REPUBLIC OF TURKEY
YILDIZ TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

LINK ADAPTIVE RELAYING WITH VIRTUAL NOISE BASED DETECTION IN COOPERATIVE WIRELESS NETWORKS

AHMET BOZDAĞ

MSc. THESIS
DEPARTMENT OF ELECTRONICS AND COMMUNICATIONS ENGINEERING
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ADVISER
ASSIST. PROF. DR. HACI İLHAN

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ADVISOR

Asst. Prof. Dr. Hacı İLHAN

Yildiz Technical University

Co Advisor

Dr. Özgür ÖZDEMİR

Selçuk University

Jury Members

Asst. Prof. Dr. Hacı İLHAN

Yildiz Technical University ______________________

Asst. Prof. Dr. Tansal GÜÇLÜOĞLU

Yildiz Technical University ______________________

Assoc. Prof. Dr. Ender Mete EKŞİOĞLU

Istanbul Technical University ______________________

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Ahmet BOZDAĞ

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LIST OF SYMBOLS

β_{ij}	Complex fading coefficient between node i and j
d_{ij}	Normalized distance between node i and j
x_r	Detected symbol by the relay node.
x	Symbol transmitted by the source
y_{ij}	Received signal
σ^2	Variance of noise component
μ	Mean
E_s	Transmitted power
n_{ij}	Additive White Gaussian Noise component
n_v	Virtual noise component
N_0	Power spectral density of the noise
υ	Path loss coefficient
f_D	Doppler frequency
Υ_{ij}	Instantaneous SNR of channel links
γ_Σ	Output SNR
$\overline{\gamma}$	Average SNR
ε_{coop}	Event of cooperation error
ε_{prop}	Event of propagation error
$P(.)$	Probability of error propagation
$P\left(\varepsilon_{e2e,silent}\right)$	End to end bit error rate when relay silent
$P\left(\varepsilon_{e2e,active}\right)$	End to end bit error rate when relay active
α	Power factor coefficient
M	Number of branches
w_i	Weighting coefficient
Δf	Coherence bandwidth
$f(.)$	Probability density function
$F(.)$	Cumulative distribution function
$I_0(.)$	Modified Bessel function
$\Gamma(.)$	Gamma function
K	Rician factor

LIST OF ABBREVIATIONS

AF	Amplify and Forward
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
D	Destination
DF	Decode and Forward
E2E	End-to-End
EGC	Equal Gain Combining
LAR	Link Adaptive Relaying
LOS	Line of Sight
MIMO	Multiple Input Multiple Output
ML	Maximum Likelihood
MRC	Maximal Ratio Combining
PL	Piecewise - Linear
PSK	Phase Shift Keying
R	Relay
S	Source
SC	Selection Combining
SNR	Signal to Noise Ratio
SWC	Switched Combining
VN	Virtual Noise

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ABSTRACT

LINK ADAPTIVE RELAYING WITH VIRTUAL NOISE BASED DETECTION IN COOPERATIVE WIRELESS NETWORKS

Ahmet BOZDAĞ

Department of Electronics and Communications Engineering

MSc. Thesis

Adviser: Assist. Prof. Dr. Hacı İLHAN

Co-Adviser: Dr. Özgür ÖZDEMİR

Wireless cooperative communications has recently gained significant attention since it provides spatial diversity and performance gain over conventional systems by eliminating the requirement of locating physical antenna arrays at terminals. In this thesis, a scheme that combines link adaptive relaying (LAR) and virtual noise (VN) modeling based detection techniques which have been introduced in the literature to prevent performance degradation in decode and forward based cooperative wireless networks due to error propagation is proposed and its error performance is investigated for Nakagami-m and Rician fading channels. The communication protocol under consideration builds upon orthogonal decode-and-forward relaying where the source terminal communicates with the relay and destination in the first phase and the second phase is allocated for transmission of the estimated data block of the source from the relay to destination. It has been shown that the proposed system (LAR with VN) provides significant performance improvement in various situations with respect to the classcial LAR structures with MRC in which maximal ratio combining is employed at the destination.

Keywords: Cooperative diversity, error propagation, link adaptive relaying, virtual noise modeling

ÖZET

İŞBİRLİKLİ TELSİZ AĞLARDA SANAL GÜRÜLTÜYE DAYALI SEZİM İLE LİNK UYARLAMALI İLETİM

Ahmet BOZDAĞ

Elektronik ve Haberleşme Anabilim Dalı
Yüksek Lisans Tezi

Tez Danışmanı: Yard. Doç. Dr. Hacı İLHAN
Eş Danışman: Dr. Özgür ÖZDEMİR

İşbirlikli iletişim, terminallerde fiziksel anten dizileri konumlandırma ihtiyacını ortadan kaldırarak, anten çeşitlemesi ve performans kazancı sağladığı için son zamanlarda önemli ilgi görmüştür. Bu tezde, çöz ve ilet tabanlı işbirlikli telsiz ağlarda hata yayılımından kaynaklanan performans düşüşlerini azaltmak için literatürde sunulmuş olan link uyarlamalı aktarım (LAR) ve sanal gürültü (VN) modellemesine dayalı sezim tekniklerini birleştiren bir tasarım önerilmiş ve Nakagami-m ve Rician sönümlemeli kanallar için hata performansı incelenmiştir. Ele alınan iletişim protokolü, ilk fazda kaynak terminalinin röle ve hedef ile iletişim yaptığı ve ikinci fazın kaynağın kestirilmiş veri bloğunun iletimi için röleye tahsis edildiği, ortogonal çöz ve ilet aktarımına dayalıdır. Önerilen LAR ve VN tabanlı yöntemin birçok durumda hedefte en yüksek oran birleştirmesinin kullanıldığı klasik link uyarlamalı aktarım yapılarına göre önemli performans iyileşmesi sağladığı gösterilmiştir.

Anahtar Kelimeler: İşbirlikli çeşitleme, hata yayılımı, link uyarlamalı aktarma, sanal gürültü modeli

CHAPTER 1

INTRODUCTION

1.1 Literature Review

Wireless communication is one of the most useful and extremely demanded communication technology in terms of mobile access. Since its beginning, it has gone through various developmental phases to meet the ever increasing needs of its wide range of applications. Signal fading is one of the major degradation to meet the demands of new generation wireless communication networks for high data rate services due to multipath propagation. In wireless transmission, the signal quality suffers severe fluctuations due to effects of fading caused by multipath propagation. These effects cause random variations of channel quality in time, frequency, and space that make conventional wireline communication techniques too difficult to employ in the wireless environment. Despite numerous proposed solutions, high efficiency methods were never realized until the proposition of diversity techniques in the past two decades [1].

Diversity can be used to transmit the different samples of the identical signal via independent channels to minimize such effects [2]. There are several ways to perform diversity in a wireless transmission. One of the most well-known diversity technique is the spatial diversity which has been studied intensively in the context of point-to-point communications, where it is introduced by using the Multiple Input Multiple Output (MIMO) systems [3]. MIMO technology provides a significiant capacity increase by positioning multiple antennas at the transmitter and receiver nodes and it has an important role in combating with the fading which is seen as the most serious interference at radio communications systems. It has been shown in the literature that utilizing MIMO systems can significantly increase the system throughput and reliability [3]. Although the use of multiple antennas is especially suitable for base stations in cellular systems, it is not a practical approach for mobile units in terms of the complexity of size, cost and hardware. The model of cooperative diversity in wireless networks has been recently presented to get over this problem, and to take advantage from the performance enhancement introduced by MIMO systems [4], [5]. The spatial diversity gains inherent in multiuser wireless systems is used in cooperative communication systems without the need of multiple antennas at each node. In such a concept, when a terminal has information to transmit, it cooperates with other single-antenna terminals to forward its data to a specific destination. The cooperating nodes act as the relay for the source node.

The beginning of cooperative communication can be traced back to the work of Cover and El Gamal on the relay channel in 1979 [6]. Their relay channel model is shown in Figure 1.1.

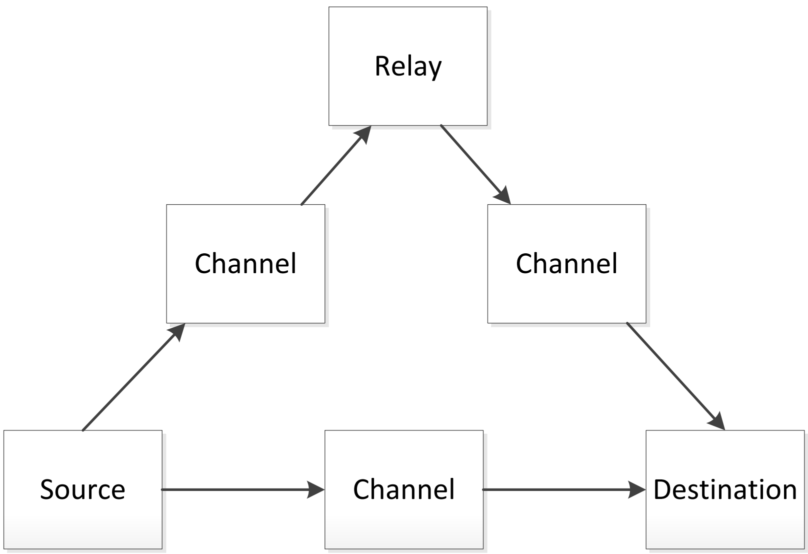

Figure 1. 1 Channel model

Their work was based on the analysis of the capacity of a three-node network consisting of a source, a relay, and a destination in which all nodes operate in the same band. In this work, an additive white Gaussian noise (AWGN) channel model is considered and it has been demonstrated that the capacity of the relay channel is better than that of direct link. Although, the main concept behind cooperative communication system from this pioneering work on relay channel in which the relay node is only used to help source, the motivation in cooperative networks is to mitigate performance degradation due to fading and improve the system flexibility by letting each terminal in the network not only transmit its own data but also relay information of other nodes.

Transmitting different samples of the same signal over essentially independent channels is a method by which transmit diversity could be implemented in wireless communications to solve the problems of fading due to multipath propagation. Especially, spatial diversity is composed by transmitting signals from different positions, thus allowing independently faded versions of the signal at the receiver.

Initial statement of the ideas behind cooperative communication is given in Figure 1.2, where the source and relay communicates with the same destination. The source and relay terminal has one antenna, so spatial diversity cannot be generated by using single terminal. However, it is possible for one terminal to receive the others signals due to the broadcast nature of wireless channel and it can send out some version of overheard information of other terminals along with its own data. This generates spatial diversity gain since the transmission from two terminals are statistically independent [7].

