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Adaptive Relay-Selection In Decode-And-Forward Cooperative Systems

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Adaptive Relay-Selection in decode-and-forward Cooperative Systems

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ABSTRACT

In the past few years adaptive decode-and-forward cooperative diversity systems have have been studied intensively in literature. Many schemes and protocols have been proposed to enhance the performance of the cooperative systems while trying to alleviate its drawbacks. One of the recent schemes that had been shown to give high improvements in performance is the best-relay selection scheme. In the best-relay selection scheme only one relaying nodes among the relays available in the system is selected to forward the source's message to the destination. The best relay is selected as the relay node that can achieve the highest end-to-end signal-to-noise ratio (SNR) at the destination node. Performance improvements have been reported as compared to regular fixed decode-and-forward relaying in which all relays are required to forward the source's message to the destination in terms of spectral efficiency and diversity order. In this thesis, we use simulations to show the improvement in the outage performance of the best-relay selection scheme.

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CHAPTER 1

INTRODUCTION

Wireless communications have experienced very fast advances in the past few years. Although separated by only a few years, each new generation of wireless devices has brought significant improvements in terms of link communication speed, device size, battery life, applications, etc. In recent years, researchers have begun to develop wireless network architectures that don't depend on the traditional idea of individual point-to-point based communications with a central controlling base station. In ad-hoc and wireless sensor networks the developed hierarchy of the network allows any node to help forward information from other nodes, thus establishing communication paths that involve multiple wireless hops. Contrary to point-to-point links, the wireless channel is broadcast by nature. This implies that any wireless transmission from an end-user, rather than being considered as interference, can be received and processed at other nodes for a performance gain. This facilitates the development of new concepts on distributed communications and networking via cooperation of nodes.

The technological advances in digital signal processing, antennas, integrated circuits and other underlying technologies have contributed to the fast progress in wireless communications. Achieving reliable and high data-rate communications over the wireless channel have been unsuccessful because of multipath fading, shadowing, and path loss effects which cause impairments in time, frequency, and space. Path loss effects arise from the fact that the strength of the signal attenuates as it traverses the wireless medium and, thus, becomes weaker as the propagation distance increases. In addition to the power loss caused by free-space attenuation, the radio waves may also be distorted by the presence of obstacles along the transmission paths that may absorb part of the signal energy, resulting in signal strength degradation or cause random scattering. The effects may vary slowly over time due to the relative motion between the transmitter, the receiver, and near-by obstacles along the propagation path, such as buildings, trees, vehicles, or airplanes. This slow-varying power variation is called the shadowing effect and is considered as a type of large-scale fading. In wireless communication systems, the multipath fading effect arises from the fact that signals received at the receiver are often the superpositions of replicas of the signals arriving from multiple propagation paths adding up either constructively or destructively at the receiver. Thus, the signal strength may fluctuate amplitude and phase distortion. These effects can be mitigated using effective transmit and receive diversity techniques to exploit the diversity in time, frequency and space achieving what is called diversity gain.

Spatial diversity can be exploited by using multiple antennas either at the transmitter or the receiver or both. Spatial diversity gains can be achieved with either precoding at the transmitter or signal combining at the destination. Three different scenarios exist, namely, single-input multiple-output (SIMO), multiple-input single-output (MISO), and multiple-input multiple-output (MIMO) systems. In single-input multiple-output (SIMO)the receiver is equipped with multiple antennas, so we can take advantage of spatial diversity at the receiver to enhance system performance. Different signal combining techniques exist to combine the signals received on multiple antennas such as: equal-gain combining (EGC), selection combining (SC), and maximal-ratio combining (MRC). In multiple-input single-output (MISO) the transmitter is equipped with multiple antennas, the data symbols can be distributed among the transmit antennas to exploit spatial diversity at the transmitter, while the receiver is equipped with a single antenna. Different signal processing techniques are employed based on the level of the channel state information (CSI) at the transmitter. In the case of full CSI, transmit beamforming is used. Antenna selection technique is employed when we have partial CSI at the transmitter. In case of total lack of CSI at the transmitter, space-time coding is used to exploit spatial diversity. In multiple-input multiple-output (MIMO) systems both the transmitter and the receiver are equipped with multiple antennas, allowing the system to exploit additional degrees of freedom through both both precoding at the transmitter and signal combining at the receiver. MIMO uses digital signal processing to combine the transmitted signals from multiple wireless paths to improve the quality of the received signal. Advances in theory on multiple-input multiple-output (MIMO) systems have made it desirable to embed multiple antennas on modern wireless transceivers, in order to achieve spatial diversity gains. However, some wireless devices are limited in size, cost and energy e.g., sensor networks or cellular phones, making it impractical to place multiple antennas on a single terminal. A desirable and promising alternative would be using cooperation between nodes in the network to form a distributed antenna system. This is achieved by the so-called cooperative communications.

1.1 Motivation and Contribution

Cooperative diversity has received great deal of attention by researchers and technology developers during the past decade as a promising solution for the deteriorated performance in high-capacity demanded mobile wireless communications systems. Moreover, cooperative communication has the potential to reduce power consumption and is expected to be included as a feature in the fifth-generation (5G) standards. The basic idea of cooperative diversity is that we don't only use the direct transmission from the source to the destination, but we also use other intermediate nodes to enhance the diversity by relaying the source signal to the destination. In cooperative diversity networks two main relaying protocols have been studied thoroughly: amplify-and-forward and decode-and-forward. In the amplify-and-forward (AF) scheme the relaying nodes receive the source message, amplify it and then transmit it to the destination node without decoding the message, and thus the relays are called non-regenerative relays. In the decode-and-forward (DF) scheme, each relay decodes the received information from the source and then generates a new message. The relay then forwards the new message to the destination. Relay selection schemes have been introduced recently to enhance the inefficient utilization of the channel resources in regular cooperative diversity networks where all relaying nodes are required to forward the source's signal to the destination node. There are different criteria upon which the relays are selected to forward the source's signal. One of the relay strategies that have been introduced in recent years is the best-relay selection scheme. In this scheme only the best relay in terms of channel conditions is allowed to forward the source's signal to the destination. This scheme has been shown to efficiently utilize the channel resources while achieving the same diversity order as regular cooperative diversity networks.

1.2 Organization of the thesis

The remainder of the thesis is organized as follows. Chapter 2 presents a detailed review on the related works that form the foundation of this thesis. In Chapter 3, we study the best-relay selection scheme. Finally some conclusions are drawn in Chapter 3.6.

CHAPTER 2

TECHNOLOGIES OVERVIEW AND STATE-OF-THE-ART

2.1 Cooperative Diversity Networks Overview

Cooperative communications refer to systems or techniques in which users transmit each others messages to the destination. In most cases, cooperative transmissions are done over two phases. The first phase is the coordination or broadcasting phase, in which the users exchange their own source signals with each other and/or the destination. The second phase is the cooperation or forwarding phase. In this phase the users retransmit the messages to the destination. A basic cooperation system consists of two users transmitting to a common destination, as illustrated in Fig. 2.1. One of the two users acts as the source while the other user serves as the relay. In the broadcasting phase (i.e., Phase I), the source user broadcasts its data to both the relay and the destination. In the forwarding phase (i.e., Phase II), the relay forwards the sources data to the destination. The two users may interchange their roles as source and relay at different instants in time.

