University of Alberta

SIMPLE DISTRIBUTED MULTIHOP DIVERSITY RELAYING BASED ON REPETITION FOR LOW-POWER-LOW-RATE APPLICATION

by

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To my family

Abstract

Low data rate, reliable wireless connectivity among inexpensive fixed, portable and mobile devices is needed in some home automation, industrial control, medical sensing, and reality applications. Such applications are the subject of the IEEE 802.15.4 Standard, and require low power, yet reliable data transfer, but have reduced requirements on data rate and throughput. Multihop relaying systems employing time diversity are proposed for these applications. The performance of repetition-based relaying with amplify-and-forward (AF) and decode-and-forward (DF) protocols operating in Rayleigh fading is studied. Analytical expressions for the symbol error probability (SEP) of the system are derived for both AF and DF relaying protocols. The repetition-based multihop transmission systems achieve diversity order equal to the number of repetitions with AF and DF relaying. It is shown that repetition-based DF relaying systems achieve better SEP than repetition-based AF relaying systems for medium to large values of signal-to-noise ratio.

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My sincere thanks to my beloved mother, Jinlan Wu and my departed father, Minhua Li. It is their continuous encouragement, great patience and love throughout that keep me moving forward.

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List of Symbols

$\arg$	Argument
$\exp(x)$	Exponential function
$\mathbb{E}\{X\}$	Statistical average of random variable X
$f_X(x)$	Probability density function of random variable X
$F_X(x)$	Cumulative distribution function of random variable X
${}_2\tilde{F}_1$	Regularized confluent hypergeometric function
${}_2F_1$	Confluent hypergeometric function
P_e	Probability of error
$P_e\|\gamma$	Conditional error probability
$Q(x)$	Standard Gaussian Q-function
$Var\{X\}$	Statistical variance of random variable X
$\binom{N}{k}$	Number of combinations of k elements from N elements
$\Gamma(x)$	Gamma function

Acronyms

AF	Amplify-and-Forward
AWGN	Additive White Gaussian Noise
BEP	Bit Error Probability
BFSK	Binary Frequency Shift Keying
CSI	Channel State Information
DF	Decode-and-Forward
i.i.d.	Independent and identically distributed
i.n.d.	Independent and non-identically distributed
LR-WPAN	Low-Rate Wireless Personal Area Network
LOS	Line-of-Sight
MFSK	M-ary Frequency Shift Keying
MGF	Moment Generating Function
MIMO	Multiple Input Multiple Output

ML	Maximum Likelihood
MRC	Maximal Ratio Combining
PDF	Probability Density Function
QoS	Quality of Service
SEP	Symbol Error Probability
SLC	Square-Law Combining
SNR	Signal-to-Noise Ratio

Chapter 1

Introduction

There is no doubt that the world is going wireless - faster and more broadly than anyone may have expected. Future wireless systems are expected to provide users with higher quality of service (QoS) in terms of data rates, reliability, and robustness. Meanwhile, in order to achieve economic feasibility, cost-efficient system architecture should be deployed. In order to tackle the challenge, there has been an increasingly interest from both academia and industry. Using multiple antennas at the transmitter and receiver in a wireless system can mitigate channel impairments such as multipath-induced fading. Multiple-input multiple-output (MIMO) technologies have provided an opportunity to significantly improve the reliability and capacity of wireless communication systems. However, due to size, cost, or hardware limitations, it may not be practical for some wireless networks.

Cooperative communication has emerged as a new class of techniques which allow single-antenna mobiles to reap some benefits of MIMO systems. The basic idea is that single-antenna mobiles can create a virtual MIMO system by sharing their antennas. Cooperative communication systems achieve higher data rates, wider coverage and better sustainable QoS. Yet, they eliminate the need for physical employment of multiple antennas at the transmitter and/or receiver as required in MIMO systems. Relay

channels are the building blocks of cooperative communication. The classic relay channel consists of a source, its destination, and a relay. Depending on the structure of the relays, the two most common relaying protocols are amplify-and-forward (AF) and decode-and-forward (DF). In AF relaying, the relay simply amplifies its received signal and forwards it to the next terminal. In DF relaying, the relay decodes its received signal, re-encodes the signal and then forwards it.

1.1 Thesis Motivations and Contributions

Multihop relay networks achieve broader coverage, lower transmit power and reduced interference over single-hop networks [1]–[4]. In addition, such networks also achieve distributed spatial diversity to enhance the system performance. Much focus in the wireless industry has been on communication with higher data throughput, leaving out a set of applications requiring simple wireless connectivity with relaxed throughput and latency requirements. On the other hand, in December 2000, the IEEE New Standards Committee (NesCom) officially sanctioned a new task group 802.15.4, which is designed for a low-rate wireless personal area network (LR-WPAN) standard. This group was aiming at providing a standard with ultra-low power, cost, and complexity for low-data-rate wireless connectivity among inexpensive fixed, portable, and moving devices. IEEE 802.15.4 is designed to be useful in a wide variety of applications, including home automation and networking, industrial control and monitoring, and medical sensing which have more relaxed throughput requirements and require lower power consumption than is currently provided in existing standard implementations [5], [6]. For applications allowing more latency, multihop network topologies provide an attractive alternative for home coverage since each device needs only enough power (and sensitiv-

ity) to communicate with its nearest neighbor.

In conventional multihop transmission systems, each relay simply processes the signal received from the immediately preceding terminal and then forwards it to the next terminal. Previous studies have shown that such multihop transmission systems employing AF and DF relaying schemes do not offer diversity order gain [7], [8]. A solution to obtaining diversity gain is to employ receiver diversity combining at the relays. This concept forms the basis of the multihop diversity system proposed in [9]. In another approach to achieving diversity gain, the authors in [10] developed a selective DF relaying protocol based on a threshold test applied to the received signal-to-noise ratio (SNR) at each relay. The results in [9] and [10] show that multihop diversity systems with fixed AF relaying and selective DF relaying achieve full diversity order (i.e. diversity order equal to the number of hops). However, such multihop diversity systems require the channel state information (CSI) of all preceding terminals to employ coherent detection using maximal ratio combining (MRC) at the relays as well as at the destination. This requirement will impose heavy overhead at the relays and propagating channel estimation errors will result in performance degradation, especially when there is a large number of relays. In addition, there could be situations where the relays cannot receive the signals from all preceding terminals. For example, when the transmissions from the source to some relays are blocked by large buildings or, when the links between relays suffer from deep fading. In such channel environments, receiver diversity combining cannot be exploited fully.

As mentioned above, the constraints of the LR-WPAN standard require the design of relays with low-complexity and high reliability to sustain a communications link with the least amount of overhead. Previous multihop diversity systems can achieve diversity order equal to the number of relays; however, each relay must estimate the channel information and

employ MRC, which makes these multihop diversity systems unfeasible in these applications. Therefore, our motivation here is to develop simple multihop systems which can achieve diversity without imposing further processing (on top of amplification) at the relays. In this thesis, we propose a simple multihop diversity relaying scheme based on repetition. In the scheme, time diversity is achieved via multiple transmissions of the same packet. In the AF relaying system considered here, the source re-transmits the same signal in every three time slots for D times to avoid the interference from the neighboring terminals. In DF relaying systems, the source re-transmits the same signal in D consecutive time slots. We consider the following scenarios. 1) Each relay has (or exploits) only knowledge of the average link SNR of its immediately preceding link. Neither instantaneous nor statistical CSI are known (or exploited) at the destination. 2) Each relay has (or exploits) only knowledge of the instantaneous CSI of its immediately preceding link. The destination has (or exploits) global CSI knowledge of all links. Our goal is to develop effective low complexity detection schemes for these scenarios.

In the first scenario, square-law combining (SLC) is employed. In the AF relaying system, each relay amplifies its received signal with fixed gain and then forwards it to the next relay, and the destination employs SLC of the received signals from the D repetition time slots. In the DF relaying system, each relay detects the received signal based on SLC and forwards the estimated signal, and the destination employs SLC. In the second scenario, the AF relays amplify the received signal with variable gain, and the destination employs MRC. In the DF relaying system, each relay as well as destination employs MRC to detect the received signal. It is shown that both the repetition-based AF relaying systems and the DF relaying systems achieve diversity order equal to the number of repetitions. Our results will show that the repetition-based DF relaying systems achieve

better error rate performance than the corresponding AF relaying systems in medium to large signal-to-noise (SNR) regions.

1.2 Thesis Outline

This thesis is organized as follows. In Chapter 2, the basic concepts of MIMO technology and cooperative communications are covered. Then we review previous works related to this thesis. The topics of these works include the system models, performance evaluation, and design of efficient receivers of different multihop relaying systems. We then propose and discuss the system model of repetition-based multihop systems. In Chapter 3, a detailed study of repetition-based multihop systems without transmitter CSI is provided. The symbol error rate performance is derived for both AF and DF relaying schemes. The advantages of repetition-based multihop systems over traditional multihop communication systems will be summarized. In Chapter 4, we consider repetition-based multihop systems with transmitter CSI. Corresponding mathematical analysis is conducted thoroughly for this model. Both the theoretical analysis and the numerical results have shown that the proposed system can achieve better performance than previous existing multihop relaying systems with less system and terminal level complexity. Chapter 5 concludes the thesis and gives ideas for future research.

Chapter 2

Background and Literature Review

2.1 Cooperative Communication Basics

2.1.1 MIMO - Multiple Input Multiple Output Systems

Unlike wired networks, which have a fixed communication infrastructure, wireless communication systems suffer from the deleterious effects of fading. There are two types of fading: large-scale fading is due to path loss from signal shadowing by large objects such as buildings and hills, and is a function of location and distance; small-scale fading is due to the constructive and destructive interference of replicas of the transmitted signal received from the multiple signal paths between the transmitter and receiver. In order to mitigate the performance degradation due to fading, multiple antennas at the transmitter and/or the receiver can be introduced. It has been shown that multiple-input multiple-output (MIMO) systems can significantly reduce symbol error probabilities and achieve higher data transmission rates. The advantages of MIMO systems are given below [11].

- **Array Gain**

  Array gain is defined as the increase in received signal-to-noise ratio (SNR) that arises from a coherent combining of the signals at a

receiver. In a MIMO system this can be realized through spatial processing at the receive antenna array and/or spatial pre-processing at the transmit antenna array. Array gain improves resistance to noise, therefore improving the coverage area of a wireless network.

- **Diversity Gain**

  Diversity gains can be achieved by providing the receiver with multiple replicas of the transmitted signal which are assumed to be independent of each other in space, frequency, or time at the receiver. With an increasing number of independent replicas, the probability that at least one of the copies does not experience a deep fade increases, thereby increasing the quality and reliability of communication. A transmission scheme is said to achieve diversity order d if the probability of error, $P_e(\mathrm{SNR})$, as a function of SNR satisfies

$$\lim_{\mathrm{SNR}\to\infty} \frac{\log P_e(\mathrm{SNR})}{\log \mathrm{SNR}} = -d \tag{2.1}$$

  A MIMO system with M_T transmit antennas and M_R receive antennas, can theoretically provide $M_T * M_R$ independent copies of the transmitted signals. This results in a diversity order of $M_T * M_R$.

- **Spatial Multiplexing Gain**

  MIMO systems offer a linear increase in transmission rate through spatial multiplexing (SM) for the same bandwidth. A transmission scheme is said to achieve multiplexing gain r if the data rate (bps) per unit hertz, $R(\mathrm{SNR})$, can satisfy

$$\lim_{\mathrm{SNR}\to\infty} \frac{R(\mathrm{SNR})}{\log_2 \mathrm{SNR}} = r \tag{2.2}$$

  The maximum of SM gain equals the number of transmit-receive antenna pairs or min (M_T, M_R).