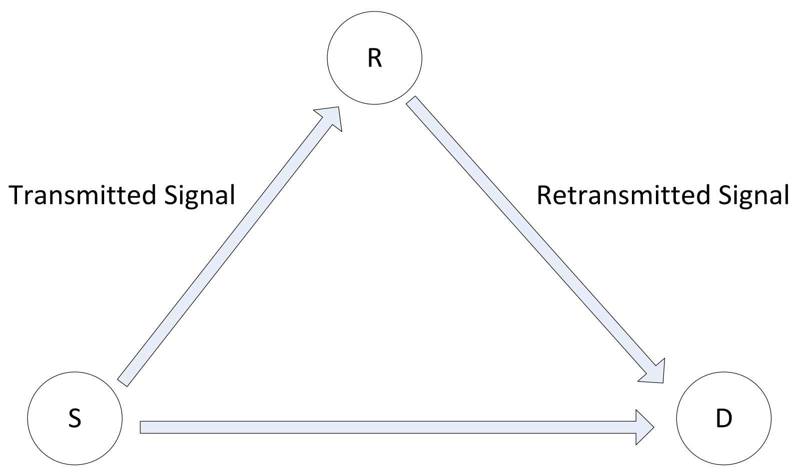

Figure 1. 2 Cooperative communication

In such a cooperative communication system which is based on the idea of assisting transmission of source to the destination with the other wireless nodes that exist in the transmission medium, detection and transmission techniques at relay nodes and combining mechanism at the destination are the distinctive system parameters. Different transfer methods can be defined based on the signal processing approach employed at the relay. One of them is the amplify-and-forward (AF) method, also known as analog relaying, where the source is forwarded to the destination after aplification process [5]. The main disadvantage of this method is forwarding the noise component at relay nodes. The second method, decode-and-forward (DF) which is also known as digital relaying is based on the principle of forwarding the source data to the destination after detection by the relay. The most important problem encountered in the DF based cooperative communication systems is the detection errors at relays and the transmission of erroneous packets to destination. There are some leading techniques such as maximum likelihood-based (ML) detection [8], [9], [10], logarithmic likelihood ratio (LLR) based transmission [11], [12], [13], selective relaying (SR) [14], [15], [16], cooperative maximal ratio combining (C-MRC) [17], link adaptive relaying (LAR) [18] and virtual noise (VN) based detection [19] in literature that can eliminate the degradation of diversity gain caused by error propagation. From them, LAR approach is based on the idea of scaling the relay power with a coefficient depending on the gain of the source-relay and relay-destination channels. In [18], performance of LAR approach is analyzed for different levels of channel state information maximal ratio combining (MRC) at destination. In [19], an approach based on the modeling of VN is analyzed for different communication scenarios. In [14], the error performance of the SR based system model is analyzed for Rayleigh fading model depending on various levels of channel state information at the relay.

1.2 Objective of the Thesis

In this thesis, a scheme that combines link adaptive relaying and virtual noise modeling based detection techniques to prevent performance degradation in decode and forward based cooperative wireless networks due to error propagation is proposed and its error performance is investigated for Nakagami-m fading channels.

This research is divided into five chapters: The first part is an overview of the literature. The general information about the wireless communication and the some leading techniques to eliminate the degradation of diversity gain are given in this chapter.

Chapter 2 focuses on the wireless communication, fading channels, diversity tecniques and combining methods. In this section, the concepts of multipath fading channels, diversity tecniques and combining methods are given for a clearer comprehension of the wireless communication methodology.

Chapter 3 introduces the cooperative communications and their forwarding protocols. Cooperative communication protocols such as amplify and forward (AF) and decode and forward (DF) are given in detail.

Chapter 4 provides the system and channel model.

Chapter 5 presents the simulation results which illustrate the potential advantages of the proposed combining techniques.

Lastly, Chapter 6 gives conclusions on our findings based on the results of the simulations.

In this thesis, one national conference paper is puplished at IEEE 21. Sinyal İşleme ve İletişim Uygulamaları Kurultayı and one international conference paper will be submitted.

1.3 Hypothesis

In this thesis, we examine the DF transmission protocols when used with detection techniques such as VN (Virtual Noise), MRC (Maximal Ratio Combining) and ML (Maximum Likelihood). The relay unit has the selective transfer structure which is used with LAR strategy. The all combination techniques are also studied with different positions of relay to investigate their effects on the error performance.

CHAPTER 2

WIRELESS COMMUNICATIONS

Wireless communication is one of the most dynamic areas in communication. While it has been a subject of study since the 1960s, the past decade has seen lots of research activities on wireless communication due to a conflux of several factors such as rising demand for wireless connection, advanced reliability, high-rate data transfer with cost efficiency and continuous improving from satellite transmission to the 4G for mobile communications.

There are two main argument of wireless communication that make the problem interesting and challenging. First is the time variation of the channel power attenuation due to the small-scale effect of multipath fading, as well as larger-scale effects like path loss via distance weakening. Second is the interference between wireless users communicating over the air [20].

In this section, multipath fading channels and diversity tecniques will be outlined for a clearer comprehension of the wireless communication methodology.

2.1 Multipath Fading Channels

In a wireless mobile system, a signal can travel from transmitter to receiver through multiple reflective paths which is also known as multipath propagation as demonsrated in Figure 2.1.

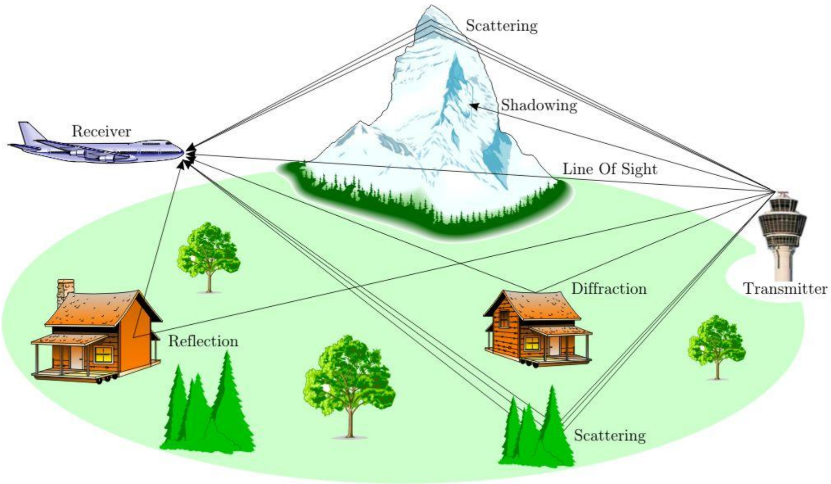

Figure 2. 1 Multipath propagation

The propagation channel changes with the operating environment. Electromagnetic waves in an environment endure scattering, reflection, and diffraction. A typical received signal include multiple components reflected off large objects like buildings that arrive with different phases and time delays.

Finally, the received signal consists of a combination of various variations of the transmitted signal. The main goal is to recover the transmitted signal at receiver efficiently. We present different classifications of multipath fading signal in the following.

2.1.1 Large Scale and Small Scale Fading

Effects of fading can be classified into two categories according to their time scales: large scale fading and small-scale fading. Small scale fading is on the order of milliseconds, while large-scale fading is on the order of seconds [21].

Large scale effects include attenuation related with distance and slow fading. Attenuation is a result of the inverse square law of electromagnetic radiation, signal absorption by transmission media, multiple reflections, and other effects. Slow fading is due to the land, buildings, and other obstacles that exist between the transmitter and receiver. Large scale fading is usually modeled as a log-normally distributed random variable.

Small scale effects are result of the scattering or reflections of the transmitted signals from surrounding objects. Small scale effects may trigger quick and large oscillations in signal strength. Small scale fading is modeled as a complex Gaussian random variable.

2.1.2 Flat and Frequency Selective Fading Channels

Signals propagating over wireless channels are subject to reflections, diffractions, and scattering effects. Transmitted signal can be exposed to different channel conditions and delays for different paths from the transmitter to the receiver as it leaves the transmitting antenna in all directions. Therefore, the transmitted signal arrive to the receiver as a superposition of scattered, nonuniformly interleaved, distinct strength signal replicas.

In flat fading, all frequency components of the received signal flutters simultaneously in the same proportion. If the channel has a constant gain and linear phase response over a bandwidth which is greater than the bandwidth of the transmitted signal, the received signal will utilize flat fading.

The channel causes frequency selective fading on the received signal if the channel has linear phase response over a bandwidth that is smaller than the bandwidth of the transmitted signal. Modeling the frequency selective fading is much difficult compared to flat fading, because each multipath signal must be modeled and the channel must be considered to be a linear filter. Signal undergoes frequency selective fading if: $B_s > B_c$ where B_S is the signal bandwidth and B_c is the coherence bandwidth of the channel and $T_S < \sigma_\tau$ where T_s is the reciprocal bandwidth and σ_τ rms delay spread.

2.1.3 Slow and Fast Fading Channels

Fast fading occurs if the channel impulse response changes rapidly within the symbol duration of the transmitted signal. It could also be defined as a situation where coherence time of the channel, which is the time duration over which two received signals have strong potential for amplitude correlation, is smaller than the symbol period of the transmitted signal.

Slow fading is caused due to the shadowing by mountains, buildings and other obstacles. In this case, the coherence time of the channel is larger than the delay of the channel.

In wideband systems, the coherence time is much larger than the signaling interval, and therefore differential perception over multiple symbols is possible. The coherence time is related to the Doppler spread by:

$$f_D \approx \frac{1}{(\Delta t)_c} \tag{2.1}$$

where Doppler spread is the maximum Doppler frequency spread obtained by the relative motion between the transmitting and receiving stations, and is only defined by the transmitting frequency and the speed of relative motion. In (2.1), f_D represents the Doppler frequency and $(\Delta t)_c$ is the coherence time.

2.1.4 Fading Statistical Models

There are several statistical models for characterizing the fading envelope of the received signal. Among them the Rayleigh model agrees very well with empirical data for multipath propagation where no line of sight (LOS) path exists between the transmitter and receiver antennas.

Other models are the Nakagami-q (Hoyt), the Nakagami-n (Rice) and Nakagami-m.The Nakagami-q is valid to satellite links and the Nakagami-n is valid to LOS paths of micro urban and suburban land mobile, and factory environments as well as to the dominant LOS path of satellite radio links. But on the other hand, the Nakagami-m is the most well rounded statistical model [22]. It can pattern a variety of fading environments, where it nearly approximates the Nakagami-q and the Nakagami-n models, and in special cases it has the Rayleigh and one sided Gaussian models.

2.1.4.1 Gaussian Distribution

The Gaussian distribution, also known as the normal distribution, is a commonly used model for the disribution of continuous variables. In the case of a single variable *x*, the probability density function of the Gaussian distribution [23] can be expressed in the form:

$$f(x \mid \mu, \sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[\frac{-(x-\mu)^2}{2\sigma^2}\right] \tag{2.2}$$

where μ is the mean and σ^2 is the variance.

The following is the plot of the Gaussian probability density function with different standart deviation of x when $\mu = 0$.

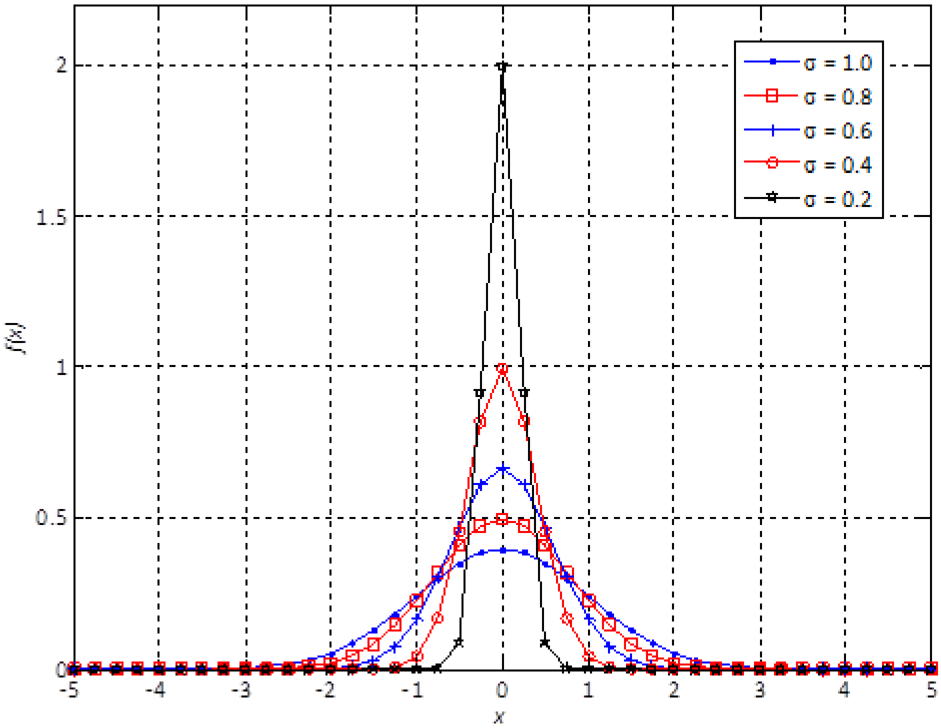

Figure 2. 2 Normal probability distribution when μ = 0

It is used in many areas of statistics such as study of the effects of measurement error and widely used as a model for random noise. The Gaussian function is a great approximation due to the its convenient mathematical properties and can be used to approximate many distributions occurring in nature.