The basic idea of cooperative diversity is that we don't only use the direct transmission from the source to the destination, but we also use other intermediate nodes to enhance the diversity by relaying the source signal to the destination. There are two main advantages of this technology; the low transmit Radio Frequency (RF) power requirements, and the spatial diversity gain [3], [8].

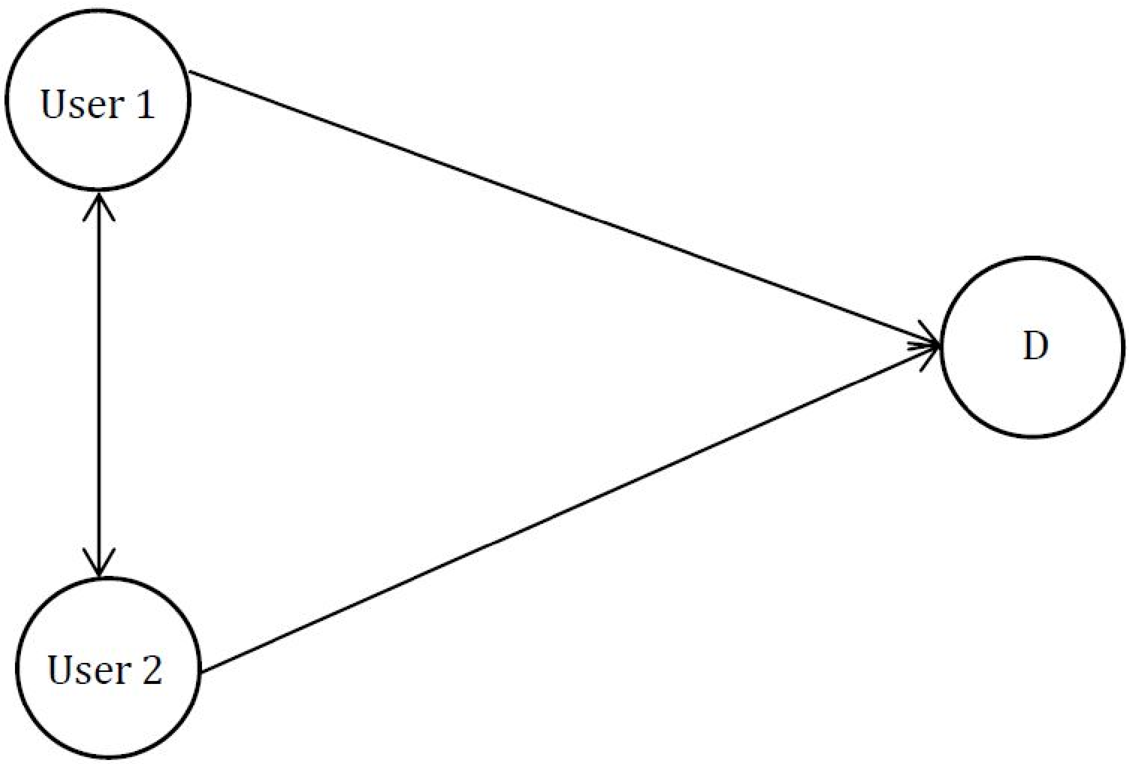

Figure 2.1. Illustration of the cooperative-diversity network

2.2 Fixed Relaying Techniques

In fixed relaying schemes all the relays in the system will forward the source message to the destination without considering the channel conditions. Many cooperation strategies have been proposed in the literature based on different relaying techniques. The most widely studied relaying techniques are: decode-and-forward (DF) and amplify-and-forward (AF).

2.2.1 Amplify and Forward Relaying Scheme

To enable cooperation among users, different relay technology can be employed depending on the relative user location, channel conditions, and transceiver complexity. In cooperative diversity networks two main relaying protocols have been studied thoroughly: amplify-and-forward and decode-and-forward [3]. In the amplify-and-forward (AF) scheme the relaying nodes receive the source message, amplify it and then transmit it to the destination node without decoding the message, and thus the relays are called non-regenerative relays This scheme is often used when the relay has limited computing time/power available or the time delay, caused by the relay to decode and encode the message, has to be minimized. In this scheme the source transmits its signal in the broadcasting phase to the destination and the relay, the received signals are given by:

$$y_{s,d} = \sqrt{E_s} h_{s,d} x + \eta_{s,d} \tag{2.2.1}$$

$$y_{s,r} = \sqrt{E_s} h_{s,r} x + \eta_{s,r} \tag{2.2.2}$$

where $x, y_{s,d}, y_{s,r}$ denote the (unit energy) transmitted signal and the received signals at the destination and relaying node respectively. $h_{s,d}$ and $h_{s,r}$ are the channel coefficients of the source-destination and source-relay channels, including the effects of shadowing, channel loss and fading. E_s is the average energy transmitted in a single time slot. Assuming all the time slots have unit durations then E_s can be considered as the transmission power. $\eta_{s,d}$

and $\eta_{s,r}$ are additive circularly symmetric white gaussian noise with variances $N_{s,d}$ and $N_{s,r}$ respectively.

In Phase II, the forwarding phase, the relay scales the received signal in eq.2.2.9 to yield a normalized transmit factor. The relay multiplies the received signal $y_{s,r}$ by the gain G, which is the reciprocal of the normalization factor and is given as:

$$G = \frac{1}{\sqrt{E_s \mid h_{s,r}^2 \mid + N_{s,r}}} \tag{2.2.3}$$

The signal transmitted from the relay is

$$\begin{aligned} x_r &= G y_{s,r} \\ &= \frac{\sqrt{E_s} h_{s,r} x + \eta_{s,r}}{\sqrt{E_s \mid h_{s,r}^2 \mid + N_{s,r}}} \end{aligned} \tag{2.2.4}$$

It is clear the gain G depends on the source-relay channel coefficient $h_{s,r}$ and therefore it changes in different transmission intervals. That's why this scheme is referred to as the variable-gain AF relaying scheme.

The signal received at the destination on the relay-destination link can be expressed as:

$$\begin{aligned} y_{r,d} &= \sqrt{E_s} h_{r,d} x_r + \eta_{r,d} \\ &= \sqrt{\frac{E_s E_r}{E_s \mid h_{s,r}^2 \mid + N_{s,r}}} h_{s,r} h_{r,d} x + \sqrt{\frac{E_s}{E_s \mid h_{s,r}^2 \mid + N_{s,r}}} h_{r,d} \eta_{s,r} + \eta_{r,d} \end{aligned} \tag{2.2.5}$$

At the destination the two signals received on the source-destination link, $y_{s,d}$, and on the relay-destination link, $y_{r,d}$, are combined using any of the different signal combining techniques discussed in Chapter 1. We will consider the case where MRC is used at the destination, the combined signal at the destination can thus be given as:

$$y_d = y_{s,d} + y_{r,d} \tag{2.2.6}$$

and the effective SNR is given as:

$$\gamma = \gamma_{s,d} + \frac{\gamma_{s,r} \gamma r, d}{\gamma_{s,r} + \gamma_{r,d} + 1} \tag{2.2.7}$$