- **Interference Reduction**

  Multiple user interference is a key performance limitation in wireless networks. Interference may be mitigated in MIMO systems by exploiting the spatial dimension to increase the separation between users. The spatial dimensions may be used for the purposes of interference avoidance, by directing signal energy towards the intended user and minimizing interference to other users. This is also known as antenna beamforming.

However, due to size, cost, and hardware limitations, multiple antennas may not be feasible for some practical wireless networks. Examples include mobile handsets (size) and the nodes in a wireless sensor network (size, power). Recently, the concept of cooperative communication has been proposed to allow a single-antenna handset to reap the benefits of MIMO systems. In a cooperative communication system, single-antenna mobiles can create a virtual MIMO system that allows them to achieve transmit diversity by sharing antennas belonging to multiple users within the network. This eliminates the need for physical deployment of antennas at the transmitters and/or receivers, which significantly reduces the system cost, complexity, and especially the size of the receivers.

2.1.2 Fixed Multihop Relaying Systems

Relay channels are the building blocks of cooperative communication. The classic relay channel consists of a source, a destination, and a relay that assists the source by relaying its message to the destination. There are two main categories of relays, decode-and-forward (DF) and amplify-and-forward (AF) relays. In systems with DF relays, the relay decodes its received signal, re-encodes it and then re-transmits. In systems employing DF relaying considered in this thesis, we focus on the simplest DF protocol, i.e., un-coded DF, in which each relay demodulates its received

signal, re-modulates and then forwards. On the other hand, in systems with AF relays, the relay amplifies its received signal and then re-transmits it. The amplification gain at each relay can be categorized into two types, variable-gain and fixed-gain. In variable-gain AF relaying systems, it is assumed that instantaneous channel state information (CSI) is known at the receiving terminals, and the amplification gain at each relay is the transmitted power over the received power at that relay. In fixed-gain AF relaying systems, the amplification gain is fixed and does not require the knowledge of instantaneous CSI at the relays. Generally, the amplification gain at fixed-gain relays can take any arbitrary value [7]. In practice, it is mostly chosen to satisfy the average power constraint at the relay.

2.1.3 Selective Multihop Relaying Systems

As we might expect, and the following analysis confirms, fixed DF relaying is limited by the direct transmission between the source and relay. However, since the relays can explore the fading coefficient using certain channel estimation measurements, they can adapt transmission based on threshold tests on the received signal-to-noise ratio (SNR). This observation suggests the selective relaying proposed in [10]. If the total instantaneous received SNR at the kth relay terminal, $T_k, k = 1, \ldots, K$, is above a certain threshold γ_{Th}, that relay will forward what it receives, using either AF or DF. However, if the received instantaneous SNR at the kth relay falls below the threshold, the source terminal repeats its signal at the next time slot.

2.2 Related Work

Cooperative networks for cellular environments were first considered and analyzed by Sendonaris et al. In [1], [2], the implementation of user co-

operation in a three-terminal CDMA system was proposed. The merits of cooperation were demonstrated in achieving higher data rates, and less sensitivity to channel variations. However, some assumptions, such as the ability of full-duplex operation and the availability of CSI at the transmitters, make it difficult to put the proposed protocol into practice. Cooperation in ad hoc networks was studied in [12], [13]. Various cooperative protocols based on AF and DF relaying were proposed, and their asymptotic outage probabilities in Rayleigh fading were evaluated. It was assumed orthogonal time or frequency channels are allocated to each node to ensure half-duplex operation. It was also assumed that CSI is only available at the receivers.

Since then, research in the area of cooperative communication has been very active. Cooperative systems with different numbers of relays and types of processing and detection at the relays and destination have been developed and evaluated in terms of various performance metrics, such as error probabilities and ergodic capacity. In the following, other literature reviews related to the systems considered in the thesis are given.

2.2.1 System Configurations and Features

A wireless cooperative system configuration employing a relaying protocol imposes different requirements on the wireless terminal hardware capabilities, channel availability, and system resources. In this thesis, we focus on the two common relaying system configurations, namely, multihop relaying systems and multihop diversity systems. In all systems considered in the following, it is assumed that the relays operate over independent, not necessarily identically distributed Rayleigh fading channels in the half-duplex mode. The fading gain of the channel between relay terminals T_i and T_j is denoted by $\alpha_{i,j}$ and is modeled as a zero-mean complex Gaussian random variable with variance $\sigma_{i,j}^2$. Moreover, we assume

additive white Gaussian noise (AWGN) with zero mean and variance N_0 at each relay node. The instantaneous SNR of the channel between terminals T_i and T_j is then defined as $\gamma_{i,j} = \frac{P_i}{N_0}|\alpha_{i,j}|^2$ and is an exponential random variable with mean value $\Gamma_{i,j} = \frac{P_i}{N_0}\sigma^2$, where P_i denotes the transmitter energy at terminal T_i.

2.2.2 Multihop Relaying Systems without Diversity

In conventional multihop transmission systems, each relay simply processes the signal received from the immediately preceding terminal and then forwards it to the next terminal in the next time slot.

In recent years, many research works have been devoted to performance analysis of multi-hop communication systems employing different relaying protocols. In [8] and [14], the authors studied the average bit error rate (BER) and outage probability of dual-hop transmission systems with DF relaying, AF variable-gain relaying, and AF fixed-gain relaying, over flat Rayleigh-fading channels. A closed-form expression for the average BER of an AF dual-hop system with a fixed-gain relay operating over Nakagami-m fading channels was derived in [15]. A general analytical framework was proposed in [16] to evaluate the outage probability of multihop communication systems with AF variable-gain relays over Nakagami fading channels. Performance bounds of multihop transmission systems with AF fixed-gain relays over generalized fading channels were derived in [17]. The performance of AF multihop relaying systems (both variable-gain relays and fixed-gain relays) operating in Nakagami-m fading was evaluated in terms of lower bounds in [18]. However, the performance bounds given in [17] and [18] are not tight, especially for moderate to large values of signal-to-noise ratio (SNR). In [19], the authors obtained a new general framework for evaluation of the error probabilities in terms of the moment generating function (MGF) of the inverse of the received

SNR. In [20], the outage probability is given in closed-form expressions for different multihop diversity systems.

Consider a K-hop wireless transmission system as shown in Figure 2.1 in which a source node, T_0, transmits its information to a destination node, T_K, with the help of $K-1$ half-duplex relay nodes denoted by $T_1, T_2, \ldots, T_{K-1}$. In general, the $(k-1)$th relay terminal, T_{k-1}, transmits signal, x_{k-1}, in the kth time slot, and the received signal at the immediately following T_k terminal, y_k, is given by

$$y_k = \alpha_{k-1,k} x_{k-1} + n_k, \quad k = 1, \ldots, K. \tag{2.3}$$

In a multihop transmission system with DF relaying, x_{k-1} is an estimate of the transmitted source signal, x_0, at the $(k-1)$th relay. In a multihop transmission system with AF relaying, the kth relay amplifies its received signal by a gain β_k, i.e. $x_k = \beta_k y_k$. In systems with variable-gain relays, β_k is given by

$$\beta_k = \sqrt{\frac{P_k}{P_{k-1}|\alpha_{k-1,k}|^2 + N_0}}. \tag{2.4}$$

Therefore, the instantaneous received SNR in an AF multihop system with an arbitrary number of variable-gain relays is given by [16, eq. (2)]

$$\gamma_K = \Big(\prod_{i=0}^{K-1} (1 + \frac{1}{\gamma_{i,i+1}}) - 1 \Big)^{-1}. \tag{2.5}$$

Note that γ_K in (2.5) can be well approximated by the bound [16, eq. (4)]

$$\gamma_K \leq (\sum_{i=0}^{K-1} \frac{1}{\gamma_{i,i+1}})^{-1} \tag{2.6}$$

especially for sufficiently large values of SNR. In systems with fixed-gain relaying, the amplification gain at the kth relay is given by

$$\beta_k = \sqrt{\frac{\frac{P_k}{N_0}}{\Gamma_{k-1,k} + 1}}. \tag{2.7}$$

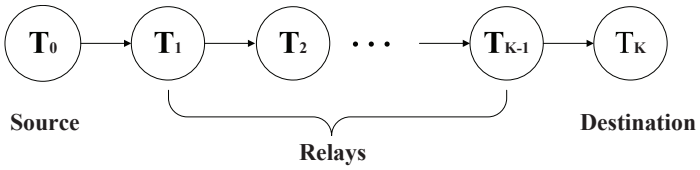

Figure 2.1. Conventional K-hop transmission system.

Note that the choice of the relay amplification gain in (2.7) ensures that the average power constraint at the relay is satisfied. The instantaneous received SNR in an AF multihop system with fixed-gain relays is given by [19, eq. (16)]

$$\gamma_K = \Big(\sum_{k=0}^{K-1} Y_k \Big)^{-1} \tag{2.8a}$$

and

$$Y_k = \prod_{i=0}^{k} \frac{C_i}{\gamma_{i,i+1}} \tag{2.8b}$$

where $C_0 = 1$ and $C_i = \frac{P_i}{N_0 G_i^2}$ are constants for a fixed gain, G_i.

2.2.3 Multihop Relaying System with Diversity

Previous studies show that such multihop transmission systems employing AF and DF relaying schemes do not offer diversity order gain [8], [14], [16]. A solution to obtaining diversity gain is to exploit the broadcast nature of wireless networks and employ diversity combining at the relays. This concept forms the basis of the multihop diversity system proposed in [21]. Figure 2.2 shows a K-hop diversity transmission system. In the system, the source terminal initiates transmission by broadcasting its signal in the first time slot. Each relay terminal can receive the signals from all preceding transmitting terminals, combine them using maximal ratio combining (MRC) diversity, and process the combined signal by either amplifying or decoding before retransmitting it. In general, in the kth time slot,

$k = 1, \ldots, K$, the $(k-1)$th relay transmits signal x_{k-1} and consequently its following relay terminals, $T_k, T_{k+1}, \ldots, T_K$, receive

$$y_i^{(k-1)} = \alpha_{k-1,i} x_{k-1} + n_i, \quad i = k, \ldots, K \tag{2.9}$$

where $y_i^{(k-1)}$ denotes the signal received signal from the $(k-1)$th relay at the ith relay terminal. The signals at the kth relay received through its preceding terminals, $y_k^{(0)}, y_k^{(1)}, \ldots, y_k^{(k-1)}$, are combined using MRC diversity and then in order to generate x_k to re-transmit in the next time slot, the combiner output is either decoded and re-encoded, or amplified. In systems employing DF relaying, we focus on the simplest DF relaying protocol, i.e. the un-coded DF [22], in which each relay demodulates its combiner output, re-modulates it and then forwards. The instantaneous received SNR at the kth relay terminal, $k = 1, \ldots, K$ is $X_k = \sum_{i=0}^{k-1} \gamma_{i,k}$ where $\gamma_{i,k} = \frac{P_i}{N_0} \alpha_{i,k}^2$ denotes the instantaneous SNR over the link between the ith and kth terminals in which P_i is the transmitted power at the ith relay terminal. In addition, note that in a DF multihop diversity system each relay terminal requires knowledge of the CSI of its adjacent links[1], that is, relay k needs to know k fading gains.