2.1.4.2 Rayleigh Distribution

Rayleigh distribution is used to characterize the statistics of signals transmitted through multipath fading channels when there is no direct link between the transmitter and receiver. In mobile radio channels, the Rayleigh distribution is widely used to characterize the statistical time varying nature of the received envelope of a flat fading signal. The envelope of the two independent complex Gaussian noise signals is Rayleigh distributed. Figure 2.3 shows the various Rayleigh distributions.

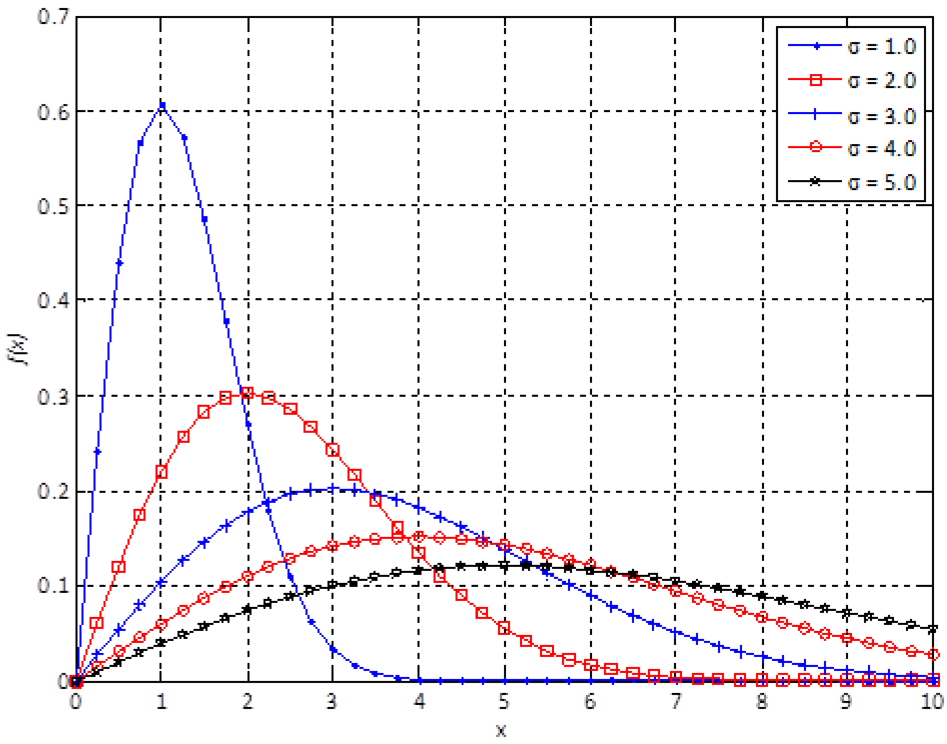

Figure 2. 3 Rayleigh distribution

Probability density function and cumulative distribution function of the Rayleigh distribution [23] can be expressed respectively by:

$$f(x) = \begin{cases} \dfrac{x}{\sigma^2} \exp\left(-\dfrac{x^2}{2\sigma^2}\right) & (0 \le x \le \infty) \\ 0 & (x < 0) \end{cases}, \tag{2.3}$$

$$F(x) = 1 - e^{-x^2/2\sigma^2} \quad x \in [0, \infty), \tag{2.4}$$

where σ^2 is the variance.

2.1.4.3 Rician Distribution

The Rician distribution, also known as the Rice distribution, is the probability distribution of the absolute value of a circular bivariate normal random variable with potentially non-zero mean. Rician distribution is observed when there exists a direct path between the transmitter and the receiver. Figure 2.4 shows the various Rician distributions.

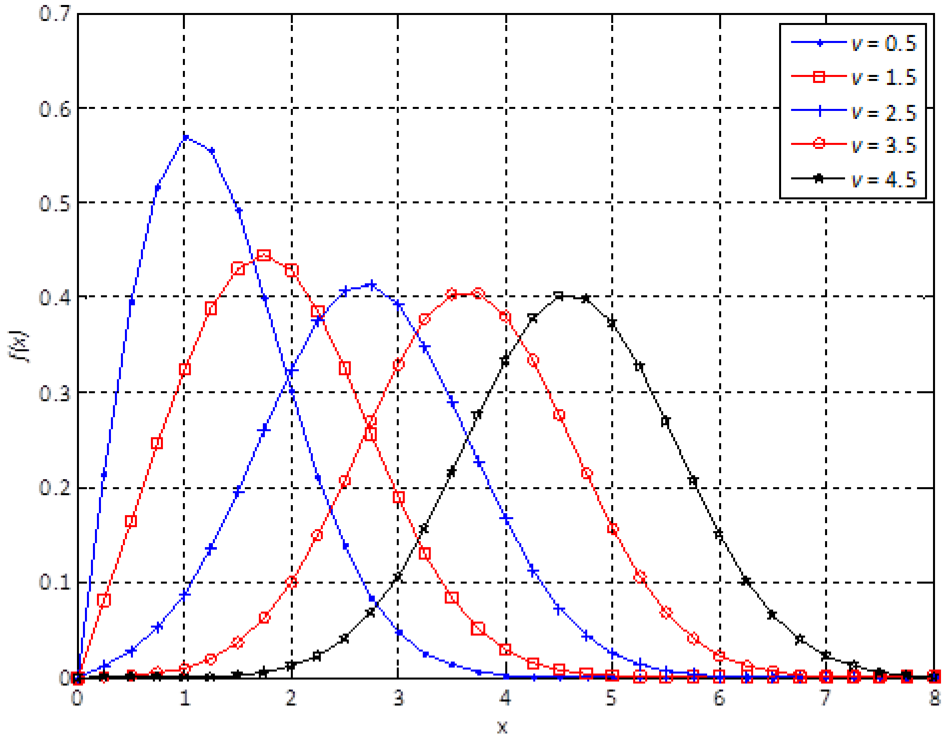

Figure 2. 4 Rician distribution when σ=1

Probability density function of Rician distribution does not have a simple form and not easy to work with. It has found limited feasibility in researchs. Probability density function and cumulative distribution function of the Rician distribution [23] can be expressed respectively in the form:

$$f(x|\nu,\sigma)=\frac{x}{\sigma^2}\exp\left(\frac{-\left(x^2+\nu^2\right)}{2\sigma^2}\right)\mathrm{I}_0\left(\frac{x\nu}{\sigma^2}\right)\quad \nu\geq 0\quad \sigma\geq 0, \tag{2.5}$$

$$F(x)=1-Q_1\left(\frac{\nu}{\sigma},\frac{x}{\sigma}\right). \tag{2.6}$$

where v is the distance between the reference point and the center of the bivariate distribution, $I_0(.)$ is the modified Bessel function of the first kind of order zero, and $Q_1(.\,,\,.)$ is the Q-function.

2.1.4.4 Nakagami Distribution

The density function of the envelope of the back scattered signal can be described in terms of the Nakagami distribution. The Nakagami model is used in modeling various propagation channels and it gives the best fit to outdoor mobile and indoor mobile multipath propagation. This has been supported by the study of Dersch et al [24], [25] where they give detailed derivation of the Nakagami-m distribution and show that it's appropriate for mobile channel modeling. The PDF of a Nakagami-m distributed random variable x [23] is given by:

$$f(x) = \frac{2m^m x^{2m-1}}{\Gamma(m)\Omega^m} \exp\left(-\frac{mx^2}{\Omega}\right) \qquad (2.7)$$

where $\Omega = E\{x^2\}$, $m = \Omega / E\{x^2 - \Omega^2\} \geq 0.5$ is the fading severity parameter, and $\Gamma(.)$ is the Gamma function. Note that Rayleigh distribution is obtained when m = 1.

2.2 Diversity Techniques

There are various techniques to reduce the effects of multipath fading. Possible techniques consists of the coding, equalization and diversity. Among them, diversity is the most important one and it improves the quality of a wireless communication link without changing the transmitted power or bandwidth. Diversity can be provided in spatial, frequency and temporal domains.

2.2.1 Space Diversity

This diversity model is given in Figure 2.5.

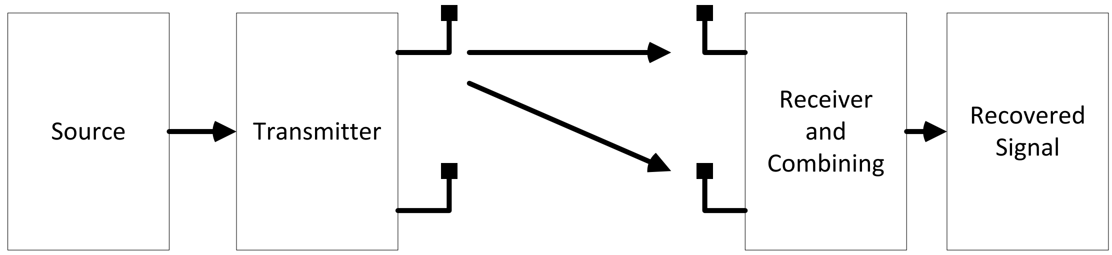

Figure 2. 5 Space diversity model

In this scenario the signal is transmitted from several different propagation paths. This can be obtained with the multiple receiving and transmitter antennas. Multiple receiving antennas obtain multiple versions of the same signal, because each antenna will be exposed to distinct interference environment. In this way, even if one antenna has experienced a fading, another one will receive a sufficient signal.

2.2.2 Frequency Diversity

This diversity model is given in Figure 2.6.

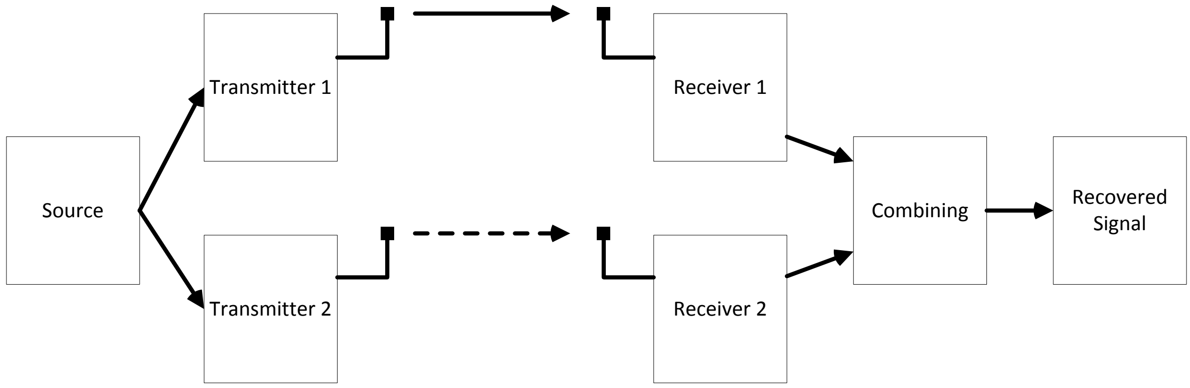

Figure 2. 6 Frequency diversity model

Several frequency channels are required in this transmission scenario to overcome the effects of multipath fading. It involves the simultaneous use of multiple frequencies for transmiting information since the wavelength for different frequencies conclude with different and uncorrelated fading characteristics.