2.2.2 Decode-and-Forward Relaying Scheme

In the decode-and-forward (DF) scheme, each relay decodes the received information from the source and then generates a new message. The relay then forwards the new message to the destination. That is why this scheme is also called regenerative relaying scheme. In this scheme, in Phase I, broadcasting phase, the source broadcasts a message to the destination and the relays. The relays regenerate the same message and forwards it to the destination in phase II, forwarding phase. The signals received by the destination and a relaying node after phase I are given by

$$y_{s,d} = \sqrt{E_s} h_{s,d} x + \eta_{s,d} \tag{2.2.8}$$

$$y_{s,r} = \sqrt{E_s} h_{s,r} x + \eta_{s,r} \tag{2.2.9}$$

The relay then decodes the source signal, the decoding is successful if the transmission rate is less than the capacity of the source-relay link, which is given by

$$C_{s,r} = log_2(1 + \gamma_{s,r}) \tag{2.2.10}$$

where $C_{s,r}$ is the capacity in bits per channel use, $\gamma_{s,r}$ is the SNR on the source-relay link. Assuming that the desired average end-to-end rate is R, and since the codeword x is transmitted twice throughout the transmissions process then it must be encoded with rate $2R$. The relay decodes the source message correctly when $2R \leq C_{s,r}$. The relay re-encodes the source message using the same codeword such that $x_r = x$ and retransmits it to the destination in Phase II. The signal received at the destination from the relay, $y_{r,d}$ can be given as

$$y_{r,d} = \sqrt{E_s} h_{r,d} x + \eta_{r,d} \tag{2.2.11}$$

Assuming a system containing one relay, the destination will then receive two copies of the source message one on the direct link between the source and the destination and the other copy from the relay. At the destination, if no diversity combining is applied then the destination only considers the signal received from the relay, and in that case the rate of the codeword transmitted over both the source-relay and relay-destination links is bounded by the capacity of both links,

$$2R \leq \min\{log_2(1+\gamma_{s,r}), log_2(1+\gamma_{r,d})\} \tag{2.2.12}$$

Hence, the average end-to-end achievable rate is given as

$$C = \frac{1}{2}\min\{log_2(1+\gamma_{s,r}), log_2(1+\gamma_{r,d})\} \tag{2.2.13}$$

In the case of using diversity combining the two signals received at the destination from the source and the relay can then be combined at the destination using any of the different signal combining techniques discussed in Chapter 1, Assuming MRC at the destination, the total received signal at the destination from both links can be given as

$$y_d = y_{s,d} + y_{r,d} \tag{2.2.14}$$

and the SNR at the output of the MRC is given by

$$\gamma = \gamma_{s,d} + \gamma_{r,d} = \frac{E_s \mid h_{s,d} \mid^2}{\sigma_d^2} + \frac{E_r \mid h_{r,d} \mid^2}{\sigma_d^2} \tag{2.2.15}$$

The achievable rate in Phase II is given by

$$\log_2(1+\gamma_{s,d}+\gamma_{r,d}) \tag{2.2.16}$$

But since the relay must successfully decode the source message in Phase I, the rate transmitted by the source must by less than the capacity of the source-relay link, therefore the maximum achievable end-to-end rate is given by

$$C = \frac{1}{2}\min\{log_2(1+\gamma_{s,r}), log_2(1+\gamma_{s,r}+\gamma_{r,d})\} \tag{2.2.17}$$

Outage happens when $R > C$, thus in the first case when no diversity combining is used, the outage probability is given by

$$\begin{aligned} P_{out} &= Pr(\min\{log_2(1+\gamma_{s,r}), log_2(1+\gamma_{r,d})\} < 2R) \\ &= 1 - Pr(\min\{log_2(1+\gamma_{s,r}), log_2(1+\gamma_{r,d})\} \geq 2R) \\ &= 1 - Pr(log_2(1+\gamma_{s,r}) \geq 2R, log_2(1+\gamma_{r,d}) \geq 2R) \end{aligned} \tag{2.2.18}$$

Considering the Rayleigh fading scenario, where $h_{s,r}$, $h_{r,d}$ and $h_{s,d}$ are independent independent circularly symmetric complex Gaussian random variables, and $\gamma_{s,r}$, $\gamma_{r,d}$ and $\gamma_{s,d}$ are exponentially distributed with mean
$\overline{\gamma}_{s,r} = \mathbf{E}(h_{s,r})E_s/N_0$, $\overline{\gamma}_{r,d} = \mathbf{E}(h_{r,d})E_r/N_0$, and $\overline{\gamma}_{s,d} = \mathbf{E}(h_{s,d})E_s/N_0$,
respectively. Then the outage probability can be given as

$$\begin{aligned} P_{out} &= 1 - Pr(\gamma_{s,r} \geq 2^{2R} - 1)Pr(\gamma_{r,d} \geq 2^{2R} - 1) \\ &= 1 - \exp(-\frac{2^{2R}-1}{\overline{\gamma}_{s,r}}) \exp(-\frac{2^{2R}-1}{\overline{\gamma}_{r,d}}). \end{aligned} \tag{2.2.19}$$

In the case of using diversity combining, MRC in our case, the outage probability of the DF relaying scheme can be given as

$$\begin{aligned} P_{out} &= Pr(\frac{1}{2}\min\{log_2(1+\gamma_{s,r}), log_2(1+\gamma_{s,d}+\gamma_{r,d})\} < R) \\ &= Pr(\frac{1}{2}log_2(1+\gamma_{s,r}) < R)) + Pr(\frac{1}{2}\{log_2(1+\gamma_{s,r}) \geq R))Pr(\frac{1}{2}log_2(1+\gamma_{s,d}+\gamma_{r,d}) < R)) \\ &= Pr(\gamma_{s,r} < 2^{2R}-1) + Pr(\gamma_{s,r} \geq 2^{2R}-1)Pr(\gamma_{s,d}+\gamma_{r,d} < 2^{2R}-1)) \end{aligned} \tag{2.2.20}$$

Assuming Rayleigh fading, the outage probability is given as

$$P_{out} = 1 - \exp(-\frac{2^{2R}-1}{\overline{\gamma}_{s,r}}) + \exp(-\frac{2^{2R}-1}{\overline{\gamma}_{s,r}})Pr(\gamma_{s,d}+\gamma_{r,d} < 2^{2R}-1) \tag{2.2.21}$$

Disadvantages of Fixed Relaying Techniques

In relay-based fixed cooperation, the advantages of cooperative diversity come at the expense of the spectral efficiency due to two main reasons:
(i) each relay cannot receive information from the source and transmit to the destination simultaneously in same frequency band (i.e., half-duplex), resulting in two transmission stages from the source to the destination
(ii) the source and relays must transmit on orthogonal channels at either frequency or time

domain to avoid interfering with each other [3] .[1] Techniques like beamforming [9] , distributed space-time coding (D-STC) [3], and incremental-relaying [8] have been used to alleviate such spectral efficiency deterioration.