In systems with AF relaying, the amplification gain used at each relay is the quotient of the transmitted power and the received power at that relay [21]. In addition, the weight factors of the MRC combiner at a terminal in an AF multihop diversity system are obtained assuming that the noise components of the signals received at that terminal are uncorrelated[2]. The received SNR at the kth terminal is given by

$$\hat{\gamma}_k = \gamma_{0,k} + \sum_{j=1}^{k-1} \tilde{\gamma}_{j,k} \tag{2.10a}$$

[1]In the thesis, adjacent links means links directly connected to the terminal.

[2]Note that the propagation noise terms received at a terminal from its preceding terminals are not independent, in general [21].

where

$$\tilde{\gamma}_{j,k} = \frac{\gamma_{j,k}\hat{\gamma}_j}{\gamma_{j,k} + \hat{\gamma}_j + 1} \tag{2.10b}$$

Note that in an AF multihop diversity system each relay terminal requires knowledge of the CSI of all its preceding terminals for the employment of a MRC scheme, that is, relay k needs to know $\frac{k(k+1)}{2}$ fading gains.

However, the performance of multihop diversity transmission systems employing fixed DF relaying strategy is limited by the direct transmission between the source and the first relay terminal. Laneman first proposed the idea of selective relaying in [13]. In the paper, the authors described selective relaying corresponding to adaptive versions of AF and DF, both of which fall back to direct transmission if the relay cannot decode. They also discussed the performance of selective decode-and-forward in a dual-hop relaying system and showed that it enables the cooperating terminals to exploit full spatial diversity and overcome the limitations of fixed DF relaying. Farhadi and Beaulieu extended the selective relaying protocol to multihop scenarios and discussed the performance of both selective AF and DF relaying [20]. It was shown that a multihop diversity transmission system employing selective AF relaying performs worse than systems employing the fixed relaying protocol. However, the results show that the relay terminals in selective AF relaying systems use less (or at most equal) power as those in the corresponding fixed AF relaying systems. On the other hand, a multihop diversity transmission system employing selective DF relaying protocol achieves diversity order equal to the number of hops without the need for additional resources (i.e. power and bandwidth). However, such multihop diversity systems require the CSI of all preceding terminals (both adjacent and non-adjacent terminals) at the relays as well as at the destination.

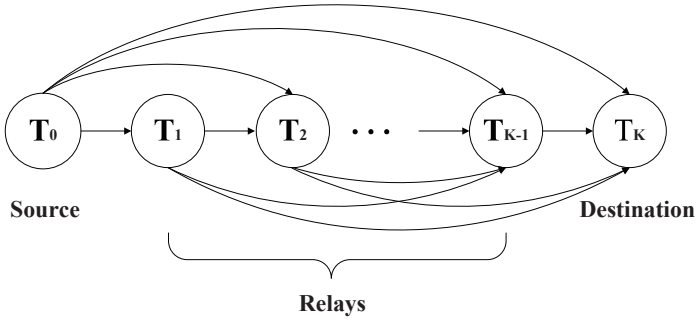

Figure 2.2. The K-hop diversity transmission system.

2.3 Repetition-Based Multihop Systems

The IEEE 802.15.4 Standard requires low power, yet reliable data transfer, but has reduced requirements on data rate and throughput. The main features of the standard are network flexibility, low cost, and low power consumption. As mentioned earlier, the existing multihop relaying schemes impose complex and costly processing tasks at the relays, which makes such multihop diversity systems unfeasible in these applications. In this thesis, multihop relaying systems employing time diversity are proposed for these applications. Simple distributed multihop diversity relaying based on repetition is investigated. Our proposed scheme operates based on multiple transmission of the same signal from the source. In AF relaying, for the special case of a dual-hop relaying system, the source re-transmits the same signal in every two time slots. In general ($K \geq 3$), the source re-transmits the same signal in every three time slots for D times. Therefore, the repetition scheme maintains the half-duplex operation at the relays and also avoids interference signals that would be reflected from the following terminals forwarding their signals at the same time slot. In DF relaying, the source re-transmits the same signal in D consecutive time slots.

Figure 2.3 shows a K-hop repetition-based multihop system where each relay receives the signal transmitted from its immediately preceding

terminal. In our proposed scheme, the source re-transmits the same signal in order to exploit time diversity. In particular, the fading gain of the channel between terminals T_{k-1} and T_k over the duration of the dth repetition, $d = 1, \ldots, D$, is denoted by $\alpha_{k,d}$ and is modeled as a zero-mean complex Gaussian random variable with variance σ_k. Moreover, we assume additive white Gaussian noise (AWGN) with zero mean and variance N_0 at each relay node. Therefore, the instantaneous SNR of the channel between terminals T_{k-1} and T_k at the dth repetition is defined as $\gamma_{k,d} = \frac{P_{k-1}}{N_0}|\alpha_{k,d}|^2$ and is an exponential random variable with mean value $\Gamma_k = \frac{P_{k-1}}{N_0}\sigma_k^2$, where $P_k, k = 0, \ldots, K-1$ denotes the transmitter energy at terminal T_k. It is assumed that the CSI is only known at the receiving terminals. Thus, the total power, P_T, is allocated to each terminal according to a uniform power allocation policy. Thus, we have $P_k = \frac{P_T}{2D}$ in the special-case of dual-hop systems and $P_k = \frac{P_T}{K+3(D-1)}$ in systems with $K \geq 3$.

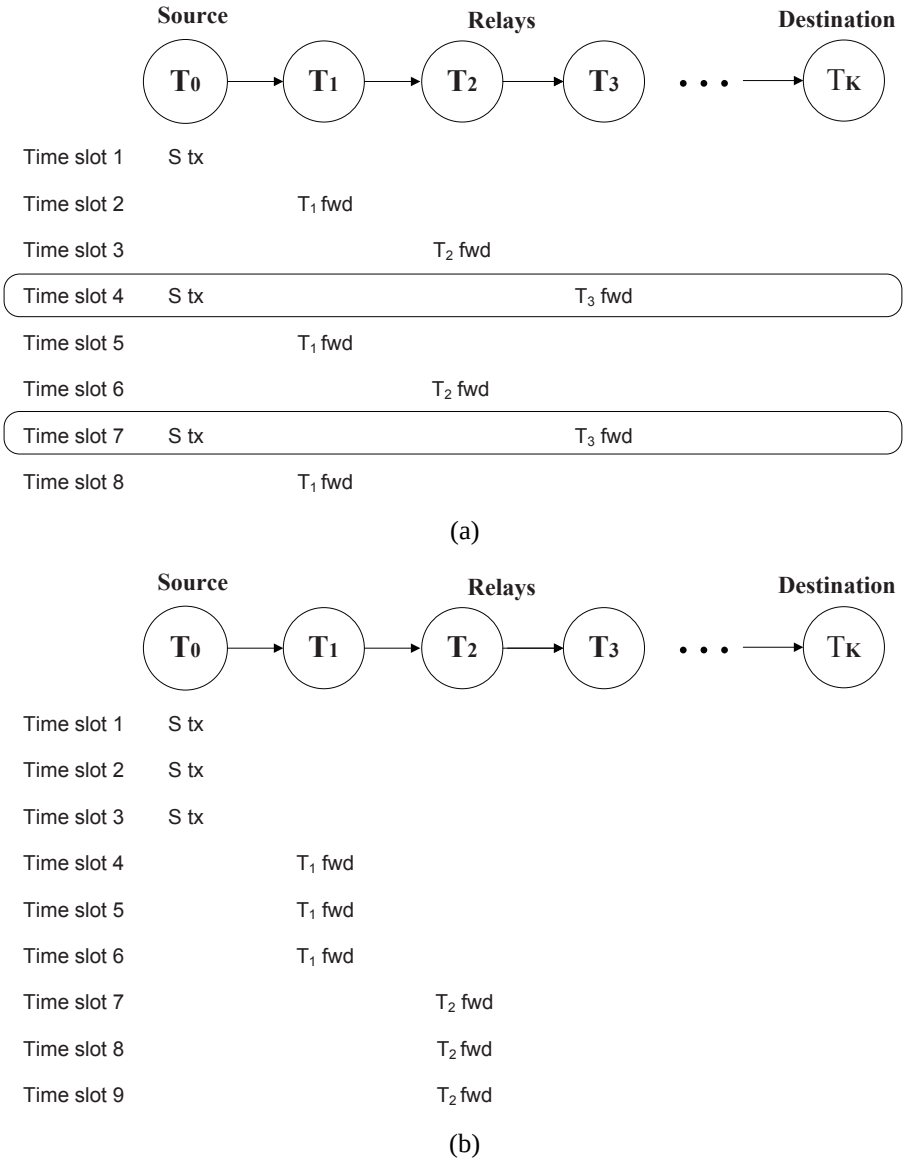

Figure 2.3. Repetition-based K-hop transmission systems employing (a) AF relaying, and (b) DF relaying.

Chapter 3

Repetition-Based Multihop Systems Without Transmitter CSI

Most previous works on multihop relaying systems have been focused on receiver structures whose operations require perfect channel state information (CSI) at the destination for coherent detection. However, channel estimation is a complex and costly task in fading environments, especially in fast fading channels. In such fading channel conditions, it is more practical to develop noncoherent detection techniques that require no instantaneous CSI knowledge. While there have been several studies on the use of noncoherent detection in multi-relay AF and DF cooperative systems [23]–[27], there has not been any investigation of noncoherent multihop relaying systems with an arbitrary number of relays.

However, the conventional AF and DF relaying systems (even with coherent detection) do not increase diversity order [28]. On the other hand, the multihop diversity systems proposed in [10] and [21] can increase diversity order but require knowledge of the instantaneous CSI at the relays as well as at the destination, which makes them infeasible in low-power-low-complexity applications as mentioned earlier. Meanwhile, it is well known that repetition coding is effective in combating Rayleigh

fading [29]. In this chapter, we develop new repetition-based noncoherent AF and DF multihop relaying systems based on square-law combining (SLC) at the destination. In particular, in our proposed schemes, the destinations requires neither instantaneous nor average CSI. The relays in the proposed DF systems do not require any CSI. The relays in the AF systems only require knowledge of the average link signal-to-noise ratio (SNR) of their immediately previous link to adjust their amplification gains. However, the average CSI can be locally obtained at each relay [30, Ch. 6]. It is shown that the repetition-based multihop systems with AF relaying and DF relaying can achieve diversity without imposing any further processing (on top of amplification) at the relays.