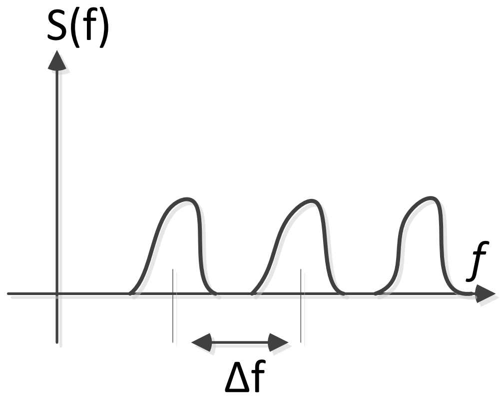

Figure 2. 7 Frequency diversity

The method for achieving the diversity is to modulate the information signal with different carriers. Each carrier should be isolated from the other carriers by at least the coherence bandwidth Δf so that different copies of the signal suffer independent fading [26]. At the receiver, the independently faded signals are combined to make a better decision.

2.2.3 Time Diversity

In digital communication systems, the transmission channel may suffer from error bursts due to time varying channel conditions. Time diversity is used to combat these error bursts and it is obtained by transmitting several versions of the same signal at different time instances. Optionally, a redundant forward error correction code can be added to organize the message in a discontiguous form before it is transmitted. In this way, error bursts are prevented and error correction is simplified.

2.2.4 Multiuser Diversity

It is also called as transmit diversity. It is a diversity technique using user scheduling in multiuser wireless channels. User scheduling enables the base station to select relatively high quality channel users to forward information through a high quality channel in time.

2.3 Combining Techniques

These techniques provide receive diversity and are used to merge the multiple received signals of a diversity reception device to obtain single improved signal since there are generally more than one received transmission with the data. In addition to choice of the diversity technique, an appropriate choice of the combining method is also necessary to performance improvement promised by diversity. Diversity combining system consists of receiving redundantly the same information via multiple fading channels, and then combining these multiple copies at the receiver in order to increase the received SNR. The main diversity combining techniques are selection combining (SC), maximal ratio combining (MRC) and equal gain combining (EGC).

2.3.1 Selection Combining

The SC system is based on the method of selecting the signal which has the largest SNR among the all signals received from different channels. It is the simplest of the diversity combining methods. This combining method is given in Figure 2.8.

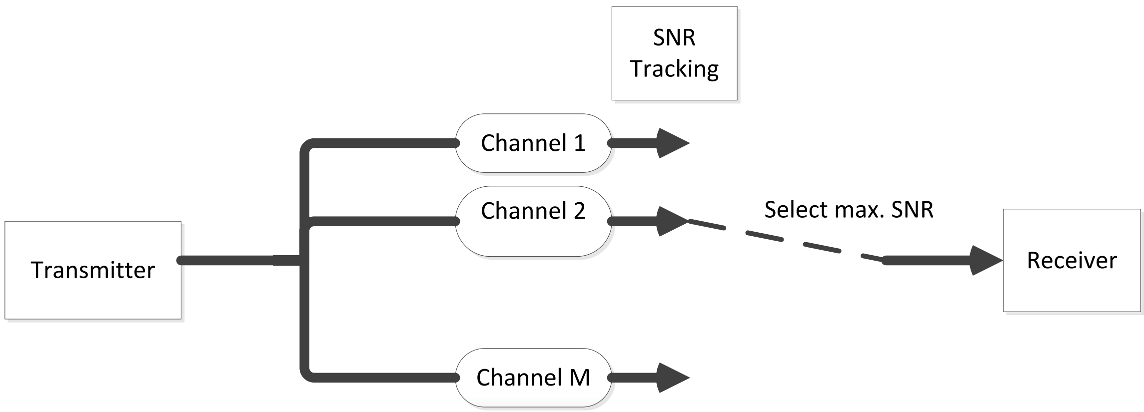

Figure 2. 8 Selection combining

According to the selection combining method, the system selects the channel that receives the signal with the largest SNR at any time and connects it to the demodulator. The higher probability of having a larger SNR at the output of system can be obtained with the larger number of available branches. In selection combining, the SNR of all the channels are tracked by the receiver and the channel with the largest SNR at any time is selected. Receiver switches between channels when one signal falls below the other and the receiver switches to the strongest channel. The output SNR of the combiner equal to the maximum SNR of all the branches in selection combining.

The output SNR of the selection combining system can be given as $\gamma_{\Sigma} = \max(\gamma_1, \gamma_2, ..., \gamma_M)$ where $\gamma_i \, (i = 1, 2, ..., M)$ is the SNR of per channel and *M* is the number of branches. Therefore, the cumulative distrubition function of considered system over independent and identically distributed (i.i.d.) Rayleigh fading channels [27] can be given as:

$$F_{\gamma_{\Sigma}}(\gamma) = \prod_{i=1}^{M} \left[1 - e^{-\gamma/\bar{\gamma}_i}\right]. \tag{2.8}$$

The outage probability of the selection combiner for the target γ_0 as follows [27] assuming M branches with uncorrelated Rayleigh fading amplitudes:

$$P_{out}(\gamma_0) = \prod_{i=1}^{M} p(\gamma_i < \gamma_0) = \prod_{i=1}^{M} \left[1 - e^{-\gamma_0/\bar{\gamma}_i}\right] \tag{2.9}$$

where $\bar{\gamma}_i$ is the average SNR on the *i*th branch.

Differentiating equation (2.8) relative to γ yields the probability density function of output SNR γ_{Σ}:

$$f_{\gamma_{\Sigma}}(\gamma) = \frac{M}{\bar{\gamma}} \left[1 - e^{-\gamma/\bar{\gamma}}\right]^{M-1} e^{-\gamma/\bar{\gamma}} \tag{2.10}$$

The average SNR of the combiner output in i.i.d. Rayleigh fading is:

$$\begin{aligned} \bar{\gamma}_{\Sigma} &= \int_0^{\infty} \gamma f_{\gamma_{\Sigma}}(\gamma) d\gamma \\ &= \int_0^{\infty} \frac{\gamma M}{\bar{\gamma}} \left[1 - e^{-\gamma/\bar{\gamma}}\right]^{M-1} e^{-\gamma/\bar{\gamma}} d\gamma \\ &= \bar{\gamma} \sum_{i=1}^{M} \frac{1}{i}. \end{aligned} \tag{2.11}$$

2.3.2 Maximal Ratio Combining

In Maximal ratio combining (MRC), all the channels are used simultaneously. It takes better advantage of all the diversity channels in the system. The system model is given in Figure 2.9 where $w_i(1,2,...,M)$ is the weighted factor.

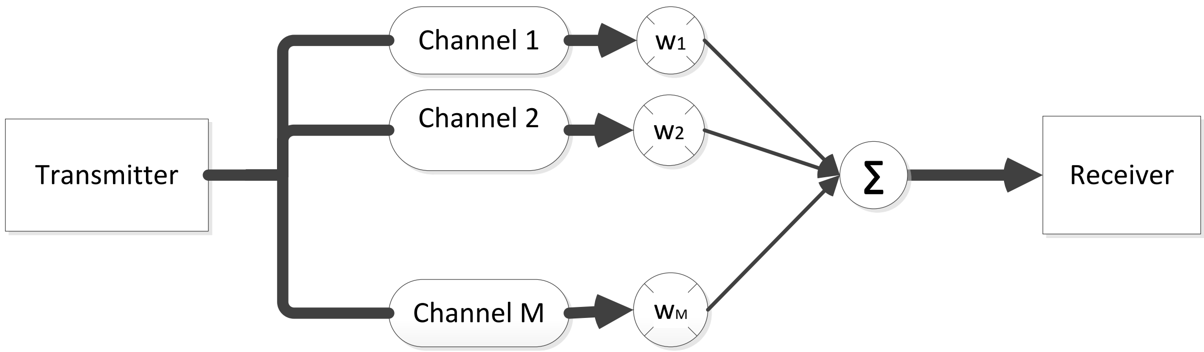

Figure 2. 9 Maximal ratio combining

All channels are weighted by their respective instantaneous SNR's. The channels are then co-phased before combining in order to make sure that all channels are appended in phase for maximum diversity gain. The combined signals are then utilized as the received signal and connected to the demodulator.

In maximal ratio combining, the output is a weighted sum of all branches, so all w_i in the Figure 2.9 are not equal to zero. The envelope of the combiner output is obtained by $x = \sum_{i=1}^{M} w_i x_i$. Thus, the output SNR of the combiner [28] can be given as:

$$\gamma_{\Sigma} = \frac{r^2}{N_{tot}} = \frac{1}{N_0} \frac{\left(\sum_{i=1}^{M} w_i x_i\right)^2}{\sum_{i=1}^{M} x_i^{\,2}}. \tag{2.12}$$

MRC is known as the optimal combiner and performs better than both SC and EGC schemes. The information on all channels is used in this technique to get a more reliable received signal.

The performance of a two sender transmission P_b with MRC at the receiver [2] can be expressed as:

$$P_b = \frac{1}{4}(1-\mu)^2(2+\mu), \tag{2.13}$$

where

$$\mu = \sqrt{\frac{\bar{\gamma}_b}{1+\bar{\gamma}_b}}, \tag{2.14}$$

$\bar{\gamma}_b$ denotes the average SNR defined as:

$$\bar{\gamma}_b = \frac{\varepsilon}{2\sigma^2} E(a^2), \tag{2.15}$$

and

$$E(a^2) = a^2. \tag{2.16}$$

This method achieves best performance since the input signal is multiplied by its corresponding conjugated channel gain assuming the channels phase shift and attenuation is known by the receiver [29].

2.3.3 Equal Gain Combining

In EGC technique, the received signals are first co-phased as in the MRC technique and then identically weighted by their amplitudes. The channel weights are all set to unity. The possibility of producing an acceptable signal from multiple unacceptable inputs is still retained. The gain factor for an equal gain system can be expressed as:

$$\alpha_i = e^{-ja_i}, \text{ for } i = 1,\ldots,M \tag{2.17}$$

With equal noise levels in each branch, the output SNR of EGC system [30] is written as:

$$\gamma_{\Sigma} = \frac{\frac{1}{2}\left(\sum_{i=1}^{M} X_i\right)^2}{Mn^2}. \qquad (2.18)$$

Where *n* is the additive noise component.

The performance of EGC receiver systems is better than the performance of selection diversity systems, however it is marginally lower compared to the performance of MRC systems. EGC is often used in practice due to the its reduced complexity relative to the MRC scheme [30].

CHAPTER 3

COOPERATIVE COMMUNICATIONS

3.1 History of Cooperative Communication

In noncooperative wireless communications, multipath fading causes the channel links to be extremely uncertain and for this reason communications between source and destination is not guaranteed [31]. To minimize this effect, the concept of cooperative communications was proposed for wireless networks [5].

