gamma_{th}] \cdot \Pr[\gamma_{SR} \geq \gamma_{th}]\\
&= \Pr[\gamma_{SD} < \gamma_{th}] \cdot \Pr[\gamma_{SR} < \gamma_{th}]\\
&+ \Pr[\gamma_{DF} < \gamma_{th}] \cdot (1 - \Pr[\gamma_{SR} < \gamma_{th}]).
\end{aligned} \tag{4.21}$$

Substituting the CDF of the combined output SNR at the destination node γ_{DF}, given by (A.2) from Appendix A, into (4.21), a closed-form expression for the outage probability of the MERS can be given by

$$P_{out}^{MERS} = 1 - e^{-\gamma_{th}/\bar{\gamma}_{SD}} - \frac{\bar{\gamma}_{RD}}{\bar{\gamma}_{SD}-\bar{\gamma}_{rd}} \left(e^{-\gamma_{th}(\frac{1}{\bar{\gamma}_{SD}}+\frac{1}{\bar{\gamma}_{SR}})} - e^{-\gamma_{th}(\frac{1}{\bar{\gamma}_{SR}}+\frac{1}{\bar{\gamma}_{RD}})} \right). \tag{4.22}$$

4.1.3 Maximum Spectral Efficiency Scheme

The objective of the maximum spectral efficiency scheme is to enhance the spectral efficiency of the MERS by avoiding cooperative transmission whenever it is not necessary (i.e., the direct transmission has a higher transmission rate). Hence, the multiplexing gain is traded against the diversity gain. Based on that, we can define the following strategy:

1) If $\gamma_{SD} \geq \gamma_{\lfloor \frac{N}{2} \rfloor +1}$, do not cooperate,

where $\lfloor k \rfloor$ is the largest integer less than or equal k.

2) If $\gamma_{SD} < \gamma_{\lfloor \frac{N}{2} \rfloor +1}$, cooperate if $\gamma_{\min} \geq \gamma_T$,

where γ_T is the switching threshold SNR, used to guarantee that the cooperative transmission can maximize the spectral efficiency. Then, the output SNR of this scheme, γ_{MSES}, can be defined as

$$\gamma_{MSES} = \begin{cases} & \text{if } (\gamma_{SD} \geq \gamma_{\lfloor \frac{N}{2} \rfloor +1}), \quad \text{or} \\ \gamma_{SD}, & \text{if } (\gamma_n \leq \gamma_{SD} \leq \gamma_{n+1} \text{ and} \\ & \gamma_{\min} < \gamma_T,\ n = 2, ..., \lfloor \frac{N}{2} \rfloor), \\ \gamma_{\min}, & \text{otherwise.} \end{cases} \tag{4.23}$$

For discrete variable-rate transmission, switching threshold γ_T can be set to be equal to γ_{2n} in order to take into account the effect of half-duplex transmission mode.

4.1.4 Derivation of Performance Metrics of MSES

4.1.4.1 Average Spectral Efficiency

The average spectral efficiency of the MSES can be expressed as

$$\eta^{MSES} = \sum_{n=\left\lfloor \frac{N}{2} \right\rfloor+1}^{N} n\,a(n) + \sum_{n=2}^{\left\lfloor \frac{N}{2} \right\rfloor} n\,c(n) + \sum_{\substack{n=0\\ n\neq 1}}^{\left\lfloor \frac{N}{2} \right\rfloor} \sum_{m=I^n}^{N} \frac{m}{2} d(n,m), \tag{4.24}$$

where $c(n)$ is the probability that $\gamma_{SD} < \gamma_{\left\lfloor \frac{N}{2} \right\rfloor+1}$ and $\gamma_{\min} < \gamma_T$, $d(n,m)$ is the probability that $\gamma_{SD} < \gamma_{\left\lfloor \frac{N}{2} \right\rfloor+1}$ and $\gamma_{\min} \geq \gamma_T$, and $I^n = 2$ if $n = 0$ and $I^n = 2\text{n}$ if $n \neq 0$. Then $c(n)$ can be represented as

$$c(n) = F_{\gamma_{\min},\gamma_{SD}}(\gamma_T, \gamma_{n+1}) - F_{\gamma_{\min},\gamma_{SD}}(\gamma_T, \gamma_n), \tag{4.25}$$

where the joint CDF of $\gamma_{\min}$ and γ_{SD}, $F_{\gamma_{\min},\gamma_{SD}}(z,x)$, and its corresponding joint PDF are derived in Appendix B, and given by

$$F_{\gamma_{\min},\gamma_{SD}}(z,x) = \begin{cases} 1 - e^{-x/\bar{\gamma}_{SD}} - \frac{\bar{\gamma}_{RD}}{\bar{\gamma}_{RD}-\bar{\gamma}_{SD}} e^{-z(\frac{1}{\bar{\gamma}_{SR}}+\frac{1}{\bar{\gamma}_{RD}})} \left(1 - e^{-x(\frac{1}{\bar{\gamma}_{SD}}+\frac{1}{\bar{\gamma}_{RD}})}\right), & x \leq z, \\ 1 - e^{-x/\bar{\gamma}_{SD}} + e^{-z/\bar{\gamma}_{SR}} e^{-x/\bar{\gamma}_{SD}} + \frac{1}{\bar{\gamma}_{RD}-\bar{\gamma}_{SD}} \Big[\bar{\gamma}_{SD} e^{-z(\frac{1}{\bar{\gamma}_{SR}}+\frac{1}{\bar{\gamma}_{SD}})} & \\ -\bar{\gamma}_{RD} e^{-z(\frac{1}{\bar{\gamma}_{SR}}+\frac{1}{\bar{\gamma}_{RD}})}\Big], & x > z, \end{cases} \tag{4.26}$$

and

$$f_{\gamma_{\min},\gamma_{SD}}(z,x)=\begin{cases}\frac{\bar{\gamma}_{SR}+\bar{\gamma}_{RD}}{\bar{\gamma}_{SR}(\bar{\gamma}_{RD}-\bar{\gamma}_{SD})}e^{-z(\frac{1}{\bar{\gamma}_{SR}}+\frac{1}{\bar{\gamma}_{RD}})}\left(1-e^{-x(\frac{1}{\bar{\gamma}_{SD}}-\frac{1}{\bar{\gamma}_{RD}})}\right), & x\leq z,\\ \frac{1}{\bar{\gamma}_{SR}(\bar{\gamma}_{RD}-\bar{\gamma}_{SD})}\Big[(\bar{\gamma}_{SR}+\bar{\gamma}_{RD})\,e^{-z(\frac{1}{\bar{\gamma}_{SR}}+\frac{1}{\bar{\gamma}_{RD}})} & \\ -\,(\bar{\gamma}_{SR}+\bar{\gamma}_{SD})\,e^{-z(\frac{1}{\bar{\gamma}_{SR}}+\frac{1}{\bar{\gamma}_{SD}})}\Big]-\frac{1}{\bar{\gamma}_{SR}}e^{-z/\bar{\gamma}_{SR}}\;e^{-x/\bar{\gamma}_{SD}}, & x>z,\end{cases} \tag{4.27}$$

respectively. $d(n,m)$ is the probability of activation the cooperative transmission which can be represented as

$$\begin{aligned}d(n,m)&=F_{\gamma_{\min},\gamma_{SD}}(\gamma_{m+1},\gamma_{n+1})-F_{\gamma_{\min},\gamma_{SD}}(\gamma_{m+1},\gamma_{n})\\&\quad-F_{\gamma_{\min},\gamma_{SD}}(\gamma_{m},\gamma_{n+1})+F_{\gamma_{\min},\gamma_{SD}}(\gamma_{m},\gamma_{n}).\end{aligned} \tag{4.28}$$

Substituting (4.26) into (4.25) and (4.28), then substituting (4.3) into (4.24), the average spectral efficiency of the MSES can be given by

$$\begin{aligned}&\eta^{MSES}\\&=\sum_{n=2}^{N}n\,\psi\left(n,1/\bar{\gamma}_{SD}\right)\\&+\frac{\bar{\gamma}_{RD}}{\bar{\gamma}_{SD}-\bar{\gamma}_{RD}}\sum_{n=2}^{\left\lfloor\frac{N}{2}\right\rfloor}n\,\psi\left(n,\frac{1}{\bar{\gamma}_{SD}}-\frac{1}{\bar{\gamma}_{RD}}\right)e^{-\gamma_{2n}(\frac{1}{\bar{\gamma}_{SR}}+\frac{1}{\bar{\gamma}_{RD}})}\\&+\frac{\bar{\gamma}_{RD}}{\bar{\gamma}_{RD}-\bar{\gamma}_{SD}}\sum_{\substack{n=0\\n\neq1}}^{\left\lfloor\frac{N}{2}\right\rfloor}\sum_{m=I^{n}}^{N}\frac{m}{2}\psi\left(n,\frac{1}{\bar{\gamma}_{SD}}-\frac{1}{\bar{\gamma}_{RD}}\right)\psi\left(m,\frac{1}{\bar{\gamma}_{SR}}+\frac{1}{\bar{\gamma}_{RD}}\right).\end{aligned} \tag{4.29}$$

4.1.4.2 Average Bit Error Rate

The ABER of the MSES can be expressed as

$$
\begin{aligned}
&\mathrm{ABER}^{MSES} \\
&= \tfrac{1}{\eta^{MSES}}\left[\sum_{n=\left\lfloor\frac{N}{2}\right\rfloor+1}^{N} n\,\mathrm{ABER}_{a(n)} + \sum_{n=2}^{\left\lfloor\frac{N}{2}\right\rfloor} n\,\mathrm{ABER}_{c(n)} + \sum_{\substack{n=0\\ n\neq 1}}^{\left\lfloor\frac{N}{2}\right\rfloor}\sum_{m=I^n}^{N} \tfrac{m}{2}\mathrm{ABER}_{d(n,m)}\right],
\end{aligned} \tag{4.30}
$$

where $\mathrm{ABER}_{c(n)}$ is the ABER when $\gamma_{\min} < \gamma_T$ (i.e., cooperative transmission is not activated), which can be determined as

$$
\begin{aligned}
&\mathrm{ABER}_{c(n)} \\
&= \int_{\gamma_n}^{\gamma_{n+1}} \mathrm{BER}(n,x)\, f_{\gamma_{\min},\gamma_{SD}}(\gamma_T, x)\, dx \\
&= A_n \Phi(\gamma_n, \gamma_{n+1}, \bar{\gamma}_{SD}, B_n) - \tfrac{A_n \bar{\gamma}_{RD}}{\bar{\gamma}_{RD}-\bar{\gamma}_{SD}} e^{-\gamma_T\left(\frac{1}{\bar{\gamma}_{SR}}+\frac{1}{\bar{\gamma}_{RD}}\right)} \Phi(\gamma_n, \gamma_{n+1}, \bar{\gamma}_{DF}, B_n),
\end{aligned} \tag{4.31}
$$

where $\bar{\gamma}_{DF} = \bar{\gamma}_{SD}\bar{\gamma}_{RD}/(\bar{\gamma}_{RD} - \bar{\gamma}_{SD})$. $\mathrm{ABER}_{d(n,m)}$ is the ABER when cooperative transmission is activated, which can be defined similar to (4.14) as

$$
\mathrm{ABER}_{d(n,m)} = \mathrm{ABER}^{SR}_{d(n,m)} \cdot \mathrm{ABER}^{SD}_{d(n,m)} + (1 - \mathrm{ABER}^{SR}_{d(n,m)}) \cdot \mathrm{ABER}^{DF}_{d(n,m)}, \tag{4.32}
$$

where

$$\begin{aligned}
&\mathrm{ABER}_{d(n,m)}^{SR} \\
&= \int_{\gamma_m}^{\gamma_{m+1}} \int_{\gamma_n}^{\gamma_{n+1}} \mathrm{BER}(m,z)(1-F_{\gamma_{RD}}(z-x)) f_{\gamma_{SD}}(x) f_{\gamma_{SR}}(z)\ dxdz \\
&+ \int_{\gamma_m}^{\gamma_{m+1}} \int_{\gamma_n}^{\gamma_{n+1}} \int_{z}^{\infty} \mathrm{BER}(m,u)\, f_{\gamma_{SR}}(u) f_{\gamma_{SD}}(x) f_{\gamma_{RD}}(z-x)\ dudxdz \\
&= \tfrac{A_m \bar{\gamma}_{DF}}{\bar{\gamma}_{SD}} \psi(n, 1/\bar{\gamma}_{DF}) \left[\Phi(\gamma_m, \gamma_{m+1}, \bar{\gamma}_{SRD}, B_m) - \sqrt{\tfrac{B_m}{\frac{2}{\bar{\gamma}_{SR}} + B_m}} \Phi(\gamma_m, \gamma_{m+1}, \bar{\gamma}_{RD}, C_m) \right],
\end{aligned} \tag{4.33}$$

and

$$\begin{aligned}
&\mathrm{ABER}_{d(n,m)}^{DF} \\
&= \int_{\gamma_m}^{\gamma_{m+1}} \int_{\gamma_n}^{\gamma_{n+1}} \mathrm{BER}(m,z)(1-F_{\gamma_{SR}}(z)) f_{\gamma_{RD}}(z-x) f_{\gamma_{SD}}(x)\ dxdz \\
&+ \int_{\gamma_m}^{\gamma_{m+1}} \int_{z}^{\infty} \int_{\gamma_n}^{\gamma_{n+1}} \mathrm{BER}(m,u)\, f_{\gamma_{RD}}(u-x) f_{\gamma_{SD}}(x) f_{\gamma_{SR}}(z)\ dxdudz \\
&= \tfrac{A_m \bar{\gamma}_{DF}}{\bar{\gamma}_{SD}} \psi(n, 1/\bar{\gamma}_{DF}) \left[\Phi(\gamma_m, \gamma_{m+1}, \bar{\gamma}_{SRD}, B_m) - \sqrt{\tfrac{B_m}{\frac{2}{\bar{\gamma}_{RD}} + B_m}} \Phi(\gamma_m, \gamma_{m+1}, \bar{\gamma}_{SR}, E_m) \right].
\end{aligned} \tag{4.34}$$

Finally,

$$\begin{aligned}
&\mathrm{ABER}_{d(n,m)}^{SD} \\
&= \int_{\gamma_m}^{\gamma_{m+1}} \int_{\gamma_n}^{\gamma_{n+1}} \mathrm{BER}(m,x)(1-F_{\gamma_{RD}}(z-x)) f_{\gamma_{SD}}(x) f_{\gamma_{SR}}(z)\ dxdz \\
&+ \int_{\gamma_m}^{\gamma_{m+1}} \int_{\gamma_n}^{\gamma_{n+1}} \mathrm{BER}(m,x)\, f_{\gamma_{RD}}(z-x) f_{\gamma_{SD}}(x)(1-F_{\gamma_{SR}}(z))\ dxdz \\
&= \tfrac{A_m \bar{\gamma}_{DF}}{\bar{\gamma}_{SD}} \psi(m, 1/\bar{\gamma}_r) \Phi(\gamma_n, \gamma_{n+1}, \bar{\gamma}_{DF}, B_m).
\end{aligned} \tag{4.35}$$

Substituting (4.33), (4.34), and (4.35) into (4.32) and then substituting (4.31) and (4.13) into (4.30), a closed-form expression for the ABER of the MSES can be obtained.

4.1.4.3 Outage Probability

The outage probability of the MSES can be defined as the probability when both γ_{SD} and γ_{min} are below the minimum switching threshold, γ_{th}. Then, the outage probability can be obtained as

$$\begin{aligned} P_{out}^{MSES} &= \Pr[\gamma_{\min} < \gamma_{th}, \gamma_{SD} < \gamma_{th}] \\ &= F_{\gamma_{\min},\gamma_{SD}}(\gamma_{th}, \gamma_{th}) \\ &= P_{out}^{MERS}. \end{aligned} \tag{4.36}$$

It is easy to show that the outage probability of the MERS and MSES are the same by substituting γ_{th} into (B.1) in Appendix B and doing some manipulation.

4.1.5 Numerical Results

This section presents the analytical results of the average spectral efficiency, the ABER, and the outage probability of the MERS and MSES. These results are verified by those of the simulations. To study the effect of the channel condition of the relay path, we consider two cases. In the first case, the relay node is close to the destination node where we have low SNR in the source-relay link. The second case assumes that both the source-relay link and relay-destination link have strong SNR. We set the maximum spectral efficiency, N, to be equal to 8, and the target BER, BER_T, to be equal to 10^{-3}. We compare the performance

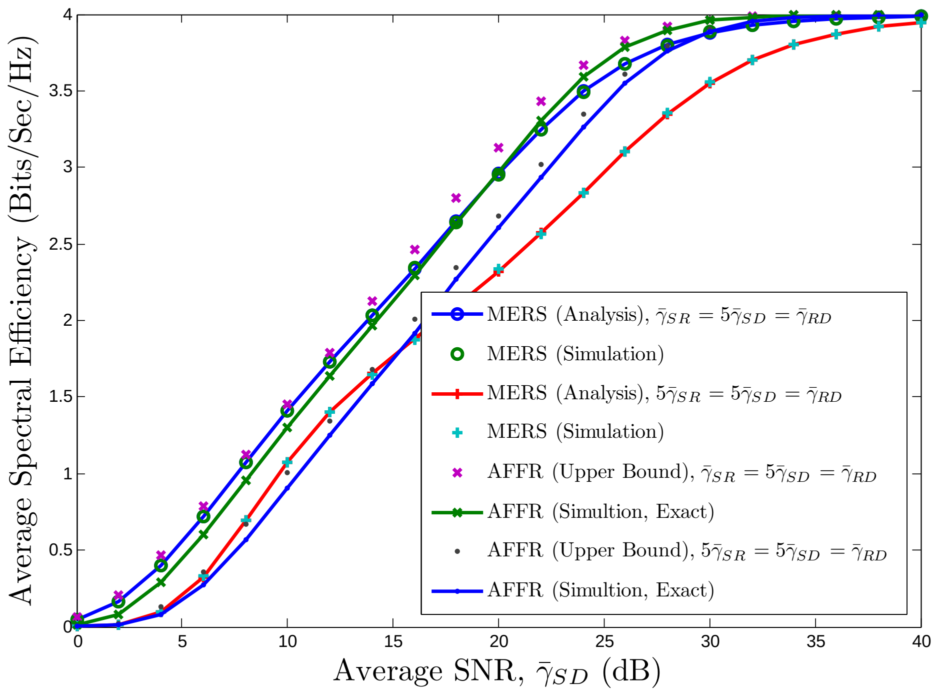

Figure 4.1: Average spectral efficiency of the MERS and AFFR.

of the two proposed schemes, MERS and MSES, with that of the amplify-and-forward fixed relaying (AFFR) [27, 73] and the direct transmission.

Fig. 4.1 shows the average spectral efficiency of the proposed MERS and the AFFR scheme. In the first case, there is a reduction in the average spectral efficiency of the MERS, since the source-relay link becomes a bottleneck in the high SNR, while in the second case, both the MERS and the AFFR have almost the same performance. Furthermore, in both cases, at relatively low average SNR (i.e., average SNR < 15 dB), the average spectral efficiency of the proposed MERS is better compared with that of the AFFR.

Fig. 4.2 shows the ABER of the proposed MERS and that of the AFFR. In both cases, MERS can significantly improve the ABER. The improvement is due to the possibility of reducing the modulation level even though the combined links at the destination node

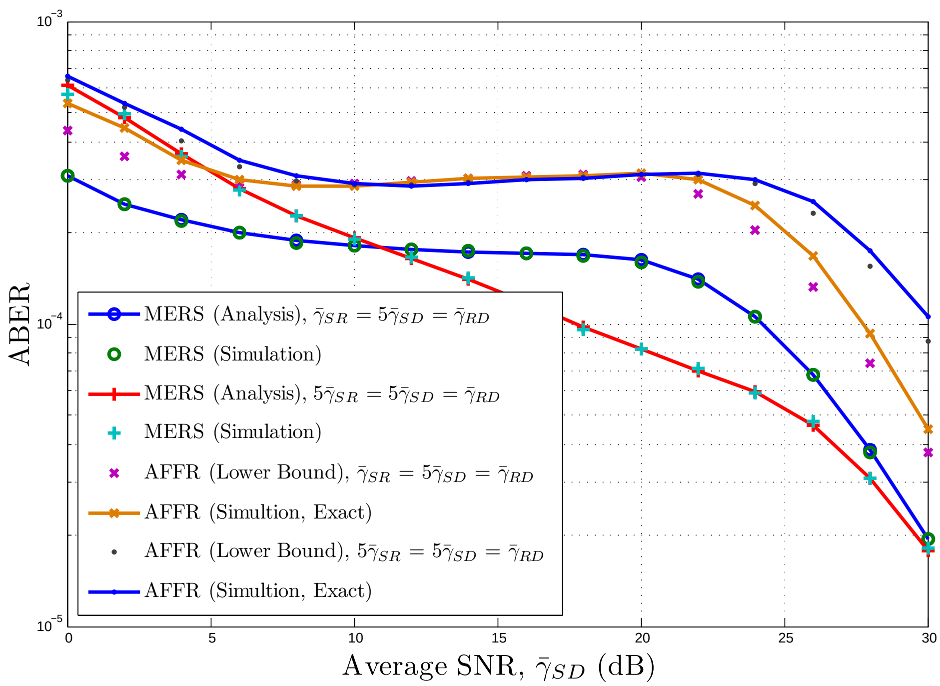

Figure 4.2: ABER of the MERS and the AFFR.

can support higher modulation level. Therefore, with high effective gain of the relay path, MERS provides better performance since the average spectral efficiency is similar to that of the AFFR.

Fig. 4.3 shows the average spectral efficiency of the two proposed schemes, MERS and MSES, the AFFR, and the direct transmission. We can see that the proposed MSES can improve the spectral efficiency at all times. This is due to the utilization of the degrees of freedom of the channels and avoiding cooperative transmission whenever it is not beneficial. For instance, in moderate average SNR (i.e., average SNR $<$ 20 dB), almost 30% gain in the spectral efficiency can be achieved compared with that of the AFFR and direct transmission. Also, if we compare the MSES with the direct transmission, the gain achieved by the MERS is notably found in the low and moderate average SNRs. This is

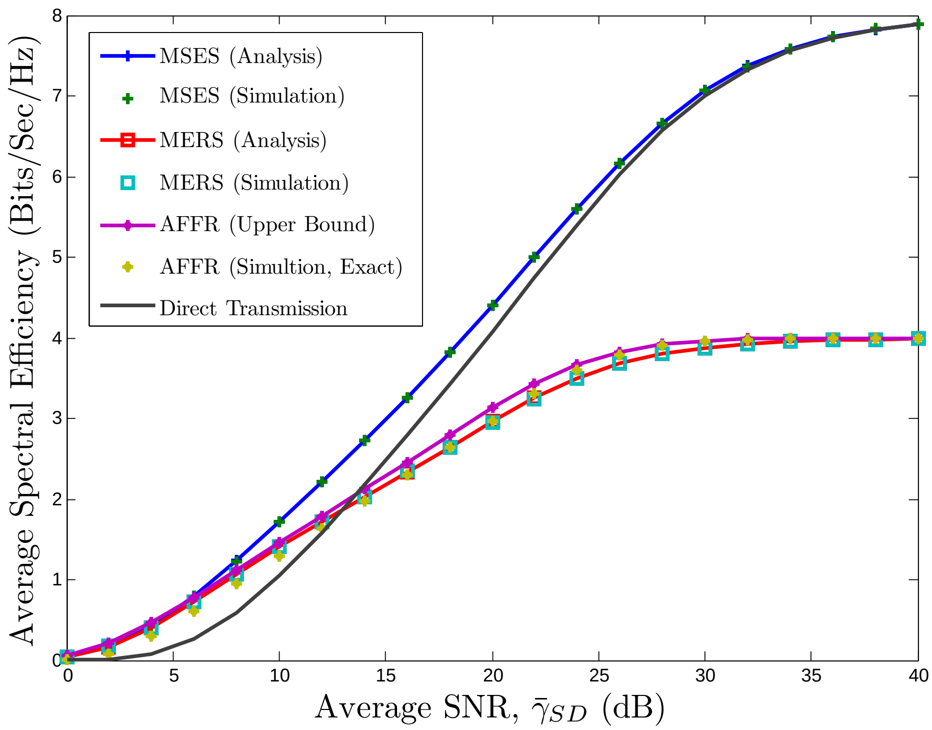

Figure 4.3: Average spectral efficiency of the MERS, the MSES, the AFFR, and the direct transmission, for $\bar{\gamma}_{SR} = 5\bar{\gamma}_{SD} = \bar{\gamma}_{RD}$.

because in the high average SNR, the cooperative transmission is rarely activated.