3.1 AF Relaying

3.1.1 System Model

In our proposed AF relaying system, the source re-transmits the same signal in every three time slots for D times; thus, the repetition scheme maintains the half-duplex operation at the relays as well as avoids the interference from the neighboring terminals. The source initiates communication by transmitting the signal x_s. Let $y_{k,d}$ denote the received signal at the k relay terminal, T_k, at the dth repetition stage, $d = 1, \ldots, D$. Then, in an AF relaying system, $y_{k,d}$ is given by

$$y_{k,d} = \beta_{k-1}\alpha_{k,d}y_{k-1,d} + n_{k,d} \tag{3.1a}$$

where $\beta_0 = 1, \beta_k, k = 1, \ldots, K-1$, is the amplification gain factor at the kth relay given by [10]

$$\beta_k = \sqrt{\frac{\frac{P_k}{N_0}}{\Gamma_k + 1}}. \tag{3.1b}$$

Note that the choice of the relay amplification gain in (3.1b) ensures that the average power constraint at the relay is satisfied [10], [25]. The signal

received at the destination at the dth repetition is given by

$$y_{K,d} = \prod_{k=1}^{K} \beta_{k-1}\alpha_{k,d}x_s + \sum_{k=1}^{K-1}\prod_{j=k+1}^{K} \beta_{j-1}\alpha_{j,d}n_{k,d} + n_{K,d},\ d = 1, \ldots, D. \tag{3.2}$$

The destination then employs a square-law detector. Without loss of generality, we can assume that the first symbol from the constellation is transmitted. The square-law detector output for the mth symbol at the dth repetition is given by

$$V_{d,m} = \begin{cases} |2\prod_{k=1}^{K} \beta_{k-1}\alpha_{k,d}P_0 \\ + \sum_{k=1}^{K-1}\prod_{j=k+1}^{K} \beta_{j-1}\alpha_{j,d}U_{k,1} + U_{K,1}|^2, \\ \qquad\qquad\qquad\qquad m = 1 \\ |\sum_{k=1}^{K-1}\prod_{j=k+1}^{K} \beta_{j-1}\alpha_{j,d}U_{k,m} + U_{K,m}|^2, \\ \qquad\qquad\qquad\qquad m = 2, \ldots, M \end{cases} \tag{3.3}$$

where $U_{k,m}, k = 1, \ldots, K, m = 1, \ldots, M$, is a zero-mean complex Gaussian random variable with variance $4P_0N_0$ [31]. After D repetitions, the destination combines the outputs of the square-law detector as

$$Z_m = \sum_{d=1}^{D} V_{d,m}, \qquad m = 1, \ldots, M. \tag{3.4}$$

The destination decision rule is

$$[\hat{m}] = \arg \max_{m=1,\ldots,M} \{Z_m\} \tag{3.5}$$

where $\hat{m}$ is the detected symbol. Note that it is assumed that the relay has knowledge only of the statistical channel information (i.e. average CSI); no channel estimation bits need to be reserved in the packet. The number of time slots required to complete communication is $K + 3(D-1)$.

3.1.2 Symbol Error Probability

Suppose the first symbol from the signal constellation is sent. Then Z_1 contains signal and noise, while $Z_m, m = 2, \ldots, M$, contains noise only. An erroneous decision occurs if any $Z_m, m = 2, \ldots, M$, is larger than Z_1. Therefore, the average symbol error probability (SEP) of a noncoherent AF multihop relaying system with M-FSK is given by

$$P_e = P_r(Z_1 < \max_{m=2,\ldots,M}\{Z_m\}). \tag{3.6}$$

Note that $V_{d,m}|\gamma_{2,d}, \ldots, \gamma_{K,d}, d = 1, \ldots, D$ are independent exponential random variables with parameters given by

$$\lambda_{d,m} = \begin{cases} 4P_0N_0\Big(1 + \sum\limits_{k=1}^{K-1}\prod\limits_{j=k+1}^{K}\frac{\gamma_{j,d}}{C_{j-1}} + \Gamma_1\prod\limits_{k=2}^{K}\frac{\gamma_{k,d}}{C_{k-1}}\Big) \triangleq \frac{1}{\lambda_d}, \\ \qquad\qquad\qquad\qquad\qquad\qquad m = 1 \\ 4P_0N_0\Big(1 + \sum\limits_{k=1}^{K-1}\prod\limits_{j=k+1}^{K}\frac{\gamma_{j,d}}{C_{j-1}}\Big) \triangleq \frac{1}{\mu_d}, \\ \qquad\qquad\qquad\qquad\qquad\qquad m = 2, \ldots, M \end{cases} \tag{3.7}$$

where $C_k \triangleq \Gamma_k + 1, k = 1, \ldots, K-1$. The average SEP in (3.6) is then evaluated as

$$P_e = E_{\boldsymbol{\gamma}_{k,d}}\underbrace{\Big\{P_r(Z_1 < \max_{m=2,\ldots,M}\{Z_m\}|\boldsymbol{\gamma}_{k,d})\Big\}}_{P_{e|\boldsymbol{\gamma}_{k,d}}} \tag{3.8}$$

where $E\{\cdot\}$ denotes the expectation operator and $\boldsymbol{\gamma}_{k,d} = [\gamma_{2,1}, \ldots, \gamma_{k,1}, \ldots, \gamma_{2,D}, \ldots, \gamma_{K,D}]$ is a vector of the instantaneous SNRs received over the relay channels at different repetition time slots. The conditional error probability $P_{e|\boldsymbol{\gamma}_{k,d}}$ is obtained as

$$\begin{aligned} P_{e|\boldsymbol{\gamma}_{k,d}} &= P_r(Z_1 < \max_{m=2,\ldots,M}\{Z_m\}|\boldsymbol{\gamma}_{k,d}) \\ &= (M-1)P_r(Z_1 < Z_2|\boldsymbol{\gamma}_{k,d})P_r(Z_3 < Z_2, \ldots, Z_M < Z_2|\boldsymbol{\gamma}_{k,d}). \end{aligned} \tag{3.9}$$

Then, we have

$$P_{e|\boldsymbol{\gamma}_{k,d}} = (M-1)\int_0^\infty P_r(Z_1 < z|Z_2 = z, \boldsymbol{\gamma}_{k,d}) P_r(Z_3 < z|Z_2 = z, \boldsymbol{\gamma}_{k,d})^{M-2} f_{Z_2|\boldsymbol{\gamma}_{k,d}}(z)dz \tag{3.10}$$

where (3.10) follows because $Z_2, \ldots, Z_m$ are independent identically distributed (i.i.d.) random variables, and $f_{Z_2|\boldsymbol{\gamma}_{k,d}}(z)$ is the conditional probability density function (PDF) of Z_2. Since $Z_m = \sum_{d=1}^{D} V_{d,m}, m = 1, \ldots, M$, is the sum of D independent exponential random variables with pairwise distinct parameters λ_d for $m = 1$, and μ_d for $m = 2, \ldots, M$. The conditional pdf of Z_m is given by

$$f_{Z_m|\boldsymbol{\gamma}_{k,d}}(z) = \begin{cases} \prod_{i=1}^{D} \lambda_i \sum_{j=1}^{D} \frac{\exp(-\lambda_j z)}{\prod_{\substack{k\neq j \\ k=1}}^{D} (\lambda_k - \lambda_j)}, z > 0, \\ \qquad\qquad m = 1 \\ \prod_{i=1}^{D} \mu_i \sum_{j=1}^{D} \frac{\exp(-\mu_j z)}{\prod_{\substack{k\neq j \\ k=1}}^{D} (\mu_k - \mu_j)}, z > 0, \\ \qquad\qquad m = 2, \ldots, M. \end{cases} \tag{3.11}$$

Therefore, $P_{e|\boldsymbol{\gamma}_{k,d}}$ can be evaluated as

$$\begin{aligned} P_{e|\boldsymbol{\gamma}_{k,d}} = & \sum_{j=1}^{D}\sum_{k=1}^{D} e_j g_k \sum_{n_0+\ldots+n_D=M-2} \\ & \binom{M-2}{n_0, \ldots, n_D} \Big(\sum_{j=1}^{D} f_j\Big)^{n_0} \prod_{i=1}^{D} (-f_i)^{n_i} \\ & \Big[\frac{1}{\sum_{i=1}^{D} \mu_i n_i + \mu_k} - \frac{1}{\sum_{i=1}^{D} \mu_i n_i + \mu_k + \lambda_j}\Big] \end{aligned} \tag{3.12a}$$

where

$$e_j = \prod_{\substack{i=1 \\ i\neq j}}^{D} \lambda_i \prod_{\substack{k=1 \\ k\neq j}}^{D} (\lambda_k - \lambda_j) \tag{3.12b}$$

$$f_j = \prod_{\substack{i=1 \\ i\neq j}}^{D} \mu_i \frac{1}{\prod\limits_{\substack{k=1 \\ k\neq j}}^{D} (\mu_k - \mu_j)} \tag{3.12c}$$

$$g_j = \prod_{i=1}^{D} \mu_i \frac{1}{\prod\limits_{\substack{k=1 \\ k\neq j}}^{D} (\mu_k - \mu_j)} \tag{3.12d}$$

where we have used the multinomial theorem [32]. The special case of binary orthogonal FSK (M=2) is given by

$$P_{e|\boldsymbol{\gamma}_{k,d}} = \sum_{j=1}^{D} \sum_{k=1}^{D} e_j g_k \Big[\frac{1}{\mu_k} - \frac{1}{\mu_k + \lambda_j} \Big]. \tag{3.13}$$

Unfortunately, exact evaluation of the expectation in (3.8) requires multi-fold numerical integration which is very involved, if not impossible. Note that evaluation of (3.8) using the approximation based on the Laguerre polynomials [32, eq. (25.4.45)] as in [26, eq. (9)] is computationally cumbersome due to the number of nested summations that grows with K and D. However, the average SEP in (3.8) can be efficiently evaluated using the Monte Carlo method.

3.1.3 Achievable Diversity Order

As mention in Section 2.1.1, the diversity order d is a measurement of how many independently fading signal replicas are combined at the receiver. The higher the diversity order, the more robust the system would be against the fading effects. The asymptotic behavior of the SEP given in (3.8) can be used to determine the achievable diversity order of the proposed repetition-based noncoherent AF relaying systems employing SLC.

However, this is not tractable due to the mathematical form of the error probability in (3.8). Thus, we will derive a simple upper bound on the error probability. Note that the conditional binary probability in an AF relaying system, denoted here by $P_{2|\boldsymbol{\gamma}_{k,d}}(D)$, is given by

$$\begin{aligned} P_{2|\boldsymbol{\gamma}_{k,d}}(D) &= P(Z_2 - Z_1 > 0|\boldsymbol{\gamma}_{k,d}) \\ &= P(X > 0) \end{aligned} \tag{3.14a}$$

where the random variable X is defined as

$$X \triangleq Z_2 - Z_1 = \sum_{d=1}^{D} (V_{d,2} - V_{d,1}) \tag{3.14b}$$

where $\triangleq$ denotes "is defined as". The Chernoff bound on the binary error probability can be obtained using [30, eq. (14.4-60)]

$$P_{2|\boldsymbol{\gamma}_{k,d}}(D) \leq \Big(\frac{4\phi_1^2\phi 2^2}{(\phi_1^2+\phi_2^2)^2}\Big)^D \tag{3.15a}$$

where

$$\phi_1^2 = 2P_0N_0\Big(1 + \sum_{k=1}^{K-1}\prod_{j=k+1}^{K}\frac{\gamma_{j,d}}{C_{j-1}} + \Gamma_1\prod_{k=2}^{K}\frac{\gamma_{k,d}}{C_{k-1}}\Big) \tag{3.15b}$$

$$\phi_2^2 = 2P_0N_0\Big(1 + \sum_{k=1}^{K-1}\prod_{j=k+1}^{K}\frac{\gamma_{j,d}}{C_{j-1}}\Big). \tag{3.15c}$$

The error probability for the noncoherent M-FSK AF multihop relaying can be upper-bounded by the union bound [30, Ch. 5], namely

$$P_{e|\boldsymbol{\gamma}_{k,d}} \leq (M-1)P_{2|\boldsymbol{\gamma}_{k,d}}(D). \tag{3.16}$$

Thus, we can write

$$P_{e|\boldsymbol{\gamma}_{k,d}} \leq \Big(\frac{4\phi_1^2\phi 2^2}{(\phi_1^2+\phi_2^2)^2}\Big)^D. \tag{3.17}$$