2.2.3 Transmit Beamforming with Fixed Relaying Techniques

A cooperative system with multiple relays resembles a distributed antenna array, in such case we can use MISO and MIMO transmission schemes that were represented in chapter 1. In general, when using beamforming in systems with a transmitter array of M antennas, the transmissions from those antennas are designed to add coherently at the receiver. Using this technique results in improvement in the SNR by a factor of M, and enhances the mutual information over systems with single-element antennas [9]. The improvements achieved using trasmit beamforming requires the accurate knowledge of the channel to the intended receiver at the transmitter

In cooperative systems with multiple relays, those relays resembles a virtual distributed antenna array. Therefore, with the knowledge of the channel state information (CSI) at the relays, the source and a relay can adjust the phase of their transmissions relying on their knowledge of the channel state information (CSI) so that the two replicas add up at the destination node. This is called distributed transmit beamforming, and can be applied on both AF and DF relaying techniques. In AF relaying, assuming the perfect knowledge of both the source-to-relay and relay-to-destination channels at the relays. In Phase I the source broadcasts its signal to the relays and the destination. The relays normalize the received signal as in regular AF, and then multiplies it with a complex beamforming coefficient. The relays then forward the signal to the destination. With the proper selection of the beamforming coefficient, phase coherent transmission can be achieved. When applying transmit beamforming with DF relaying, the relays decode the source message first

[1] In such cooperative networks, with M relaying nodes, the information transmission is performed over $M+1$ orthogonal channels. This results in system spectral efficiency reduction by $M+1$.

and then forward the re-encoded message coherently to the destination. If error-detection is performed at the relays and only relays that had successfully decoded the source message can forward the message to the destination, then the beamforming coefficient takes only the relay-to-destination channel in consideration. If n error-detection techniques are applied at the relays, then the probability of error at the relays must be taken into consideration when choosing the beamforming coefficient. In [1] and [2], the authors inspired by the results in [9] presented an information theoretic model for cooperative communication network taking advantage of beamforming. The results of their analysis show that the net effects are higher data rates, at a given power level, as compared to non-cooperative strategy; or if keeping the same data rate as can achieved by the non-cooperative strategy then the required transmit power is reduced and hence increasing the mobile battery life.

2.2.4 Distributed Space-Time Coding (DSTC)

Using transmit beamforming with relaying techniques has shown to enhance the performance of such techniques. But the drawback of using transmit beamforming is that at least channel phase information must be available at the relays which is not always practical. Space-time coding can be used at the transmitter without the knowledge of the CSI. Many authors have examined space-time codes in literature [10], [11], and [12]. In cooperative diversity networks we use a class of space-time coding called distributed space-time coding (DSTC) since the antennas belonging to each relay in the network are located away from eachother. cooperative relaying with DSTC operate in the same manner as the regular fixed repetition cooperative diversity techniques discusses in sections 2.2.1 and 2.2.2, except that the relays will transmit simultaneously on the same subchannel using a designed space-time code, thus enhancing the bandwidth efficiency compared to regular fixed repetition relaying. The use of DSTC in cooperative networks to achieve spatial diversity was first studied in [3].

Distributed Space-Time Coding (DSTC) can be used with both AF and DF. In AF based cooperative networks, DSTC is applied at the relays to achieve spatial diversity gain without the knowledge of CSI at the relays. Laneman et al. studied DSTC with DF relaying technique in [3]. The authors showed that by using space-time coding a considerable improvement in performance could be reached as all relays can now transmit on the same subchannel during same time slot; although at the expense of higher complexity at the decoder. Both beamforming and space-time coding schemes come with increased transceivers complexity in terms of hardware and time computation and hence increased power consumption.

2.3 Opportunistic Cooperative Relaying

The drawbacks of regular fixed relaying that was stated in section 2.2.2, and the increased transceivers complexity accompanied with implementing techniques like transmit beamforming and distributed space-time coding made it required from researchers to find new techniques and protocols to overcome such drawbacks. Opportunistic relaying was introduced through selection relaying and incremental relaying to decrease the complexity and cost of transceivers while improving the spectral efficiency.

2.3.1 Incremental Relaying

In the incremental-relaying strategy [8], the relaying process is restricted to pre-specified conditions this results in saving the channels. This is done by using limited feedback from the destination which determines the action to be taken by the relays whether to forward the source's message if the feedback indicates the failure of the transmission on the direct link or to do nothing in the case of the success of the direct transmission.

The idea of the incremental relaying protocols is similar to that of hybrid automatic-repeat-request (ARQ) when viewed in a context involving relaying nodes. In phase I the source broadcasts its signal to the destination and the relay. The source and relay then listens for a feedback from the destination. The destination broadcasts a feedback bit, either ACK, i.e. acknowledge, or NACK, i.e. negative acknowledge, depending on the success or failure of the direct transmission. If the SNR of the source-destination channel is sufficiently high this results in a successful transmission of the source signal on the direct link. The feedback broadcasted from the destination will indicate the success of the transmission and the relay will do nothing. In the case when the source-destination link signal-to-noise ratio (SNR) is not high enough, the feedback broadcasted from the destination requests that the relay re-sends the source signal to the destination. The relay will forward the source signal in phase II to the destination the combines both messages from the direct link and the indirect link using maximum ratio combining (MRC) or any other combining technique [8].

Incremental relaying can be applied with AF or DF cooperative networks. In incremental amplify-and-forward relaying scheme, in Phase II if the feedback from the destination indicates the failure of the direct transmission,the relay will then amplify the source signal it received in phase I and then send it to destination in Phase II. In incremental decode-and-forward relaying scheme, the relay first detects the source signal and in the case of the failure of the direct transmission it will re-encode it and forwards it to the destination.

The main advantage of incremental-relaying is that it saves the resources of the channel and only uses them when necessary. It was shown in [8] and [**?**] that incremental relaying achieve high spatial diversity and higher achievable rate compared to regular fixed cooperative networks.

2.3.2 Selection Relaying

In the previous sections we studied fixed cooperative relaying schemes in which a relay or multiple relays will forward the source signal to a destination regardless of the channel conditions and whether they successfully decoded the source signal or not in the case of decode-and-forward relaying scheme. We then discussed two techniques that has been used in literature to enhance spectral efficiency; beamforming and distributed space-time coding. Then we discussed the incremental relaying schemes in which the relay is required to forward the source signal only if the destination doesn't receive the source signal correctly on the direct transmission. That's why incremental relaying is considered an opportunistic relaying scheme.

Another opportunistic relaying scheme is selection relaying. In selection relaying a pre-defined criterion is tested at the relaying nodes, and depending on it the relays or a subset of them will forward the source signal. Selection relaying has been studied intensively in literature [4], [8], [14], [17], [18], [26], [27], and [19]. Among the earliest proposed selection schemes are the ones reported in [4], [8]. In [4], the authors proposed a nearest relay selection criterion that is based on selecting the relay nearest to the source or to the destination based on either the physical distance or the pathloss. The authors in [4] considered their scheme in a cellular network and provided performance analysis in terms of system coverage for a pre-specified SNR under different scenarios of nearest distance and pathloss criteria. The authors in [] chose the geographic position as their selection criterion. In [8], the authors studied a relay selection scheme for DF relay cooperative network where a pre-chosen relay cooperates only if its source-relay channel gain magnitude is above a certain threshold. In this case the relay does not have to participate in the cooperative transmission if its conditions do not meet the selection criterion. Specifically in the selection DF relaying scheme, the source can choose to retransmit its signal to the destination itself if the relay was not able to decode the source signal successfully in Phase I. The source can infer whether the relay successfully decoded its message or not through the knowledge of the CSI on the source-relay link. If the measured $h_{s,r}^2$ is below a certain threshold then the relay doesn't forward the message to the destination, if it is higher than that threshold then the relay will forward the source signal to the destination. The destination combines both signals using MRC. In the case of selection AF relaying scheme, the relay will amplify the source signal before forwarding it to the destination. Outage performance analysis of the proposed scheme [8] was provided assuming Rayleigh channel fading, with relay nodes operating in the half-duplex mode. The authors showed that the selection relaying enables the cooperating nodes to exploit full spatial diversity compared to fixed relaying. For the case of selection DF relaying, the effective SNR at the output of the MRC at the destination is be given by