In cooperative communications, all mobile users in a wireless network can assist each other to send received signals to the destination and it is the principal idea of the cooperative communications. The main attribute of cooperative transmission is to encourage multiple single-antenna nodes to share their antennas cooperatively. In this way, a virtual antenna array can be established and consequently, the overall quality of the wireless transmission, in terms of the reliability, energy efficiency and network capacity can be improved considerably. Each mobile user's data information is forwarded not only by one user, but also by other users. On account of this, the transmitted information is naturally more reliable to be detected at the destination. Multiple replicas of the transmitted signals due to the cooperation between each users conclude with the new kind of diversity as cooperative diversity. Cooperative diversity can considerably improve the system stability and performance.

The begining of cooperative communications can be traced back in 1970s, in which a concept of relay channel model consists of a source, destination and relay was first introduced and studied by Van der Meulen in the context of common information [7]. A more consummate capacity analysis of the relay channel was provided later in [6] by Cover and El Gamal. In order to combat the effects of multiple fading in wireless channels, many researches recently have been focused on design of cooperative diversity protocols. A lot of cooperation protocols are suggested for wireless networks, when a mobile user as a relay helps other mobile users to sent out information. The received signal first can be decoded and then forwarded to the destination by the relay, which is referred as a decode-and-forward (DF) cooperation protocol, or the received information simply can be amplified and sent out to the destination, which is referred as an amplify-and-forward (AF) cooperation protocol. Both source and relay send signal data to the destination through orthogonal channels in both DF and AF cooperation protocols.

In noncooperative wireless communications, information is transmitted from source to destination, and no user assist to one another as seen in Figure 3.1.

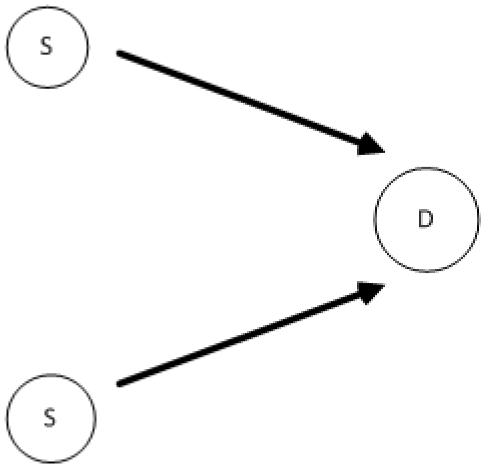

Figure 3. 1 Conventional communication model

On the other hand, there are many other useful user nodes in a cooperative wireless communication network, which could be of great assistance. All the nearby nodes listen the transmissions of the other nodes when one node sends its data.

The purpose of cooperative communication is to create spatial diversity by processing the received information and sent out it to the relative destination. The system performance is improved in this way. The system model of the cooperative communication is simply presented in Figure 3.2. Here, in the first phase, the source 'S' transmits data to the destination 'D', while the relay terminal 'R' is also listening the transmission. The relay terminal process and sent out this message to the destination in the second phase. Then, both of the received signals are combined at the destination. As both replicas of the signals are transmitted through independent paths, this results into spatial diversity.

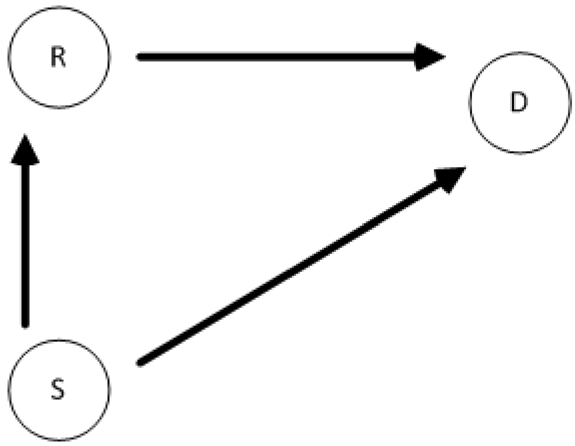

Figure 3. 2 Cooperative communication model

3.2 Cooperative Communication Protocols

Different cooperative communication protocols and techniques can be employed at relay nodes depending on the relative user location and channel conditions between mobile users. These techniques determine the system behaviour on how to handle the received data at the relays before sending out to the destination. These are the mainly amplify and forward (AF) and decode and forward (DF) relaying protocols.

3.2.1 Amplify and Forward (AF) Relaying

AF relaying technique was proposed by J. N. Laneman and G. W. Wornell [32]. It is also known as analog relaying and the idea behind this protocol is simple. During the first phase, the transmitter sends the signal data to the relay and destination terminals. Then each relay scales its received signal and forwards the processed signal to the destination in the second phase. In this protocol, the noise in the signal is also amplified. This technique is preferred when the relay terminal has minimal computing power. The model of the AF technique is shown in Figure 3.3.

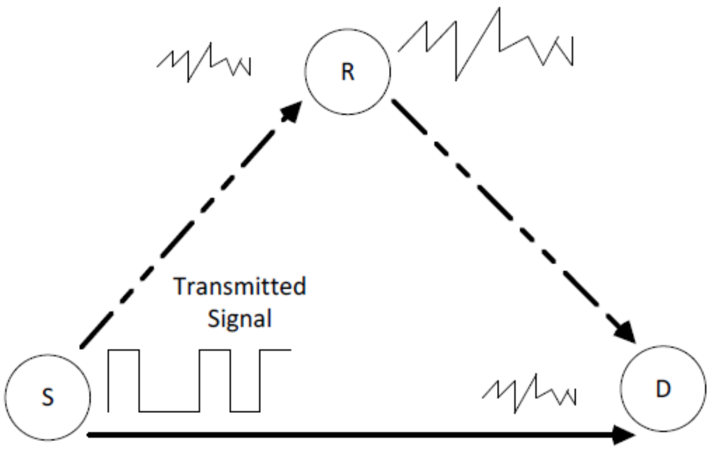

Figure 3. 3 AF relaying system

The disadvantage of AF relaying method is that the noise component in the signal is also amplified at the relay before forwarding to the destination.

3.2.2 Decode and Forward (DF) Relaying

DF relaying technique is the most preferred method for processing data in the relay. In this approach, the relay terminal decodes the received signal from the source terminal, re-encodes it and forwards it to the destination terminal. The model of the DF technique is shown in Figure 3.4.

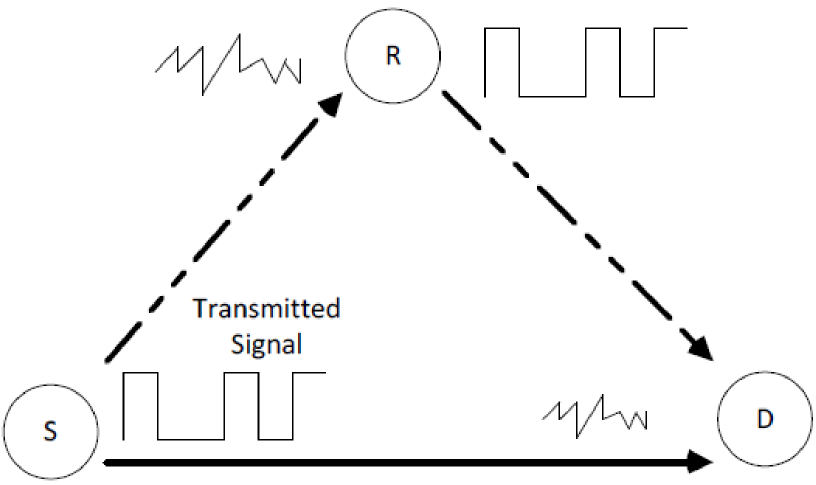

Figure 3. 4 DF relaying system

The most important problem encountered in the DF based cooperative communication systems is the detection errors at relays as a result of distorting effects in the channel between source-relay and the transmission of erroneous packets from relay to destination. An error correcting code can be used at the relay terminal in order to assist the received bit errors to be corrected at the relay nodes. However, this is only possible, if the relay terminal has enough computing power [33].

There are different techniques for encoding and decoding at the relay nodes, such as selection relaying and link adaptive relaying. In selection relaying protocol, when the received signal SNR is high, the relay decodes and re-encodes the received signal. On the other hand if the received signal SNR is low, the relay could switch to amplify and forward protocol or it will stop relaying information and the source simply continues to sent out signal information only to the destination.

CHAPTER 4

SYSTEM AND CHANNEL MODEL

4.1 System Model

In this thesis, a cooperative communication system where data of source (S) is sent to the destination (D) with the help of relay (R) was examined as seen in Figure 4.1.

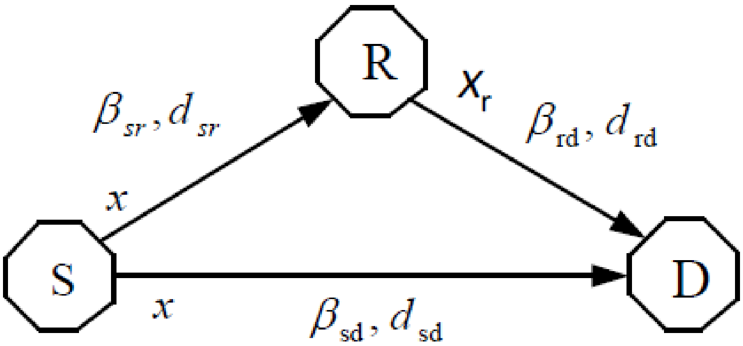

Figure 4. 1 System model

It is assumed that all terminals have one receive and transmit antenna. β_{sd}, β_{sr} and β_{rd} respectively show the complex fading coefficients related with S→D, S→R and R→D links. It is also assumed that the envelopes of these coefficients are modeled as Nakagami-m distribution. d_{sd}, d_{sr} and d_{rd} respectively show the normalized distances related with S→D, S→R and R→D links.

Binary Phase Shift Keying (BPSK) modulation is used for the transmission and communication protocol is divided into two phases. In first phase, the source transmits and the relay and destination listen. In second phase, the relay detects the source signal and either remain silent, in which source starts first phase with the next data, or retransmits the estimated data. DF relaying method is used at the relay and if the signal is sent to the destination by the relay in second phase, destination combines the signals received at the end of both phases using combining tecniques.

4.2 Channel Model

In this thesis, the wireless channel is supposed to be Nakagami-m faded in the presence of AWGN as shown in Figure 4.2. The channel is statistically independent and equally distributed complex Gaussian random process, that has zero mean and variance equal to unity. Noise term is a complex random process denoted as:

$$n = n_i + jn_r \tag{4.1}$$

where n_i shows the real part while n_r is the imaginay part. Therefore, the noise follows the complex Gaussian distribution with zero mean and variance:

$$\sigma^2 = N_0 / 2 \tag{4.2}$$

where N_0 is the power spectral density of the noise. Further, it is supposed that the channel is slowly faded, so that we have constant fading coefficients for any symbol period.