Then, an upper bound on the SEP is obtained as

$$\begin{aligned} P_e &\leq E_{\boldsymbol{\gamma}_{k,d}}\Big\{\Big(\frac{4\phi_1^2\phi 2^2}{(\phi_1^2+\phi_2^2)^2}\Big)^D\Big\} \\ &= \underbrace{\int_0^\infty \cdots \int_0^\infty}_{(K-1)D-\text{fold}} \Big[\Big(\frac{4\phi_1^2\phi 2^2}{(\phi_1^2+\phi_2^2)^2}\Big)^D \prod_{k=2}^{K}\prod_{d=1}^{D} f_{\gamma_{k,d}}(\gamma_{k,d})d_{\gamma_{k,d}}\Big]. \end{aligned} \tag{3.18}$$

The multi-fold integral in (3.18) has no closed-form solution. However, since its integrand is in terms of smooth well-behaved functions for diversity order analysis, we can use the numerical integration method in [32, eq. (25.4.45)] for evaluation of (3.18). Thus,

$$P_e \leq \sum_{n_1=1}^{N_p} \cdots \sum_{n_{(K-1)D=1}}^{N_p} \prod_{i=1}^{(K-1)D} \xi_{n_i} \Big(\frac{4\phi_1^2 \phi 2^2}{(\phi_1^2+\phi_2^2)^2} \Big)^D |_{\substack{\gamma_{k,d}=\zeta_{n_{(k-1)d}}\Gamma_k \\ k=2,\ldots,K \\ d=1,\ldots,D}} \tag{3.19}$$

where ξ_i and ζ_i are the weights and zeros of the Laguerre polynomial of order N_p [32, Table 25.9], respectively. Now note that

$$\Gamma_1 = \frac{\mathrm{SNR}\sigma_1^2}{p} \tag{3.20}$$

and

$$\lim_{\mathrm{SNR}\to\infty} \frac{\gamma_{j,d}}{C_{j-1}} = \frac{\xi_{n_{(j-1)d}}\sigma_j^2}{\sigma_{j-1}^2}, \quad j = 2,\ldots,K, d = 1,\ldots,D \tag{3.21}$$

where $\mathrm{SNR} \triangleq \frac{P_T}{N_0}$ and $p = 2D$ in dual-hop systems and $p = K + 3(D-1)$ in systems with more than 2 relays ($K \geq 3$). Then, we have

$$\lim_{\mathrm{SNR}\to\infty} \Big(\frac{4\phi_1^2 \phi 2^2}{(\phi_1^2+\phi_2^2)^2} \Big)^D |_{\substack{\gamma_{k,d}=\zeta_{n_{(k-1)d}}\Gamma_k \\ k=2,\ldots,K \\ d=1,\ldots,D}} \to \frac{\kappa(n_1,\ldots,n_{(K-1)D})}{\mathrm{SNR}^D} \tag{3.22}$$

where $\kappa(n_1,\ldots,n_{(K-1)D})$ is constant but depends on the channel parameters. Thus,

$$\lim_{\mathrm{SNR}\to\infty} P_e \to \frac{M-1}{\mathrm{SNR}^D} \sum_{n_1=1}^{N_p} \cdots \sum_{n_{(K-1)D}=1}^{N_p} \prod_{i=1}^{(K-1)D} \xi_{n_i} \kappa(n_1,\ldots,n_{(K-1)D}). \tag{3.23}$$

Eq. (3.23) shows that the repetition-based noncoherent AF relaying system achieves diversity order equal to the number of repetitions.

3.2 DF Relaying

3.2.1 System Model

In our proposed DF relaying system, the source re-transmits its signal to the relay in D subsequent time slots[1]. In general, the received signal at the kth relay terminal, T_k, at the dth repetition stage is given by

$$y_{k,d} = \alpha_{k,d} x_{k-1,p} + n_{k,d} \tag{3.24}$$

where $x_{0,p} = x_s$ and $x_{k,p}$, $k = 1, \ldots, K-1$ denotes the pth symbol from the constellation estimated at the kth relay. The output of the square-law detector employed at the kth relay for the dth repetition is given by

$$V_{k,\{d,m\}} = \begin{cases} |2\alpha_{k,d} P_k + U_{k,1}|^2, & m = p \\ |U_{k,m}|^2, & \text{otherwise.} \end{cases} \tag{3.25}$$

After D repetitions, relay T_k computes the output of the square-law detector as

$$Z_{k,m} = \sum_{d=1}^{D} V_{k,\{d,m\}}. \tag{3.26}$$

The decision rule at the kth relay is given by

$$[\hat{p}] = \arg \max_{p=1,\ldots,M} \{Z_{k,m}\} \tag{3.27}$$

where $\hat{p}$ is the detected symbol at the kth relay. Then, the relay re-transmits the estimated symbol, $x_{k,\hat{p}}$, to the next relay terminal, T_{k+1}, in the next D time slots. The destination employs noncoherent detection using SLC of the signals received from the last relay in the D repetition time slots and then makes the final decision on the transmitted symbol. The number of time slots required to complete communication is KD. It is not needed to reserve channel estimation bits in the packet transmission.

[1] It is shown in [33] that if the source re-transmits the original signal in every three time slots as in the AF case, the proposed system with DF relaying cannot achieve diversity order gain without increased processing.

3.2.2 Symbol Error Probability

For a DF multihop relaying system, the authors in [34] derived an exact expression for the end-to-end average bit error probability (BEP), P_b, using a recursive relation. Using [34, eq. (3)], P_b is given by

$$P_b = \sum_{k=1}^{K} \Big(P_{bk} \prod_{l=k+1}^{K} (1 - 2P_{bl}) \Big) \tag{3.28}$$

where P_{bk} is the average BEP at the kth relay as a function of the average link SNR between the terminals T_{k-1} and T_k, Γ_k. If all the links between terminals are i.i.d with equal average received SNR, then $P_{bk} = P_{bl}$ and the end-to-end average BEP can be simplified as

$$P_b = \frac{1}{2}\Big(1 - (1 - 2P_{bk})^K\Big), \quad \forall k. \tag{3.29}$$

This is a special case where the link SNRs are different at each hop. This case is of interest [35] and leads to a more tractable mathematical analysis. For consistency and comparisons with the other results derived in this thesis, we need to convert BEP into SEP. The relationship between SEP and BEP for orthogonal MFSK is given by [36, eq. (8)]

$$P_b = \frac{2^{\log_2 M - 1}}{2^{\log_2 M} - 1} P_e. \tag{3.30}$$

Note that $V_{k,\{d,m\}}, k = 1, \ldots, K-1$ and $d = 1, \ldots, K$, are independent exponential random variables with parameters given by

$$\lambda_{k,\{d,m\}} = \begin{cases} 4P_0N_0(1+\Gamma_k) \triangleq \lambda_k, & m = 1 \\ 4P_0N_0 \triangleq \mu, & m = 2, \ldots, M. \end{cases} \tag{3.31}$$

Then, we have the decision variables at the kth relay, $Z_{k,m}, k = 1, \ldots, K, m = 1, \ldots, M$, are distributed according to a chi-square probability distribution with $2D$ degrees of freedom, that is,

$$f_{Z_m}(z) = \begin{cases} \frac{1}{{\lambda_K}^D (D-1)!} z^{D-1} \exp(-\frac{z}{\lambda_K}), & m = 1 \\ \frac{1}{\mu^D (D-1)!} z^{D-1} \exp(-\frac{z}{\mu}), & m = 2, \ldots, M. \end{cases} \tag{3.32}$$

The average SEP at the kth relay is given by [30, eq. (14.4-49)]

$$P_{ek} = \frac{1}{(D-1)!}\sum_{m=1}^{M-1}\frac{(-1)^{m+1}\binom{M-1}{m}}{(1+m+m\Gamma_k)^D} \sum_{l=0}^{m(D-1)}\beta_{lm}(D-1+l)!\Big(\frac{1+\Gamma_k}{1+m+m\Gamma_k}\Big)^l \tag{3.33a}$$

where β_{km} is the set of coefficients in the expression given by

$$\Big(\sum_{k=0}^{D-1}\frac{x^k}{k!}\Big)^m = \sum_{k=0}^{m(D-1)}\beta_{km}x^k. \tag{3.33b}$$

For the special case of orthogonal BFSK, P_{ek} can be simplified as

$$P_{ek} = \frac{1}{(D-1)!}\frac{1}{(2+\Gamma_k)^D}\sum_{l=0}^{D-1}\frac{1}{l!}(D-1+l)!\Big(\frac{1+\Gamma_k}{2+\Gamma_k}\Big)^l. \tag{3.34}$$

Using the relationship between SEP and BEP given in (3.30), we can evaluate the end-to-end average SEP of DF relaying systems.

3.2.3 Achievable Diversity Order

Similar to AF relaying systems, an upper bound on the SEP of DF relaying systems can be obtained using

$$P_{ek} \le (M-1)\Big(\frac{4\phi_{k,1}^2\phi_{k,2}^2}{(\phi_{k,1}^2+\phi_{k,2}^2)^2}\Big)^D \quad k=1,\ldots,K \tag{3.35a}$$

where

$$\phi_{k,1}^2 = 2P_0N_0(1+\Gamma_k), \qquad k=1,\ldots,K \tag{3.35b}$$

$$\phi_{k,2}^2 = 2P_0N_0, \qquad k=1,\ldots,K. \tag{3.35c}$$

Note that P_{ek} decays as $\frac{1}{(\mathrm{SNR})^D}$ at large values of SNR. Therefore, the average SEP in (3.35) decays as $\frac{1}{(\mathrm{SNR})^D}$ when $\mathrm{SNR}\to\infty$. This indicates that a repetition-based noncoherent multihop system with DF relaying also achieves diversity order equal to the number of repetitions.

3.3 Simulation Results

In this section, we evaluate the performance of the repetition-based multihop AF and DF relaying systems with both balanced links (i.i.d case) and unbalanced links (non i.d. case). We assume that CSI is only known at the receiving terminal. Therefore, equal portions of the transmission power per symbol, P, are allocated among transmitting terminals, that is, $P_k = \frac{1}{KD}P$. In systems with balanced links, it is assumed that the relay terminals are located equi-distant from each other on a straight line of length l. The average link SNR between the terminals T_{k-1} and T_k is $\Gamma_k = \frac{1}{\tau}K^{\delta}\Gamma_0, k = 1, \ldots, K$, where δ is the path loss exponent and $\Gamma_0 = \frac{P}{N_0}$ is the average link SNR between the source and destination in direct transmission. In systems with unbalanced links, we assume that the kth relay is placed at a distance $\frac{2k}{K(K+1)}l$ from its previous terminal on a straight line. The average link SNR is given by $\Gamma_k = \frac{1}{\tau}\left(\frac{(K+1)K}{2k}\right)^{\delta}\Gamma_0, k = 1, \ldots, K$. In the numerical examples, we assume δ=3 and orthogonal BFSK modulation.

Figure 3.1 shows the SEP versus relay location in different dual-hop relaying systems assuming $\Gamma_0 = 10$ dB with noncoherent detection. It is assumed that the relay is located at a distance ρ from the source. It is clearly seen from the curves that both the AF and DF relaying systems achieve better performance when the relay gets closer to the middle of the link. In particular, the optimal relay location that minimizes the symbol error probabilities is at the midpoint between the source and the destination in repetition-based DF relaying systems. It is also seen that the proposed repetition-based transmission system performs worse than direct transmission if the relay is very close to the source or the destination. In addition, DF relaying always attains better symbol error rate performance than AF relaying no matter where the relay is located.