$$\gamma_{eff} = \begin{cases} 2\gamma_{s,d}, & if \gamma_{s,r} < \gamma_{th} \\ \gamma_{s,d} + \gamma_{r,d}, & if \gamma_{s,r} \geq \gamma_{th} \end{cases}, \tag{2.3.1}$$

where $\gamma_{th} = 2^{2R} - 1$ and the achievable end-to-end rate of the selection DF scheme is given by

$$C = \begin{cases} \frac{1}{2}\log_2(1 + 2\gamma_{s,d}), & if \gamma_{s,r} < \gamma_{th} \\ \frac{1}{2}\log_2(\gamma_{s,d} + \gamma_{r,d}), & if \gamma_{s,r} \geq \gamma_{th} \end{cases}, \tag{2.3.2}$$

from which the outage probability can be computed as

$$P_{out} = Pr(\gamma_{s,r} < \gamma_{th})Pr(2\gamma_{s,d} < \gamma_{th}) + Pr(\gamma_{s,r} \geq \gamma_{th})Pr(\gamma_{s,d} + \gamma_{r,d} < \gamma_{th}) \tag{2.3.3}$$

The authors in [16] assumed the DF system model in [8], in which a decoding set C, out of M total relays, containing the relays that fully decode the source message based on pre-specified channel conditions, is selected to forward the message to the destination. They derived closed-form expressions for the mutual information outage probability of the system considering MRC combining at the destination. The authors in [16] demonstrated that the outage performance doesn't improve with increasing the number of participating relays.

In [26], a scaled-SNR-based selection combining scheme is proposed where a deterministic scale factor (β) is used to incorporate the effect of the source-to-relay link in selecting between the direct link and the indirect link for transmission. The authors derived a closed-form for the end-to-end Symbol error probability (SEP) of this scheme for Binary Phase Shift Keying (BPSK) signaling and studied the relation between the scale factor (β) and SEP and identified an optimum value of (β) at which the SEP is minimum. In [27], the authors proposed smart relaying strategies for selection-combining-based decode-and-forward cooperative networks with a network consisting of source, single relay, and destination nodes in which the transmit power of the source and relay node are scaled by specific factors which are optimized at the relay to mitigate the error propagation problem and minimize the BER of the system.

It is clear from the previous analysis that the diversity gain allows the outage probability of the selection DF scheme to remain low even when the channel conditions on the source-relay link deteriorates, which is not the case with fixed DF scheme in which the outage probability increases with the increase in the distance between the source and the relay as the performance is limited by the source-relay conditions in that case. In summary, the selection relaying schemes utilize the CSI of the source-relay link to achieve higher bandwidth efficiency and full diversity order.

CHAPTER 3

ADAPTIVE DECODE-AND-FORWARD COOPERATIVE DIVERSITY NETWORKS WITH BEST-RELAY SELECTION

3.1 Overview

In chapter 2 we gave a literature review for cooperative diversity networks. We classified them into cooperative networks using fixed techniques and opportunistic techniques. In fixed relaying techniques all relaying nodes in the system are required to relay the source message to the destination regardless of the channel quality on the source-relay and relay-destination links. We reviewed two techniques that were used in literature to overcome the spectral inefficiency of regular fixed cooperative networks; transmit beamforming and distributed space-time coding. Then we reviewed two opportunistic techniques; incremental relaying and selection relaying. Both techniques require only partial CSI knowledge and offer performance improvements over fixed cooperative relaying. In incremental relaying a limited feedback from the destination determines the action to be taken by the relays whether or not to forward the source's message to the destination. In selection relaying the relays will forward the source message if they meet a certain predefined criterion. In this chapter we will study a relay-selection scheme in which only the best relay in the system is chosen to relay the source message. The best-relay selection scheme enhances the inefficient utilization of the channel resources in regular fixed cooperative diversity networks while achieving full diversity.

This chapter is organized as follows: We give a literature review for the best-relay selection scheme in section3.2, we present our system model in section 3.3 and provide performance analysis in section 3.4, finally we show our numerical analysis in section 3.5.

3.2 Best-Relay Selection Scheme

The best-relay selection scheme was introduced in [17]. In this scheme, after the source broadcasts its information to all the relays, the relay with the best instantaneous end-to-end channel conditions is selected to forward the source message to the destination. In DF relaying with best-relay selection, all the relays will try to decode the source's message that was broadcasted by the source in phase I; the broadcasting phase. If they successfully decode the source's message they act as candidate relays for selection. The best relay among the candidate relays in terms of channel conditions is selected to forward the source's message to the destination in phase II; the forwarding phase. The overhead in this scheme is minimal since no feedback is required and no prior knowledge of topology is required in selecting the best relay [17].

The authors in [17] proposed a simple signaling method by which the best relay is selected in a distributed manner, in which each relay sets a timer at the beginning of the transmission period. The timer is set to be inversely proportional to a parameter that is based on the instantaneous source to i-th relay, $S - R_i$, and i-th-relay to destination, $R_i - D$, channel gains, say h_i and g_i, respectively. The timer of the relay with the best end-to-end channel conditions will expire first (i.e., reduces to 0). The relay whose timer reduces to 0 first will then be the one that possesses the maximum selection criterion and the one selected to retransmit the source message. That relay broadcasts a short-duration flag packet, signaling its presence as the selected relay. All other relays, while waiting for their timer to reduce to zero (i.e., to expire), are in listening mode. As soon as they hear another relay to flag its presence to forward information (the best relay), they back off. This scheme doesn't require any knowledge of the topology or its estimation. Asymptotic analysis (at high SNR) reported in [17] showed that best-relay selection scheme achieves the same diversity order[1] as cooperative diversity using space-time-coding reported in [3].

In [18], the authors proposed opportunistic reactive and proactive relaying schemes where the relay selection is performed in distributed manner as well. In the reactive opportunistic relaying, after the source broadcasts its information to the relays, the best relay among the $R_i - D$ links, in terms of instantaneous signal strength, is chosen from a decoding set to retransmit the source message to the destination. In the proactive opportunistic relaying the best relay is selected, before the source transmits its message, in a distributed manner based on the instantaneous signal strength on both $S - R_i$ and $R_i - D$ links. While the selected relay broadcasts a flag packet notifying the rest of the network about its availability, the other relays will enter an idle mode even during the source transmission afterward. At this point, the source will transmits its message only to that selected relay. This way of relay selection in the proactive strategy makes it energy-efficient scheme since all relays except the best relay can enter an idle mode during both phases of cooperative transmission; i.e. broadcasting and forwarding phases. However, at the expense of extra CSI computation. The authors in [18] showed that both reactive and proactive opportunistic relaying selection strategies give same outage behavior as the decode-and-forward strategy where all potential relays participate in the cooperation process.