Fig. 4.4 shows the ABER of all above schemes. It can be seen that the proposed MERS outperforms all the other schemes. Also, in low average SNR, even though the MSES has the best average spectral efficiency, the ABER is still below that of the AFFR and the direct transmission. This observation, along with the previous one in Fig. 4.3, indicates the benefit of using the proposed MSES over the existing ones.

Fig. 4.5 shows the last performance measure, which is the outage probability. The direct observation is the improvement of the outage probability of all cooperative schemes when compared with that of direct transmission due to the diversity gain. Also, the slopes

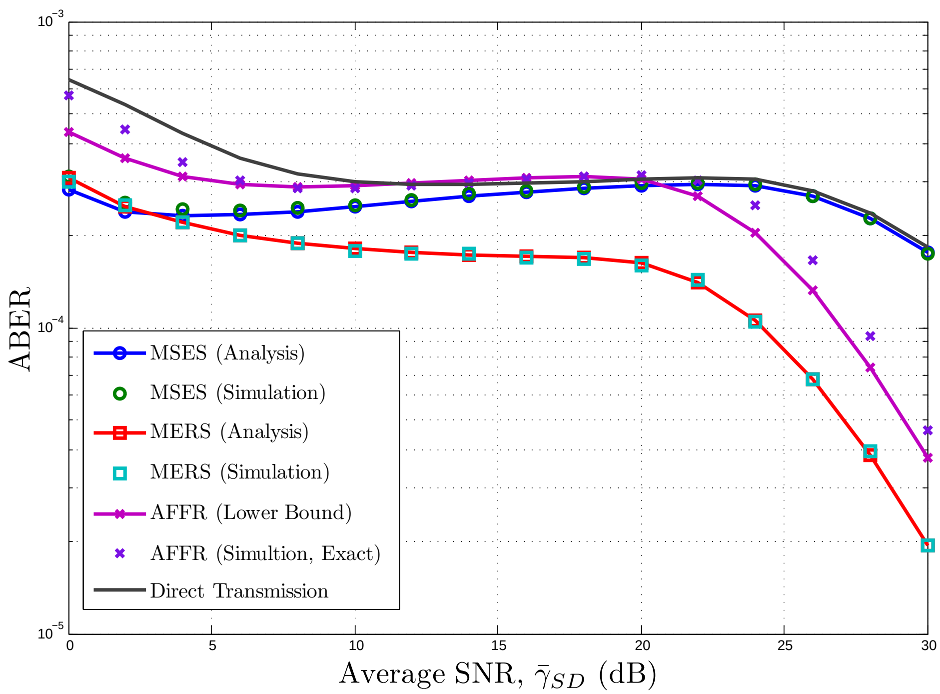

Figure 4.4: ABER of the MERS, the MSES, the AFFR, and the direct transmission, for $\bar{\gamma}_{SR} = 5\bar{\gamma}_{SD} = \bar{\gamma}_{RD}$.

of the outage curves of the cooperative schemes are the same, because they have equal diversity orders. Furthermore, the outage probability of the MERS and the MSES has a slight reduction due to the effect of the channel condition in the source-relay link. This reduction is decreased as the channel condition improves. Finally, there is a good match between analytical and simulation results.

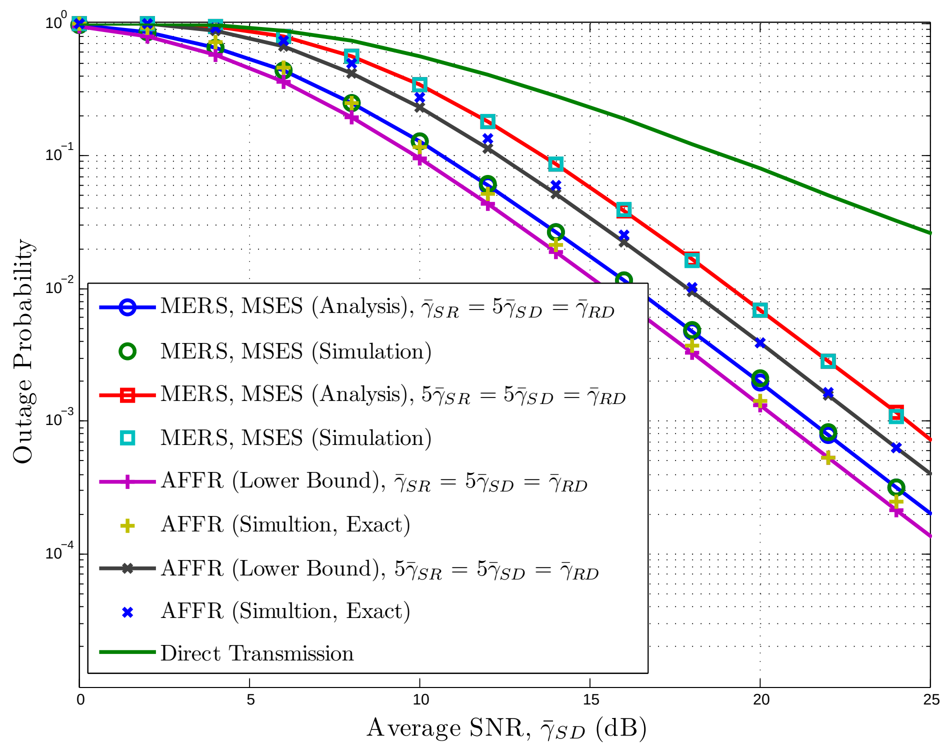

Figure 4.5: Outage probability of the MERS, the MSES, the AFFR, and the direct transmission.

4.2 Multiple-Relay System

4.2.1 Variable-Rate based Relay Selection Scheme

In the single-relay cooperative communication system, numerical results show the effect of the channel quality of the relay path on the performance. For instance, the MERS suffers a reduction in spectral efficiency when the channel gain in the source-relay link is low. This suggests that by allowing the system to have multiple relay nodes and select the relay node that has the best channel quality, this can improve the spectral efficiency of the system. Therefore, we propose the variable-rate based relay selection scheme which also exploits the adaptive modulation technique. Based on the operation of the DF protocol and the definition of the adaptive modulation, the selection strategy can be defined as

$$b = \arg \max_{i=1,\dots,L} \left\{ \gamma^{i}_{VRRS} \right\}, \tag{4.37}$$

where $\gamma^{i}_{VRRS} = \min(\gamma_{SR_i}, \gamma^{i}_{DF})$, and $\gamma^{i}_{DF} = \gamma_{SD} + \gamma_{R_i D}$.

4.2.1.1 Mode of Operation

One way of designing the system is to let the relay nodes estimate the relay links after receiving a ready-to-send (RTS) signal from the source node and a clear-to-send (CTS) signal which includes the SNR of the source-destination link from the destination node. Each relay node is then able to calculate γ^{i}_{VRRS}. Within a time period, which represents the maximum listening time by which the system can use one of the relay nodes, each relay node sets a timer, τ_i, which is inversely proportional to γ^{i}_{VRRS}. If the timer of the i^{th} relay node expires first, a $flag_i$ will be sent by the i^{th} relay node to announce its existence to the source and destination nodes, and to inform other relay nodes to keep silent. Fig. 4.6 shows a flow chart of the selection process of the proposed VRRS scheme.

4.2.2 Derivation of Performance Metrics of VRRS Scheme

4.2.2.1 Average Spectral Efficiency

The average spectral efficiency of the proposed VRRS scheme can be expressed as

$$\eta^{VRRS} = \sum_{m=2}^{N} \frac{m}{2}\, e(m), \tag{4.38}$$

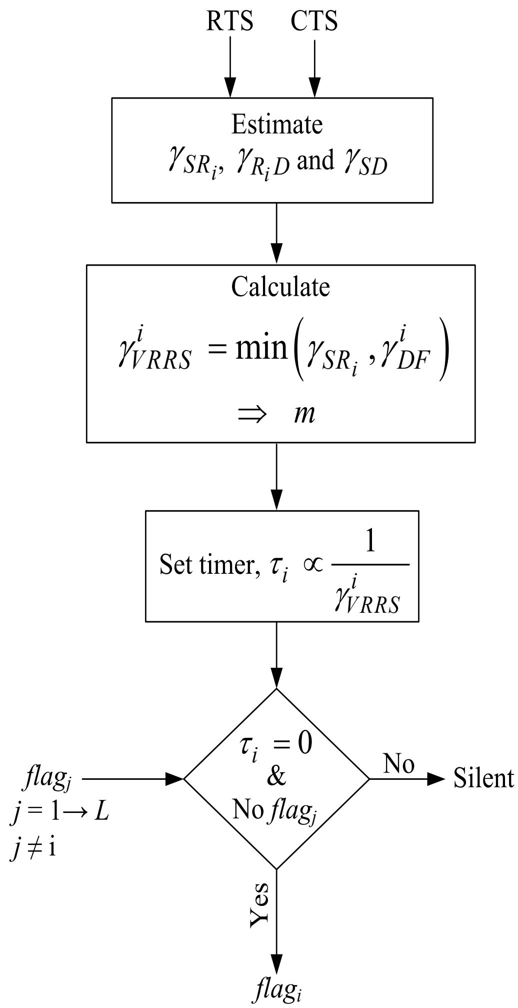

Figure 4.6: Flow chart of the selection process of the proposed VRRS scheme at the i^{th} relay node.

where m is the spectral efficiency of cooperative transmission, and $e(m)$ is the probability that the output SNR of the proposed VRRS scheme, γ^b_{VRRS}, falls in region m which can be represented as

$$e(m) = \int_{\gamma_m}^{\gamma_{m+1}} f_{\gamma^b_{VRRS}}(\gamma)\, d\gamma = F_{\gamma^b_{VRRS}}(\gamma_{m+1}) - F_{\gamma^b_{VRRS}}(\gamma_m), \tag{4.39}$$

where $f_{\gamma^b_{VRRS}}(\cdot)$ is the PDF of γ^b_{VRRS}, and $F_{\gamma^b_{VRRS}}(\cdot)$ is its corresponding CDF. For independent identically distributed (iid) Rayleigh fading channels over the relay nodes, the CDF of γ^b_{VRRS} is derived in Appendix D, and given by

$$\begin{aligned} & F_{\gamma^b_{VRRS}}(\gamma) \\ & = L\left\{\frac{\bar{\gamma}_S\bar{\gamma}_{SRD}}{\bar{\gamma}_{RD}-\bar{\gamma}_{SD}}\sum_{i=0}^{L-1}\sum_{r=0}^{i}\begin{pmatrix} L-1 \\ i \end{pmatrix}\begin{pmatrix} i \\ r \end{pmatrix}(-1)^{i+r}\frac{\bar{\gamma}_{SD}^{r}\bar{\gamma}_{RD}^{i-r}}{(\bar{\gamma}_{RD}-\bar{\gamma}_{SD})^{i+1}}\right. \\ & \left.\times\left[\frac{\bar{\gamma}_{SR}+\bar{\gamma}_{RD}}{\bar{\gamma}_{SR}(r\bar{\gamma}_{SRD}+(i-r+1)\bar{\gamma}_S)}\left(1-e^{-\gamma\left(\frac{r}{\bar{\gamma}_S}+\frac{i-r+1}{\bar{\gamma}_{SRD}}\right)}\right)-\frac{\bar{\gamma}_{SD}+\bar{\gamma}_{SR}}{\bar{\gamma}_{SR}((r+1)\bar{\gamma}_{SRD}+(i-r)\bar{\gamma}_S)}\left(1-e^{-\gamma\left(\frac{r+1}{\bar{\gamma}_S}+\frac{i-r}{\bar{\gamma}_{SRD}}\right)}\right)\right]\right\}. \end{aligned} \tag{4.40}$$

Substituting (4.40) into (4.39), and then substituting the result into (4.38), a closed-form expression of the average spectral efficiency can be obtained.

4.2.2.2 Average Bit Error Rate

The ABER of the proposed VRRS scheme can be expressed as

$$\mathrm{ABER}^{\mathrm{VRRS}} = \frac{1}{\eta^{VRRS}}\sum_{m=2}^{N}\frac{m}{2}\,\mathrm{ABER}^b_{e(m)}, \tag{4.41}$$

where $\mathrm{ABER}^b_{e(m)}$ is the ABER of the best relay DF cooperative transmission when modulation mode m is selected, which can be approximated as

$$\text{ABER}_{e(m)}^{b} = \text{ABER}_{e(m)}^{SR_b} \cdot \text{ABER}_{e(m)}^{SD_b} + (1 - \text{ABER}_{e(m)}^{SR_b}) \cdot \text{ABER}_{e(m)}^{DF_b}, \tag{4.42}$$

where $\text{ABER}_{e(m)}^{SD_b}$, $\text{ABER}_{e(m)}^{SR_b}$, and $\text{ABER}_{e(m)}^{DF_b}$ are the ABER of the source-destination link, source-relay link, and the combined links at the destination node, respectively. The ABER of the source-destination link can be give by

$$\text{ABER}_{e(m)}^{SD_b} = \int_0^\infty \text{BER}(\text{m}, \gamma) f_{\gamma_{SD}}(\gamma) d\gamma, \tag{4.43}$$

where $\text{BER}(m, \gamma)$ is the BER of the M-QAM, as given previously by (4.10). Using (4.11) and its expansion as shown in Appendix C, the ABER of the source-destination link becomes

$$\text{ABER}_{e(m)}^{SD_b} = A_m \left(1 - \sqrt{\frac{B_m}{\frac{2}{\bar{\gamma}_{SD}} + B_m}}\right). \tag{4.44}$$

The ABER of the source-relay link, $\text{ABER}_{e(m)}^{SR_b}$, and the combined links at the destination node, $\text{ABER}_{e(m)}^{DF_b}$, can be written as

$$\text{ABER}_{e(m)}^{SR_b} = L \left(\int_{\gamma_m}^{\gamma_{m+1}} A_m Q(\sqrt{B_m u}) f_{\gamma_{SR}}(u)\, F_{\gamma_{other}}(u)(1 - F_{\gamma_{DF}}(u)) du + \int_{\gamma_m}^{\gamma_{m+1}} f_{\gamma_{DF}}(u) F_{\gamma_{other}}(u) \int_u^\infty A_m Q(\sqrt{B_m x}) f_{\gamma_{SR}}(x) dx du \right), \tag{4.45}$$

and

$$\mathrm{ABER}_{e(m)}^{DF_b} = L\left(\int\limits_{\gamma_m}^{\gamma_{m+1}} A_m Q(\sqrt{B_m u}) f_{\gamma_{DF}}(u)\, F_{\gamma_{other}}(u)(1-F_{\gamma_{SR}}(u))du \right.$$
$$\left. + \int\limits_{\gamma_m}^{\gamma_{m+1}} f_{\gamma_{SR}}(u) F_{\gamma_{other}}(u) \int\limits_{u}^{\infty} A_m Q(\sqrt{B_m x}) f_{\gamma_{DF}}(x) dx du \right), \tag{4.46}$$

respectively, where $f_{\gamma_{DF}}(.)$ and $F_{\gamma_{DF}}(.)$ are the PDF and CDF of the combined output SNR at the destination node which are given in closed-form by (D.2) and (D.3) in Appendix D, respectively. Also $F_{\gamma_{other}}(.)$ is the CDF of the output SNR of other relay nodes that are below the output SNR of the best relay node. $F_{\gamma_{other}}(.)$ is given in a closed-form by (D.5) in Appendix D as well. Using the results of appendix D, (4.45) and (4.46) can be solved and given by

$$\mathrm{ABER}_{e(m)}^{SR_b} = L\left\{ A_m \sum_{i=0}^{L-1}\sum_{r=0}^{i} \begin{pmatrix} L-1 \\ i \end{pmatrix} \begin{pmatrix} i \\ r \end{pmatrix} (-1)^{i+r} \frac{\bar{\gamma}_{SD}^{r}\bar{\gamma}_{RD}^{i-r}}{(\bar{\gamma}_{RD}-\bar{\gamma}_{SD})^{i+1}} \right.$$
$$\times \left[\frac{(\bar{\gamma}_{SR}+\bar{\gamma}_{RD})\bar{\gamma}_{i,r}^{(1)}}{\bar{\gamma}_{SR}} \Phi(\gamma_m, \gamma_{m+1}, \bar{\gamma}_{i,r}^{(1)}, B_m) - \frac{(\bar{\gamma}_{SD}+\bar{\gamma}_{SR})\bar{\gamma}_{i,r}^{(2)}}{\bar{\gamma}_{SR}} \Phi(\gamma_m, \gamma_{m+1}, \bar{\gamma}_{i,r}^{(2)}, B_m) \right.$$
$$\left.\left. - \sqrt{\frac{B_m}{\frac{2}{\gamma_{SR}}+B_m}} \left(\bar{\gamma}_{i,r}^{(3)}\ \Phi(\gamma_m, \gamma_{m+1}, \bar{\gamma}_{i,r}^{(3)}, C_m) - \bar{\gamma}_{i,r}^{(4)} \Phi(\gamma_m, \gamma_{m+1}, \bar{\gamma}_{i,r}^{(4)}, C_m) \right) \right] \right\}, \tag{4.47}$$

and

$$
\begin{aligned}
&\text{ABER}_{e(m)}^{DF} \\
&= L\left\{A_m \sum_{i=0}^{L-1}\sum_{r=0}^{i}\left(\begin{array}{c} L-1 \\ i \end{array}\right)\left(\begin{array}{c} i \\ r \end{array}\right)(-1)^{i+r}\frac{\bar{\gamma}_{SD}^{r}\bar{\gamma}_{RD}^{i-r}}{(\bar{\gamma}_{RD}-\bar{\gamma}_{SD})^{i+1}}\right. \\
&\times\left[\frac{(\bar{\gamma}_{SR}+\bar{\gamma}_{RD})\bar{\gamma}_{i,r}^{(1)}}{\bar{\gamma}_{SR}}\,\Phi(\gamma_m,\gamma_{m+1},\bar{\gamma}_{i,r}^{(1)},B_m)-\frac{(\bar{\gamma}_{SD}+\bar{\gamma}_{SR})\bar{\gamma}_{i,r}^{(2)}}{\bar{\gamma}_{SR}}\Phi(\gamma_m,\gamma_{m+1},\bar{\gamma}_{i,r}^{(2)},B_m)\right. \\
&\left.\left.\left.-\bar{\gamma}_{RD}\bar{\gamma}_{i,r}^{(5)}\sqrt{\frac{B_m}{\frac{2}{\gamma_{RD}}+B_m}}\,\Phi(\gamma_m,\gamma_{m+1},\bar{\gamma}_{i,r}^{(5)},E_m)-\bar{\gamma}_{SD}\bar{\gamma}_{i,r}^{(5)}\sqrt{\frac{B_m}{\frac{2}{\gamma_{SD}}+B_m}}\Phi(\gamma_m,\gamma_{m+1},\bar{\gamma}_{i,r}^{(5)},D_m)\right)\right]\right\},
\end{aligned} \tag{4.48}
$$

respectively, where

$$
\begin{aligned}
\bar{\gamma}_{i,r}^{(1)} &= \frac{\bar{\gamma}_{SRD}\bar{\gamma}_S}{r\bar{\gamma}_{SRD}+(i-r+1)\bar{\gamma}_S}, \\
\bar{\gamma}_{i,r}^{(2)} &= \frac{\bar{\gamma}_{SRD}\bar{\gamma}_S}{(r+1)\bar{\gamma}_{SRD}+(i-r)\bar{\gamma}_S}, \\
\bar{\gamma}_{i,r}^{(3)} &= \frac{\bar{\gamma}_{SD}\bar{\gamma}_{RD}\bar{\gamma}_{SRD}}{r\bar{\gamma}_{RD}\bar{\gamma}_{SRD}+(i-r)\bar{\gamma}_{SD}\bar{\gamma}_{RD}+\bar{\gamma}_{SD}\bar{\gamma}_{SRD}}, \\
\bar{\gamma}_{i,r}^{(4)} &= \frac{\bar{\gamma}_{SD}\bar{\gamma}_{SRD}\bar{\gamma}_S}{r\bar{\gamma}_{SD}\bar{\gamma}_{SRD}+(i-r)\bar{\gamma}_{SD}\bar{\gamma}_S+\bar{\gamma}_{SRD}\bar{\gamma}_S}, \text{ and} \\
\bar{\gamma}_{i,r}^{(5)} &= \frac{\bar{\gamma}_{SR}\bar{\gamma}_{SRD}\bar{\gamma}_S}{r\bar{\gamma}_{SR}\bar{\gamma}_{SRD}+(i-r)\bar{\gamma}_{SR}\bar{\gamma}_S+\bar{\gamma}_{SRD}\bar{\gamma}_S}.
\end{aligned}
$$

Substituting (4.44), (4.47), and (4.48) into (4.42), the overall ABER can be obtained.

4.2.3 Numerical Results

We set the maximum spectral efficiency N to be equal to 8, the target BER to be equal to 10^{-3}, and the average SNRs for the links as $\bar{\gamma}_{SR} = \bar{\gamma}_{RD} = 5\bar{\gamma}_{SD}$. We also consider the different numbers of relays L available in the system.

Fig. 4.7 shows the average spectral efficiency of the proposed VRRS scheme for different numbers of available relay nodes ($L = 1$, 2, and 6). We can see the improvement in the average spectral efficiency due to the use of cooperative transmission. This improvement is significant in the low average SNR region. In the high average SNR region, as expected, the average spectral efficiency saturates to half of the maximum spectral efficiency due to the half-duplex constraint. Furthermore, by increasing the number of available relay nodes in the system, the chance of selecting a higher modulation level becomes high, and thus the average spectral efficiency is increased. For instance, 2.2 dB and 5 dB can be saved in order to achieve the same average spectral efficiency when L increases from 1 to 2 and from 1 to 6, respectively.

Fig. 4.8 shows the average spectral efficiency of the VRRS scheme and the AFFR when the number of available relay nodes is set to be 4. It is clear that the average spectral efficiency of the VRRS scheme is significantly improved. In particular, the gain ranges from almost $10\% - 100\%$ in the relatively low average SNR region.

Fig. 4.9 shows the ABER of the proposed VRRS scheme with different numbers of available relay nodes ($L = 1$, 2, and 6). We can see that the ABER of our scheme outperforms the ABER of the conventional direct transmission at all times. In the high average SNR region, the improvement of the ABER is noticeable due to the diversity gain improvement in the cooperative transmission. Increasing the number of available relay nodes can further improve the diversity gain. Furthermore, the ABER of the proposed VRRS scheme is verified to be below the target BER. Finally, there is a good match between analytical and simulation results.