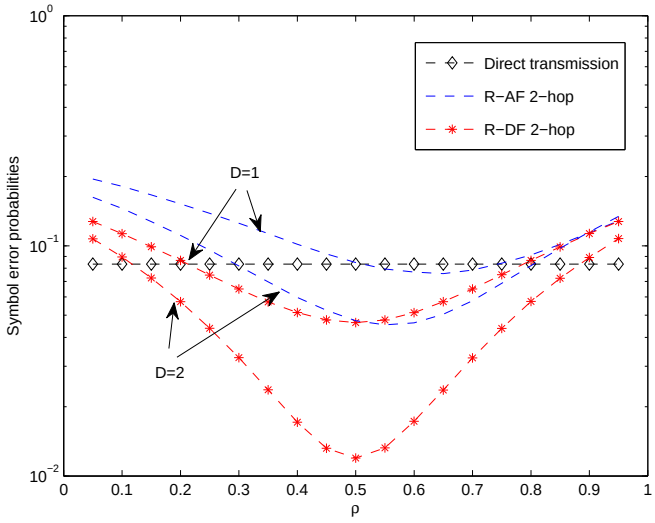

Figure 3.1. Symbol error probabilities for noncoherent BFSK dual-hop systems.

Figures 3.2 and 3.3 show the average error probabilities of noncoherent BFSK 3-hop relaying systems with balanced links and unbalanced links. It is clearly seen from these figures that the simulation results match precisely the theoretical results obtained using eq. (3.13) for the SEP of AF relaying systems and eq. (3.34) for the DF relaying systems. It is seen that both AF and DF relaying systems achieve diversity order equal to the number of repetitions, as shown in Section **??** and Section 3.2.3. It is also seen that noncoherent DF relaying systems achieve significantly better symbol error probability performance than AF relaying systems in medium to large SNRs. This implies that the noise amplification in AF systems in those regions has more severe effects than the error propagation in DF systems. In addition, observe that in small SNR regions, the square-law detection is very likely to result in noisy outputs, and hence combining them does not result in performance improvement.

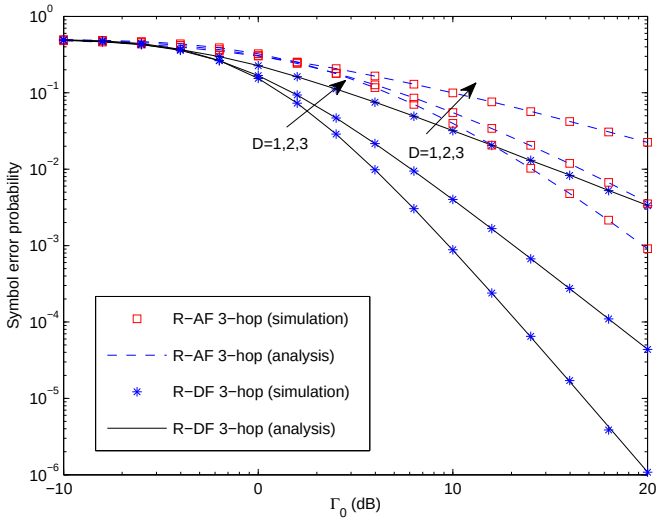

Figure 3.2. Symbol error probabilities for noncoherent BFSK 3-hop systems with balanced links.

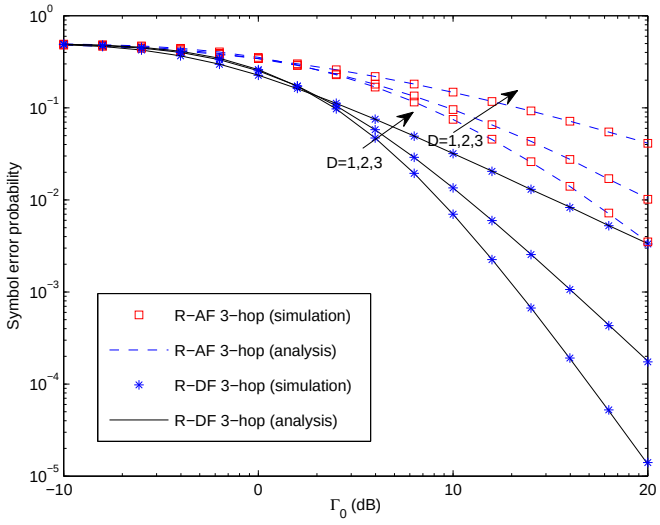

Figure 3.3. Symbol error probabilities for noncoherent BFSK 3-hop systems with unbalanced links.

3.4 Summary

In this chapter, new repetition-based noncoherent multihop AF and DF relaying systems were proposed. We studied the symbol error probabil-

ity and diversity order performance in different repetition-based noncoherent multihop systems. The analytical results were verified by comparing them with Monte Carlo simulation results. It was shown that the repetition-based noncoherent AF relaying and DF relaying can achieve diversity order with no requirement for knowledge of channel state information. This makes them useful in low-rate wireless personal area networks (LR-WPANs), which require low power consumption and reduced system complexity. It was also shown that the DF relaying scheme achieves better performance than AF relaying in medium to large SNRs.

Chapter 4

Repetition-Based Multihop Systems With Transmitter CSI

As mentioned in Chapter 3, multihop diversity systems need CSI of all links between that terminal and all its preceding terminals (both adjacent and non-adjacent terminals) involved in the cooperation. The requirement will impose overhead in data transmission and propagating channel estimation errors will result in performance degradation. In addition, there could be situations where the relays cannot receive the signals from all preceding terminals, and are just in range of one terminal at a time. In such channel environments, we cannot exploit diversity combining. In the systems discussed in this chapter, we assume that each relay has (or exploits) only knowledge of the instantaneous CSI of its immediately preceding link. The destination has (or exploits) global CSI knowledge of all links. It is shown that repetition-based relaying systems with coherent detection also achieve full diversity order and better performance than the corresponding systems with noncoherent detention, as expected. Therefore, the proposed scheme has less complexity while still offering diversity order gain.

4.1 AF Relaying

4.1.1 System Model

In AF relaying systems, the source re-transmits the same packet in every three time slots, thus the repetition scheme avoids the interference from neighboring terminals. In general, the $(k-1)$th relay terminal, T_{k-1}, transmits signal $x_{k-1,d}$ at the dth repetition stage, $d = 1, \ldots, D$, and the received signal at the immediately following T_k terminal, $y_{k,d}$, is given by

$$y_{k,d} = \alpha_{k,d} x_{k-1,d} + n_{k,d}, \qquad k = 1, \ldots, K \tag{4.1}$$

where $\alpha_{k,d}$ is the fading gain of the channel between the $(k-1)$th and the kth terminal over the duration of the dth repetition, modeled as a zero-mean complex Gaussian random variable with variance σ_k^2. The noise at the kth terminal for the dth repetition, $n_{k,d}$, is modeled as zero-mean complex Gaussian with power N_0. The instantaneous SNR between terminals T_{k-1} and T_k at the dth repetition is defined as $\gamma_{k,d} = \frac{P_{k-1}}{N_0}|\alpha_{k,d}|^2$, where P_k denotes the transmitter power at the kth terminal, $k = 1, \ldots, K-1$. Note that $\gamma_{k,d}$ is an exponential random variable with mean $\Gamma_k = \frac{P_{k-1}}{N_0}\sigma_k^2$. According to the assumption of uniform power allocation, $P_k = \frac{P_T}{K+3(D-1)}$, where P_T is the transmission power per symbol. The received signal at the kth relay terminal is processed by amplifying and then forwarding to the next terminal, T_{k+1}. After D repetitions, the destination combines the received signals from all repetitions using MRC and employs coherent detection.

4.1.2 System Error Probability

In AF multihop relaying system with instantaneous CSI, the kth relay terminal amplifies its received signal by a variable gain, which is given by [7]

$$\beta_k = \sqrt{\frac{P_k}{P_{k-1}\alpha_{k,d}^2 + N_0}}, \qquad k = 1, \ldots, K-1. \tag{4.2}$$

In a K-hop system, the signal received at the destination at the dth repetition, $y_{K,d}$, is

$$y_{K,d} = \prod_{i=1}^{K} \beta_{i-1,d}\alpha_{i,d}x_s + \sum_{j=1}^{K-1}\Big\{ \prod_{i=j+1}^{K} \beta_{i-1,d}\alpha_{i,d}\Big\}n_{j,d} + n_{K,d}. \tag{4.3}$$

After D repetitions, the destination employs MRC. Since the noise terms from different repetition are uncorrelated, the instantaneous received SNR at the destination can be expressed as

$$\gamma_K = \sum_{d=1}^{D} \gamma_{K,d} \tag{4.4a}$$

where $\gamma_{K,d}$ is the instantaneous received SNR at the destination for the dth repetition and is given by [16]

$$\gamma_{K,d} = \Big(\prod_{i=1}^{K} (1 + \frac{1}{\gamma_{i,d}}) - 1 \Big)^{-1}. \tag{4.4b}$$

The average SEP for coherent orthogonal MFSK is given by [30]

$$P_e = \int_0^\infty P_e(\gamma) f_{\gamma_K}(\gamma) d\gamma \tag{4.5a}$$

where $P_e(\gamma)$ is given by [36, eq. (8.40)]

$$P_e(\gamma) = 1 - \int_{-\infty}^{\infty} \Big[Q(-q - \sqrt{2\gamma}) \Big]^{M-1} \frac{1}{\sqrt{2\pi}} exp(-\frac{q^2}{2}) dq \tag{4.5b}$$

where

$$Q(z) = \frac{1}{\sqrt{2\pi}} \int_z^\infty \exp(-\frac{u^2}{2}) du \tag{4.5c}$$

is the Gaussian probability integral. Unfortunately, for arbitrary M, P_e in (4.5a) can not be expressed in closed-form. Using the union bound, P_e can be upper bounded by

$$P_e \leq (M-1) P_{eBFSK} \tag{4.6a}$$

where P_{eBFSK} is given by

$$P_{eBFSK} = \int_{-\infty}^{\infty} Q(\sqrt{\gamma}) f_{\gamma_K}(\gamma) d\gamma. \tag{4.6b}$$

Now reference [16] shows that $\gamma_{K,d}$ can be tightly upper bounded by a more tractable form

$$\gamma_{K,d} = \Big(\sum_{i=1}^{K} \frac{1}{\gamma_{i,d}} \Big)^{-1}. \tag{4.7}$$

Using the method developed in [37], P_{eBFSK} can be well approximated by

$$P_{eBFSK} \approx \frac{\prod_{i=1}^{D}(2i-1)}{2D!} (\sum_{i=1}^{K} \frac{1}{\Gamma_k})^D. \tag{4.8}$$

Therefore, P_e can be approximated by

$$P_e \approx (M-1) \frac{\prod_{i=1}^{D}(2i-1)}{2D!} (\sum_{i=1}^{K} \frac{1}{\Gamma_k})^D. \tag{4.9}$$