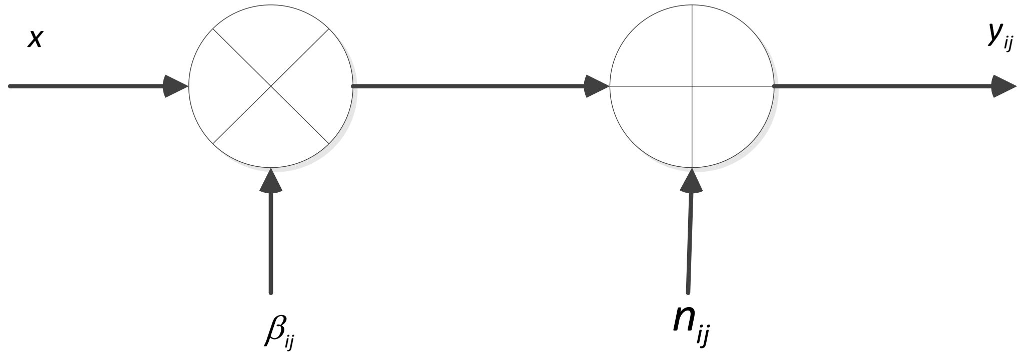

Figure 4. 2 Channel model

In Figure 4.2, x is the input signal or the transmitted signal which then passes through a noisy channel and faded during propagation whereas y is the corresponding output at the destination. So, the output of channel can mathematically expressed as:

$$y_{ij} = \sqrt{E_s}\beta_{ij}x + n_{ij} \qquad (4.3)$$

where y_{ij} denotes the noisy symbol when x is transmitted, and β_{ij} represent the fading coefficient. n_{ij} is the AWGN term while E_s is the symbol energy.

According to system model in Figure 4.1, in the first phase the source terminal transmits the BPSK symbol *x* to the relay and destination terminals. The received noisy signal at the relay and destination terminal can be expressed respectively as:

$$y_{sr} = \beta_{sr}\sqrt{E_s}x + n_{sr}, \qquad (4.4)$$

$$y_{sd} = \beta_{sd}\sqrt{E_s}x + n_{sd}. \qquad (4.5)$$

In the second phase, the relay terminal transmits the detected BPSK symbol x_r to the destination. The received signal at the destination can be given by:

$$y_{rd} = \beta_{rd}\sqrt{\alpha E_s}x_r + n_{rd} \qquad (4.6)$$

where α is the scaling factor, which is used to reduce the effect of error propagation by adapting the relay transmit power taking the source-relay and relay-destination link SNRs into consideration. E_s is the symbol energy and x_r is the detected signal at the relay and determined by:

$$x_r = \arg\min_{x\in\{+1,-1\}} \left|y_{sr} - \beta_{sr}x\right|^2. \qquad (4.7)$$

4.3 Source Model

In this thesis, the source is supposed to generate random information which is a sequence of bits that is achieved by random generator. Data is then modulated with BPSK modulation.

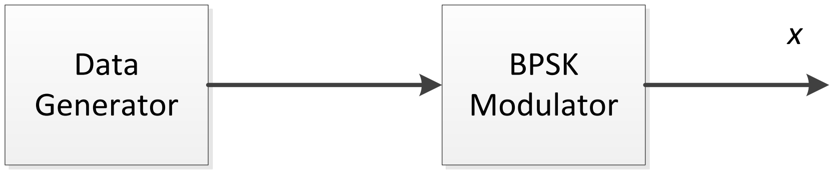

Figure 4. 3 Source model

BPSK modulation is the simplest form of phase shift keying (PSK) and it has the symbol stand for just one bit. Binary data are represented by two signals with different two phases which are separated by 180° as shown in Figure 4.4.

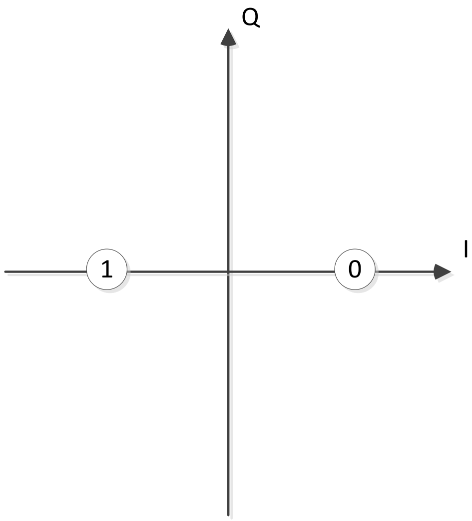

Figure 4. 4 BPSK constellation diagram

Table 4.1 lists the two symbols and the signals used to represent the binary data for BPSK modulation.

Table 4. 1 Mapping rules for BPSK

Bit	Signal	Modulated Signal
1	$A\cos(2\pi f_c t+\pi)$	-1
0	$A\cos(2\pi f_c t)$	1

4.4 Relay Model

Relay uses BPSK modulation, so the relayed signal is similar with the source which is a sequence of -1's and 1's. Effect of source-relay channel can be equalized by the relay and it uses maximum likelihood (ML) detector for the detection of source signal. At the relay, the received noisy signal is processed and sent to the destination. The block diagram of the relay node is shown in Figure 4.5.

Figure 4. 5 Relay model

4.4.1 Modes of Relaying

There are several methods like amplify and forward (AF) and decode and forward (DF) that describes how the received data is processed at the relays before forwarding to the destination. In this thesis, decode and forward method is studied.

4.4.2 Relay Positioning

In this thesis, linear placement is considered for simulation. The channel structure is obtained by assuming that source, relay and destination are placed linearly on the same axis and the distance between source and destination normalized to one.

In this scenario, the variance of fading coefficient between two terminals (i, j) is assumed to be inversely proportional with distance such as $\sigma_{ij}^2 = d_{ij}^{-\upsilon}$ form and path loss coefficient is assumed as $\upsilon = 4$ [8]. In that channel structure, the relay is placed in different positions between the source and the destination. Here, three separate scenarios are considered.

4.4.2.1 Relay Centered

The relay is positioned between the source and receiver with equal distances to both terminals as shown in Figure 4.6.

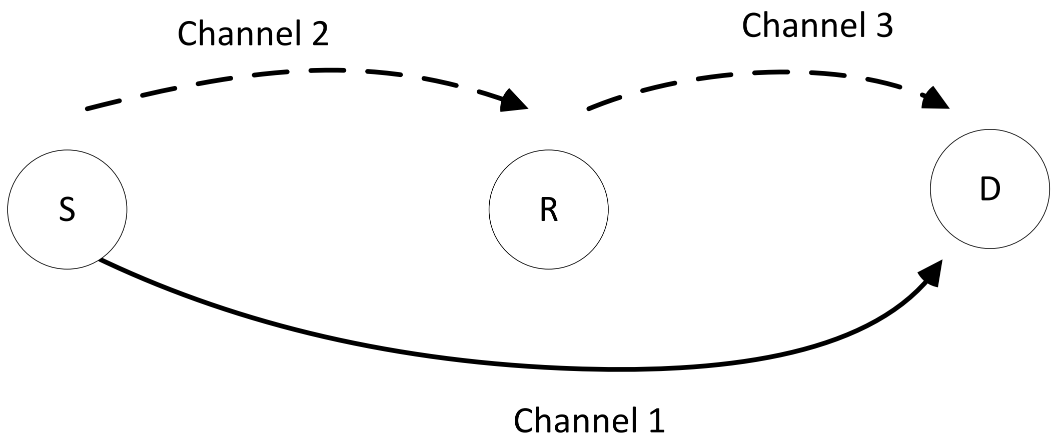

Figure 4. 6 Relay centered

4.4.2.2 Relay Close to Source

In this scenario, the relay terminal is placed close to the source terminal as illustrated in Figure 4.7.

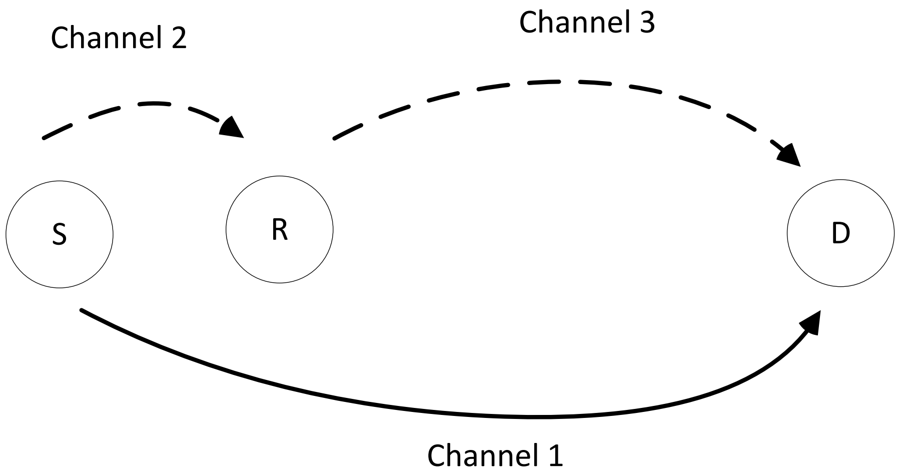

Figure 4. 7 Relay closed to source

4.4.2.3 Relay Close to Destination

Finally, the relay terminal is placed close to the destination terminal as illustrated in Figure 4.8.

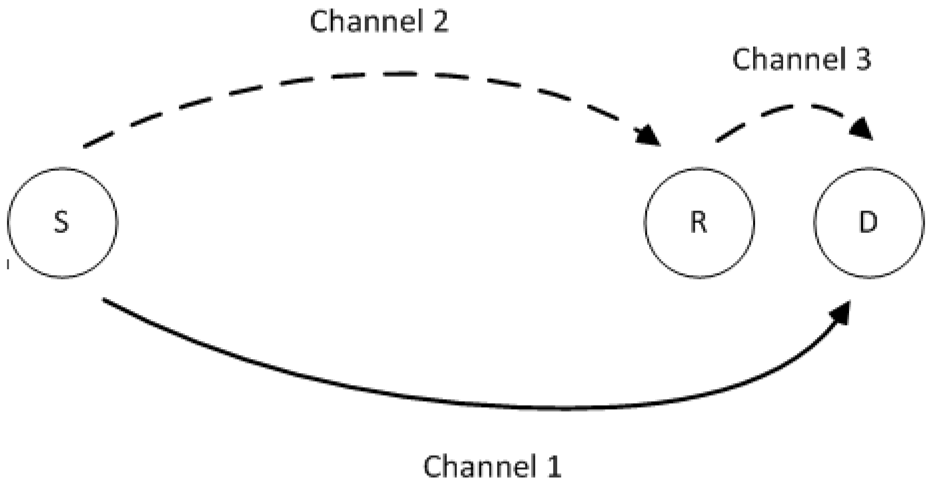

Figure 4.8 Relay closed to destination

4.4.3 Relaying Techniques

There are some techniques that can be performed at the relay node with decode and forward in order to decrease the bit error rate. In this thesis, the selective relaying and link adaptive relaying (LAR) techniques are used at the relay.

4.4.3.1 Selective Relaying

In this technique, relay decides either to detect the signals coming from the source and transfer them to destination or to remain silent in order to decrease the error distribution and decrease the bit error rate. Decision of the relay depends on the SNRs of the source-relay, relay-destination, and source-destination links.