In [19] the authors derive an approximation to the outage probability of the best-relay selection at high SNRs for the case when only the best relay among the decoding set C will forward the source message to the destination. In [20], the authors considered the decode-and-forward cooperative diversity with best-relay selection scheme, proposed in [17], over independent non-identical Rayleigh fading channels and derived an exact closed-form expression for the probability density function (PDF) of the total SNR at the destination assuming MRC combining. Using that expression the authors derived exact closed-form

[1] Diversity order is defined as the number of independent channels available through which replicas of the same information signal can be transmitted simultaneously [35], [38, pp. 689-692].

expressions for the error probability and average channel capacity. In [21], the authors the authors extended their previous analysis in [20] and using that expression that they had derived for the PDF of the total SNR at the destination they derived an exact closed-form expression for the outage probability for the model under consideration that are valid for all SNR regions. In [22], the authors proposed a modified version of the best-relay selection scheme. In best-relay selection scheme, only the best relay forwards the source signal to the destination. But the selected best relay might be unavailable, in this cause the proposed scheme by the authors will choose the second best relay. If the second best relay is also unavailable then the third relay is selected or generally the N^{th} best relay among the decoding set C is selected to forward the source signal. The authors derive the closed-form expression for the probability density function (PDF) of the SNR of the signal received at the destination from the relay. Then the authors use the moment generating function (MGF) to derive the closed-form expression of the PDF of the SNR of the total received signal at the destination coming on both the direct and the indirect links. The authors use the PDF of the SNR to derive the symbol error probability, outage performance, and asymptotic error probability of the system. The best-relay selection scheme can be considered as a special case of this scheme when $N = 1$.

In [23] and [24] the authors proposed a new scheme that incorporates the best-relay selection strategy with the incremental relaying. In this scheme the best relay among M relays is selected to retransmit the source message to the destination only in the case when the feedback sent from the destination to the source indicates the failure of transmission on the direct link. In such a case, when the direct link fails, the two signals received at the destination are then combined using MRC. The authors consider the case of amplify-and-forward transmission and they analyze the performance of the systems in terms of the average spectral efficiency, the average BER, and the outage probability showing improvements in the spectral efficiency and outage probability and satisfying the required BER performance in the same time. In [25], the authors derive closed-form expressions for the bit error rate, outage probability and average channel capacity for the best-relay selection scheme with the incremental relaying in both amplify-and-forward and decode-and-forward transmissions.

3.3 System Model

We consider a dual-hop N_r-relay DF cooperative network as shown in Fig. 3.1, where a source node S is communicating with a destination node D via a potential relaying node R_i ($i = 1, 2, ..., N_r$), that is willing to cooperate and relay the source message to the destination. The links during the broadcasting stage, i.e. between S and R_i, and during the forwarding stage, i.e. between R_i and D, are assumed to experience fading with channel gains h_i and g_i, respectively. In addition, all these links are assumed to be independent and experience AWGN with zero mean and power spectral density (PSD) $\mathcal{S}_n = \mathcal{N}_0/2$ where $\mathcal{N}_0$ is a constant. In the general case of the dual-hop N_r-relay DF relaying cooperative wireless communication system, a time-division channel allocation scheme with $N_r + 1$ time slots is used to facilitate orthogonal transmission [8]. In the first time slot, the source broadcasts its signal to the set of N_r-relay nodes and the destination node; while the N_r relay nodes during the remaining N_r time slots the relays will, after decoding and encoding, forward the source information to the destination in some predetermined order over the N_r time slots. In the model we are considering in this thesis, no direct link between S and D is assumed to be available due to severe channel impairments conditions and hence the signal on the direct link between the source and destination nodes is assumed to be insignificant and is ignored in our analysis. This assumption is practical due to sever channel impairments conditions, which justifies cooperative communication. All nodes are also assumed to be single-antenna devices. Let the symbol transmitted from the source, during the first time slot, be denoted by $x(t)$ with average energy E_s; then the received signal from the source at a relay R_i, during the first time slot, denoted by $y_{S,R_i}(t)$), is given by

$$y_{S,R_i}(t) = h_i \sqrt{E_s} x(t) + n(t) \tag{3.3.1}$$

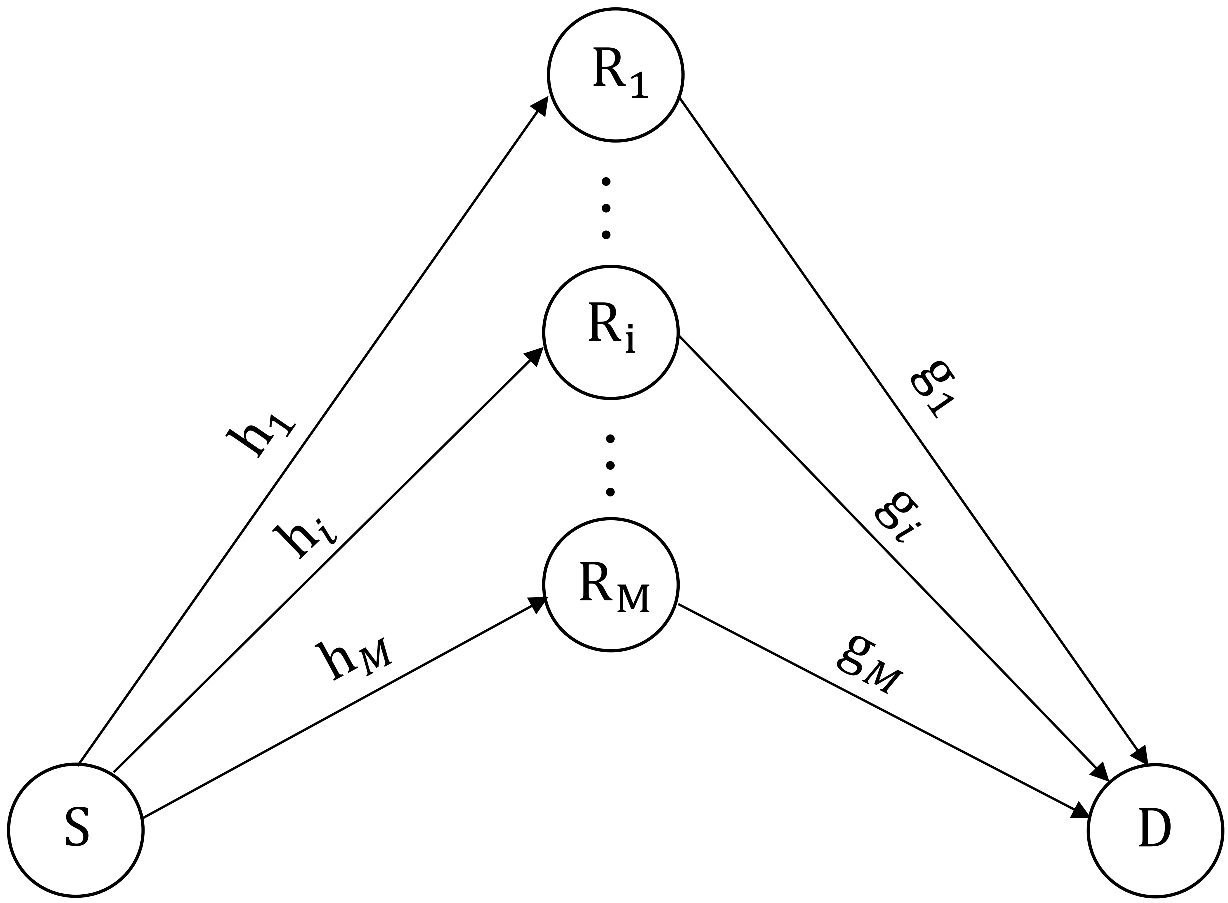

Figure 3.1. Illustration of the cooperative-diversity network

where $n(t)$ is the channel AWGN signal. We assume that the signal strength on the direct link is insignificant and hence the received signal from the source at the destination is absent. Therefore, the received signal at the destination from the relay, during the i-th time slot, is given by