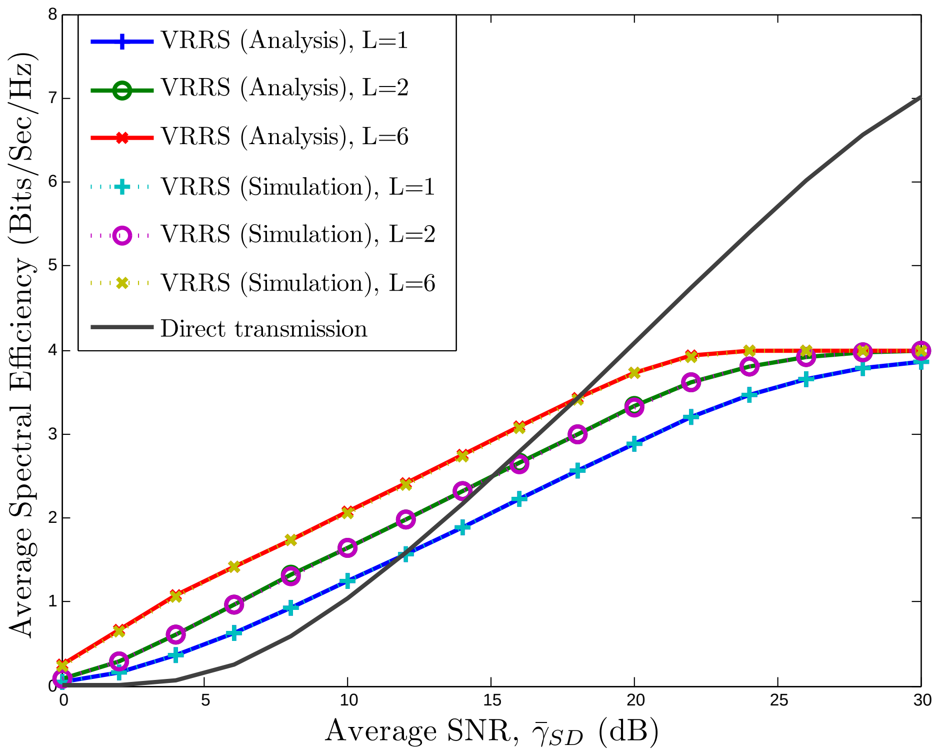

Figure 4.7: Average spectral efficiency of the VRRS scheme for different number of relay nodes.

4.3 Summary

In this chapter, we have proposed two decode-and-forward adaptive cooperative schemes: the minimum error rate scheme and the maximum spectral efficiency scheme for a single-relay system. We have derived the average spectral efficiency, the ABER, and the outage probability. Both analytical and simulation results show that our schemes can achieve better performance than previous schemes. More specifically, the minimum error rate scheme improves the ABER significantly and provides acceptable average spectral efficiency when the channel gain of the relay path is good. On the other hand, the maximum spectral efficiency scheme provides the best average spectral efficiency while maintaining

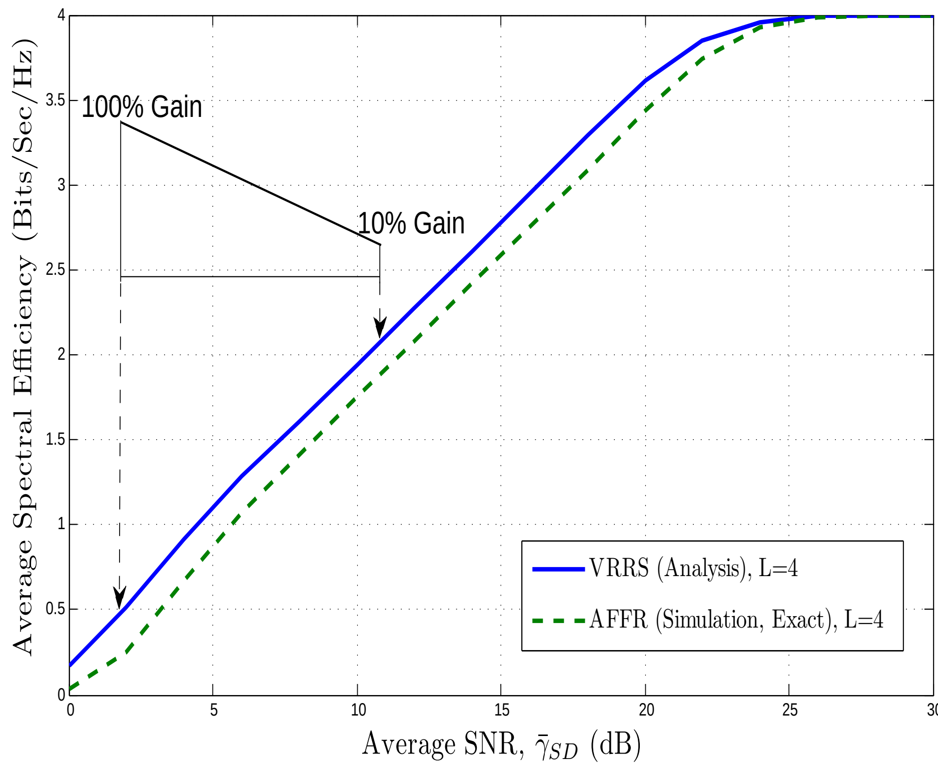

Figure 4.8: Average spectral efficiency of the VRRS and the AFFR schemes.

the required BER performance, so it is characterized by efficient utilization of the resources. Furthermore, the minimum error rate scheme suffers a reduction in spectral efficiency when the channel gain of the source-relay link is low. Therefore, we have proposed another scheme, called a variable-rate based relay selection scheme, for the decode-and-forward multiple-relay cooperative system. The scheme has the capability to improve the average spectral efficiency and the ABER. The advantages of the proposed scheme are due to two factors: exploiting the variable-rate transmission in which the maximum rate is selected at all times, and selecting the relay node that has the best end-to-end path between the source and destination nodes. Finally, although the DF protocol has better performance than the AF protocol in the low SNR region, the complexity of the DF protocol is higher due to

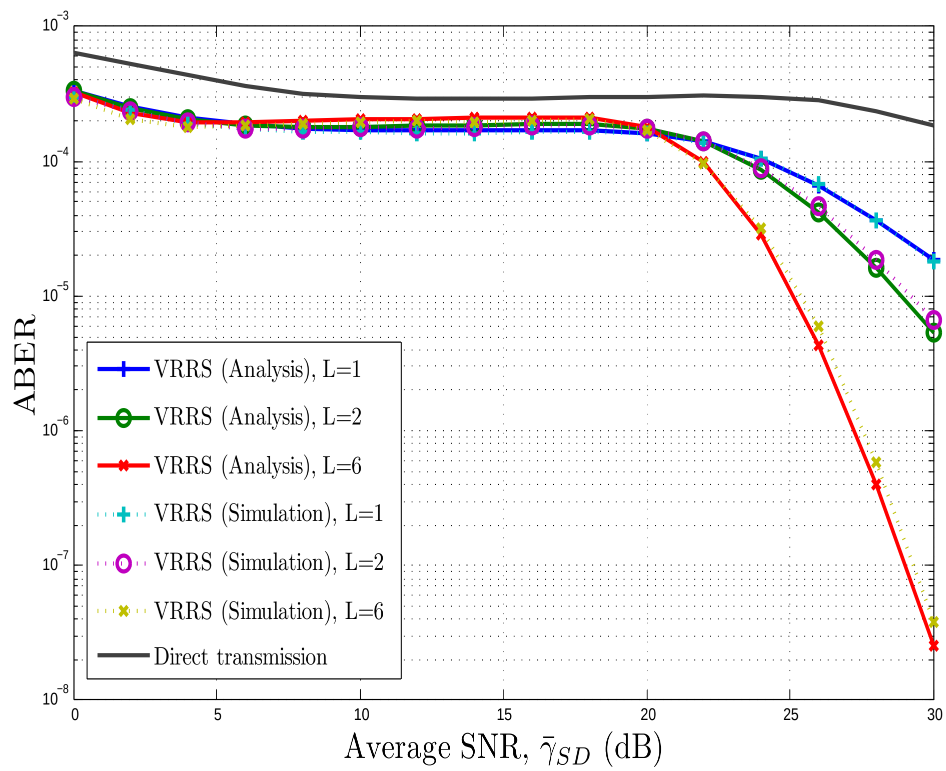

Figure 4.9: ABER of the VRRS scheme for different number of relay nodes.

the requirement of extra signal processing and error correcting code. This encourages us to study the adaptive cooperative systems under AF protocol in the next chapter.

Chapter 5

AF Adaptive Cooperative System with Variable-Rate Transmission

The amplify-and-forward (AF) protocol, which represents the main approach of non-regenerative protocols, is characterized by simple operation due to the requirement of only amplifying the signal and forwarding it to the destination node. In Chapter 4, we showed how the decode-and-forward (DF) cooperative system can be designed under the concept of adaptation. In this chapter, we showed how the decode-and-forward (DF) cooperative system can be designed under the concept of adaptation. In this chapter, we aim to design efficient adaptive cooperative schemes under AF protocol, which have the capability of improving the spectral efficiency while maintaining the target quality (i.e., bit error rate (BER) and outage probability). In Section 5.1, we introduce a policy for an AF single-relay system which gives the useful cooperative regions and chooses a switching threshold signal-to-noise ratio (SNR) that guarantees that the BER of the cooperative transmission is below the target. For simplicity, we show that this switching threshold SNR can be approximated from its original definition without affecting performance. Next, we derive closed-form expressions for the average spectral efficiency, average bit error rate, and outage probability when an upper bound for the SNR of the end-to-end relay path is used, and adaptive discrete rate M-ary quadrature amplitude modulation (M-QAM) is considered. In Section 5.2, we extend the proposed switching policy to include the relay selection technique. The same performance metrics as considered previously are derived in closed-form expressions for the proposed AF efficient relay selection (AFERS) scheme, and the numerical results are provided. Finally, the chapter is summarized in Section 5.3.

5.1 Single-Relay System

5.1.1 Generalized Switching Policy

In general, there are two paths in cooperative transmission, direct and relay paths, but the channel gain of these paths cannot be assumed to be equal or constant all the time due to the effect of multipath fading. As a result, the spectral efficiency achieved by cooperative transmission cannot be guaranteed to outperform that of direct transmission, especially under half-duplex transmission mode. Therefore, in order to maximize the spectral efficiency, it is important to let the transmission be adaptive in terms of both cooperative and non-cooperative transmission and rate selection. Therefore, we can define the following policy:

1) If $\gamma_{SD} \geq \gamma_{\left\lfloor \frac{N}{2} \right\rfloor +1}$, do not cooperate,

where $\lfloor k \rfloor$ is the largest integer less than or equal k.

2) If $\gamma_{SD} < \gamma_{\left\lfloor \frac{N}{2} \right\rfloor +1}$, cooperate if $\gamma_{AF} \geq T_n$,

where T_n is the switching threshold SNR, used to guarantee that the cooperative transmission can maximize the spectral efficiency. The mathematical model of the switching threshold SNR can be represented by

$$T_n = \begin{cases} \gamma_2, & n = 0, \\ \frac{2^{2n}-1}{3}\left\{Q^{-1}\left[\frac{2^{n+1}}{2^n+\sqrt{2^n}}Q\left(\sqrt{\frac{3\gamma_{SD}}{2^n-1}}\right)\right]\right\}^2, & 2 \leq n \leq \left\lfloor \frac{N}{2} \right\rfloor. \end{cases} \quad (5.1)$$

When $n = 0$, the minimum requirement of γ_{AF} is to be larger than or equal to γ_2, otherwise the cooperative transmission is under outage as well. When $2 \leq n \leq \lfloor \frac{N}{2} \rfloor$, not only should the cooperative transmission rate be doubled but also the target BER is not larger than the direct transmission BER (i.e., $\text{BER}(2n, \gamma_{AF}) \leq \text{BER}(n, \gamma_{SD})$). Furthermore, we can approximate the expression of T_n for the analysis tractability and simplifying the calculation at the relay node. In a successful wireless transmission, the target BER is usually less than 10^{-3}, so the Q-function inside the inverse of the Q-function as shown in (5.1) is very small compared to the fraction multiplied with it, (i.e., $Q(\cdot) \ll 1$ and $2^{n+1}/(2^n + \sqrt{2^n}) > 1$). Therefore, this fraction can be approximated to be equal to 1. Then, (5.1) can be approximated by

$$T_n \approx \begin{cases} \gamma_2, & n = 0, \\ (2^n + 1)\gamma_{SD}, & 2 \leq n \leq \left\lfloor \frac{N}{2} \right\rfloor. \end{cases} \quad (5.2)$$

Fig. 5.1 shows how tight this approximation is when compared to the one in (5.1). The effect of this approximation on the performance of the proposed scheme is further analyzed in Section 5.2.3 (see Fig. 5.4).

5.1.1.1 Special Cases

Various schemes can be obtained based on the values of γ_{SD} and γ_{AF}, and the mode of operation as follows:

i) $\gamma_{AF} = 0$ (i.e., no cooperation) $\Rightarrow$ The conventional direct transmission.

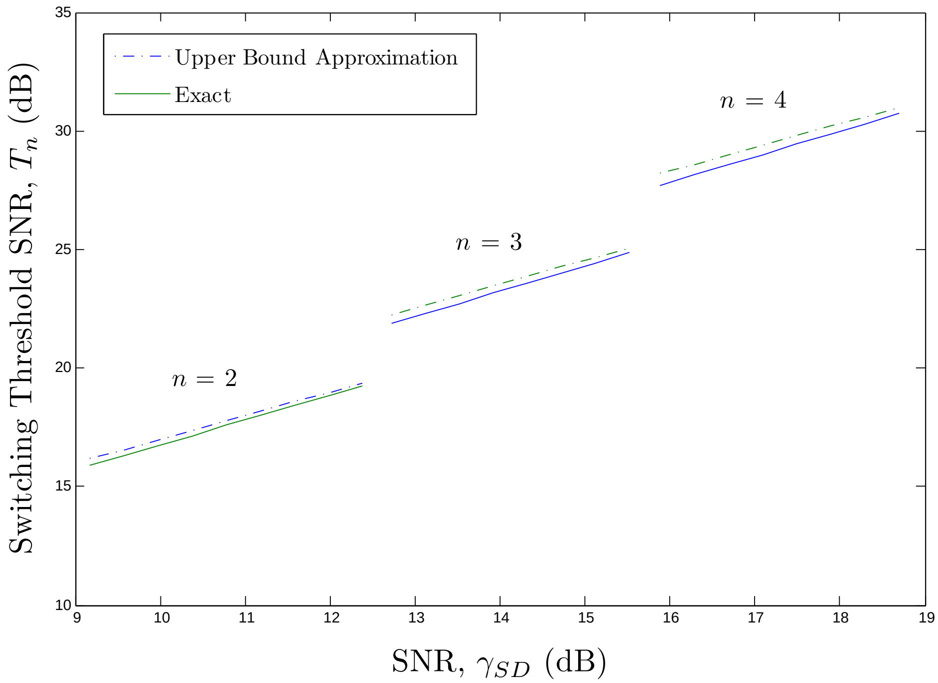

Figure 5.1: Switching threshold SNR, T_n, and its upper bound approximation.

ii) $(\gamma_{SD}, \gamma_{AF}) < \infty$ (i.e., no restriction on their values), cooperate all the time $\Rightarrow$ AF fixed relaying scheme [73, 27].

iii) iff $\gamma_{SD} < \gamma_2$ (i.e., the direct transmission experiences an outage), cooperate $\Rightarrow$ AF outage-based adaptive cooperative scheme [47]. Note that γ_2 is the minimum switching threshold SNR for the case of M-QAM.

5.1.2 Performance Analysis of GSP

5.1.2.1 Average Spectral Efficiency

The average spectral efficiency of the generalized switching policy (GSP) of a single-relay AF adaptive cooperative system can be expressed as

$$\eta^{GSP} = \sum_{n=\left\lfloor \frac{N}{2} \right\rfloor+1}^{N} n\,\alpha(n) + \sum_{n=2}^{\left\lfloor \frac{N}{2} \right\rfloor} n\,\beta(n) + \sum_{\substack{n=0 \\ n\neq 1}}^{\left\lfloor \frac{N}{2} \right\rfloor} \sum_{m=I^n}^{N} \frac{m}{2}\mu(n,m), \tag{5.3}$$

where m is the spectral efficiency of the cooperative transmission and divided by two due to the half duplex constraint. $\alpha(n)$ is probability that γ_{SD} falls in region n, $\beta(n)$ is the probability when $\gamma_2 \le \gamma_{SD} \le \gamma_{\left\lfloor \frac{N}{2} \right\rfloor}$ and $\gamma_{AF} < T_n$, and $\mu(n,m)$ is the probability when $\gamma_2 \le \gamma_{SD} \le \gamma_{\left\lfloor \frac{N}{2} \right\rfloor}$ and $\gamma_{AF} \ge T_n$, also $I^n = 2$ if $n = 0$ and $I^n = 2$n if $n \neq 0$. $\alpha(n)$ can be obtained as

$$\begin{aligned} \alpha(n) &= \int_{\gamma_n}^{\gamma_{n+1}} f_{\gamma_{SD}}(x)dx = F_{\gamma_{SD}}(\gamma_{n+1}) - F_{\gamma_{SD}}(\gamma_n), \\ &= e^{-\gamma_n/\bar{\gamma}_{SD}} - e^{-\gamma_{n+1}/\bar{\gamma}_{SD}}. \end{aligned} \tag{5.4}$$

Let $\psi(n,\lambda) = e^{-\lambda\gamma_n} - e^{-\lambda\gamma_{n+1}}$, then $\alpha(n)$ can be rewritten as $\alpha(n) = \psi(n, 1/\bar{\gamma}_{SD})$. $\beta(n)$ can be represented by

$$\beta(n) = \int_{\gamma_n}^{\gamma_{n+1}} F_{\gamma_{SRD}}(T_n - x) f_{\gamma_{SD}}(x)dx, \tag{5.5}$$

where $F_{\gamma_{SRD}}(.)$ is the cumulative distribution function (CDF) of the upper bound SNR of the end-to-end relay path which can be given by [71, 53]

$$F_{\gamma_{SRD}}(\gamma) = \Pr\left[\min\left(\gamma_{SR}, \gamma_{RD}\right) \le \gamma\right],$$
$$= 1 - \left(1 - F_{\gamma_{SR}}(\gamma)\right)\left(1 - F_{\gamma_{RD}}(\gamma)\right),$$
$$= 1 - e^{-\frac{\gamma}{\bar{\gamma}_{SRD}}}, \tag{5.6}$$

where $\bar{\gamma}_{SRD} = \bar{\gamma}_{SR} \cdot \bar{\gamma}_{RD}/(\bar{\gamma}_{SR} + \bar{\gamma}_{RD})$. The probability density function (PDF) of γ_{SRD}, $f_{\gamma_{SRD}}(.)$, can be calculated by differentiating (5.6) with respect to γ. Substituting (5.6) into (5.5), $\beta(n)$ can be given by

$$\beta(n) = \psi\left(n, \frac{1}{\bar{\gamma}_{SD}}\right) - \frac{1}{1 + \frac{2^n \bar{\gamma}_{SD}}{\bar{\gamma}_{SRD}}}\psi\left(n, \frac{1}{\bar{\gamma}_{SD}} + \frac{2^n}{\bar{\gamma}_{SRD}}\right). \tag{5.7}$$

The cooperative transmission mode is activated if the second condition holds. Then it is easy to show that the probability of activating the cooperative transmission mode can be represented as

$$\mu(n,m) = \int_{\gamma_n}^{\gamma_{n+1}} \int_{AF_R} f_{\gamma_{SRD}}(z-x) f_{\gamma_{SD}}(x) dz dx, \tag{5.8}$$

where AF_R represents the regions that γ_{AF} may fall in, which can be defined as

$$AF_R = \begin{cases} [\gamma_m, \gamma_{m+1}), & if\, cond1 \text{ or } cond2 \\ [T_n, \gamma_{m+1}), & if\, cond3 \end{cases} \tag{5.9}$$

where $cond1 \equiv (n = 0, m \ge 2)$, $cond2 \equiv (2 \le n \le \left\lfloor \frac{N}{2} \right\rfloor, m \ge 2n+1)$, and $cond3 \equiv (2 \le n \le \left\lfloor \frac{N}{2} \right\rfloor, m = 2n)$. Note that if $n = 0$, $[\gamma_n, \gamma_{n+1}) = [0, \gamma_2)$ since $n = 1$ is not considered. Based on the conditions of cooperative regions, $\mu(n,m)$ has two values, $\mu_1(n,m)$ and

$\mu_2(n,m)$. For $AF_R = [\gamma_m, \gamma_{m+1})$, substituting $f_{\gamma_{SRD}}(.)$ into (5.8) and solving the double integral, $\mu_1(n,m)$ is given by

$$\mu_1(n,m) = \frac{1}{1-\frac{\bar{\gamma}_{SD}}{\bar{\gamma}_{SRD}}}\psi\left(n, \frac{1}{\bar{\gamma}_{SD}} - \frac{1}{\bar{\gamma}_{SRD}}\right)\psi\left(m, \frac{1}{\bar{\gamma}_{SRD}}\right). \tag{5.10}$$

Similarly, For $AF_R = [T_n, \gamma_{m+1})$, $\mu_2(n,m)$ is given by

$$\mu_2(n,m) = \frac{1}{1+\frac{2^n\bar{\gamma}_{SD}}{\bar{\gamma}_{SRD}}}\psi\left(n, \frac{1}{\bar{\gamma}_{SD}} + \frac{2^n}{\bar{\gamma}_{SRD}}\right) - \frac{e^{-\frac{\gamma_{m+1}}{\bar{\gamma}_{SRD}}}}{1-\frac{\bar{\gamma}_{SD}}{\bar{\gamma}_{SRD}}}\psi\left(n, \frac{1}{\bar{\gamma}_{SD}} - \frac{1}{\bar{\gamma}_{SRD}}\right). \tag{5.11}$$

Substituting (5.4), (5.7), (5.10), and (5.11) into (5.3) and doing some manipulation and simplification techniques, the average spectral efficiency of the GSP of a single-relay AF adaptive cooperative system becomes

$$\begin{aligned}
&\eta^{GSP} \\
&= \sum_{n=2}^{N} n\psi\left(n, \tfrac{1}{\bar{\gamma}_{SD}}\right) \qquad \Leftarrow \text{ Contribution of the direct transmission} \\
&\left.\begin{aligned}
&+\frac{1}{1-\frac{\bar{\gamma}_{SD}}{\bar{\gamma}_{SRD}}} \sum_{\substack{n=0\\ n\neq 1}}^{\left\lfloor \frac{N}{2}\right\rfloor} \sum_{\substack{m=2 \text{ if } n=0\\ m=2n+1 \text{ if } n\neq 0}}^{N} \frac{m}{2}\psi\left(n, \tfrac{1}{\bar{\gamma}_{SD}} - \tfrac{1}{\bar{\gamma}_{SRD}}\right)\psi\left(m, \tfrac{1}{\bar{\gamma}_{SRD}}\right) \\
&-\frac{1}{1-\frac{\bar{\gamma}_{SD}}{\bar{\gamma}_{SRD}}} \sum_{n=2}^{\left\lfloor \frac{N}{2}\right\rfloor} n\psi\left(n, \tfrac{1}{\bar{\gamma}_{SD}} - \tfrac{1}{\bar{\gamma}_{SRD}}\right) e^{-\frac{\gamma_{2n+1}}{\bar{\gamma}_{SRD}}}.
\end{aligned}\right\} \Leftarrow \begin{array}{l}\text{Contribution of}\\ \text{the cooperative}\\ \text{transmission}\end{array}
\end{aligned} \tag{5.12}$$