Instantaneous SNRs of channel links defined by $\gamma_{sr} = \left(E_s |\beta_{\mathrm{sr}}|^2\right)/N_0$, $\gamma_{rd} = \left(E_s |\beta_{\mathrm{rd}}|^2\right)/N_0$ and $\gamma_{sd} = \left(E_s |\beta_{\mathrm{sd}}|^2\right)/N_0$ are used for the relaying decision. In case the relay stays silent, the instantaneous bit error rate depends only on the source-destination link and is expressed as:

$$P\left(\varepsilon_{e2e,silent}\right)=P\left\{\varepsilon_{sd} \mid \gamma_{sd}\right\}=Q(\sqrt{2\gamma_{sd}}) \quad (4.8)$$

where, $Q(x)=\left(1/\sqrt{2\pi}\right)\int_x^{\infty}\exp(-t^2/2)dt$ [2]. If the relay node re-transmits the source signal, the instantaneous bit error rate depends on the source-relay, relay-destination, and source-destination links and it is expressed as:

$$\begin{aligned}P\left(\varepsilon_{e2e,active}\right)&=P\left\{\varepsilon_{sr} \mid \gamma_{sr}\right\}P\left\{\varepsilon_{prop} \mid \gamma_{rd},\gamma_{sd}\right\}\\&+\left(1-P\left\{\varepsilon_{sr} \mid \gamma_{sr}\right\}\right)P\left\{\varepsilon_{coop} \mid \gamma_{rd},\gamma_{sd}\right\}\end{aligned}. \quad (4.9)$$

The cooperative error term is used for the event that an error occurs after the destination combines the source signal and the correctly regenerated relay signal . The cooperative error event is denoted by ε_{coop} and the instantaneous probability of cooperative error [14] is expressed as follows:

$$\begin{aligned}P\left\{\varepsilon_{coop} \mid \gamma_{rd},\gamma_{sd}\right\}&=\mathrm{BER}_{awgn}(\gamma_{rd}+\gamma_{sd})\\&=Q\left(\sqrt{2(\gamma_{rd}+\gamma_{sd})}\right)\end{aligned}. \quad (4.10)$$

The event that an error occurs after the destination combines the source signal and the incorrectly regenerated relay signal is referred to as error propagation and is denoted by ε_{prop}. The instantaneous probability of error propagation [14] can be calculated by:

$$P\left\{\varepsilon_{prop} \mid \gamma_{rd},\gamma_{sd}\right\}=Q\left(\frac{\gamma_{sd}-\gamma_{rd}}{\sqrt{\left(\gamma_{sd}+\gamma_{rd}\right)/2}}\right) \quad (4.11)$$

when VN based detection used at the destination, which is the detection technique that models the detection error occured at the relay as an additional noise term at the destination, the instantaneous bit error rate [19] is determined as:

$$P\left(\varepsilon_{e2e,active}\right)=\left(1-Q\left(\sqrt{2\gamma_{\text{sr}}}\right)\right)\,Q\left(\sqrt{\frac{2\left(\gamma_{sd}+\gamma_{EQ}\right)^{2}}{\gamma_{sd}+\gamma'_{EQ}}}\right)$$
$$+Q\left(\sqrt{2\gamma_{\text{sr}}}\right)\,Q\left(\sqrt{\frac{2\left(\gamma_{sd}-\gamma_{EQ}\right)^{2}}{\gamma_{sd}+\gamma'_{EQ}}}\right) \tag{4.12}$$

where

$$\gamma'_{EQ}=\frac{\left|\beta_{\text{sr}}\right|^{4}\left|\beta_{\text{rd}}\right|^{2}}{\left(\left(\left|\beta_{\text{sr}}\right|^{2}+\left|\beta_{\text{rd}}\right|^{2}\right)^{2}\sigma_{\text{n}}^{2}\right)}, \tag{4.13}$$

$$\gamma_{EQ}=\frac{\left|\beta_{\text{sr}}\right|^{2}\left|\beta_{\text{rd}}\right|^{2}}{\left(\left(\left|\beta_{\text{sr}}\right|^{2}+\left|\beta_{\text{rd}}\right|^{2}\right)^{2}\sigma_{\text{n}}^{2}\right)}, \tag{4.14}$$

with $\sigma_n^2 = N_0/2$.

Finally, the obtained bit error rates for both active and inactive relay status are compared by the relay, then relay decides to either to remain silent or to be active in order to forward the source data depending on the obtained bit error rates.

4.4.3.2 Link Adaptive Relaying

In link adaptive relaying (LAR), the error propagation is reduced by adapting the relay transmit power taking the source-relay and relay-destination link SNRs into consideration [34]. In this tecnique, decoded bits at the relay nodes are scaled in power before being forwarded to the destination. Transmitted symbols by source in the first phase are decoded at relay and forwarded to the destination with power scaling factor adapted to the instantaneous γ_{sr} and γ_{rd} [34] as:

$$\alpha=\frac{\min(\gamma_{\text{sr}},\gamma_{\text{rd}})}{\gamma_{\text{rd}}}=\begin{cases}\gamma_{\text{sr}}/\gamma_{\text{rd}}, & \gamma_{\text{sr}}<\gamma_{\text{rd}}\\ 1, & \gamma_{\text{sr}}\geq\gamma_{\text{rd}}\end{cases}. \tag{4.15}$$

At the end of the second phase, the received signal at the destination can be re-written in terms of α as:

$$y_{\mathrm{rd}} = \beta_{\mathrm{rd}} \sqrt{\alpha E_s} x_{\mathrm{r}} + n_{\mathrm{rd}} \quad (4.16)$$

where β_{rd} is the fading coefficient in R→D link.

4.5 Destination Model

Two received signals by the destination are the direct signals from the source terminal and the relay terminal. These transmissions are combined at destination. Afterwards, the destination terminal decides the symbols transmitted by the source. The detection model at the destination is shown in Figure 4.9.

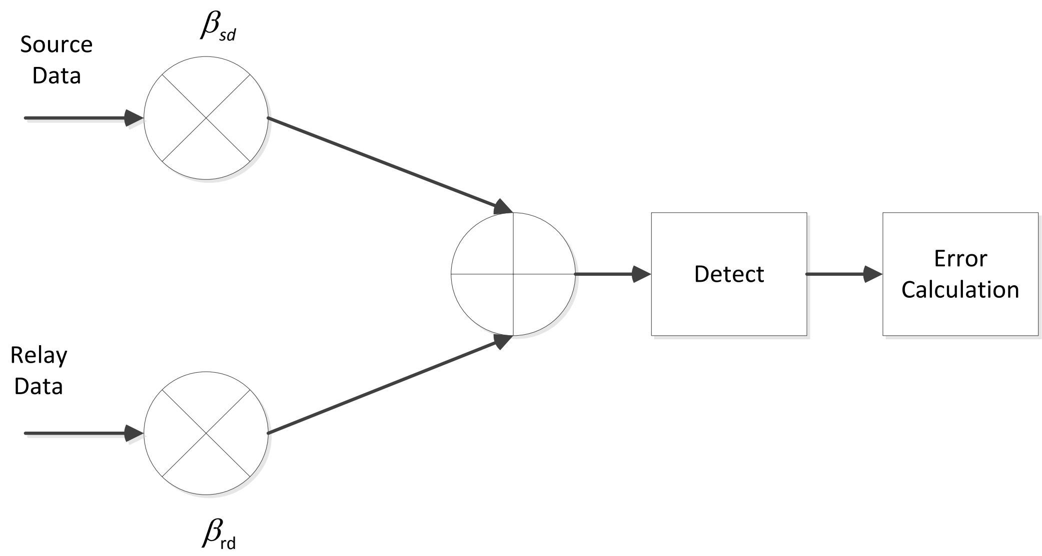

Figure 4. 9 Destination model

4.5.1 Detection Techniques

Diversity combining is used to combine various received signals at the destination. Diversity combining system consists of receiving redundantly the same information signal over multiple fading channels, and then combining these multiple copies at the receiver in order to increase the received SNR. In this thesis, three different detection algorithms known as Virtual Noise (VN) based detection [19], Maximal Ratio Combining (MRC) and Maximum Likelihood (ML) [35] are used at the destination.

4.5.1.1 MRC Technique

MRC is the optimal combining approach in which the direct and relayed signals are linearly processed. Thus, these two received signal components are used simultaneously and weighted by their respective instantaneous SNR's. In this case, the decision rule is defined as:

$$\hat{x}_d = \arg\min_{x\in\{+1,-1\}} \left|\beta_{sd}^* y_{sd} + \beta_{\mathrm{rd}}^* y_{\mathrm{rd}} - (\left|\beta_{sd}\right|^2 \sqrt{E_s} + \left|\beta_{\mathrm{rd}}\right|^2 \sqrt{E_s\alpha})x\right|^2 \tag{4.17}$$

where $\hat{x}_d$ is the detected symbol at the destination.

4.5.1.2 VN based Detection

The performance of DF based cooperative networks can degrade due to the error propagation which is caused by detection errors at the relay. To overcome this problem, the detection error occured at the relay is modeled at the destination as an additional noise term named as virtual noise [19]. In this tecnique, unlike classic LAR technique, a combining approach depending on holistic virtual noise modeling is used instead of classical MRC. In this case, the forwarded signal from the relay is corrupted by both AWGN and the virtual noise which corresponds to the error propagation [19]. Thus, the signal obtained at the destination in the second phase given in (4.16) can be rewritten as follows:

$$\begin{aligned} y_{\mathrm{rd}} &= \beta_{\mathrm{rd}}\sqrt{E_s\alpha}x_{\mathrm{r}} + n_{\mathrm{rd}} \\ &= \beta_{\mathrm{rd}}\sqrt{E_s\alpha}x + \beta_{\mathrm{rd}}\sqrt{E_s\alpha}e_{\mathrm{r}} + n_{\mathrm{rd}} \\ &= \beta_{\mathrm{rd}}\sqrt{E_s\alpha}x + n_{\mathrm{v}} + n_{\mathrm{rd}}\ . \end{aligned} \tag{4.18}$$

The introduction of virtual noise n_{v} at the destination is the basic idea of this concept. The virtual noise component is supposed to be generated by error propagation which is caused by the detection errors at the relay. Virtual noise is shown as n_{v} and it is independent from Gaussian noise. It is assumed that the variance of e_{r} is $N_0/\left|\beta_{\mathrm{sr}}\right|^2$ [19]. Then, the decision rule for BPSK signaling in case of VN and LAR structure is given as [19]:

$$\hat{x}_s = \arg \max_{x \in \{+1,-1\}} \exp\left(\frac{-\left| y_{sd} - \beta_{sd}\sqrt{E_s}x \right|^2}{N_0} \right) \times \sum_{\forall \bar{x} \in \{+1,-1\}} \exp\left(\frac{-\left| y_{\text{rd}} - \beta_{\text{rd}}\sqrt{\alpha E_s}\bar{x} \right|^2}{N_0} \right) \Pr(x \to \bar{x}) \tag{4.19}$$

where $\Pr(x \to \bar{x})$ is a symbol transition probability which addresses the detection error at the relay.

Although this decision rule doesn't cause to a calculation complexity for the signal sets consisting of two elements such as BPSK, in signaling techniques with increased number of elements, it makes the receiver structure too much complex. To overcome this problem, the mentioned decision rule is simplified by taking the approximation one step further and pretending that the virtual noise is a Gaussian random variable [19] as:

$$\begin{aligned} \hat{x}_s &\approx \arg\max_{x \in A_x} \exp\left(-\frac{\left| y_{sd} - \beta_{sd}\sqrt{E_s}x \right|^2}{N_0} - \frac{\left| y_{\text{rd}} - \beta_{\text{rd}}\sqrt{\alpha E_s}x \right|^2}{\sigma_v^2} \right) \\ &= \arg\min_{x \in A_x} \exp\left\{ \left| y_{sd} - \beta_{sd}\sqrt{E_s}x \right|^2 + \left(\frac{\sigma_{\text{n}}^2}{\sigma_v^2} \right) \left| y_{\text{rd}} - \beta_{\text{rd}}\sqrt{\alpha E_s}x \right|^2 \right\} \\ &= \arg\min_{x \in A_x} \exp\left\{ \left| y_{sd} - \beta_{sd}\sqrt{E_s}x \right|^2 \right. \\ &\quad \left. + \left(\frac{|\beta_{\text{sr}}|^2}{\left(|\beta_{\text{sr}}|^2 + |\beta_{\text{rd}}|^2 \right)} \right) \left| y_{\text{rd}} - \beta_{\text{rd}}\sqrt{\alpha E_s}x \right| \right\} . \end{aligned} \tag{4.20}$$

Here, $\sigma_v^2 = \left(1 + \frac{|\beta_{\text{rd}}|^2}{|\beta_{\text{sr}}|^2} \right) N_0$ shows the variance of the effective noise at the destination.