$$y_{R_i,D}(t) = g_i \sqrt{E_s} x_{R_i}(t) + n(t) \tag{3.3.2}$$

where $x_{R_i}(t)$ is the signal transmitted from the relay to the destination, during the i-th time slot, after decoding and encoding. Let's denote the average signal-to-noise power ratio (SNR) per symbol at the output of the AWGN channel (input to the receiver) by γ_s. The SNR is defined as the ratio of the received signal power to the power of the noise within the bandwidth of the transmitted modulated signal. The SNR per symbol can be easily shown to be expressed as $\gamma_s = \frac{E_s}{\mathcal{N}_0}$, where $\mathcal{N}_0 = 2\mathcal{S}_n$ [36, pp. 172-173]. Given that all the links are experiencing fading with channel gains h_i, in the broadcasting stage, and g_i, in the forwarding stage, the instantaneous SNRs at the broadcasting and forwarding phases can be, respectively, given as $\gamma_i = h_i^2 \frac{E_s}{\mathcal{N}_0}$ and $\gamma_i' = g_i^2 \frac{E_s}{\mathcal{N}_0}$.

Within the whole set of N_r relays, $S_{N_r} = \{R_i, i = 1, ..., N_r\}$, in the cooperative model we define the decoding set, C, as the set of relays with the ability to fully decode the source message by achieving a certain minimum mutual information R in bit/sec/Hz. That is, if the channel condition between the source and the relay node is sufficiently good enough to allow for successful decoding, the relay node is said to belong to the decoding set C. The mutual information between the source and the i-th relay, in a dual-hop cooperative network, is given by [8]

$$I_i = \frac{1}{N_r + 1} \log_2(1 + \gamma_{h_i}) \tag{3.3.3}$$

The set of candidate relays in each transmission period can be represented by the decodable set $C = \{R_i : I_i \geq R\}$. Defining C in terms of an SNR threshold, γ_T, as $C = \{R_i : \gamma_i \geq \gamma_T\}$ can also provide the value of γ_T in terms of the mutual information R by solving $\frac{1}{N_r+1} \log_2(1 + \gamma_{h_i}) = R$, which results in $\gamma_T = 2^{(N_r+1)R} - 1$. For example, assuming $N_r = 1$ (e.g., in best relay selection) and $R = 1$ (e.g., in BPSK scheme) provides $\gamma_T = 3$.

There are time instances at which we do not have a best-relay. This can happen for many reasons; the deocdable set C might be empty, indicating that none of the source-relay links had good channel conditions leading to the failure of all relays to correctly decode the source message in phase I. The other reason for the absence of a best-relay is that the channel conditions on the relay-destination links for all the relays in the decodable set are not good enough for the destination to receive the message correctly on any of them. In this case one choice is that none of the relays forward the source-message and an ARQ can be used so that the source retransmits the same message in the next time instant. Another choice is to chose the relay that possesses the best conditions on the relay-destination link provided that it was selected in the decodable set in phase I.

3.4 Performance Analysis

In this thesis we study the outage performance of the adaptive decode-and-forward cooperative diversity networks with best-relay selection scheme. The outage probability is the probability that the signal-to-noise ratio falls below a certain threshold γ_0;

$$P_{out} = p(\gamma_s < \gamma_T) = \int_0^{\gamma_T} p_{\gamma_s}(\gamma) d\gamma \tag{3.4.1}$$

where γ_T typically specifies the minimum SNR required for acceptable performance.

The outage probability can also be defined with respect to the spectral efficiency R.

$$P_{out} = Pr(I_{DF} \leq R) \tag{3.4.2}$$

Where I_{DF} is the mutual information between the source and destination, using decode-and-forward cooperative diversity.

$$I_{DF} = \frac{1}{2}\log_2(1 + \max_{i\in C}(\gamma_{g_i})) \tag{3.4.3}$$

where $\gamma_{g_i} = \frac{g_i^2 E_s}{N_0}$ is the instantaneous SNR between the relay R_i and C.

Following the analysis in [16] and [21], and specific to our model, we can derive the probability density function (PDF) for the effective SNR at the destination as follows. The cooperative diversity network can be visualized as a system that has effectively N_r indirect paths between the source and the destination. We introduce a random variable y_i that will represent the equivalent instantaneous SNR at the destination. The random variable y_i will take account of the channels at both links (the source to the i^{th} relay link and the i^{th} relay to destination link).

The PDF of y_i is given as

$$f_{y_i}(x) = f_{y_i|R_i\ is\ off}(x)Pr(R_i \text{ is off}) + f_{y_i|R_i\ is\ on}(x)Pr(R_i \text{ is on}) \tag{3.4.4}$$

$Pr(R_i \text{ is off})$ is the probability that the relay R_i is not forwarding the source message, that means that relay R_i is not in the decodable set C, i.e. $I_i \le R$. This probability is given as

$$Pr(R_i \text{ is off}) = Pr(\gamma_{h_i} \le 2^{2R} - 1) = 1 - \exp\left(-\frac{2^{2R}-1}{\overline{\gamma}_{h_i}}\right) \tag{3.4.5}$$

where $\overline{\gamma}_{h_i} = \mathbf{E}(h_i^2 E_s/N_0)$ is average SNR between S and R_i and $\mathbf{E}(\bullet)$ is the statistical average operator.

When relay R_i is off, i.e. R_i is not in the decodable set C then R_i is not allowed to retransmit the source message to the destination. Therefore the SNR at the destination by R_i will be 0 so the conditional PDF $f_{y_i|R_i\ is\ off}(x)$ is given as

$$f_{y_i|R_i\ is\ off}(x) = \delta(x) \tag{3.4.6}$$

The Probability that the R_i is on is obviously equal to $1 - Pr(R_i\ is\ off)$. The R_i link is on when the relay R_i is in the decodable set C, this happens when $I_i > R$ or $\gamma_{h_i} > 2^{2R} - 1$.

Hence, The Probability that the R_i is on can be written as

$$Pr(R_i \text{ is on}) = Pr(\gamma_{h_i} > 2^{2R} - 1) = \exp\left(-\frac{2^{2R}-1}{\overline{\gamma}_{h_i}}\right) \tag{3.4.7}$$

The conditional PDF $f_{y_i|R_i\ is\ on}(x)$, is given as

$$f_{y_i|R_i\ is\ on}(x) = \frac{1}{\overline{\gamma}_{g_i}}\exp\left(-\frac{x}{\overline{\gamma}_{g_i}}\right), \quad x \geq 0 \tag{3.4.8}$$

where $\overline{\gamma}_{g_i} = \mathbf{E}(g_i^2 E_s/N_0)$ is the average SNR between R_i and D.