5.1.2.2 Average Bit Error Rate

The ABER of the GSP of a single-relay AF adaptive cooperative system can be expressed as

$$\text{ABER}^{\text{GSP}} = \frac{1}{\eta^{GSP}}\left(\sum_{n=\left\lfloor\frac{N}{2}\right\rfloor+1}^{N} n\,\text{ABER}_{\alpha(n)} + \sum_{n=2}^{\left\lfloor\frac{N}{2}\right\rfloor} n\,\text{ABER}_{\beta(n)} + \sum_{\substack{n=0\\n\neq1}}^{\left\lfloor\frac{N}{2}\right\rfloor}\sum_{m=I^n}^{N}\frac{m}{2}\text{ABER}_{\mu(n,m)}\right), \tag{5.13}$$

where $\text{ABER}_{\alpha(n)}$ and $\text{ABER}_{\beta(n)}$ are the ABER when the direct transmission is activated, while $\text{ABER}_{\mu(n,m)}$ is the ABER when cooperative transmission is activated. $\text{ABER}_{\alpha(n)}$ can be written as

$$\text{ABER}_{\alpha(n)} = \int_{\gamma_n}^{\gamma_{n+1}} \text{BER}(\text{n},\gamma) f_{\gamma_{SD}}(\gamma)d\gamma, \tag{5.14}$$

where $\text{BER}(n,\gamma)$ is the BER of the M-QAM which can be approximated as

$$\text{BER}(n,\gamma) \approx \frac{2(\sqrt{2^n}-1)}{n\sqrt{2^n}}Q\left(\sqrt{\frac{3\gamma}{2^n-1}}\right) = A_nQ\left(\sqrt{B_n\gamma}\right), \quad n \geq 2, \tag{5.15}$$

where $A_n = 2(\sqrt{2^n}-1)/(n\sqrt{2^n})$ and $B_n = 3/(2^n-1)$. As in Chapter 4, It is useful to define a common finite integral as

$$\Phi(\gamma_{s1},\gamma_{s2},\bar{\gamma},B) = \int_{\gamma_{s1}}^{\gamma_{s2}} Q\left(\sqrt{Bx}\right)\frac{e^{-x/\bar{\gamma}}}{\bar{\gamma}}dx. \tag{5.16}$$

By using the result of Appendix C, (5.16) is given by

$$\Phi(\gamma_{s1},\gamma_{s2},\bar{\gamma},B)=Q\left(\sqrt{B\gamma_{s1}}\right)\,e^{-\gamma_{s1}/\bar{\gamma}}-\sqrt{\frac{B}{\frac{2}{\bar{\gamma}}+B}}Q\left(\sqrt{2\gamma_{s1}\left(\frac{1}{\bar{\gamma}}+\frac{B}{2}\right)}\right)$$
$$-Q\left(\sqrt{B\gamma_{s2}}\right)\,e^{-\gamma_{s2}/\bar{\gamma}}+\sqrt{\frac{B}{\frac{2}{\bar{\gamma}}+B}}Q\left(\sqrt{2\gamma_{s2}\left(\frac{1}{\bar{\gamma}}+\frac{B}{2}\right)}\right), \tag{5.17}$$

then, $\mathrm{ABER}_{\alpha(n)}$ becomes

$$\mathrm{ABER}_{\alpha(n)}=A_n\Phi(\gamma_n,\gamma_{n+1},\bar{\gamma}_{SD},B_n). \tag{5.18}$$

The second part of the ABER of the direct transmission, $\mathrm{ABER}_{\beta(n)}$, can be written as

$$\mathrm{ABER}_{\beta(n)}=\int_{\gamma_n}^{\gamma_{n+1}}\mathrm{BER}(\mathrm{n},x)F_{\gamma_{SRD}}(T_n-x)f_{\gamma_{SD}}(x)dx, \tag{5.19}$$

substituting (5.6) and (5.15) into (5.19) and solving the integral, $\mathrm{ABER}_{b(n)}$ is rewritten as

$$\mathrm{ABER}_{\beta(n)}=A_n\Phi\left(\gamma_n,\gamma_{n+1},\bar{\gamma}_{SD},B_n\right)-\frac{A_n}{1+\frac{2^n\bar{\gamma}_{SD}}{\bar{\gamma}_{SRD}}}\Phi\left(\gamma_n,\gamma_{n+1},\frac{1}{\frac{1}{\bar{\gamma}_{SD}}+\frac{2^n}{\bar{\gamma}_{SRD}}},B_n\right). \tag{5.20}$$

The ABER of the cooperative transmission, $\mathrm{ABER}_{\mu(n,m)}$, can be written as

$$\mathrm{ABER}_{\mu(n,m)}=\int_{\gamma_n}^{\gamma_{n+1}}\int_{AF_R}\mathrm{BER}(m,u)f_{\gamma_{SRD}}(z-x)f_{\gamma_{SD}}(x)dzdx, \tag{5.21}$$

Substituting $f_{\gamma_{SRD}}(.)$ and (5.15) into (5.21) and using the definition of the cooperative regions in (5.9), $\mathrm{ABER}_{\mu_1(n,m)}$ and $\mathrm{ABER}_{\mu_2(n,m)}$ can be given by

$$\text{ABER}_{\mu_1(n,m)} = \frac{A_m}{1-\frac{\bar{\gamma}_{SD}}{\bar{\gamma}_{SRD}}} \Phi\left(\gamma_m, \gamma_{m+1}, \bar{\gamma}_{SRD}, B_m\right) \psi\left(n, \frac{1}{\bar{\gamma}_{SD}} - \frac{1}{\bar{\gamma}_{SRD}}\right), \tag{5.22}$$

and

$$\begin{aligned} &\text{ABER}_{\mu_2(n,m)} \\ &= \frac{A_m}{1+\frac{2^n \bar{\gamma}_{SD}}{\bar{\gamma}_{SRD}}} \Phi\left(\gamma_n, \gamma_{n+1}, \frac{1}{\frac{1}{\bar{\gamma}_{SD}}+\frac{2^n}{\bar{\gamma}_{SRD}}}, C_m\right) - \frac{A_m}{1-\frac{\bar{\gamma}_{SD}}{\bar{\gamma}_{SRD}}} \sqrt{\frac{B_m}{\frac{2}{\bar{\gamma}_{SRD}}+B_m}} \Phi\left(\gamma_n, \gamma_{n+1}, \frac{1}{\frac{1}{\bar{\gamma}_{SD}}-\frac{1}{\bar{\gamma}_{SRD}}}, D_m\right) \\ &- \frac{A_m}{1-\frac{\bar{\gamma}_{SD}}{\bar{\gamma}_{SRD}}} \psi\left(n, \frac{1}{\bar{\gamma}_{SD}} - \frac{1}{\bar{\gamma}_{SRD}}\right) \left[Q\left(\sqrt{B_m \gamma_{m+1}}\right) e^{-\frac{\gamma_{m+1}}{\bar{\gamma}_{SRD}}} - Q\left(\sqrt{E_m \gamma_{m+1}}\right) \sqrt{\frac{B_m}{\frac{2}{\bar{\gamma}_{SRD}}+B_m}} \right]. \end{aligned} \tag{5.23}$$

respectively, where $C_m = (2^n + 1) B_m$, $D_m = 2(2^n + 1)\left(\frac{1}{\bar{\gamma}_{SRD}} + \frac{B_m}{2}\right)$, and $E_m = 2\left(\frac{1}{\bar{\gamma}_{SRD}} + \frac{B_m}{2}\right)$. Substituting (5.18), (5.20), (5.22), and (5.23) into (5.13), the overall ABER of the GSP of the single-relay AF adaptive cooperative system can be obtained.

5.1.2.3 Outage Probability

In our case, the outage probability is basically the probability when the SNR of both direct and cooperative modes are below γ_2. Hence, the outage probability can be given by

$$\begin{aligned} P_{out}^{GSP} &= \Pr[\gamma_{SD} < \gamma_2, \gamma_{AF} < \gamma_2] \\ &= \int_0^{\gamma_2} \int_0^{z} f_{\gamma_{SRD}}(z-x) f_{\gamma_{SD}}(x) dx dz \\ &= 1 - \frac{1}{\bar{\gamma}_{SRD} - \bar{\gamma}_{SD}} \left(\bar{\gamma}_{SRD} e^{-\frac{\gamma_2}{\bar{\gamma}_{SRD}}} - \bar{\gamma}_{SD} e^{-\frac{\gamma_2}{\bar{\gamma}_{SD}}} \right). \end{aligned} \tag{5.24}$$

5.2 Multiple-Relay System

5.2.1 AF Efficient Relay Selection Scheme

In a multiple-relay cooperative system, the number of relay nodes used for cooperative transmission has an impact on the spectral efficiency. Although the diversity is high (i.e., $L+1$ diversity order can be achieved), the operation becomes very complicated and the system suffers low spectral efficiency due to the transmission over orthogonal channels. Also, the characteristics of the channel are usually under continuous change due to multipath fading. Therefore, in order to maximize the spectral efficiency, it is important to use a relay selection technique and let the cooperative transmission be adaptive in terms of both cooperative and non-cooperative transmission as well as rate selection. Therefore, in addition to the criteria of the generalized switching policy mentioned earlier, we need to include the relay selection criterion in the decision to use the mode of transmission, either cooperative or direct transmission, under variable-rate consideration. Hence, the output SNR of the proposed AFERS scheme can be defined as

$$\gamma_{AFERS}^{b} = \begin{cases} \gamma_{SD}, & \begin{array}{l} \text{if } (\gamma_{SD} \geq \gamma_{\lfloor \frac{N}{2} \rfloor + 1}), \quad \text{or} \\ \text{if } (\gamma_n \leq \gamma_{SD} \leq \gamma_{n+1} \text{ and} \\ \gamma_{AF}^{b} < T_n,\ n = 2, ., \lfloor \frac{N}{2} \rfloor), \end{array} \\ \gamma_{AF}^{b}, & \text{otherwise.} \end{cases} \tag{5.25}$$

where T_n is defined previously in (5.2), and AF^b is the combined SNR at the destination node when the best rely node is selected from the available relay nodes, which can be represented as

$$\gamma_{AF}^{b} = \gamma_{SD} + \max_{i \in \{1,2,\ldots,L\}} \left[\frac{\gamma_{SR_i}\gamma_{R_iD}}{\gamma_{SR_i} + \gamma_{R_iD} + 1} \right], \tag{5.26}$$

where γ_{SR_i} and γ_{R_iD} are the instantaneous SNRs between the source and the i^{th} relay nodes and the i^{th} relay and destination nodes, respectively. For derivation tractability, (5.26) can be approximated by its upper bound as [71, 53]

$$\gamma_{AF}^{b} \leq \gamma_{SD} + \max_{i \in \{1,2,\ldots,L\}} \left[\min\left(\gamma_{SR_i}, \gamma_{R_iD}\right)\right], \\ = \gamma_{SD} + \gamma_{SR_bD}, \tag{5.27}$$

where γ_{SR_bD} is the upper bound of the end-to-end SNR of the best relay path.

5.2.1.1 Mode of Operation

The decision to cooperate or not and the selection of the best relay node under variable-rate transmission require that each relay node estimate the relay links by receiving a ready-to-send (RTS) signal from the source node, and a clear-to-send (CTS) signal from the destination node which includes the SNR of the direct link, γ_{SD}. Based on this information, each relay node is able to apply the proposed policy, as shown in Fig. 5.2, which shows a flow chart of the proposed scheme. Each relay node, R_i, $i = 1, 2, \ldots L$, finds the spectral efficiency of the direct link, n, and calculates γ_{SR_iD} and γ_{AF}^{i}. If the spectral efficiency of the direct link, n, is below half of the maximum spectral efficiency and $\gamma_{AF}^{i} > T_n$, the relay node sets a timer which is inversely proportional to γ_{SR_iD}. If the timer of the i^{th} relay node expires first, a flag packet, $flag_i$, which includes γ_{SR_iD}, will be sent by the i^{th} relay node to announce its existence to the source and destination nodes, and to keep other relay nodes silent. The source node is then able to select the modulation level for the cooperative transmission mode. If the maximum listening time by which the system can use one of the relay nodes expires (i.e., all the relay nodes are silent), the source node will use the received CTS signal from the destination node to select the modulation level for the direct transmission mode.

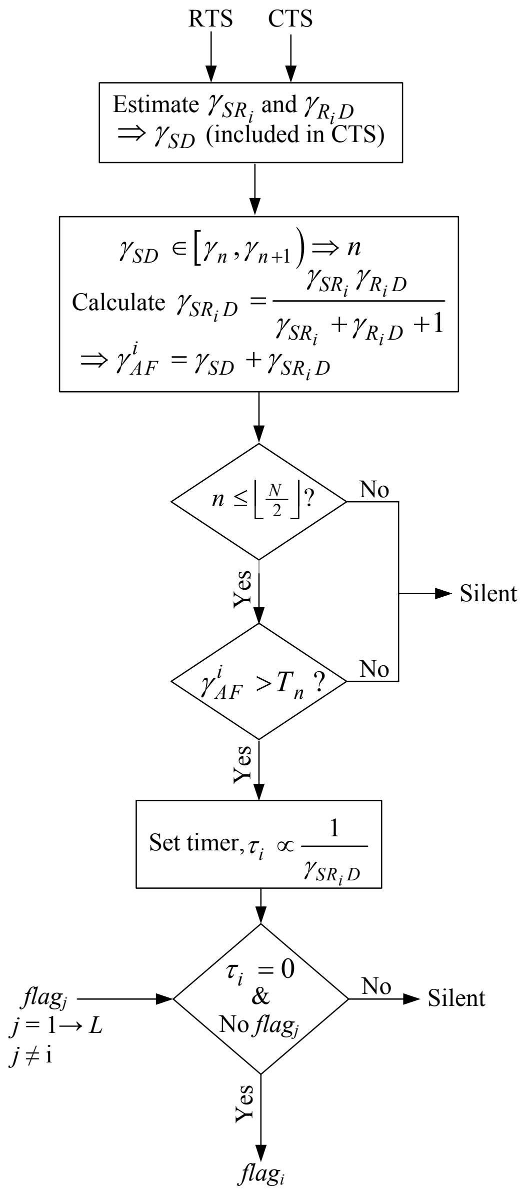

Figure 5.2: Flow chart of the proposed AFERS scheme at the i^{th} rely node, R_i, i = 1, 2, ... L.

5.2.2 Performance Analysis of AFERS Scheme

5.2.2.1 Average Spectral Efficiency

Based on the mode of operation, the average spectral efficiency of the AFERS scheme can be expressed as

$$\eta^{AFERS} = \sum_{n=\left\lfloor \frac{N}{2} \right\rfloor+1}^{N} n\,\alpha(n) + \sum_{n=2}^{\left\lfloor \frac{N}{2} \right\rfloor} n\,\sigma(n) + \sum_{\substack{n=0\\ n\neq 1}}^{\left\lfloor \frac{N}{2} \right\rfloor} \sum_{m=I^n}^{N} \frac{m}{2}\rho(n,m), \tag{5.28}$$

where $\alpha(n)$ is given by (5.4), $\sigma(n)$ is the probability when $\gamma_2 \leq \gamma_{SD} \leq \gamma_{\left\lfloor \frac{N}{2} \right\rfloor}$ and $\gamma_{AF}^{b} < T_n$, and $\rho(n,m)$ is the probability when $\gamma_2 \leq \gamma_{SD} \leq \gamma_{\left\lfloor \frac{N}{2} \right\rfloor}$ and $\gamma_{AF}^{b} \geq T_n$. Then, $\sigma(n)$ can be represented by

$$\sigma(n) = \int_{\gamma_n}^{\gamma_{n+1}} F_{\gamma_{SR_bD}}(T_n - x) f_{\gamma_{SD}}(x)dx, \tag{5.29}$$

where $F_{\gamma_{SR_bD}}(.)$ is the CDF of the upper bound of the best-relay end-to-end path SNR which can be given by

$$\begin{aligned} F_{\gamma_{SR_bD}}(\gamma) &= \Pr\left\{ \max_{i\in\{1,2,\ldots,L\}} \left[\min\left(\gamma_{SR_i}, \gamma_{R_iD}\right)\right] < \gamma \right\}, \\ &= \prod_{i=1}^{L} \left[1 - (1 - F_{\gamma_{SR_i}}(\gamma))(1 - F_{\gamma_{R_iD}}(\gamma))\right], \\ &= \prod_{i=1}^{L} \left(1 - e^{-\frac{\gamma}{\bar{\gamma}_{SR_iD}}}\right), \end{aligned} \tag{5.30}$$

where $\bar{\gamma}_{SR_iD} = \bar{\gamma}_{SR_i}\bar{\gamma}_{R_iD}/(\bar{\gamma}_{SR_i} + \bar{\gamma}_{R_iD})$. $F_{\gamma_{SR_bD}}(\cdot)$ can be rewritten as

$$F_{\gamma_{SR_bD}}(\gamma) = 1 - \sum_{i=1}^{L} (-1)^{i-1} \sum_{k_1=1}^{L-i+1} \sum_{k_2=k_1+1}^{L-i+2} \cdots \sum_{k_i=k_{i-1}+1}^{L} e^{-\gamma \sum_{d=1}^{i} \frac{1}{\bar{\gamma}_{SR_{k_d}D}}}. \tag{5.31}$$

The corresponding PDF is obtained by differentiating (5.31) with respect to γ, yielding

$$f_{\gamma_{SR_bD}}(\gamma) = \sum_{i=1}^{L}(-1)^{i-1}\sum_{k_1=1}^{L-i+1}\sum_{k_2=k_1+1}^{L-i+2}\cdots\sum_{k_i=k_{i-1}+1}^{L}\left(\sum_{d=1}^{i}\frac{1}{\bar{\gamma}_{SR_{k_d}D}}e^{-\gamma\sum\limits_{d=1}^{i}\frac{1}{\bar{\gamma}_{SR_{k_d}D}}}\right), \tag{5.32}$$

by substituting (5.31) into (5.29) and solving the integral, $\sigma(n)$ can be rewritten as

$$\sigma(n) = \psi\left(n, \frac{1}{\bar{\gamma}_{SD}}\right) - \sum_{i=1}^{L}(-1)^{i-1}\sum_{k_1=1}^{L-i+1}\sum_{k_2=k_1+1}^{L-i+2}\cdots\sum_{k_i=k_{i-1}+1}^{L}$$
$$\times\left[\frac{1}{1+2^n\bar{\gamma}_{SD}\sum\limits_{d=1}^{i}\frac{1}{\bar{\gamma}_{SR_{k_d}D}}}\psi\left(n, \frac{1}{\bar{\gamma}_{SD}}+2^n\sum_{d=1}^{i}\frac{1}{\bar{\gamma}_{SR_{k_d}D}}\right)\right]. \tag{5.33}$$

Also $\rho(n,m)$ can be represented by

$$\rho(n,m) = \int_{\gamma_n}^{\gamma_{n+1}}\int_{AF_R} f_{\gamma_{SR_bD}}(u-x)f_{\gamma_{SD}}(x)dudx, \tag{5.34}$$

Based on the conditions of the cooperative regions, $\rho(n,m)$ has two values, $\rho_1(n,m)$ and $\rho_2(n,m)$. For $AF_R = [\gamma_m, \gamma_{m+1})$, substituting (5.32) into (5.34) and solving the double integral, $\rho_1(n,m)$ is given by

$$\rho_1(n,m) = \sum_{i=1}^{L}(-1)^{i-1}\sum_{k_1=1}^{L-i+1}\sum_{k_2=k_1+1}^{L-i+2}\cdots\sum_{k_i=k_{i-1}+1}^{L}$$
$$\left[\frac{1}{1-\bar{\gamma}_{SD}\sum\limits_{d=1}^{i}\frac{1}{\bar{\gamma}_{SR_{k_d}D}}}\psi\left(n, \frac{1}{\bar{\gamma}_{SD}}-\sum_{d=1}^{i}\frac{1}{\bar{\gamma}_{SR_{k_d}D}}\right)\psi\left(m, \sum_{d=1}^{i}\frac{1}{\bar{\gamma}_{SR_{k_d}D}}\right)\right], \tag{5.35}$$

similarly, For $AF_R = [T_n, \gamma_{m+1})$, $\rho_2(n,m)$ is given by

$$\rho_2(n,m) = \sum_{i=1}^{L} (-1)^{i-1} \sum_{k_1=1}^{L-i+1} \sum_{k_2=k_1+1}^{L-i+2} \cdots \sum_{k_i=k_{i-1}+1}^{L} \left[\frac{1}{1+2^n \bar{\gamma}_{SD} \sum\limits_{d=1}^{i} \frac{1}{\bar{\gamma}_{SR_{k_d}D}}} \psi\left(n, \frac{1}{\bar{\gamma}_{SD}} + 2^n \sum_{d=1}^{i} \frac{1}{\bar{\gamma}_{SR_{k_d}D}}\right) - \frac{e^{-\gamma_{m+1} \sum\limits_{d=1}^{i} \frac{1}{\bar{\gamma}_{SR_{k_d}D}}}}{1-\bar{\gamma}_{SD} \sum\limits_{d=1}^{i} \frac{1}{\bar{\gamma}_{SR_{k_d}D}}} \psi\left(n, \frac{1}{\bar{\gamma}_{SD}} - \sum_{d=1}^{i} \frac{1}{\bar{\gamma}_{SR_{k_d}D}}\right) \right]. \tag{5.36}$$

Substituting (5.4), (5.33), (5.35), and (5.36) into (5.28), a closed-form expression for the average spectral efficiency of the proposed AFERS scheme can be obtained.

Note that by letting $L = 1$ in (5.33), (5.35), and (5.36), the closed-form expression of the spectral efficiency of the AFERS scheme returns back to the one of the GSP of the single-relay AF adaptive cooperative system as given by (5.12).