4.1.3 Achievable Diversity Order

Since the theoretical error probability given in (4.5a) is not mathematically tractable, we derive here a simple upper bound on the SEP. Using the union bound, we have

$$P_e < (M-1) P_{eBFSK}. \tag{4.10}$$

First we derive a closed-form expression for P_{eBFSK}. Using (4.7) and noting that $\gamma_{K,d} \geq \frac{1}{K} \min_{i=1,\ldots,K} \{\gamma_{i,d}\}$, since $\gamma_K = \sum_{d=1}^{D} \gamma_{K,d}$, we have

$$\gamma_K \geq \sum_{d=1}^{D} \frac{1}{K} \min_{i=1,\ldots,K} \{\gamma_{i,d}\} \triangleq \gamma_{low} \tag{4.11}$$

for $\gamma_{i,d} > 0$. The inequality in (4.10) becomes an equality if $\gamma_{i,d} = \gamma_{j,d}$, for $i \neq j, i, j = 1, \ldots, K$. Since the minimum of a set of independent exponential random variables is also exponentially distributed [38],

$\min\limits_{i=1,\ldots,K}\{\gamma_{i,d}\}$ is an exponentially-distributed random variable with mean $\left(\sum\limits_{i=1}^{K}\frac{1}{\Gamma_i}\right)^{-1} \triangleq \bar{\gamma_c}, d = 1,\ldots,D$. Hence, the PDF of γ_{low} is given by [30, eq. (14.4-13)], that is,

$$f_{\gamma_{low}}(\gamma) = \frac{K}{(D-1)!\bar{\gamma_c}^{D}} K\gamma^{D-1}e^{-K\gamma/\bar{\gamma_c}}. \tag{4.12}$$

Since the SEP decreases with increasing SNR, γ_K, substituting (4.10) in (4.6b) gives an upper bound on the SEP of the system. Therefore,

$$P_{eBFSK} \leq P_{up}. \tag{4.13}$$

Using [30, eq. (14.4-15)], P_{up} can be evaluated in closed-form as

$$P_{up} = \left[\frac{1}{2}(1-\mu)\right]^{D}\sum_{k=0}^{D-1}\binom{D-1+k}{k}\left[\frac{1}{2}(1+\mu)\right]^{k} \tag{4.14a}$$

where the parameter μ is defined as

$$\mu = \sqrt{\frac{\bar{\gamma_c}}{\bar{\gamma_c}+2K}}. \tag{4.14b}$$

For large values of SNR, $\bar{\gamma_c} \gg 1$, the term $\frac{1}{2}(1+\mu) \approx 1$, and the term $\frac{1}{2}(1-\mu) \approx \frac{K}{2\bar{\gamma_c}}$. Furthermore, according to [30, eq. (14.4-17)],

$$\sum_{k=0}^{D-1}\binom{D-1+k}{k} = \binom{2D-1}{D}. \tag{4.15}$$

Therefore, P_{up} in (4.14) can be approximated as

$$P_{up} \approx \left(\frac{K}{2\bar{\gamma_c}}\right)^{D}\binom{2D-1}{D}. \tag{4.16}$$

We observe that for large SNR, P_{up} decays as $\frac{1}{(\mathrm{SNR})^D}$. This indicates that the proposed repetition-based coherent AF relaying systems achieve diversity order equal to the number of repetitions, D.

4.2 DF Relaying

In DF multihop relaying systems with instantaneous CSI, the relays as well as the destination employ MRC. The source re-transmits the same packet in every time slot for D times. In general, the received signal at the kth relay terminal, T_k, at the dth repetition stage is given by

$$y_{k,d} = \alpha_{k,d} x_{k-1,m} + n_{k,d}, \qquad m = 1, 2, k = 1, \ldots, K-1 \tag{4.17}$$

where $x_{k-1,m}$ denotes the mth symbol in the alphabet estimated at the $(k-1)$th relay. The kth relay, T_k, detects the output of the maximal ratio combiner and re-transmits the estimated signal to the next relay terminal, T_k, for D repetition time slots. The destination employs MRC of the received signals from the D repetition time slots and makes the final decision on the transmitted signal.

4.2.1 Symbol Error Probability

As in the AF case discussed above, the instantaneous received SNR at the kth relay, T_k, can be expressed as

$$\gamma_k = \sum_{d=1}^{D} \gamma_{k,d}, \qquad k = 1, \ldots, K \tag{4.18}$$

where $\gamma_{k,d}$ is the instantaneous received SNR at T_k at the dth repetition. Note that γ_k is a sum of exponential random variables, and the PDF of γ_k can be expressed as [30, eq. (14.4-13)]

$$f_{\gamma_k}(\gamma) = \frac{1}{\Gamma_k^D (D-1)!} \gamma^{D-1} \exp\Big(-\frac{\gamma}{\Gamma_k}\Big). \tag{4.19}$$

Therefore, P_{ek} can be derived as a closed-form expression given by

$$P_{ek} = \frac{2^{-D}(2D)!}{\Gamma_k^D (D-1)!} {}_2\tilde{F}_1(D, \frac{1}{2} + D; 1 + D; -\frac{2}{\Gamma_k}) \tag{4.20}$$

where ${}_2\tilde{F}_1(a,b;c;z)$ is the regularized confluent hypergeometric function of the confluent hypergeometric function ${}_2F_1(a;b;z)$ [39, p. 771]. As mentioned in Section 3.2.2, the end-to-end average BEP, P_b, is given by

$$P_b = \sum_{k=1}^{K} \Big(P_{bk} \prod_{l=k+1}^{K} (1 - 2P_{bl}) \Big) \tag{4.21}$$

where P_{bk} is the average BEP at the kth relay. And for the special case with equal average received SNR, then $P_{bk} = P_{bl}$ and the end-to-end average BEP can be simplified as

$$P_b = \frac{1}{2}\Big(1 - (1 - 2P_{bk})^K\Big), \quad \forall k. \tag{4.22}$$

Substituting (4.20) in (4.21) and using the relationship between SEP and BEP given in (3.30), we can evaluate the end-to-end average SEP of DF relaying systems.

4.2.2 Achievable Diversity Order

Recall that in Section 4.2.1, P_{ek} is given by

$$P_{ek} = \frac{2^{-D}(2D)!}{\Gamma_k^D (D-1)!} {}_2\tilde{F}_1(D, \frac{1}{2} + D; 1 + D; -\frac{2}{\Gamma_k}). \tag{4.23}$$

According to [39, p. 771]

$${}_2\tilde{F}_1(a,b;c;z) \propto \frac{1}{\Gamma(c)}(1 + O(z)); (z \to 0). \tag{4.24}$$

For large values of SNR, $P_{ek} \to \frac{2^{-D}(2D)!}{\Gamma_k^D (D-1)!(D+1)!}$, which indicates that a repetition-based coherent multihop system with DF relaying also achieves diversity order equal to the number of repetitions.

4.3 Simulation Results

In the numerical examples, we consider different multihop transmission systems both with balanced and unbalanced links in which the terminals

are located on a straight line of length l meters between the source and destination, as described in Chapter 3. Recall that in systems with balanced links, the average link SNR between the terminals T_{k-1} and T_k is $\Gamma_k = \frac{1}{\tau} K^{\delta} \Gamma_0, k = 1, \ldots, K$. In unbalanced links, the average link SNR is given by $\Gamma_k = \frac{1}{\tau} \left(\frac{(K+1)K}{2k} \right)^{\delta} \Gamma_0, k = 1, \ldots, K$. In the numerical examples, we assume δ=3 and orthogonal BFSK modulation. In the figures, R-AF and R-DF denote the repetition-based AF relaying and repetition-based DF relaying, respectively.

Figure 4.1 shows the SEP versus relay location in different dual-hop relaying systems assuming $\Gamma_0 = 10$ dB with coherent detection. It is assumed that the relay is located at a distance ρ from the source. It is seen from the curves that the proposed repetition-based dual-hop relaying systems can always achieve better performance than direct transmission no matter where the relay is located on the straight line. In addition, it is clearly seen from the figures that both the AF and DF relaying systems achieve better performance when the relay gets closer to the middle of the link. It should be noted that in the DF relaying system, the relays need to employ MRC, however there is no such burden on the relays in the AF relaying system.

Figures 4.2 and 4.3, respectively, show the average error probabilities of coherent BFSK 3-hop relaying systems with balanced links and unbalanced links. The analytical results for repetition-based AF relaying are obtained from eq. (4.9). As seen from the figures the proposed approximation is tight, particularly in medium-to-high SNR regimes. It is seen that coherent AF and DF relaying systems also achieve diversity order, and that systems employing coherent detection perform better than those employing noncoherent detection, as expected.

Figures 4.4 and 4.5 respectively, show the average error probabilities of different multihop diversity transmission systems with balanced links

and unbalanced links. In the AF diversity relaying and selective DF relaying considered here, we also use BFSK modulation for consistency and comparisons with the other results. For repetition-based systems shown in these two figures, we considered repetition time $D = 3$. We note that in both balanced links and unbalanced links, repetition-based coherent DF relaying achieves the best performance, and the superiority is larger in balanced links. As mentioned earlier, in repetition-based DF relaying systems, each relay only needs to know the CSI of its immediately preceding terminal, while in AF diversity relaying systems and selective DF relaying systems, each relay requires the CSI of all its preceding terminals. This means repetition-based coherent DF relaying achieves better symbol error rate performance than previous multihop diversity relaying schemes with less terminal-level complexity. Importantly, we note that repetition-based noncoherent DF relaying does not need any CSI, however it outperforms both AF diversity relaying and selective DF relaying in balanced links. In addition, as seen from these two figures, selective DF relaying achieves better performance in unbalanced links than in balanced links. This means that selective DF relaying is more useful in communication links where the links closest to the source are better than the links closest to the destination.

4.4 Summary

A new repetition-based multihop relaying scheme with coherent detection was developed. For repetition-based AF relaying systems, where the source re-transmits the same signal in every three time slots, each relay only needs the CSI of its immediately preceding link and does not need the employment of MRC as does a multihop diversity system, although the destination needs the CSI of all preceding links to employ MRC. For

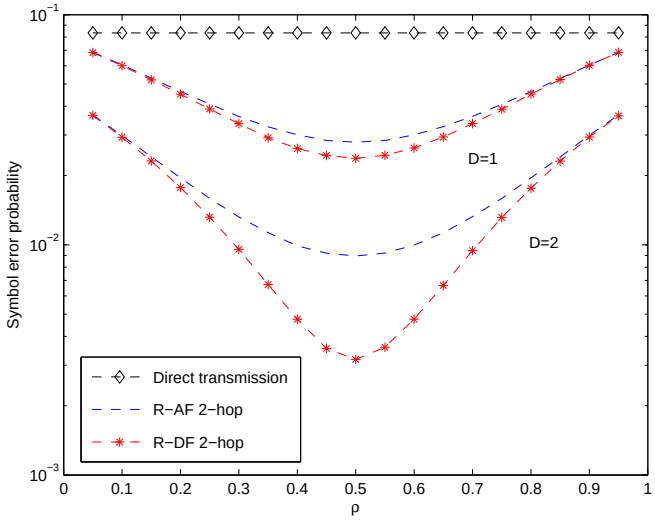

Figure 4.1. Symbol error probabilities for coherent BFSK dual-hop systems.

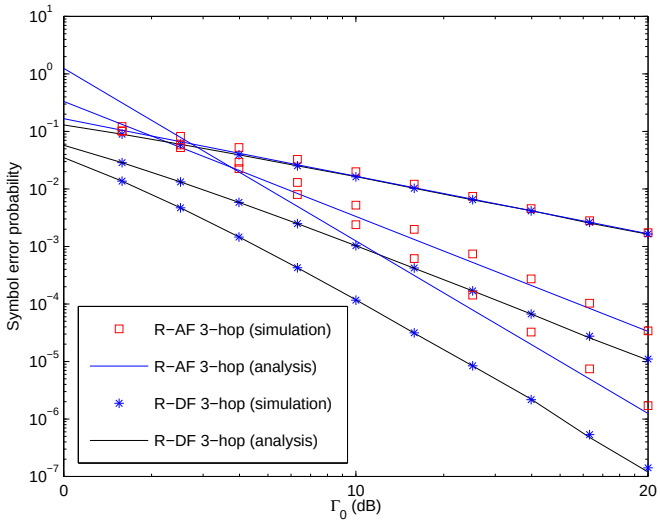

Figure 4.2. Symbol error probabilities for coherent BFSK 3-hop systems with balanced links.