Hence, the PDF of y_i can be now be written as

$$f_{y_i}(x) = \left[1 - \exp\left(-\frac{2^{2R}-1}{\overline{\gamma}_{h_i}}\right)\right]\delta(x) + \left[\exp\left(-\frac{2^{2R}-1}{\overline{\gamma}_{h_i}}\right)\right]\left[\frac{1}{\overline{\gamma}_{g_i}}\exp\left(-\frac{x}{\overline{\gamma}_{g_i}}\right)\right], \quad x \geq 0 \tag{3.4.9}$$

Eq. 3.4.9 represents the unconditional PDF of the instantaneous SNR of the i^{th} indirect link ($S \rightarrow R_i \rightarrow C$).

The CDF of y_i can be easily found by integrating eq. 3.4.9, so $F_{y_i}(x)$ is given as

$$F_{y_i}(x) = 1 \ - \ \exp\left(-\frac{2^{2R}-1}{\overline{\gamma}_{h_i}}\right)\exp\left(-\frac{x}{\overline{\gamma}_{g_i}}\right) \tag{3.4.10}$$

We are interested in the maximum of the set of random variables y_i as only the best relay from the decodable set C is selected to forward the source message to the destination.

$$\begin{aligned} P_{out} &= Pr(\max_{i \in C} y_i \leq \gamma_{th}) \\ &= \prod_{i=1}^{N_r} Pr(y_i \leq \gamma_{th}) \\ &= \prod_{i=1}^{N_r} F_{y_i}(\gamma_{th}) \end{aligned} \tag{3.4.11}$$

Using the result in eq. 3.4.11 in eq. 3.4.10, the outage probability for our system is given as

$$P_{out} = \prod_{i=1}^{N_r}[1 \ - \ \exp\left(-\frac{2^{2R}-1}{\overline{\gamma}_{h_i}}\right)\exp\left(-\frac{\gamma_{th}}{\overline{\gamma}_{g_i}}\right)] \tag{3.4.12}$$

3.5 Numerical Analysis

In this section, we show the numerical results of the outage probability (P_{out}) for binary phase shift keying (BPSK) modulation using MATLAB to build a Monte-Carlo simulation. We assume the absence of a direct link between the source and destination nodes in our model. We plot the performance curve of the outage probability versus the SNR of the transmitted signal ($E_S/N_0 dB$) We compare the results obtained from the simulation with those found from our analytical analysis earlier in this thesis.

Fig. 3.2 shows the outage probability for R = 1 bit/sec/Hz of the best-relay selection adaptive decode-and-forward scheme. For R = 1 bit/sec/Hz, $\gamma_{th} = 2^{2R} - 1 = 3 = 4.771\ db$. The analytical results and the simulation results are in excellent agreement.

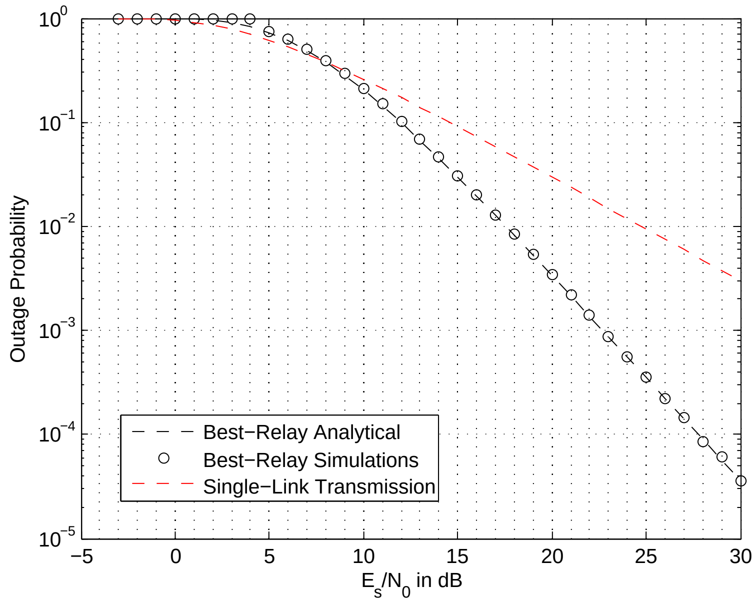

Figure 3.2. Outage performance for the Best-relay adaptive selection scheme over Rayleigh fading channels

Fig. 3.3 shows the probability of the correct reception of the source message at the destination versus the average SNR at $\gamma_{th} = 4.771\ db$. It is obvious that probability of correct reception increases rapidly at average SNR values above the threshold SNR. At high average SNR the probability is equal to one assuring the correct reception of the message at the destination.

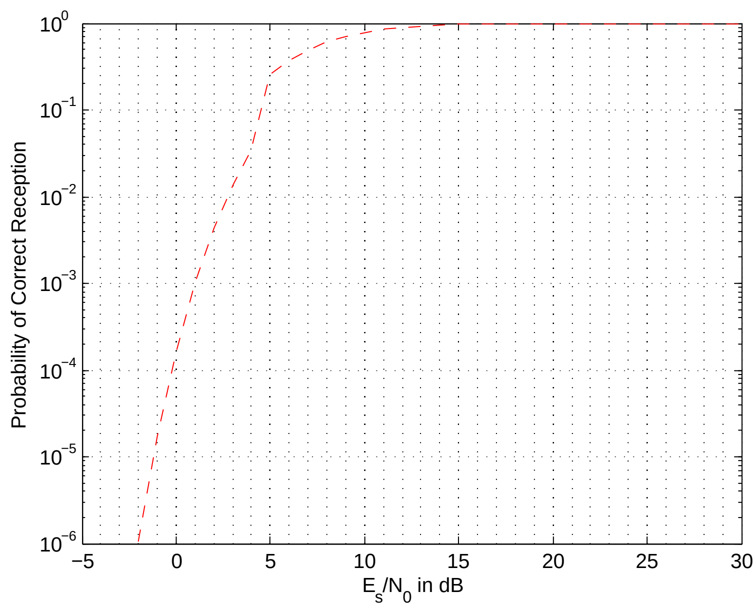

Figure 3.3. Outage performance for the Best-relay adaptive selection scheme over Rayleigh fading channels

3.6 Conclusion and Future Work

In this thesis the best-relay selection scheme for cooperative diversity networks is studied. The relay-selection scheme is based on the selection of the best relay for a dual-hop decode-and-forward cooperative diversity system under binary phase shift keying (BPSK) modulation over independent identical distributed Rayleigh fading channel with the absence of the direct link between the source and destination nodes.

For future work we will extend our analysis considering the error performance and the average channel capacity of the adaptive decode-and-forward network employing our system model. We will also consider multiple hop cooperative networks instead of the dual hop case studied in this thesis. We will also consider other modulation schemes as well. We will also study other relay selection schemes that employ selecting relays other than the one with the best end-to-end channel conditions in different SNR regions. We are looking into the case of the adaptive best-and-worse relay selection motivated by the study we have made based on the best relay selection in this thesis.

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