5.2.2.2 Average Bit Error Rate

The ABER of the proposed AFERS scheme can be expressed as

$$\mathrm{ABER}^{\mathrm{AFERS}} = \frac{1}{\eta^{AFERS}} \left(\sum_{n=\left\lfloor \frac{N}{2} \right\rfloor+1}^{N} n\,\mathrm{ABER}_{\alpha(n)} + \sum_{n=2}^{\left\lfloor \frac{N}{2} \right\rfloor} n\,\mathrm{ABER}_{\sigma(n)} + \sum_{\substack{n=0 \\ n\neq 1}}^{\left\lfloor \frac{N}{2} \right\rfloor} \sum_{m=I^n}^{N} \frac{m}{2} \mathrm{ABER}_{\rho(n,m)} \right), \tag{5.37}$$

where $\mathrm{ABER}_{\alpha(n)}$ is given by (5.18), $\mathrm{ABER}_{\sigma(n)}$ is the second term of the ABER when the direct transmission is activated, and $\mathrm{ABER}_{\rho(n,m)}$ is the ABER when cooperative transmission is activated. The $\mathrm{ABER}_{\sigma(n)}$, can be written as

$$\text{ABER}_{\sigma(n)}= \int\limits_{\gamma_n}^{\gamma_{n+1}} \text{BER}(\text{n}, x) F_{\gamma_{SR_bD}}(T_n - x) f_{\gamma_{SD}}(x) dx, \tag{5.38}$$

where $\text{BER}(n, \gamma)$ is the BER of the M-QAM, as given by (5.15). Substituting (5.31) and (5.18) into (5.38) and solving the integral using (5.16) and its closed-form expression as given by (5.17), $\text{ABER}_{\sigma(n)}$ can be given by

$$\begin{aligned}\text{ABER}_{\sigma(n)} &= A_n \Phi(\gamma_n, \gamma_{n+1}, \bar{\gamma}_{SD}, B_n) - A_n \sum_{i=1}^{L} (-1)^{i-1} \sum_{k_1=1}^{L-i+1} \sum_{k_2=k_1+1}^{L-i+2} \cdots \sum_{k_i=k_{i-1}+1}^{L} \\ &\times \left[\frac{1}{1 + 2^n \bar{\gamma}_{SD} \sum\limits_{d=1}^{i} \frac{1}{\bar{\gamma}_{SR_{k_d}D}}} \Phi \left(\gamma_n, \gamma_{n+1}, \frac{1}{\frac{1}{\bar{\gamma}_{SD}} + 2^n \sum\limits_{d=1}^{i} \frac{1}{\bar{\gamma}_{SR_{k_d}D}}}, B_n \right) \right].\end{aligned} \tag{5.39}$$

The ABER of the cooperative transmission, $\text{ABER}_{\rho(n,m)}$, can be written as

$$\text{ABER}_{\rho(n,m)} = \int\limits_{\gamma_n}^{\gamma_{n+1}} \int\limits_{AF_R} \text{BER}(m, u) f_{\gamma_{SR_bD}}(u - x) f_{\gamma_{SD}}(x) du dx, \tag{5.40}$$

substituting (5.32) and (5.15) into (5.40) and using the definition of the cooperative regions in (5.9), $\text{ABER}_{\rho_1(n,m)}$ and $\text{ABER}_{\rho_2(n,m)}$ can be given by

$$\begin{aligned}\text{ABER}_{\rho_1(n,m)} &= A_m \sum_{i=1}^{L} (-1)^{i-1} \sum_{k_1=1}^{L-i+1} \sum_{k_2=k_1+1}^{L-i+2} \cdots \sum_{k_i=k_{i-1}+1}^{L} \\ &\times \left[\frac{1}{1 - \bar{\gamma}_{SD} \sum\limits_{d=1}^{i} \frac{1}{\bar{\gamma}_{SR_{k_d}D}}} \psi \left(n, \frac{1}{\bar{\gamma}_{SD}} - \sum_{d=1}^{i} \frac{1}{\bar{\gamma}_{SR_{k_d}D}} \right) \Phi \left(\gamma_m, \gamma_{m+1}, \frac{1}{\sum\limits_{d=1}^{i} \frac{1}{\bar{\gamma}_{SR_{k_d}D}}}, B_m \right) \right],\end{aligned} \tag{5.41}$$

and

$$
\begin{aligned}
&\text{ABER}_{\rho_2(n,m)} \\
&= A_m \sum_{i=1}^{L} (-1)^{i-1} \sum_{k_1=1}^{L-i+1} \sum_{k_2=k_1+1}^{L-i+2} \cdots \sum_{k_i=k_{i-1}+1}^{L} \\
&\times \Bigg\{ \frac{1}{1+2^n \bar{\gamma}_{SD} \sum\limits_{d=1}^{i} \frac{1}{\bar{\gamma}_{SR_{k_d}D}}} \Phi \left(\gamma_n, \gamma_{n+1}, \frac{1}{\frac{1}{\bar{\gamma}_{SD}} + 2^n \sum\limits_{d=1}^{i} \frac{1}{\bar{\gamma}_{SR_{k_d}D}}}, (2^n+1) B_m \right) \\
&- \sqrt{\frac{B_m}{2\sum\limits_{d=1}^{i} \frac{1}{\bar{\gamma}_{SR_{k_d}D}} + B_m}} \frac{1}{1-\bar{\gamma}_{SD} \sum\limits_{d=1}^{i} \frac{1}{\bar{\gamma}_{SR_{k_d}D}}} \Phi \left(\gamma_n, \gamma_{n+1}, \frac{1}{\frac{1}{\bar{\gamma}_{SD}} - \sum\limits_{d=1}^{i} \frac{1}{\bar{\gamma}_{SR_{k_d}D}}}, 2(2^n+1) \left(\frac{B_m}{2} + \sum_{d=1}^{i} \frac{1}{\bar{\gamma}_{SR_{k_d}D}} \right) \right) \\
&- \frac{1}{1-\bar{\gamma}_{SD} \sum\limits_{d=1}^{i} \frac{1}{\bar{\gamma}_{SR_{k_d}D}}} \psi \left(n, \frac{1}{\bar{\gamma}_{SD}} - \sum_{d=1}^{i} \frac{1}{\bar{\gamma}_{SR_{k_d}D}} \right) \Bigg[Q\left(\sqrt{B_m \gamma_{m+1}}\right) e^{-\gamma_{n+1} \sum\limits_{d=1}^{i} \frac{1}{\bar{\gamma}_{SR_{k_d}D}}} \\
&- \sqrt{\frac{B_m}{2\sum\limits_{d=1}^{i} \frac{1}{\bar{\gamma}_{SR_{k_d}D}} + B_m}} Q \left(\sqrt{2\gamma_{m+1} \left(\frac{B_m}{2} + \sum_{d=1}^{i} \frac{1}{\bar{\gamma}_{SR_{k_d}D}} \right)} \right) \Bigg] \Bigg\},
\end{aligned}
\tag{5.42}
$$

respectively. Finally, substituting (5.18), (5.39), (5.41), and (5.42) into (5.37), the overall ABER of the proposed AFERS scheme can be obtained.

5.2.2.3 Outage Probability

The outage event occurs when both the direct link SNR, γ_{SD}, and the best AF output SNR, γ_{AF}^b, are below γ_2. Then, the outage probability can be written as

$$
\begin{aligned}
P_{out}^{AFERS} &= \Pr[\gamma_{SD} < \gamma_2, \gamma_{AF}^b < \gamma_2], \\
&= \int_0^{\gamma_2} \int_0^{u} f_{\gamma_{SR_bD}}(u-x) f_{\gamma_{SD}}(x) dx du.
\end{aligned}
\tag{5.43}
$$

Substituting (5.32) into (5.43) and solving the double integral, the outage probability of the proposed AFERS scheme can be given by

$$P_{out}^{AFERS} = \sum_{i=1}^{L} (-1)^{i-1} \sum_{k_1=1}^{L-i+1} \sum_{k_2=k_1+1}^{L-i+2} \cdots \sum_{k_i=k_{i-1}+1}^{L}$$
$$\times \left[1 - \frac{1}{1 - \bar{\gamma}_{SD} \sum\limits_{d=1}^{i} \frac{1}{\bar{\gamma}_{SR_{k_d}D}}} e^{-\gamma_2 \sum\limits_{d=1}^{i} \frac{1}{\bar{\gamma}_{SR_{k_d}D}}} + \frac{\sum\limits_{d=1}^{i} \frac{1}{\bar{\gamma}_{SR_{k_d}D}}}{\frac{1}{\bar{\gamma}_{SD}} - \sum\limits_{d=1}^{i} \frac{1}{\bar{\gamma}_{SR_{k_d}D}}} e^{-\frac{\gamma_2}{\bar{\gamma}_{SD}}} \right]. \tag{5.44}$$

The proposed scheme has same outage probability as the outage-based AF adaptive cooperative scheme [47] and the AF fixed relying scheme [73]. This is due to the fact that if $\gamma_{AF}^{b} < \gamma_2$, γ_{SD} is also less than γ_2 because $\gamma_{SD} \leq \gamma_{AF}^{b}$, then $\Pr[\gamma_{SD} < \gamma_2, \gamma_{AF}^{b} < \gamma_2] = \Pr[\gamma_{AF}^{b} < \gamma_2]$. Notice that, even though the proposed scheme aims to improve the spectral efficiency, the outage probability can still be maintained. Further evaluation of the performance of the proposed scheme is presented in the following section.

5.2.3 Comparative Study

In this section, we provide some numerical examples to evaluate the performance of the proposed scheme in terms of average spectral efficiency, average bit error rate, and outage probability. We compare our proposed AFERS scheme with the outage-based AF adaptive cooperative scheme [47], the AF fixed relaying (AFFR) [73], and the conventional direct transmission. Table 6.1 gives the average SNR for each relay link (i.e., $\bar{\gamma}_{SR_i}$ and $\bar{\gamma}_{R_iD}$) as a function of the average SNR, ζ, in which all the performance measures are depicted versus ζ. We also set $\bar{\gamma}_{SD} = 13dB$, the maximum spectral efficiency, N, to be equal to 8, and the target BER, BER_T, to be equal to 10^{-3} and 10^{-6}.

Fig. 5.3 shows the average spectral efficiency of the proposed AFERS scheme, the outage-based AF adaptive cooperative scheme, the AF fixed relaying, and the conventional direct transmission. We set $\text{BER}_\text{T} = 10^{-3}$ and $L = 1$ and 5. At a low average SNR (i.e., average SNR < 10 dB), the average spectral efficiency of the proposed scheme is similar to the outage-based AF adaptive cooperative scheme due to rarely selecting cooperative transmission. In contrast, AFFR experiences a reduction in the spectral efficiency due

Table 5.1: Setting of the number of relay nodes in the system and their links average SNRs

Number of Relay nodes	Relay Path Average SNRs
L=5	$\bar{\gamma}_{SR_i} = [5.0,\ 4.5,\ 4.0,\ 4.1,\ 3.7]\zeta$ $\bar{\gamma}_{R_iD} = [4.6,\ 4.1,\ 3.8,\ 3.4,\ 3.1]\zeta$
L=3	$\bar{\gamma}_{SR_i} = [5.0,\ 4.5,\ 4.0]\zeta$ $\bar{\gamma}_{R_iD} = [4.6,\ 4.1,\ 3.8]\zeta$
L=1	$\bar{\gamma}_{SR_i} = 5.0\zeta$ $\bar{\gamma}_{R_iD} = 4.6\zeta$

to the continuous use of cooperative transmission, even though the channel gain is low. On the other hand, at a high average SNR (i.e., average SNR $>$ 25 dB), the average spectral efficiency of the proposed scheme converges to that of the AFFR because the direct transmission is rarely activated. It is clear that in this region, the spectral efficiency saturates to half of the maximum spectral efficiency due to the half-duplex transmission mode. Furthermore, at a moderate average SNR, the proposed scheme has its maximum gain since it has the capability to optimize the mode of operation efficiently. The gain ranges from 1 to 3 dB compared to the same average spectral efficiency of the outage-based and AFFR schemes. Finally, average spectral efficiency benefits from increasing the number of available relay nodes; for instance, the proposed scheme can achieve a 4dB gain on increasing the number of relay nodes from 1 to 5.

Fig. 5.4 shows the average spectral efficiency of the proposed scheme when the switching threshold SNR, T_n, is either calculated by (5.1) or by its approximated expression given by (5.2). We set $L = 3$ and use two different target BERs, 10^{-3} and 10^{-6}. We observe that the approximated value of T_n has no impact on the average spectral efficiency for both target BERs. Furthermore, there is a reduction in the average spectral efficiency due to the increase in the quality of transmission in terms of target BER, which shows a tradeoff between spectral efficiency and target quality. This verifies that the approximate expression of T_n is simple and yet accurate.

Fig. 5.5 shows the ABER of the proposed scheme, the outage-based AF adaptive cooperative scheme, the AFFR, and the conventional direct transmission. We set $L = 1$ and $\text{BER}_\text{T} = 10^{-3}$ and 10^{-6}. At low and moderate average SNRs, all schemes have the same

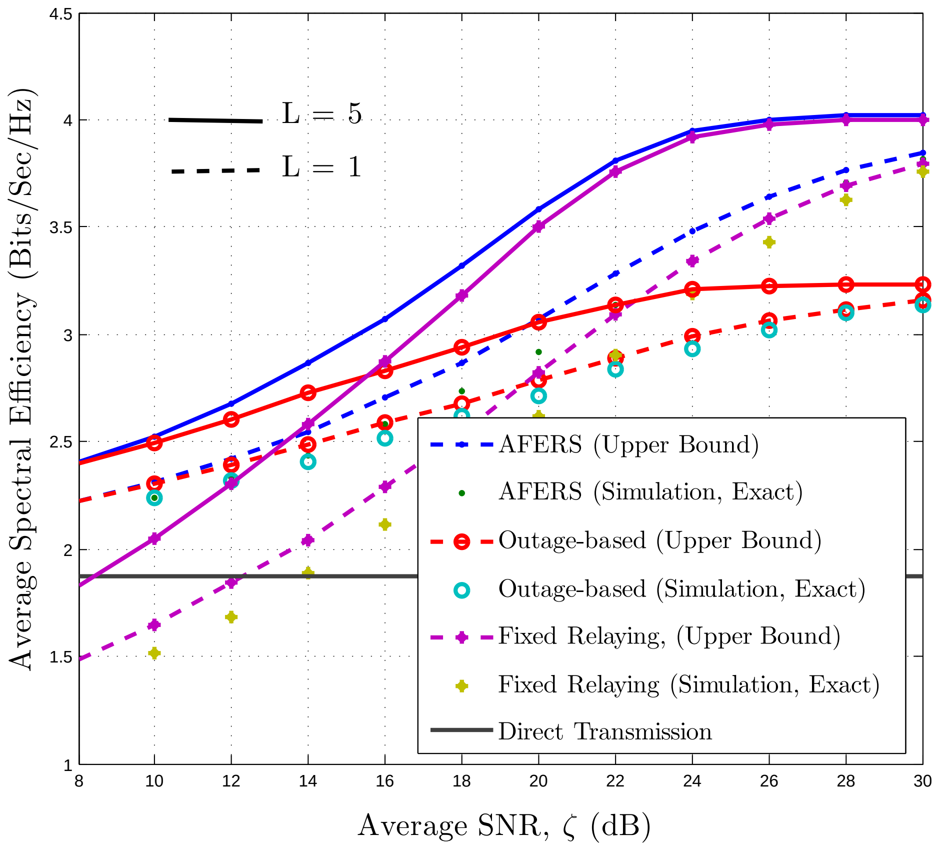

Figure 5.3: Average spectral efficiency of the proposed AFERS, the outage-based, the AFFR, and the direct transmission schemes for target BER of 10^{-3} and different values of L.

and almost constant ABER due to the use of adaptive modulation. At a high average SNR, the ABERs of the proposed and AFFR schemes outperform the outage-based and direct transmission schemes due to diversity gain improvement. Furthermore, for each target BER value, all schemes provide ABER below the target, as desired.

Fig. 5.6 shows the outage probability of the proposed scheme for a target BER of 10^{-3} and using different numbers of relay nodes: $L = 1$, 3, and 5. It is clear that cooperative transmission improves the outage probability significantly as compared to the conventional direct transmission. This improvement increases with a larger number of relay nodes. Finally, the previous results and the fact that the proposed scheme has the same outage

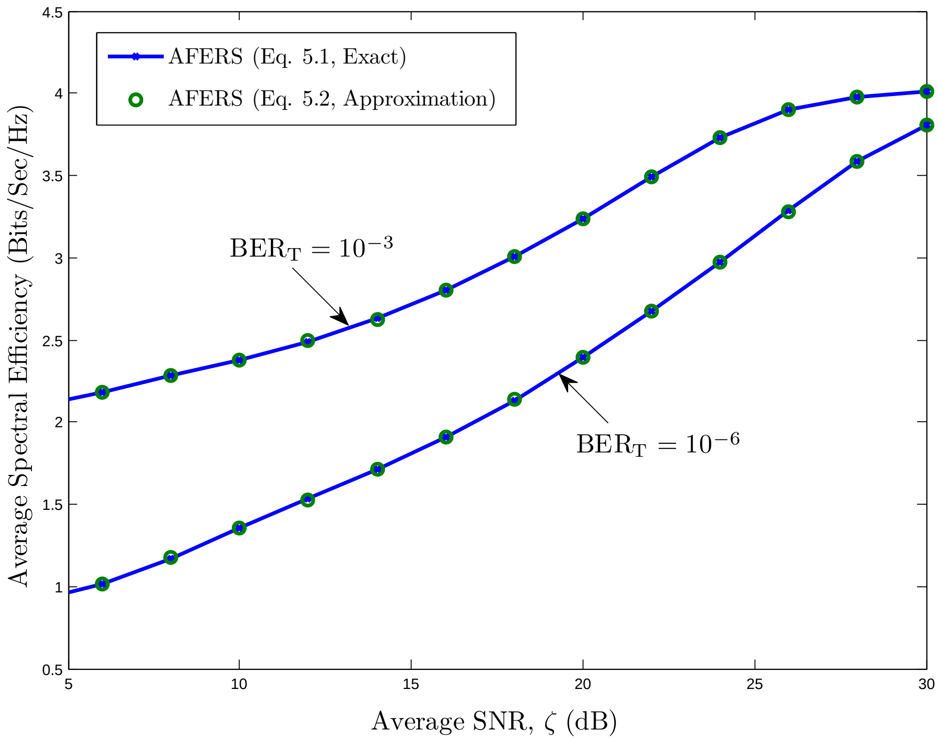

Figure 5.4: Comparison between the average spectral efficiency of the proposed scheme using (5.1) and its approximation given by (5.2) for $L = 1$, and for two different target BERs.

probability as the other cooperative schemes verify that our proposed AFERS scheme is a spectrally efficient scheme.

5.3 Summary

In this chapter, we have proposed a generalized switching policy for an amplify-and-forward adaptive cooperative system with variable-rate transmission. The policy has been proven to improve spectral efficiency, not only for the conventional direct transmission but also for both the AF fixed relaying and outage-based AF adaptive cooperative schemes. This improvement in spectral efficiency can be further increased by using a relay selection method

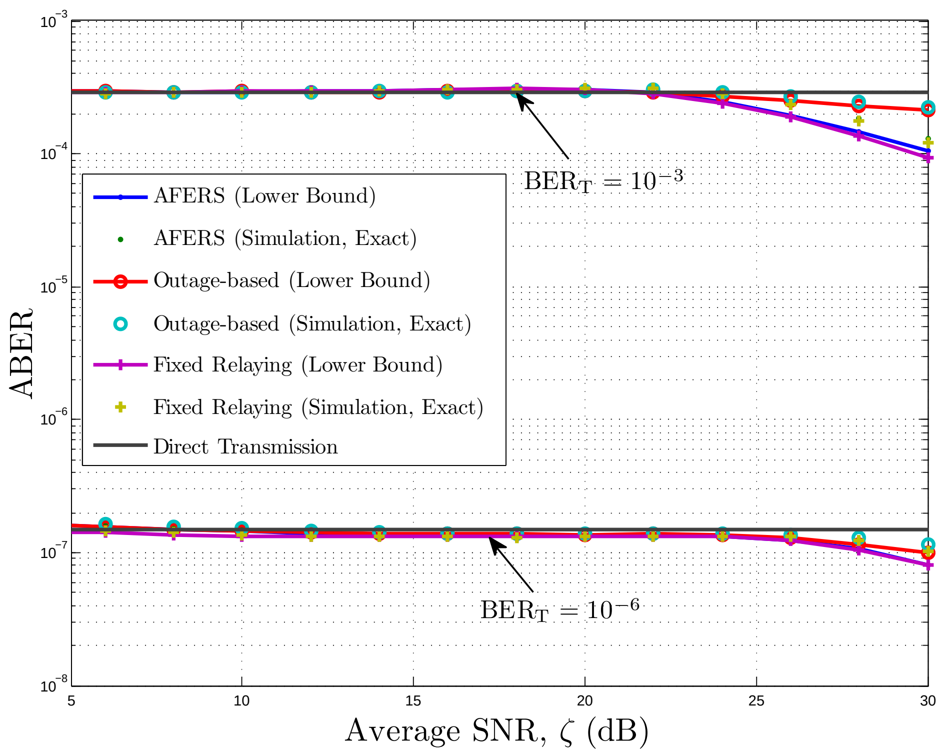

Figure 5.5: ABER of the proposed AFERS, the outage-based, the AFFR, and the direct transmission schemes for target BER of 10^{-3} and 10^{-6} and $L = 1$.

in which the best end-to-end path between the source and destination nodes is always selected. Finally, we have shown in Chapters 4 and 5 how a user can benefit from cooperative transmission by exploiting the existing nodes to serve as relays and form a virtual antenna array. This benefit may raise an issue regarding the resources of the relay nodes (e.g., energy and bandwidth). In the next chapter, we will investigate the cooperative wireless communication system when a power consumption constraint is considered.

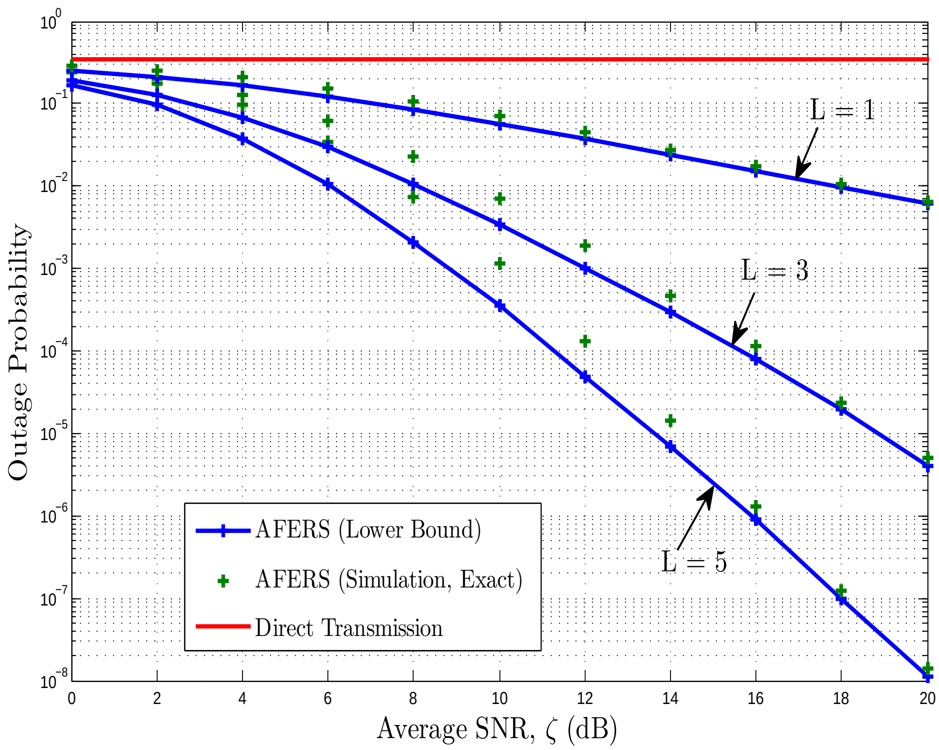

Figure 5.6: Outage probability of the proposed AFERS, the outafe-based, the AFFR, and the direct transmission schemes for target BER of 10^{-3} and different values of L.

Chapter 6

AF Cooperative System with Power Consumption Constraint

The increasing interest in cooperative communications is not surprising because of its abilities to enlarge coverage areas, reduce transmission power, increase transmission rates under a deep fading environment, and improve communication reliability. All these advantages rely on the usage of resources by the relay nodes. In other words, the extra bill (i.e., resources in terms of power consumption and bandwidth) should be paid by the relay node that cooperates with the source node to transfer the information to the destination node. Excessive selection of a particular relay node will increase the usage of its resources. Therefore, it is important to consider the fairness in the relay selection strategy. In this chapter, we investigate relay selection strategies under fair power consumption of the relay nodes for amplify-and-forward (AF) cooperative wireless systems. The fairness is defined as to achieve equal power consumption over the relay nodes. We propose a distributed relay selection strategy that aims to reduce the complexity of the existing centralized strategy. Our proposed strategy provides a simple closed-form expression for the weight coefficient used to achieve the considered fairness that depends only on the local average channel conditions of the relay path. We also derive closed-form expressions of the weighted outage probability and average bit error rate by using an upper bound for the signal-to-noise ratio (SNR) of the end-to-end relay path. We show that our proposed strategy not only has less complexity than the conventional centralized one but also provides better accuracy in distributing the total consumed power equally among the relay nodes without degrading the performance of the system.

The remainder of this chapter is organized as follows. In Section 6.1, we present how opportunistic relaying (OR) can be controlled under a power consumption constraint, and obtain the average power consumption of the relay node. In Section 6.2, we discuss some issues related to the conventional centralized strategy. This leads us to introduce our proposed distributed strategy, which provides an alternative solution for equal average power consumption. In Section 6.3, we derive closed-form expressions for the weighted outage probability and the average bit error rate. In Section 6.4, we present some numerical examples to evaluate our proposed strategy. Finally, the chapter is summarized in Section 6.5.