DF relaying systems, where the source re-transmits the same signal in subsequent time slots, each relay as well as the destination only needs the CSI of its immediately preceding link to employ MRC. The performance in Rayleigh fading of the proposed system with AF and DF relays was stud-

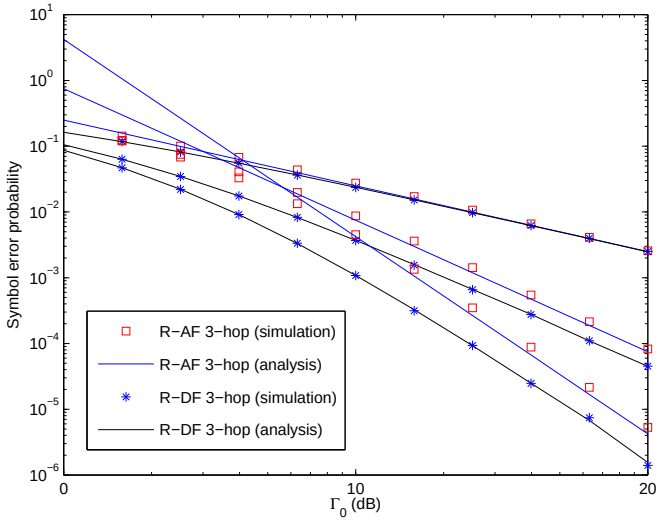

Figure 4.3. Symbol error probabilities for coherent BFSK 3-hop systems with unbalanced links.

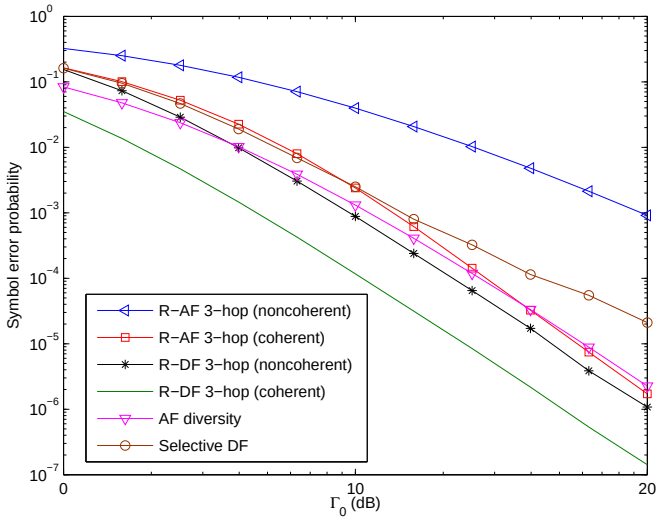

Figure 4.4. Symbol error probabilities for different 3-hop diversity transmission systems with balanced links.

ied. Using simple closed-form bounds on the average error probability, it was shown that the proposed repetition-based multihop transmission systems with AF relaying and DF relaying achieve diversity order equal to the number of repetitions. Numerical results were provided to assess the tight-

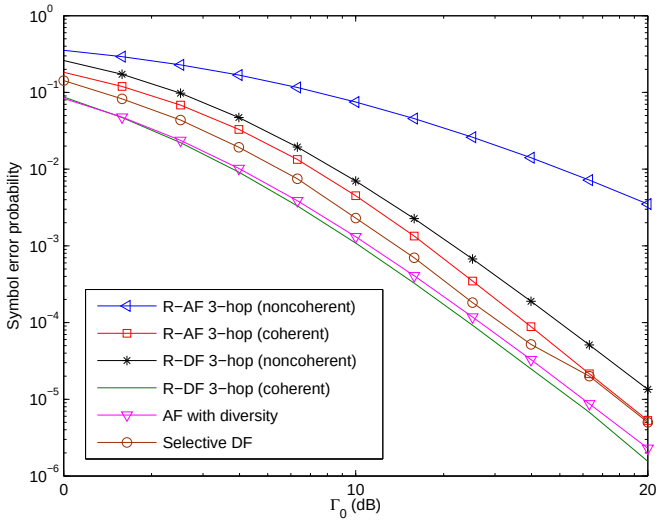

Figure 4.5. Symbol error probabilities for different 3-hop diversity transmission systems with unbalanced links.

ness of the proposed bounds. It was shown that repetition-based DF relaying systems achieve better symbol error rate performance than repetition-based AF relaying systems in medium to large SNRs. It was also shown that DF relaying systems can achieve better symbol error rate performance than conventional AF diversity systems and selective DF diversity systems with less complexity at the relays, in repetition-based relaying sytems.

Chapter 5

Conclusion and Suggestions for Future Work

In this chapter, first we present a summary of the contributions of the thesis. Then, we suggest some areas for future research.

5.1 Conclusion

As stated in Chapter 1, IEEE 802.15.4 is a proposed standard addressing the needs of wireless personal area networks or LR-WPAN. The standard is characterized by maintaining a high level of simplicity, allowing for low cost and low power for wireless connectivity among inexpensive, fixed, portable and moving devices [40]. Multihop relay networks achieve broader coverage, lower transmit power and reduced interference over single-hop networks. Therefore, it would be intuitive to employ multihop topologies in the 802.15.4 standard. However, conventional multihop transmission systems do not offer diversity order. Multihop diversity systems employing diversity combining at the relays show superior performance over the corresponding systems without diversity. However, such multihop diversity systems require CSI of all preceding terminals to employ MRC at the relays, which imposes increased complexity at both the system and terminal levels. In this thesis, we proposed a new repetition-

based multihop relaying system. We focused on performance evaluation of a variety of repetition-based multihop relaying systems. Analytical expressions for the symbol error probability were derived for both AF and DF relaying protocols. It was shown that the repetition-based multihop transmission systems can achieve diversity order without imposing complex processing at the relays.

In Chapter 2, we reviewed previous work on conventional multihop relaying systems and multihop diversity systems. Conventional multihop relaying systems realize a number of benefits over traditional systems in the area of deployment, adaptability, coverage, and capacity. However, these systems do not increase diversity order. On the other hand, the multihop diversity systems can increase diversity order but require knowledge of the instantaneous CSI of all preceding terminals to employ MRC at the relays as well as the destination. This requirement will impose large overhead in data transmission and complex processing burdens on the relays. Therefore, we proposed a new multihop relaying system employing time diversity. The system model of the repetition-based relaying system was discussed.

In Chapter 3, we proposed a repetition-based multihop relaying system based on noncoherent detection. We derived low complexity square-law receivers for both AF and DF relaying systems. A theoretical closed-form expression for the symbol error probability of noncoherent multihop DF relaying schemes and a theoretical upper bound for the noncoherent multihop AF relaying schemes were presented to evaluate the achievable diversity order of the systems. It was shown that both repetition-based noncoherent AF and DF relaying schemes achieve diversity order equal to the number of repetitions. In particular, the relays in the proposed DF systems do not require any CSI. The relays in the AF systems only require the average link SNR of their immediately previous link to adjust their ampli-

fication gains. The destination requires neither instantaneous nor average CSI. The analytical results were verified by comparing them with Monte Carlo simulation results.

In Chapter 4, we proposed a repetition-based multihop relaying system based on coherent detection. To implement the proposed scheme, for AF relaying systems, each relay only needs the CSI of its immediately preceding link and does not need the employment of MRC as does a multihop diversity system. For DF relaying systems, each relay needs the CSI of its immediately preceding link to employ MRC. Using simple closed-form bounds on the average error probability, it was shown that the proposed repetition-based multihop transmission systems with AF relaying and DF relaying achieve diversity order equal to the number of repetitions. Numerical results were provided to assess the tightness of the proposed bounds. It was shown that repetition-based DF relaying systems achieve better symbol error rate performance than repetition-based AF relaying systems in medium to large SNRs.

5.2 Suggestions for Future Research

The research work in this thesis provides a foundation for analysis and design of repetition-based multihop transmission systems with both coherent and noncoherent detection. The methodology and techniques adopted in the research also give insights into possible future topics in this area.

In Chapter 4, we consider perfect channel estimation for tractability. The quality of channel estimates inevitably affects the overall performance of relay-assisted transmission and might become a performance limiting factor. Therefore, a more realistic assessment should consider the effects of practical channel estimation schemes. It would be very intuitive to address issues such as the estimator design, pilot symbol spacing based

upon realistic channel models, and an approximate symbol error probability analysis that accounts for imperfect channel estimation.

In the thesis, uniform power allocation policy is employed due to its simplicity. In reality, power efficiency is an important topic in wireless communication systems. Therefore, choosing the optimal power coefficients for the source and the relays is an important design issue. It would be of benefit to consider optimal power allocation schemes for the proposed repetition-based AF and DF relaying systems more fully.

Furthermore, we focused on the repetition coding throughput the thesis, for its low implementation complexity and ease of exposition. However, diversity benefits of these repetition-based algorithm come at a price of decreasing bandwidth efficiency. In the future, more complex and superior multihop relaying schemes should be analyzed and studied in addition to this repetition-based scheme.

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Vitae

Education

2009 – 2011.12 (expected)	Master of Science in Electrical and Computer Engineering, University of Alberta, Canada, *GPA: 4.0/4.0*
2005 – 2009	Bachelor of Engineering in Electrical Engineering (with honors), Zhejiang University, China, *GPA: 3.95/4.0 (major), 3.85/4.0 (overall)*

Selected Awards

- Alberta Innovates Technology Futures (AITF) Scholarship ($ 31,500, 2011)
- Alberta Informatics Circle of Research Excellence (iCORE) Scholarship (2010, 2011)
- Excellent Student Scholarship (2006, 2007, 2008)
- Motorola Scholarship (2008)
- First Class of Mathematical Contest in Modeling (2007)
- Student Leader Award (2007)

Research Experience

2010 – Present	Research Assistant, iCORE Wireless Communication Lab, University of Alberta, Canada Developed a novel multi-hop wireless network protocol for low-rate applications which significantly improves the reliability of the message signal with reduced system complexity.
2008 – 2009	Research Assistant, Department of Information and Communication Engineering, Zhejiang University, China Investigated power and channel allocation techniques in an orthogonal frequency division multiplexing (OFDM)-cooperative communication system to improve symbol error rate performance.

Publications

1 Y. Li, G. Farhadi, and N. C. Beaulieu, "Repetition-based Non-coherent Multihop Relaying in Block Rayleigh Fading", IEEE International Conference on Communications (ICC), 2011.

2 Y. Li, G. Farhadi, and N. C. Beaulieu, "A Simple Distributed Multihop Diversity Relaying Scheme Based on Repetition", IEEE Global Communications Conference (GLOBECOM), 2011.

3 Y. Li, G. Farhadi and N. C. Beaulieu, "Simple Distributed Multihop Diversity Relaying Based on Repetition", IEEE Transactions on Wireless Communications (In review), 2011.

Computer Skills

- Proficient with C/C++, MATLAB, VHDL.
- Proficient with Microsoft Office including Word, PowerPoint and Excel.