6.1 Opportunistic Relaying with Power Consumption Constraint

In general, relay selection schemes exploit channel state information (CSI) of the relay path and/or other performance metrics in order to define the selection criteria. OR considers only CSI, while other schemes take account of bit error rate (BER) or outage probability in order to optimize power, spectral efficiency, or delay. In this section, we study how relay selection can be controlled if there is a power consumption constraint over the relay nodes.

6.1.1 Relay Selection

Beside the simplicity of OR, which can be considered as an alternative solution to the distributed space time coding (DSTC) system that requires complex synchronization, the fairness among relay nodes is not considered, which may affect or limit network operation. For example, if there is a constraint on power consumption, the best relay node consumes much more power than the others due to frequent selection. Moreover, the relay node may become busy with transmitting or receiving data, which decreases the possibility of helping others and hence increasing delay time. Therefore, it is feasible to control the selection strategy of OR by adding a weight coefficient, w_i. The mathematical model of selecting a relay node, R_b, can be equivalently represented by

$$b = \arg \max_{i=1,\dots,L} (\gamma_{w_i}), \tag{6.1}$$

where $\gamma_{w_i} = \gamma_{R_i}/w_i$ is the weighted end-to-end SNR of the relay path. The output SNR at the destination node can be written as

$$\gamma_{AF}^{b} = \gamma_{SD} + \gamma_{R_b}. \tag{6.2}$$

6.1.2 Average Power Consumption of the relay node

In the AF protocol, the amplifying gain at the relay node depends primarily on the channel condition of the source-relay link. By neglecting the power consumption of the transceiver radio circuitry, since it is very small compared to the power consumption of the radio frequency (RF) amplifier, the power consumption of the i^{th} relay node can be given by [65]

$$P_{R_i}^{cons} = \begin{cases} P_R \left(1 - \frac{1}{G_{R_i}^2}\right), & if\, G_{R_i}^2 > 1, \\ 0, & if\, G_{R_i}^2 \leq 1. \end{cases} \tag{6.3}$$

Note that, at high SNR, $G_{R_i}^2 = 1/|h_{SR_i}|^2$, so we can write $G_{R_i}^2 = SNR/\gamma_{SR_i}$, where $SNR = P_S/N_o$ is the common SNR without fading, and $\gamma_{SR_i} = |h_{SR_i}|^2 P_S/N_o$. The average power consumption of the i^{th} relay node can be approximated by

$$\bar{P}_{R_i}^{cons} \approx P_R \int_0^{SNR} \left(1 - \frac{x}{SNR}\right) f_{\gamma_{SR_i}}(x) \Pr[i = b|x] dx, \tag{6.4}$$

where $\Pr[i = b|x]$ is the conditional probability of selecting the i^{th} relay node given that the SNR of the source-relay link is known which can be represented as

$$\Pr[i = b|x] = \Pr\left[\frac{\gamma_{R_i}}{w_i} > \max_{\substack{j=1,\ldots,L \\ j\neq i}} \frac{\gamma_{R_j}}{w_j}|x\right]. \tag{6.5}$$

By using the upper bound of the end-to-end SNR of the relay path, which can be written as

$$\begin{aligned}\gamma_{R_i} &= \frac{\gamma_{SR_i}\gamma_{R_iD}}{\gamma_{SR_i} + \gamma_{R_iD} + 1} \\ &\leq \gamma_{SR_iD} = \min(\gamma_{SR_i}, \gamma_{R_iD}),\end{aligned} \tag{6.6}$$

the conditional probability can be then represented as

$$\begin{aligned}\Pr[i = b|x] \approx &\int_0^x f_{\gamma_{R_iD}}(y) \prod_{\substack{j=1 \\ j\neq i}}^{L} F_{\gamma_{SR_jD}}\left(\frac{w_j}{w_i}y\right)dy \\ &+ \int_x^\infty f_{\gamma_{R_iD}}(y) \prod_{\substack{j=1 \\ j\neq i}}^{L} F_{\gamma_{SR_jD}}\left(\frac{w_j}{w_i}x\right)dy,\end{aligned} \tag{6.7}$$

where $F_{\gamma_{SR_jD}}(\cdot)$ is the cumulative distribution function (CDF) of the upper bound of the end-to-end SNR of the relay path which can be calculated as

$$\begin{aligned}F_{\gamma_{SR_jD}}(\gamma) &= \Pr\left[\min\left(\gamma_{SR_j}, \gamma_{R_jD}\right) \leq \gamma\right], \\ &= 1 - \left(1 - F_{\gamma_{SR_j}}(\gamma)\right)\left(1 - F_{\gamma_{R_jD}}(\gamma)\right), \\ &= 1 - e^{-\frac{\gamma}{\bar{\gamma}_{SR_jD}}},\end{aligned} \tag{6.8}$$

where $\bar{\gamma}_{SR_jD} = \bar{\gamma}_{SR_j} \cdot \bar{\gamma}_{R_jD}/(\bar{\gamma}_{SR_j} + \bar{\gamma}_{R_jD})$, and $\bar{\gamma}_{SR_j}$ and $\bar{\gamma}_{R_jD}$ are the average SNRs of the source-relay link and relay-destination link, respectively. Substituting (6.8) and (6.7) into (6.4) and solving the integral with some manipulations, $\bar{P}_{R_i}^{cons}$ is given by

$$
\begin{aligned}
&\bar{P}^{cons}_{R_i} \\
&\approx P_R \left\{ \left(1 - \frac{\bar{\gamma}_{SR_i}}{SNR}\left(1 - e^{-\frac{SNR}{\bar{\gamma}_{SR_i}}}\right)\right) \left(1 - \sum_{d=1}^{L-1} (-1)^{d-1} \sum_{k_1=1}^{L-d} \sum_{k_2=k_1+1}^{L-d+1} \cdots \sum_{k_d=k_{d-1}+1}^{L-1} \frac{1}{1+\frac{\bar{\gamma}_{R_iD}}{w_i}\sum_{j=1}^{d}\frac{w_{k_j}}{\bar{\gamma}_{SR_{k_j}D}}}\right)\right. \\
&- \frac{1}{\bar{\gamma}_{SR_i}} \sum_{d=1}^{L-1} (-1)^{d-1} \sum_{k_1=1}^{L-d} \sum_{k_2=k_1+1}^{L-d+1} \cdots \sum_{k_d=k_{d-1}+1}^{L-1} \left[\frac{1}{\frac{1}{\bar{\gamma}_{SR_iD}} + \frac{1}{w_i}\sum_{j=1}^{d}\frac{w_{k_j}}{\bar{\gamma}_{SR_{k_j}D}}}\left(1 - \frac{1}{1+\frac{\bar{\gamma}_{R_iD}}{w_i}\sum_{j=1}^{d}\frac{w_{k_j}}{\bar{\gamma}_{SR_{k_j}D}}}\right)\right. \\
&\left.\left.\times \left(1 - \frac{1/SNR}{\frac{1}{\bar{\gamma}_{SR_iD}} + \frac{1}{w_i}\sum_{j=1}^{d}\frac{w_{k_j}}{\bar{\gamma}_{SR_{k_j}D}}}\left(1 - e^{-SNR\left(\frac{1}{\bar{\gamma}_{SR_iD}} + \frac{1}{w_i}\sum_{j=1}^{d}\frac{w_{k_j}}{\bar{\gamma}_{SR_{k_j}D}}\right)}\right)\right)\right]\right\}.
\end{aligned}
\tag{6.9}
$$

Note that d in (6.9) represents a new counter for all relay nodes except the i^{th} relay node (e.g., for $R_1 :\ \{R_d, d = 1, 2, \cdots, L-1\} \rightarrow \{R_2, R_3, \cdots, R_L\}$).

6.2 Achieving Equal Average Power Consumption

6.2.1 Conventional Centralized Strategy

The classical solution of equal average power consumption is to solve the following system of equations [65, 67]

$$
\bar{P}^{cons}_{R_1} = \bar{P}^{cons}_{R_2} = \cdots = \bar{P}^{cons}_{R_L}, \tag{6.10}
$$

in order to find the corresponding weight coefficient, w_i, for each relay node. The implementation issues related to this solution can be summarized as follows:

- Involvement of the average SNRs of the relay path for all relay nodes in calculating each weight coefficient
- Requirement of having a central controller to receive all the estimated average SNRs

- The central controller can only obtain the weight coefficients numerically by using one of the system of nonlinear-equations-solving methods such as Newton's method
- Requirement of having control channels to transmit the average SNRs and receive the corresponding weight coefficient for each relay node and to also account for errors that may occur on these channels

Note that the computational complexity as well as the communication overhead increase with the number of relay nodes. Based on these drawbacks of the centralized strategy, we propose a distributed solution in the following Section.

6.2.2 Proposed Distributed Strategy

Another approach to reduce the complexity of the above solution is to basically estimate the weight coefficients in closed-form, and to make these estimates independent from each other in order to allow each relay node to obtain its weight coefficient locally so that there is no need for a central controller as well as associated control channels.

From the expression of the average power consumption in (6.4), we can interpret the factors that affect the power consumption of the relay node as the required amplifying gain, which depends on the channel condition of the source-relay link, and the probability of selection, which depends on the selection criterion (i.e., the opportunistic relaying criterion in our case). Therefore, it is valid to estimate the weight coefficients in such a way that can comprise both factors:

$$w_i = A_i B_i, \tag{6.11}$$

where A_i and B_i correspond to the probability of selecting a relay node and the amount of amplifying gain, respectively. In the direct transmission system, if there are L nodes in the network and the MAC uses the max-min protocol [74] that depends on the CSI and residual energy, the average power consumption can be balanced across the nodes, even though the channels are not identical. Therefore, in our cooperative system, we can exploit the concept of residual energy to achieve equal power consumption over the relay nodes. To make this possible in a distributed manner, we should model the decay rate of the residual energy of the relay node to be dependent only on the local information for the average channel condition.

Assume first that each relay node has a normalized residual energy with an exponential decay rate. The normalization is used to let the relay nodes start with the same initial value. Then, A_i can be set as a function of the average end-to-end SNR of the relay path, $\bar{\gamma}_{R_i}$. Hence,

$$A_i = 1 - e^{-\frac{\bar{\gamma}_{R_i}}{c}}, \tag{6.12}$$

where c is a constant to normalize $\bar{\gamma}_{R_i}$. On the other hand, a relay node with high channel gain in the source-relay link consumes less power due to the lower amplifying gain required. Therefore, we should decrease B_i so that relay nodes with a higher channel gain in the source-relay link are selected, which can be given by

$$B_i = e^{-\frac{\bar{\gamma}_{SR_i}}{c}}. \tag{6.13}$$

Since at a high SNR the amplifying gain can be approximated by SNR/γ_{SR_i}, the constant c can be set to be equal to SNR. The weight coefficient of the i^{th} relay node becomes

$$w_i = \left(1 - e^{-\frac{\bar{\gamma}_{R_i}}{SNR}}\right) e^{-\frac{\bar{\gamma}_{SR_i}}{SNR}}. \tag{6.14}$$

It is obvious that this estimate of the weight coefficients requires simple calculation and can be obtained locally at each relay node. A tight approximation of $\bar{\gamma}_{R_i}$ can be obtained by taking the average of half of the harmonic mean [75] of γ_{SR_i} and γ_{R_iD}, as shown in Appendix E. Hence,

$$\bar{\gamma}_{R_i} = \frac{r_i - \frac{1}{r_i} - 2\ln(r_i)}{\frac{1}{\bar{\gamma}_{SR_i}}(r_i - 3) - \frac{1}{\bar{\gamma}_{R_iD}}\left(\frac{1}{r_i} - 3\right)}, \tag{6.15}$$

where $r_i = \bar{\gamma}_{R_iD}/\bar{\gamma}_{SR_i}$.

Fig. 6.1 shows a flow chart of the proposed distributed strategy and the additional requirements by the centralized one. The relay selection process starts by allowing each relay node to receive ready-to-send (RTS) signals from the source node and clear-to-send (CTS) signals from the destination node in order to estimate γ_{SR_i} and γ_{R_iD}, and their average SNRs by using a training sequence. Each relay node is then able to calculate the weight coefficient using (6.14) and the weighted end-to-end SNR of the relay path, γ_{w_i}. Within a time period, which represents the maximum listening time by which the system can use one of the relay nodes, each relay node sets a timer, τ_i, which is inversely proportional to γ_{w_i}. If the timer of the i^{th} relay node expires first, a $flag_i$ will be sent by the i^{th} relay node to announce its existence to the source and destination nodes, and to inform other relay nodes to keep silent. For the centralized strategy, all relay nodes need to send the estimated average SNRs of the relay path, $(\bar{\gamma}_{SR_i}, \bar{\gamma}_{R_iD})$ to a central controller to obtain the approximated values of the weight coefficients. The central controller then sends each weight coefficient to the corresponding relay node.

The power consumption of the relay nodes, using the proposed estimate of the weight coefficients, can be illustrated by having an example of two relay nodes in the system. The average power consumption in (6.9) becomes

$$\bar{P}_{R_i}^{cons} \approx P_R \left(\frac{1}{1 + \frac{w_i \bar{\gamma}_{SR_jD}}{w_j \bar{\gamma}_{R_iD}}} \right) \Bigg[1 - \frac{\bar{\gamma}_{SR_i}}{SNR} \left(1 - e^{-\frac{SNR}{\bar{\gamma}_{SR_i}}} \right) - \frac{1/\bar{\gamma}_{SR_i}}{\frac{1}{\bar{\gamma}_{SR_iD}} + \frac{w_j}{w_i \bar{\gamma}_{SR_jD}}} \times \left(1 - \frac{1/SNR}{\frac{1}{\bar{\gamma}_{SR_iD}} + \frac{w_j}{w_i \bar{\gamma}_{SR_jD}}} \left(1 - e^{-SNR\left(\frac{1}{\bar{\gamma}_{SR_iD}} + \frac{w_j}{w_i \bar{\gamma}_{SR_jD}} \right)} \right) \right) \Bigg]. \quad (6.16)$$

Substituting (6.14) into (6.16) with $\bar{\gamma}_{R_i} = \bar{\gamma}_{SR_iD}$[1], $\bar{P}_{R_1}^{cons}$ and $\bar{P}_{R_2}^{cons}$ are obtained by substituting $(i, j) = (1, 2)$ and $(i, j) = (2, 1)$ into (6.16), respectively. Fig. 6.2 shows the average power consumption of the two relay nodes versus $\bar{\gamma}_{SR_1}$ and $\bar{\gamma}_{R_1D}$, for $(\bar{\gamma}_{SR_2}, \bar{\gamma}_{R_2D}) = (19$

[1]We set $\bar{\gamma}_{R_i} = \bar{\gamma}_{SR_iD}$ since the average power consumption is derived based on the upper bound of the SNR of the relay path, otherwise, $\bar{\gamma}_{R_i}$ should be calculated using (6.15).

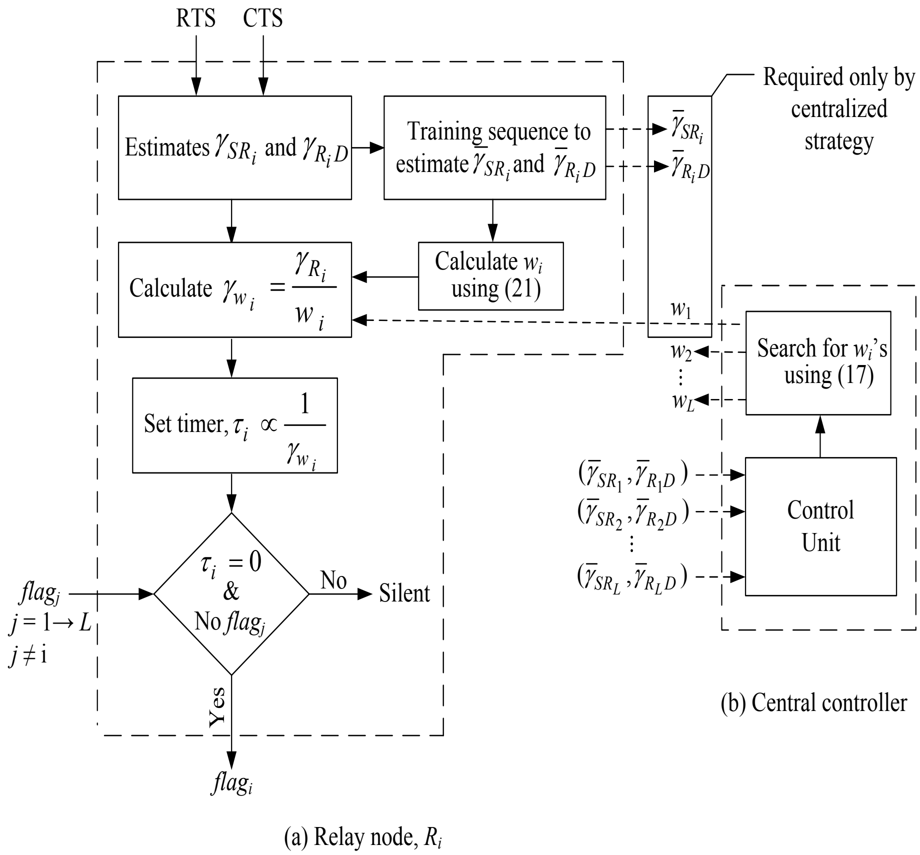

Figure 6.1: Flow chart of OR with equal average power consumption: a) Proposed distributed strategy; b) The additional requirements by the centralized strategy.

dB, 8 dB). The initial observation is the capability of the proposed estimate to allow the first relay node to consume almost same average power as the second one regardless of the channel conditions of the first relay node. Further evaluations of the proposed distributed strategy can be found in Section 6.4. To study the effect of the required fairness on the performance of the system, the next section presents the derivations of the outage probability and average bit error rate as a function of the weight coefficients and average channel conditions of the relay path.

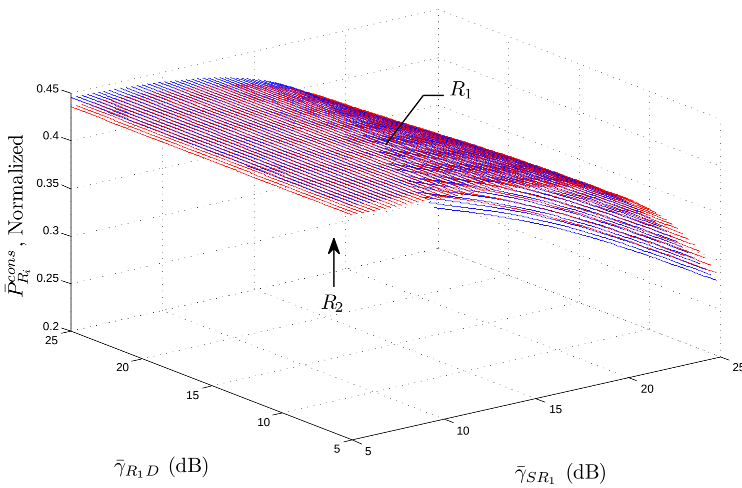

Figure 6.2: Average power consumption of the two relay nodes for ($\bar{\gamma}_{SR_2}$,$\bar{\gamma}_{R_2D}$) = (19 dB, 8 dB).

6.3 Performance Analysis

6.3.1 Weighted Outage Probability

The outage probability of the AF opportunistic relaying with weight coefficients can be written as

$$P^{out} = \Pr[\gamma_{AF}^{b} < \gamma_{th}] \approx \int_{0}^{\gamma_{th}} \int_{0}^{u} f_{\gamma_{SR_bD}}(u-x) f_{\gamma_{SD}}(x) dx du, \tag{6.17}$$

where γ_{th} represents the minimum SNR in which the quality of transmission is maintained, and $f_{\gamma_{SR_bD}}(.)$ is the probability density function (PDF) of the upper bound of the end-to-end path SNR of the selected relay node which can be obtained as

$$
\begin{aligned}
f_{\gamma_{SR_bD}}(\gamma) &= \sum_{i=1}^{L}\left[f_{\gamma_{SR_iD}}(\gamma)\prod_{\substack{j=1\\ j\neq i}}^{L}F_{\gamma_{SR_jD}}\left(\frac{w_j}{w_i}\gamma\right)\right],\\
&= \sum_{i=1}^{L}\left[\frac{e^{-\frac{\gamma}{\bar{\gamma}_{SR_iD}}}}{\bar{\gamma}_{SR_iD}}\left(1-\sum_{d=1}^{L-1}(-1)^{d-1}\sum_{k_1=1}^{L-d}\sum_{k_2=k_1+1}^{L-d+1}\sum_{k_d=k_{d-1}+1}^{L-1}e^{-\frac{\gamma}{w_i}\sum_{j=1}^{d}\frac{w_{k_j}}{\bar{\gamma}_{SR_{k_j}D}}}\right)\right].
\end{aligned}
\tag{6.18}
$$

Substituting (6.18) into (6.17) and solving the double integral, the outage probability becomes

$$
\begin{aligned}
P^{out} \approx \sum_{i=1}^{L}\Bigg\{&\frac{1}{\bar{\gamma}_{SR_iD}-\bar{\gamma}_{SD}}\left[\bar{\gamma}_{SR_iD}\left(1-e^{-\frac{\gamma_{th}}{\bar{\gamma}_{SR_iD}}}\right)-\bar{\gamma}_{SD}\left(1-e^{-\frac{\gamma_{th}}{\bar{\gamma}_{SD}}}\right)\right]\\
&-\frac{1}{\bar{\gamma}_{SD}\bar{\gamma}_{SR_iD}}\sum_{d=1}^{L-1}(-1)^{d-1}\sum_{k_1=1}^{L-d}\sum_{k_2=k_1+1}^{L-d+1}\cdots\sum_{k_d=k_{d-1}+1}^{L-1}\left[\frac{1}{\frac{1}{\bar{\gamma}_{SD}}-\frac{1}{\bar{\gamma}_{SR_iD}}-\frac{1}{w_i}\sum_{j=1}^{d}\frac{w_{k_j}}{\bar{\gamma}_{SR_{k_j}D}}}\right.\\
&\times\left.\left.\left(\frac{1}{\frac{1}{\bar{\gamma}_{SR_iD}}+\frac{1}{w_i}\sum_{j=1}^{d}\frac{w_{k_j}}{\bar{\gamma}_{SR_{k_j}D}}}\left(1-e^{-\gamma_{th}\left(\frac{1}{\bar{\gamma}_{SR_iD}}+\frac{1}{w_i}\sum_{j=1}^{d}\frac{w_{k_j}}{\bar{\gamma}_{SR_{k_j}D}}\right)}\right)-\bar{\gamma}_{SD}\left(1-e^{-\frac{\gamma_{th}}{\bar{\gamma}_{SD}}}\right)\right)\right]\right\}.
\end{aligned}
\tag{6.19}
$$

6.3.2 Weighted Average Bit Error Rate

In general, the BER for M-ary modulation under additive white Gaussian noise (AWGN) conditioned on the instantaneous link SNR is given by

$$
\mathrm{BER} = \alpha \mathrm{Q}(\sqrt{\beta\gamma}), \tag{6.20}
$$

where the $Q(\cdot)$ is the Gaussian Q-function, and (α, β) are constants depending on the type of modulation (e.g. binary phase shift keying (BPSK): $\alpha = 1.0$ and $\beta = 2.0$, quadrature phase shift keying (QPSK): $\alpha = 1.0$ and $\beta = 1.0$). At the destination node, the received signals from the source and selected relay nodes are combined using maximum ratio combining (MRC). The corresponding ABER of the AF opportunistic relaying with weight coefficients can be written as

$$\mathrm{ABER} = \alpha \int_0^\infty \mathrm{Q}(\sqrt{\beta \mathrm{z}}) \mathrm{f}_{\gamma^{\mathrm{b}}_{\mathrm{AF}}}(\mathrm{z}) \mathrm{dz}, \tag{6.21}$$

where $f_{\gamma^b_{AF}}(.)$ is the PDF of the output SNR at the destination node which can be written as

$$f_{\gamma^b_{AF}}(z) \approx \int_0^z f_{\gamma_{SR_bD}}(z-x) f_{\gamma_{SD}}(x) dx. \tag{6.22}$$

Substituting (6.18) into (6.22) and solving the integral, $f_{\gamma^b_{AF}}(.)$ can be given by

$$\begin{aligned} &f_{\gamma^b_{AF}}(z) \\ &\approx \sum_{i=1}^{L} \Bigg\{ \frac{1}{\bar{\gamma}_{SR_iD} - \bar{\gamma}_{SD}} \left(e^{-\frac{z}{\bar{\gamma}_{SR_iD}}} - e^{-\frac{z}{\bar{\gamma}_{SD}}} \right) - \frac{1}{\bar{\gamma}_{SD}\bar{\gamma}_{SR_iD}} \sum_{d=1}^{L-1} (-1)^{d-1} \sum_{k_1=1}^{L-d} \sum_{k_2=k_1+1}^{L-d+1} \cdots \sum_{k_d=k_{d-1}+1}^{L-1} \\ &\times \left[\frac{1}{\frac{1}{\bar{\gamma}_{SD}} - \frac{1}{\bar{\gamma}_{SR_iD}} - \frac{1}{w_i} \sum_{j=1}^{d} \frac{w_{k_j}}{\bar{\gamma}_{SR_{k_j}D}}} \left(e^{-z\left(\frac{1}{\bar{\gamma}_{SR_iD}} + \frac{1}{w_i} \sum_{j=1}^{d} \frac{w_{k_j}}{\bar{\gamma}_{SR_{k_j}D}} \right)} - e^{-\frac{z}{\bar{\gamma}_{SD}}} \right) \right] \Bigg\}. \end{aligned} \tag{6.23}$$

Substituting (6.23) into (6.21) and using Appendix C, the average bit error rate is given by

ABER

$$\approx \sum_{i=1}^{L} \left\{ \frac{\alpha}{\bar{\gamma}_{SR_iD} - \bar{\gamma}_{SD}} \left[\bar{\gamma}_{SR_iD} \left(1 - \sqrt{\frac{\beta}{\frac{2}{\bar{\gamma}_{SR_iD}} + \beta}}\right) - \bar{\gamma}_{SD} \left(1 - \sqrt{\frac{\beta}{\frac{2}{\bar{\gamma}_{SD}} + \beta}}\right) \right] \right.$$
$$- \frac{\alpha}{\bar{\gamma}_{SD}\bar{\gamma}_{SR_iD}} \sum_{d=1}^{L-1} (-1)^{d-1} \sum_{k_1=1}^{L-d} \sum_{k_2=k_1+1}^{L-d+1} \cdots \sum_{k_d=k_{d-1}+1}^{L-1} \left[\frac{1}{\frac{1}{\bar{\gamma}_{SD}} - \frac{1}{\bar{\gamma}_{SR_iD}} - \frac{1}{w_i} \sum_{j=1}^{d} \frac{w_{k_j}}{\bar{\gamma}_{SR_{k_j}D}}} \right.$$
$$\left.\left. \times \left(\frac{1}{\frac{1}{\bar{\gamma}_{SR_iD}} + \frac{1}{w_i} \sum_{j=1}^{d} \frac{w_{k_j}}{\bar{\gamma}_{SR_{k_j}D}}} \left(1 - \sqrt{\frac{\beta}{2\left(\frac{1}{\bar{\gamma}_{SR_iD}} + \frac{1}{w_i}\sum_{j=1}^{d}\frac{w_{k_j}}{\bar{\gamma}_{SR_{k_j}D}}\right) + \beta}}\right) - \bar{\gamma}_{SD}\left(1 - \sqrt{\frac{\beta}{\frac{2}{\bar{\gamma}_{SD}} + \beta}}\right) \right) \right] \right\}. \tag{6.24}$$

6.4 Numerical Examples

In this section, we present some numerical examples to evaluate the performance of our proposed distributed relay selection strategy. We compare our proposed strategy with the centralized one [65] as well as the best path selection strategy [17]. To have more realistic examples, two cases are considered, as shown in Table 6.1, with $L = 4$. The first case follows the same setting as in [65], which assumes that the relay nodes are sorted in a descending order in terms of the source-relay link gain and forces the relay-destination link gain to follow the same order. In the second case, we assume that there is no dependency between the two previous links' gains to make sure that there is no bias in the evaluation. ϵ_1 and ϵ_2 are the average SNRs for each hop. We also set $\bar{\gamma}_{SD} = \gamma_{th} = 10dB$.

Fig. 6.3 shows the normalized average power consumption for each relay node when Case 1 is considered. We set $\epsilon_1 = 22$dB and $\epsilon_2 = 25$dB, and use the exact expression of the average power consumption in (6.4) in order to have a valid comparison. It can be

Table 6.1: Channel parameters for case 1 and case 2.

Case		1	2	3	4
1	$\bar{\gamma}_{SR_i}/\varepsilon_1$	2.576	0.95	0.349	0.128
	$\bar{\gamma}_{R_iD}/\varepsilon_2$	2.576	0.95	0.349	0.128
2	$\bar{\gamma}_{SR_i}/\varepsilon_1$	2.576	0.95	0.349	0.128
	$\bar{\gamma}_{R_iD}/\varepsilon_2$	0.128	0.349	0.95	2.576

seen that the best path selection strategy fails to distribute the power consumption fairly among the relay nodes. Specifically, Relay 1 consumes almost 40% of its residual energy while Relay 4 consumes just 0.3% of its residual energy. This validates the importance of introducing the concept of equalizing the power consumption in the relay networks. Our proposed distributed strategy along with its simple implementation is able to achieve fairness by distributing the power consumption almost equally over all relay nodes. In fact, it approaches the exact solution of equal power consumption, as desired. It is also noticed that the centralized strategy deviates slightly from the exact solution because of the use of necessary approximation during the derivation of the average power consumption [65]. To further check how these strategies react for different environments, Fig. 6.4 shows the same results, but for Case 2. We can see that the proposed distributed strategy is still able to approach the exact equal power consumption. However, the centralized strategy does not achieve the same accuracy of results as in Case 1. This is because the setting of Case 2 permits the best end-to-end path to have a weaker source-relay link, which affects the resulting power consumption. So far, all the above results are for one setting of the average SNRs of the two hops, ϵ_1 and ϵ_2.

Fig. 6.5 shows the standard deviation of the average power consumption for the proposed distributed and centralized strategies for different values of the average SNR of the source-relay link, ϵ_1, and for the two cases. We set $\epsilon_1 = 2\epsilon_2$. It is obvious that our proposed distributed strategy outperforms the centralized one in terms of the accuracy of distributing the total consumed power among the relay nodes. This verifies that our estimation of the weight coefficients is accurate and can maintain the fairness objective.

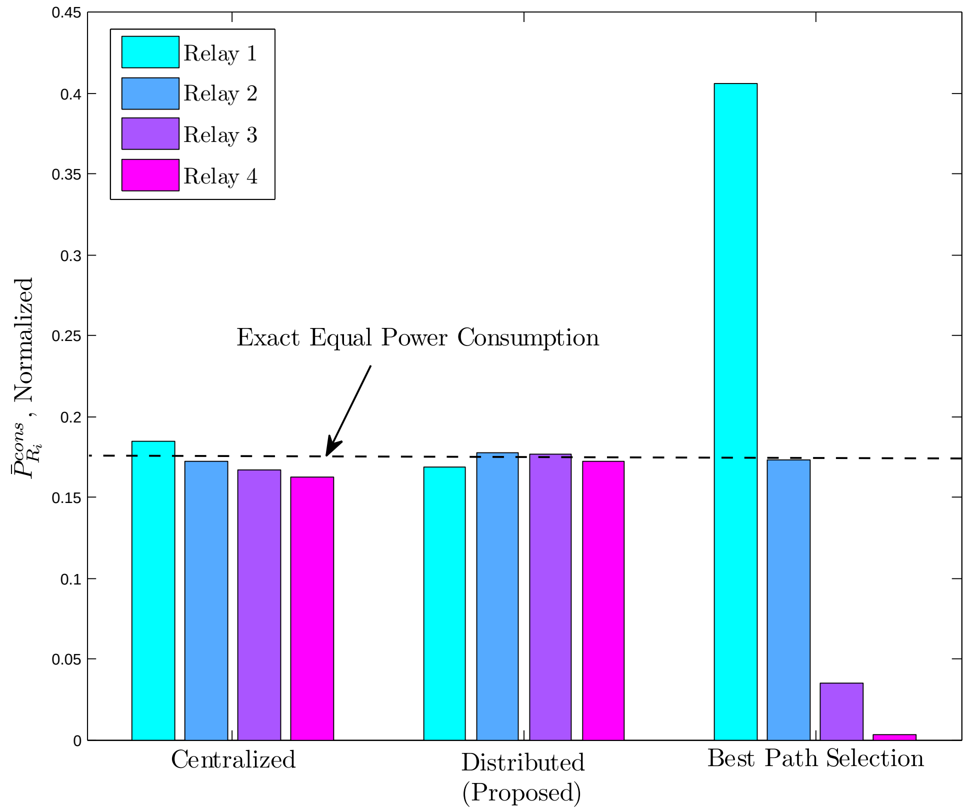

Figure 6.3: Average power consumption of the relay node for three selection strategies (case 1).

Fig. 6.6 shows the dynamic behavior of the proposed distributed and centralized strategies and provides the average selection of each relay node during frame transmission. We set $\epsilon_1 = 22$dB and $\epsilon_2 = 25$dB, and compare our proposed strategy with the centralized one only since both of them try to achieve equal power consumption. We can see how the weight coefficients obtained by both strategies affect the relay selection. It is observed that there is no unique solution for the weight coefficients. For instance, in the centralized strategy, the weight coefficient for the first relay node can be chosen arbitrarily, and the other weight coefficients can be determined based on that specific choice.

Another important evaluation of the proposed scheme is to study the effect of estimat-

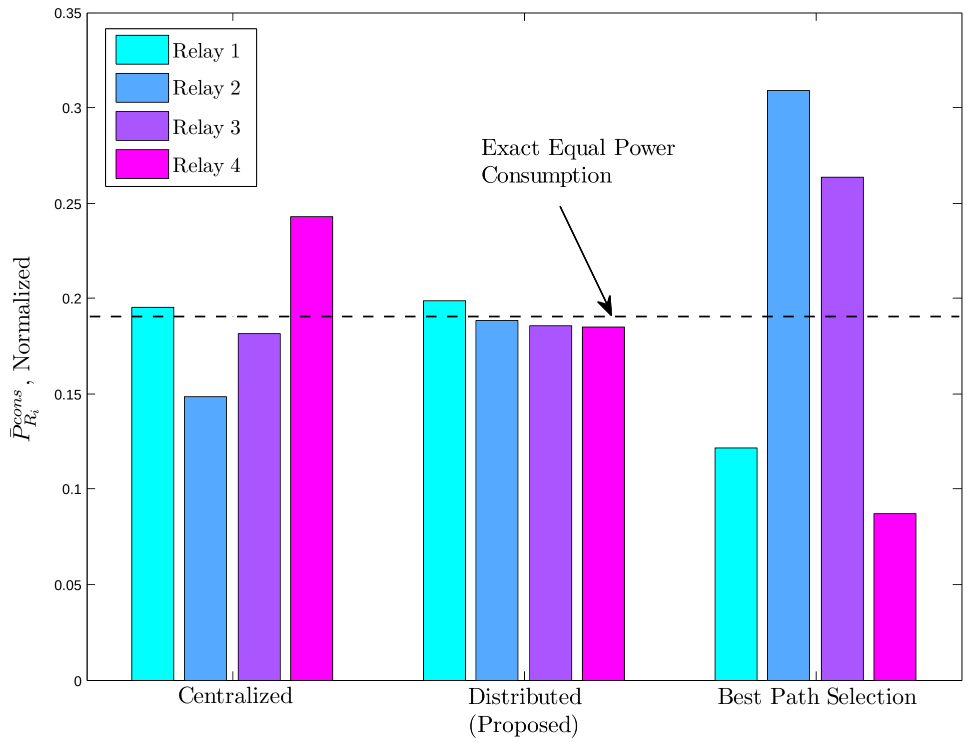

Figure 6.4: Average power consumption of the relay node for three selection strategies (case 2).

ing the weight coefficients on the performance of the system. Fig. 6.7 shows the outage probability of the proposed distributed strategy, centralized one, and the best path selection strategy. We plot the outage probability versus ϵ_1, and set $\epsilon_1 = 2\epsilon_2$. In both cases, the first observation is the increase in the outage probability of the centralized and distributed strategies due to the selection of relay node with poor channel conditions in favor of equalizing the power consumption. However, this performance reduction is less in Case 2, since the variation between the end-to-end path quality of the relay nodes is less than that of Case 1. Also, our proposed distributed strategy has equal and better outage probability when compared with that of the centralized one for Case 1 and Case 2 respectively.

Fig. 6.8 shows the average bit error rate of the proposed distributed strategy, the centralized one, and the best path selection strategy with the same setting as in Fig. 6.7

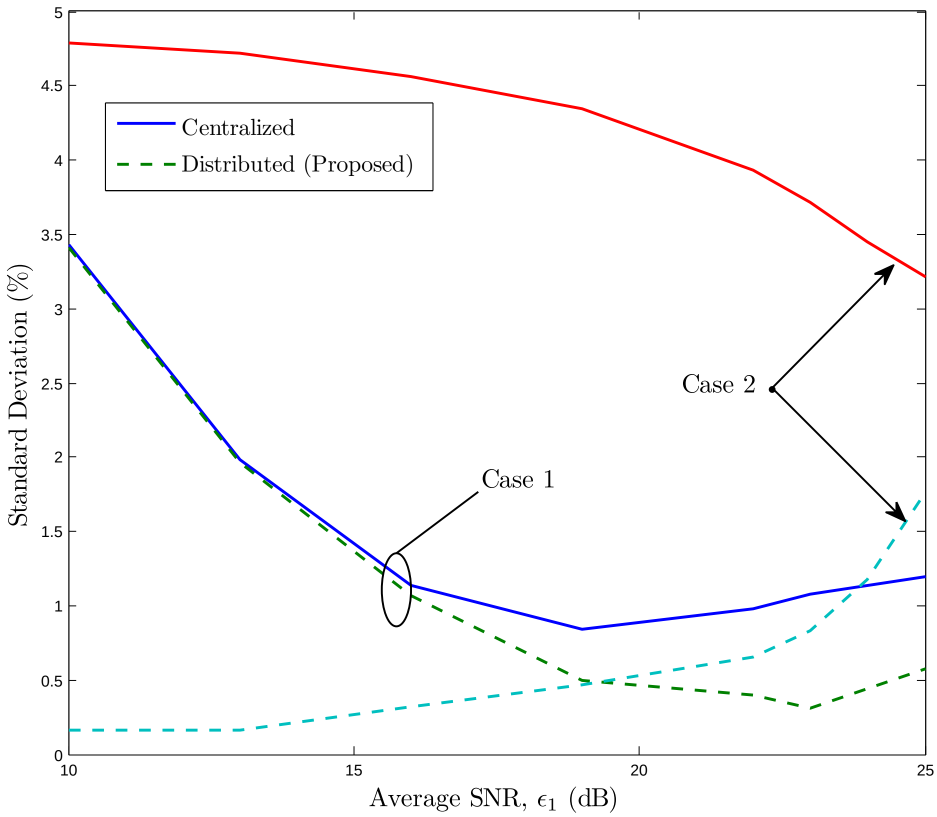

Figure 6.5: Standard deviation of the average power consumption for the proposed and centralized strategies for case 1 and case 2.

and considering BPSK modulation. We can observe similar results as in the previous figure, which demonstrates that our proposed distributed strategy with its simple and accurate estimate of the weight coefficients is able to achieve either the same or better performance when compared with the centralized one.

6.5 Summary

In this chapter, we have studied how the relay selection process can be controlled in a distributed manner so that the power consumption of the relay node can be included in

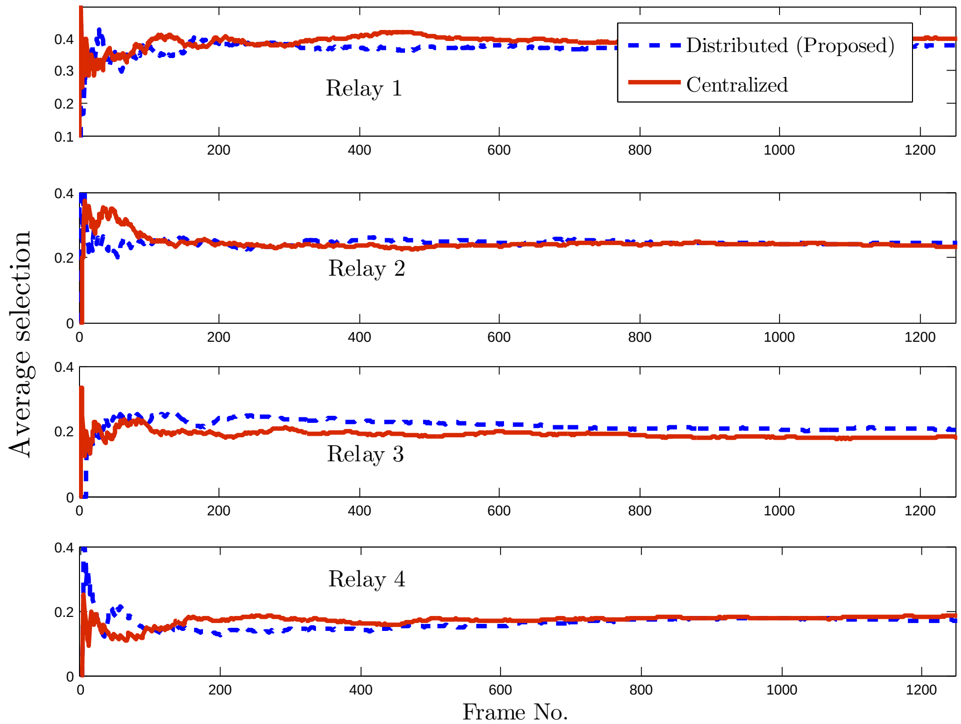

Figure 6.6: Average selection of the relay node during frames transmission.

relay selection. We have proved that fairness in terms of equal power consumption over the relay nodes can be achieved distributedly by estimating the weight coefficient locally at each relay node. This estimate reduces the complexity of the conventional centralized strategy significantly and achieves better fairness.

There is a reduction in the system performance (i.e., outage probability and ABER) for both the proposed and centralized strategies when compared to the best path selection strategy due to the selection of a relay node with bad channel conditions. This is the tradeoff between performance and fairness in terms of power consumption of the relay nodes.

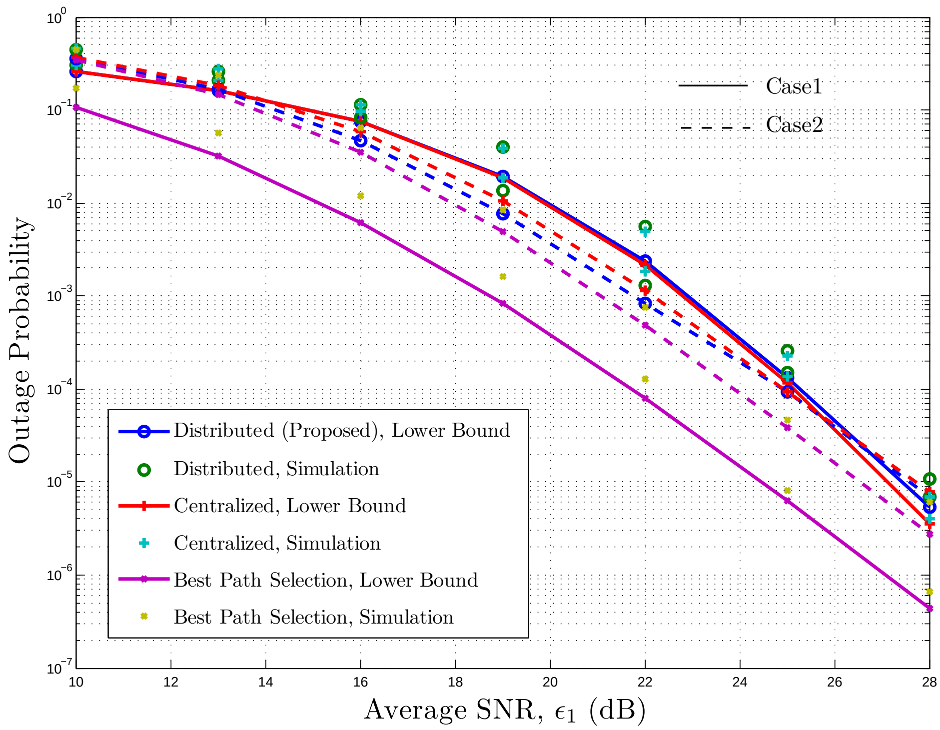

Figure 6.7: Outage probability for L = 4 versus the average channel condition of the source-relay link for case 1 and case 2.

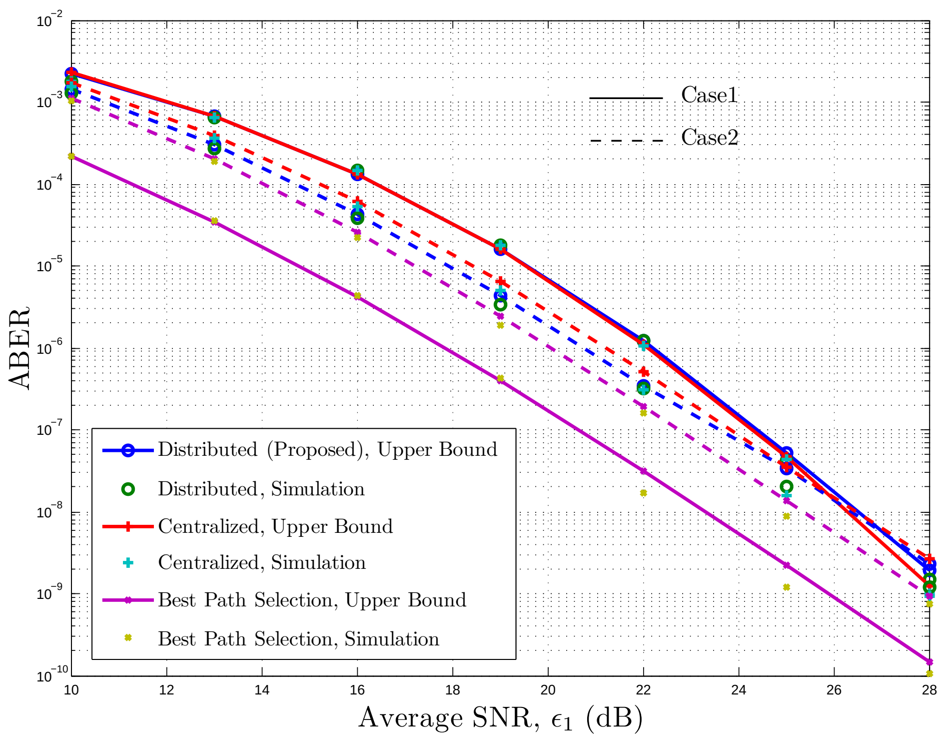

Figure 6.8: Average bit error rate for L = 4 versus the average channel condition of the source-relay link for case 1 and case 2.

Chapter 7

Conclusions and Future Works

In this chapter, the contributions of the thesis are summarized along with some concluding remarks, and future research directions are presented.

7.1 Summary of Contributions and Concluding Remarks

7.1.1 Adaptive Cooperative System with Variable-Rate Transmission

Firstly, two decode-and-forward (DF) adaptive cooperative schemes, the minimum error rate scheme (MERS) and the maximum spectral efficiency scheme (MSES), have been proposed and analyzed. The performance analysis is presented in terms of average spectral efficiency, average bit error rate (ABER), and outage probability. The MERS can improve the ABER significantly and achieve equal or better average spectral efficiency compared to the existing schemes when the channel gain strength of the relay path increases. In contrast, the MSES can provide the best average spectral efficiency due to its ability to not only adapt to the channel variation but also to switch between cooperative and non-cooperative transmissions. Secondly, a DF relay selection scheme with adaptive modulation has been proposed and analyzed. The scheme is called variable-rate based relay selection (VRRS), in which the best relay node is selected among the available relay nodes according to a predefined criterion. It is shown that the VRRS scheme can achieve 10%-100% gain in average spectral efficiency compared to AF fixed relaying.

Furthermore, we have proposed a generalized switching policy (GSP) for an AF adaptive cooperative system that employs variable-rate transmission. We also derived closed-form expressions for the average spectral efficiency, ABER, and outage probability using the upper bound for the SNR of the relay path. The GSP determines the useful cooperative regions in order to maximize the spectral efficiency at all times. To reduce the operation complexity of the GSP, we have proved that the approximate value of the switching threshold, used to switch between cooperative and non-cooperative transmissions, is accurate and can be calculated easily at the relay node. The proposed policy has been modified to allow the system to select the best relay node from the available relay nodes. Hence, a new scheme called the AF efficient relay selection (AFERS) has been proposed and analyzed. Analytical and simulation results proved that the AFERS scheme can improve the average spectral efficiency of AF cooperative systems. Finally, the success of the proposed adaptive cooperative schemes is due to three factors:

- Exploiting the variable-rate transmission in which the maximum rate is selected at all times
- Selecting the best relay node that has the best end-to-end path between the source

and destination nodes

- Flexibility of the system to avoid cooperative transmission whenever it is not beneficial

7.1.2 Cooperative System with Power Consumption Constraint

We have proposed a distributed fair relay selection strategy for AF cooperative wireless communication systems. The fairness is basically defined as to achieve equal power consumption over the relay nodes. To evaluate this strategy, we have derived closed form expressions for the outage probability and ABER as a function of the average channel condition of the relay path and the weight coefficients introduced in order to achieve the required fairness. We have proved that the proposed strategy not only has the capability to reduce the complexity of the conventional centralized strategy, but also achieves better accuracy in distributing the total consumed power equally among the relay nodes without affecting performance.

Furthermore, there is a reduction in the system performance (i.e., outage probability and ABER) for both the proposed and centralized strategies when compared to the best path selection strategy due to the selection of relay nodes with bad channel conditions. This is the tradeoff between performance and fairness in terms of power consumption of the relay nodes. Finally, the success of such a strategy relies on achieving acceptable fairness between the requirements of the source node and the constraints on the relay nodes. Also, the selection process should be designed in such a way that it can be implemented with low complexity and minimum overhead. In addition, the relay selection strategy should avoid a centralized design in order for simple implementation.

7.2 Future Works

In this dissertation, several contributions have been made for cooperative communication systems which can be extended or used to explore new research topics.

7.2.1 Cooperative Communication for Vehicular Networks

The channel model considered in this dissertation is the block Rayleigh fading channel, in which the channel is constant during the transmission of a frame. When we assume a high mobility environment, such as vehicular networks where the mobile user changes their location frequently, the proposed adaptive cooperative schemes should accommodate techniques such as channel prediction and efficient error correcting codes in order to mitigate the highly fluctuating channel. In this context, we would like to study the impact of the channel estimation errors, outdated channel prediction, and feedback channel errors on the performance of our proposed schemes. Furthermore, the channel model for vehicular networks could be changed to consider line-of-sight cases, which can be represented by the Nakagami fading model. In this case, performance analysis could be reinvestigated in order to study the capacity and the error rate. Finally, since the vehicle can be equipped with a multi-antenna system, we would like to investigate how much gain we could achieve using a multiple-input multiple-output (MIMO) system.

7.2.2 Multihop Cooperative Communications

In this dissertation, we consider systems by which source and destination nodes can be connected via a set of parallel relay nodes in which we have two-hop transmission. For serial relaying, the destination node receives the source signal via a series of relay nodes which form a multihop transmission. In this case, we would like to investigate the proposed relay selection polices and the possible changes required to guarantee the end-to-end quality.

7.2.3 Relay Station Placement in Cooperative Wireless Communication Systems

In Chapters 4 and 5, we designed different policies to optimize the performance of cooperative wireless communication systems. It has been shown that the gain achieved by the proposed schemes varies according to the channel conditions. In other words, the placement of the relay nodes and the type of environment have a direct impact on performance. Therefore, for a predefined traffic demand and target QoS, we would like to investigate the optimal placement of relay stations.

7.2.4 Wireless Sensor Networks with Cooperative Transmission

Energy-constrained networks, such as wireless sensor networks, consist of nodes powered by batteries. With finite energy, the nodes can transmit a finite amount of information. Therefore, the important design objective in such networks is to minimize the average power consumption for data transmission. However, minimizing only the average power consumption in cooperative networks may not maximize the network lifetime, since the lifetime depends also on the residual energy of the nodes. In this context, we would like to investigate the lifetime of wireless sensor networks using our proposed distributed strategy, as proposed in Chapter 6.

APPENDICES

Appendix A

Conditional Statistics of γ_{min}

The conditional CDF of γ_{min} given that γ_{SR} is greater than the minimum switching threshold,γ_{th}, can be obtained as

$$\begin{aligned} F_{\gamma_{\min}}(z|\gamma_{SR} > \gamma_{th}) &= \Pr[\min(\gamma_{SR}, \gamma_{DF}) \leq z|\gamma_{SR} > \gamma_{th}] \\ &= 1 - \Pr[(\gamma_{DF} > z, \gamma_{SR} > z)|\gamma_{SR} > \gamma_{th}] \\ &= \begin{cases} 1 - \left[\frac{1-F_{\gamma_{SR}}(z)}{1-F_{\gamma_{SR}}(\gamma_{th})}(1 - F_{\gamma_{DF}}(z))\right], & \text{if } z > \gamma_{th}, \\ F_{\gamma_{DF}}(z), & \text{if } z \leq \gamma_{th}, \end{cases} \end{aligned} \tag{A.1}$$

where $F_{\gamma_{DF}}(z)$ is the CDF of the combined output SNR at the destination node,γ_{DF}, which can be determined as

$$\begin{aligned} F_{\gamma_{DF}}(z) &= \int_0^z F_{\gamma_{RD}}(z-x)\, f_{\gamma_{SD}}(x)\, dx \\ &= 1 - e^{-z/\bar{\gamma}_{SD}} - \frac{\bar{\gamma}_{RD}}{\bar{\gamma}_{RD} - \bar{\gamma}_{SD}} \left(e^{-z/\bar{\gamma}_{RD}} - e^{-z/\bar{\gamma}_{SD}}\right). \end{aligned} \tag{A.2}$$

Substituting (A.2) into (A.1), we have $F_{\gamma_{\min}}(z|\gamma_{SR} > \gamma_{th})$ given in (4.5). Differentiating

(A.2) with respect to z, the PDF of γ_{DF} can be written as

$$f_{\gamma_{DF}}(z) = \int_0^z f_{\gamma_{RD}}(z-x)\, f_{\gamma_{SD}}(x)\, dx$$
$$= \frac{1}{\bar{\gamma}_{RD} - \bar{\gamma}_{SD}} \left(e^{-z/\bar{\gamma}_{RD}} - e^{-z/\bar{\gamma}_{SD}} \right). \tag{A.3}$$

The conditional PDF of γ_{min} can be obtained by differentiating (A.1) with respect to z, yielding

$$f_{\gamma_{\min}}(z|\gamma_{SR} > \gamma_{th}) = \begin{cases} \frac{1}{1-F_{\gamma_{SR}}(\gamma_{th})} \left[f_{\gamma_{SR}}(z)(1 - F_{\gamma_{DF}}(z)) \right. \\ \left. + f_{\gamma_{DF}}(z)(1 - F_{\gamma_{SR}}(z)) \right], & z > \gamma_{th}, \\ f_{\gamma_{DF}}(z), & z \leq \gamma_{th}. \end{cases} \tag{A.4}$$

Similarly, substituting (A.3) into (A.4), we have $f_{\gamma_{\min}}(z|\gamma_{SR} > \gamma_{th})$ given by (4.6).

Appendix B

Joint Statistics of $\gamma_{\min}$ and γ_{SD}

The joint CDF of $\gamma_{\min}$ and γ_{SD} can be obtained as

$$\begin{aligned} F_{\gamma_{\min},\gamma_{SD}}(z,x) &= \Pr[\min(\gamma_{SR},\gamma_{DF}) \le z|\gamma_{SD} \le x]\Pr[\gamma_{SD} \le x] \\ &= (1-\Pr[(\gamma_{SR} > z]\Pr[\gamma_{DF} > z|\gamma_{SD} \le x])\Pr[\gamma_{SD} \le x] \\ &= (1-F_{\gamma_{SR}}(z))\,F_{\gamma_{DF},\gamma_{SD}}(z,x) + F_{\gamma_{SR}}(z)F_{\gamma_{SD}}(x), \end{aligned} \tag{B.1}$$

where $F_{\gamma_{DF},\gamma_{SD}}(z,x)$ is the joint CDF of γ_{DF} and γ_{SD} which can be determined as

$$F_{\gamma_{DF},\gamma_{SD}}(z,x) = \begin{cases} \int_0^x F_{\gamma_{RD}}(z-t)\,f_{\gamma_{SD}}(t)\,dt, & x \le z, \\ \int_0^z \int_0^u f_{\gamma_{RD}}(u-t)\,f_{\gamma_{SD}}(t)\,dtdu, & x > z, \end{cases}$$

$$= \begin{cases} 1 - e^{-x/\bar{\gamma}_{SD}} - \frac{\bar{\gamma}_{RD}}{\bar{\gamma}_{RD}-\bar{\gamma}_{SD}} e^{-z/\bar{\gamma}_{RD}} \\ \times \left(1 - e^{-x(\frac{1}{\bar{\gamma}_{SD}} - \frac{1}{\bar{\gamma}_{RD}})}\right), & x \le z, \\ \\ \frac{1}{\bar{\gamma}_{RD}-\bar{\gamma}_{SD}} \left[\bar{\gamma}_{RD}\left(1-e^{-z/\bar{\gamma}_{RD}}\right) \right. \\ \left. -\bar{\gamma}_{SD}\left(1-e^{-z/\bar{\gamma}_{SD}}\right)\right], & x > z. \end{cases} \tag{B.2}$$

Differentiating (B.2) with respect to z, the joint PDF of γ_{DF} and γ_{SD} can be given as

$$
\begin{aligned}
f_{\gamma_{DF},\gamma_{SD}}(z,x) &= \int_0^{\min[x,z]} f_{\gamma_{RD}}(z-t)\, f_{\gamma_{SD}}(t)\, dt \\
&= \frac{e^{-z/\bar{\gamma}_{RD}}}{\bar{\gamma}_{RD}-\bar{\gamma}_{SD}} \left(1 - e^{-\min[x,z](\frac{1}{\bar{\gamma}_{SD}}-\frac{1}{\bar{\gamma}_{RD}})}\right).
\end{aligned} \tag{B.3}
$$

Substituting (B.2) into (B.1), $F_{\gamma_{\min},\gamma_{SD}}(z,x)$ is given in (4.26). Similarly, differentiating $F_{\gamma_{\min},\gamma_{SD}}(z,x)$ with respect to z, the joint PDF of γ_{min} and γ_{SD} can be written as

$$
f_{\gamma_{\min},\gamma_{SD}}(z,x) = \begin{cases}
\begin{aligned}
&(1-F_{\gamma_{SR}}(z)) \int_0^x f_{\gamma_{RD}}(z-t) f_{\gamma_{SD}}(t) dt \\
&+ f_{\gamma_{SR}}(z) \int_0^x (1-F_{\gamma_{RD}}(z-t)) f_{\gamma_{SD}}(t) dt,
\end{aligned} & x \le z, \\
\\
\begin{aligned}
&(1-F_{\gamma_{SR}}(z)) \int_0^z f_{\gamma_{RD}}(z-x) f_{\gamma_{SD}}(x) dx \\
&+ f_{\gamma_{SR}}(z) \left[F_{\gamma_{SD}}(x) - \int_0^z \int_0^u f_{\gamma_{RD}}(u-t) \right. \\
&\left. \times f_{\gamma_{SR}}(t) dt du \right],
\end{aligned} & x > z.
\end{cases} \tag{B.4}
$$

Solving (B.4) yields to closed-form of the joint PDF of γ_{min} and γ_{SD}, as given in (4.27).

Appendix C

Solving the finite integral in (4.11)

$$\Phi(\gamma_{s_1}, \gamma_{s_2}, \bar{\gamma}, B) = \int_{\gamma_{s1}}^{\gamma_{s2}} Q(\sqrt{Bx}) \frac{e^{-x/\bar{\gamma}}}{\bar{\gamma}}\, dx. \tag{C.1}$$

The integration in (C.1) can be solved using integration by parts, which can be defined as

$$\int u\, dv = u\, v - \int v\, du, \tag{C.2}$$

where $u = Q(\sqrt{Bx})$, $du = -\frac{\sqrt{B}}{2\sqrt{2\pi x}}\, e^{-xB/2}\, dx$, $dv = \frac{e^{-x/\bar{\gamma}}}{\bar{\gamma}}\, dx$, and $v = -e^{-x/\bar{\gamma}}$, then

$$\Phi(\gamma_{s_1}, \gamma_{s_2}, \bar{\gamma}, B) = \left[-e^{-x/\bar{\gamma}}\, Q(\sqrt{Bx})\right]_{\gamma_{s1}}^{\gamma_{s2}} - \int_{\gamma_{s_1}}^{\gamma_{s_2}} \frac{\sqrt{B}}{2\sqrt{2\pi x}}\, e^{-(\frac{B\bar{\gamma}+2}{2\bar{\gamma}})x} dx. \tag{C.3}$$

The second part of (C.3) can be written as

$$q = \int_{\gamma_{s_1}}^{\gamma_{s_2}} \frac{\sqrt{B}}{2\sqrt{2\pi x}}\, e^{-xB/(\frac{2B\bar{\gamma}}{B\bar{\gamma}+2})} dx. \tag{C.4}$$

Let $w^2 = Bx/(\frac{B\bar{\gamma}}{B\bar{\gamma}+2})$, and $dx = 2\sqrt{\frac{x}{B}}\sqrt{\frac{B\bar{\gamma}}{B\bar{\gamma}+2}}\, dw$, then (C.4) can be expressed as

$$q = \sqrt{\frac{B\bar{\gamma}}{B\bar{\gamma}+2}} \frac{1}{\sqrt{2\pi}} \int e^{-w^2/2} dw, \tag{C.5}$$

this yields

$$q = \sqrt{\tfrac{B\bar{\gamma}}{B\bar{\gamma}+2}} \left[Q\left(\sqrt{B\gamma_{s_1} + \tfrac{2\gamma_{s_1}}{\bar{\gamma}}}\right) - Q\left(\sqrt{B\gamma_{s_2} + \tfrac{2\gamma_{s_2}}{\bar{\gamma}}}\right)\right], \tag{C.6}$$

and finally, substituting (C.6) into (C.3), we have the solution of the finite integral in (4.11)), which is given by

$$\begin{aligned}\Phi(\gamma_{s1}, \gamma_{s2}, \bar{\gamma}, B) = Q\left(\sqrt{B\gamma_{s1}}\right)\, e^{-\gamma_{s1}/\bar{\gamma}} - \sqrt{\tfrac{B}{\frac{2}{\bar{\gamma}}+B}}Q\left(\sqrt{2\gamma_{s1}\left(\tfrac{1}{\bar{\gamma}} + \tfrac{B}{2}\right)}\right) \\ -Q\left(\sqrt{B\gamma_{s2}}\right)\, e^{-\gamma_{s2}/\bar{\gamma}} + \sqrt{\tfrac{B}{\frac{2}{\bar{\gamma}}+B}}Q\left(\sqrt{2\gamma_{s2}\left(\tfrac{1}{\bar{\gamma}} + \tfrac{B}{2}\right)}\right).\end{aligned} \tag{C.7}$$

Appendix D

Statistics of γ_{VRRS}^{b}

The CDF of γ_{VRRS}^{b} under iid Rayleigh fading channels can be represented as

$$F_{\gamma_{VRRS}^{b}}(\gamma) = L\left(\int_{0}^{\gamma} f_{\gamma_{SR}}(u)\int_{0}^{u} f_{\gamma_{other}}(y)\int_{u}^{\infty} f_{\gamma_{DF}}(x)dxdydu \right. \\ \left. + \int_{0}^{\gamma} f_{\gamma_{DF}}(u)\int_{0}^{u} f_{\gamma_{other}}(y)\int_{u}^{\infty} f_{\gamma_{SR}}(x)dxdydu\right), \tag{D.1}$$

where $f_{\gamma_{DF}}(\gamma)$ is the PDF of the combined output SNR at the destination node, γ_{DF}, which can be obtained as

$$\begin{aligned} f_{\gamma_{DF}}(\gamma) &= \int_{0}^{\gamma} f_{\gamma_{RD}}(\gamma - x)\, f_{\gamma_{SD}}(x)\, dx \\ &= \frac{1}{\bar{\gamma}_{RD} - \bar{\gamma}_{SD}}\left(e^{-\gamma/\bar{\gamma}_{RD}} - e^{-\gamma/\bar{\gamma}_{SD}}\right). \end{aligned} \tag{D.2}$$

Then the corresponding CDF of γ_{DF} can be obtained as

$$F_{\gamma_{DF}}(\gamma) = \int_0^\gamma F_{\gamma_{RD}}(\gamma - x)\, f_{\gamma_{SD}}(x)\, dx$$
$$= 1 - e^{-\gamma/\bar{\gamma}_{SD}} - \frac{\bar{\gamma}_{RD}}{\bar{\gamma}_{RD} - \bar{\gamma}_{SD}} \left(e^{-\gamma/\bar{\gamma}_{RD}} - e^{-\gamma/\bar{\gamma}_{SD}} \right). \tag{D.3}$$

$f_{\gamma_{other}}(\gamma)$ represents the PDF of the output SNR of other relay nodes which are below the output SNR of the best relay node. The CDF of γ_{other} can be calculated as

$$F_{\gamma_{other}}(\gamma) = \left[1 - (1 - F_{\gamma_{SR}}(\gamma))(1 - F_{\gamma_{DF}}(\gamma))\right]^{L-1}$$
$$= \left[1 - \frac{1}{\bar{\gamma}_{RD} - \bar{\gamma}_{SD}} \left(\bar{\gamma}_{RD} e^{-\gamma/\bar{\gamma}_{SRD}} - \bar{\gamma}_{SD} e^{-\gamma/\bar{\gamma}_{s}} \right) \right]^{L-1}. \tag{D.4}$$

After some manipulation and simplification, the CDF of γ_{other} can be given by

$$F_{\gamma_{other}}(\gamma) = \sum_{i=0}^{L-1} \sum_{r=0}^{i} \binom{L-1}{i} \binom{i}{r} (-1)^{i+r} \frac{\bar{\gamma}_{SD}^{r} \bar{\gamma}_{RD}^{i-r}}{(\bar{\gamma}_{RD} - \bar{\gamma}_{SD})^{i}} e^{-\gamma\left(\frac{r}{\bar{\gamma}_S} + \frac{i-r}{\bar{\gamma}_{SRD}}\right)}, \tag{D.5}$$

where $\bar{\gamma}_{SRD} = \bar{\gamma}_{SR}\bar{\gamma}_{RD}/(\bar{\gamma}_{SR} + \bar{\gamma}_{RD})$, and $\bar{\gamma}_S = \bar{\gamma}_{SD}\bar{\gamma}_{SR}/(\bar{\gamma}_{SD} + \bar{\gamma}_{SR})$. The corresponding PDF can be easily calculated by differentiating (D.5) with respect to γ as

$$f_{\gamma_{other}}(\gamma) = \frac{d}{d\gamma} F_{\gamma_{other}}(\gamma). \tag{D.6}$$

Substituting (D.2) and (D.6) into (D.1), the closed-form expression of $F_{\gamma^b_{VRRS}}(\cdot)$ is given by (4.40).

Appendix E

Derivation of (6.15): The Average end-to-end SNR of the relay path

The average end-to-end SNR of the relay path, $\bar{\gamma}_{R_i}$, can be written as

$$\bar{\gamma}_{R_i} = \frac{1}{\bar{\gamma}_{SR_i}\bar{\gamma}_{R_iD}} \int_0^\infty \int_0^\infty \frac{xy}{x+y} e^{-\frac{x}{\bar{\gamma}_{SR_i}}} e^{-\frac{y}{\bar{\gamma}_{R_iD}}} dxdy,$$

$$= \frac{1}{\bar{\gamma}_{SR_i}\bar{\gamma}_{R_iD}} \int_0^\infty y e^{-\frac{y}{\bar{\gamma}_{R_iD}}} \underbrace{\int_0^\infty \frac{x}{x+y} e^{-\frac{x}{\bar{\gamma}_{SR_i}}} dx}_{A}\, dy. \tag{E.1}$$

Using ([76], Eq. (3.353.5)), A can be given by

$$A = y e^{\frac{y}{\bar{\gamma}_{SR_i}}} E_i\left(-\frac{y}{\bar{\gamma}_{SR_i}}\right) + \bar{\gamma}_{SR_i}, \tag{E.2}$$

where $E_i(\cdot)$ is the exponential-integral function defined as $E_i(-x) = -\int_x^\infty t^{-1}e^{-t}dt$. Since the upper incomplete gamma function is defined as $\Gamma(s,x) = \int_x^\infty t^{s-1}e^{-t}dt$, we can substitute $E_i(-\frac{y}{\bar{\gamma}_{SR_i}})$ by $-\Gamma(0, \frac{y}{\bar{\gamma}_{SR_i}})$ in (E.2). Substituting (E.2) into (E.1), $\bar{\gamma}_{R_i}$ can be obtained by using ([76], Eq. (6.455.1)) and integration by parts, yielding

$$\bar{\gamma}_{R_i} = -\frac{2\bar{\gamma}_{R_iD}^2}{3\bar{\gamma}_{SR_i}}{}_2F_1\left(1,3;4;1-\frac{\bar{\gamma}_{R_iD}}{\bar{\gamma}_{SR_i}}\right)+\bar{\gamma}_{R_iD}, \tag{E.3}$$

where ${}_2F_1\left(\cdot,\cdot;\cdot;\cdot\right)$ is the hypergeometric function defined as

$${}_2F_1\left(\alpha,\beta;\mu;\lambda\right) = \tfrac{\Gamma(\mu)}{\Gamma(\beta)\Gamma(\mu-\beta)}\int\limits_0^1 \tfrac{t^{\beta-1}(1-t)^{\mu-\beta-1}}{(1-\lambda t)^{\alpha}}dt, \tag{E.4}$$

where $\Gamma(\cdot)$ is the gamma function defined as $\Gamma\left(n\right)=\left(n-1\right)!$ if n is integer. Substituting (E.4) into (E.3) and using polynomial long division to solve the integral, $\bar{\gamma}_{R_i}$ can be given by (6.15).

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