4.5.1.3 Maximum Likelihood (ML) Detection

ML detection is one of the most effective solutions to combat error propagation. It is used to overcome performance degradation in MRC structure when the effect of error propagation from the relay to the destination is not negligible.

The optimum ML receiver at the destination for the DF cooperative protocol [35] can be expressed by:

$$\frac{P(x=1\,|\,y_{sd},y_{rd})}{P(x=-1\,|\,y_{sd},y_{rd})}\overset{1}{>}1,\ \ \frac{P(x=1\,|\,y_{sd},y_{rd})}{P(x=-1\,|\,y_{sd},y_{rd})}\overset{-1}{<}1\,. \tag{4.21}$$

Assuming that the source transmits the symbol x = 1, the instantaneous error probability at the destination [35] can be developed as:

$$P=\left(\frac{2\sqrt{E_s}y_{sd}\beta_{\mathrm{sd}}}{\sigma^2}<\ln\left(\frac{\varepsilon+(1-\varepsilon)e^{-\frac{2\sqrt{E_s}y_{rd}\beta_{\mathrm{rd}}}{\sigma^2}}}{(1-\varepsilon)+\varepsilon e^{-\frac{2\sqrt{E_s}y_{rd}\beta_{\mathrm{rd}}}{\sigma^2}}}\right)\right). \tag{4.22}$$

Where E_s is the transmitted power, σ is the standart deviation of AWGN noise and ε is the probability of error calculated by:

$$\varepsilon=Q\left(\frac{\sqrt{E_s}\,|\beta_{\mathrm{sr}}|}{\sigma}\right) \tag{4.23}$$

where $\mathrm{Q}(\mathrm{x})=\left(1/\sqrt{2\pi}\right)\int_{\mathrm{x}}^{\infty}\exp(-\mathrm{t}^2/2)\mathrm{dt}$.

Piecewise-linear (PL) approximation is developed since it is very challenging to calculate the overall system BER using (4.22) directly. The PL approximation specifically simplifies the function [35]:

$$f(t)=\ln\left(\frac{\varepsilon+(1-\varepsilon)e^t}{(1-\varepsilon)+\varepsilon e^t}\right) \tag{4.24}$$

as

$$f_i(t_i)\cong f_{PL}(t_i)=\begin{cases}-T_i & \mathit{for} \quad t_i\le -T_i\\ t_i & \mathit{for} \ -T_i\le t_i\le T_i\,,\\ T_i & \mathit{for} \quad t_i\ge T_i\end{cases} \tag{4.25}$$

where

$$T_i=\ln\left[\frac{(1-\varepsilon_i)}{\varepsilon_i}\right], \tag{4.26}$$

Detectors using the approximation (4.25) rather than (4.24) are called detectors with PL combiner. Although the PL approximation extends to the case of multiple relays, we focus on the case of one relay to obtain a closed-form BER expression in this work. The log-likelihood ratio (LLR) of the ML detection for the DF cooperation [8] are given by:

$$LLR = t_0 + f_{PL}\left(t_1\right) \overset{0}{>} 0,\ \ LLR = t_0 + f_{PL}\left(t_1\right) \overset{1}{<} 0\,, \tag{4.27}$$

where

$$t_0 = \frac{4\sqrt{E_0}\,\Re\left\{\beta_{sd}^{*} y_{sd}\right\}}{N_0}, \tag{4.28}$$

$$t_1 = \frac{4\sqrt{E_1}\,\sqrt{\alpha}\,\Re\left\{\beta_{rd}^{*} y_{rd}\right\}}{N_0}\ . \tag{4.29}$$

Where $\Re\{.\}$ is the operator for taking real part of a complex term and E_i is the average transmission power.

SECTION 5

SIMULATION RESULTS

In this chapter, Monte-Carlo simulation results for different combining techniques are presented. Performance of the proposed VN and LAR structure is compared with the performance of classical MRC based LAR structure and ML based LAR structure. The BER perfprmance of DF relaying cooperative system is obtained for BPSK modulation under different channel conditions and relay positions with respect to the source and destination location. Linear placement is considered for simulation. The channel structure is obtained by assuming that source, relay and destination are placed linearly on the same axis and the distance between the source and destination normalized to one. The variance of fading coefficient between two terminals (i, j) is assumed to be inversely proportional with distance such as $\sigma_{ij}^2 = d_{ij}^{-\upsilon}$ form and path loss coefficient is assumed as υ =4 [8].

Respectively in Figure 5.1, 5.2 and 5.3, average BER curves obtained for d_{sr} = 0.1, d_{sr} = 0.5 and d_{sr} = 0.9 without using the selective transfer algorithm at the relay are given. When the relay is placed close to the source (d_{sr} = 0.1), the LAR techniques using VN and LAR techniques using MRC at the destination show almost the same performance for all values of the channel parameter (m).

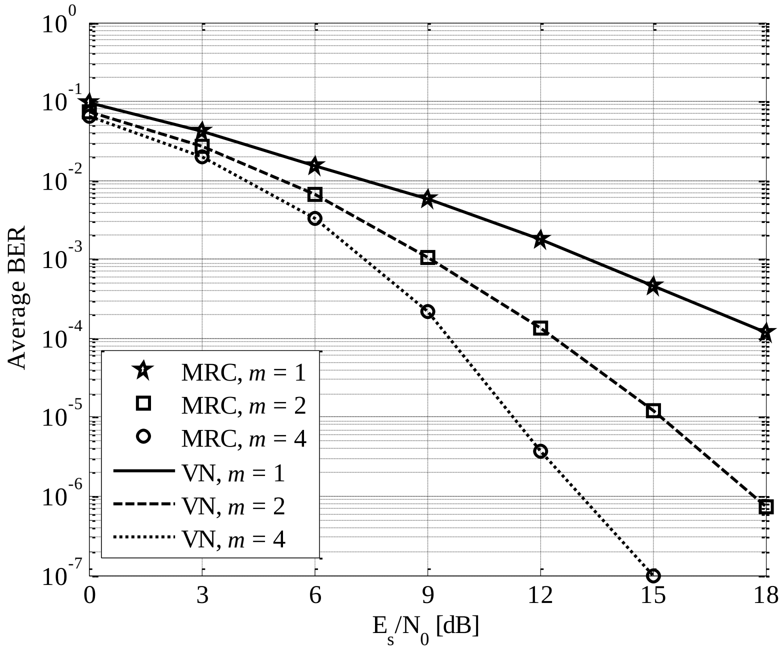

Figure 5. 1 Error performance curves when the relay is close to source

In case the relay is in the middle of source and destination (d_{sr} = 0.5), the LAR technique using VN at destination shows better performance compared to LAR technique using MRC and this improvement increases as the channel parameter value increases.

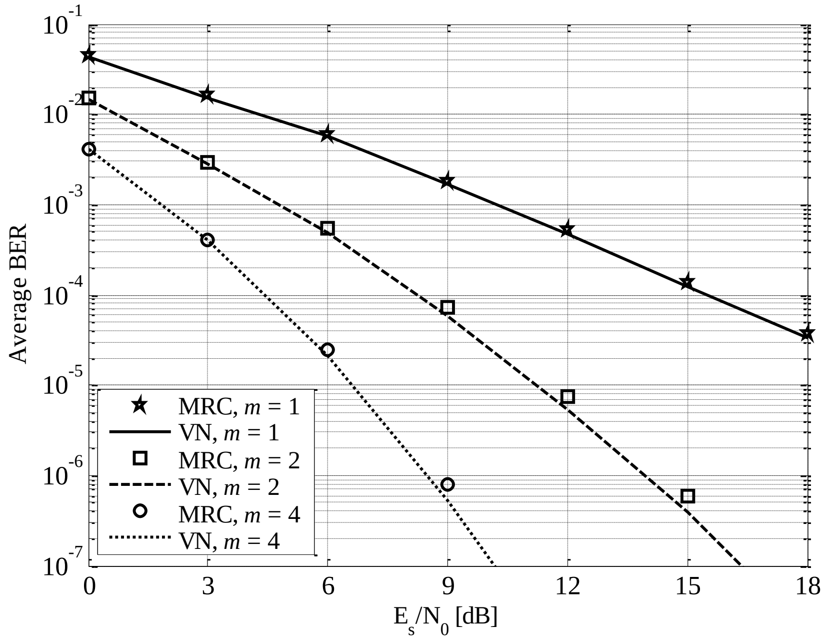

Figure 5. 2 Error performance curves when the relay is located in the middle

A similar situation is observed in Figure 5.3 when the relay is close to the destination.

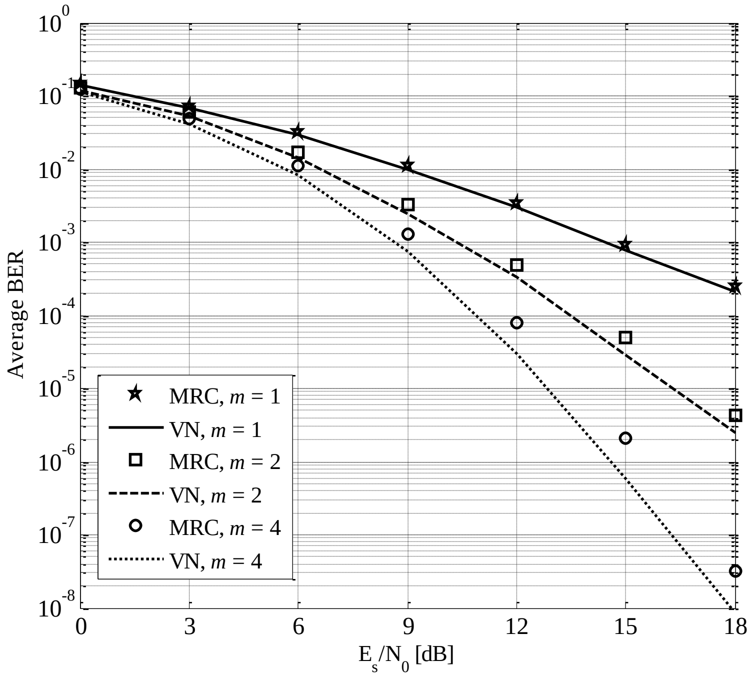

Figure 5. 3 Error performance curves when the relay is close to destination

In table 5.1, the BER gain values obtained by proposed approach (LAR with VN) compared to the classical approach (LAR wİth MRC) for various SNR values are given. Here, SNR is defined as SNR = E_s/N_0 (dB).

Table 5. 1 Average BER gain of proposed LAR with VN approach compared to LAR with MRC

Channel Structure	SNR [dB]	$d_{sr}(0.9)$ $d_{rd}(0.1)$	$d_{sr}(0.1)$ $d_{rd}(0.9)$	$d_{sr}(0.5)$ $d_{rd}(0.5)$
Nakagami m = 1	12	0.6364	0	0.4317
	15	0.7301		0.4673
	18	0.7387		0.4994
Nakagami m = 2	12	1.7806	0	1.4057
	15	2.2368		1.7513
	18	2.4612		1.8293
Nakagami m = 4	12	4.0781	0	0.6109
	15	5.4406		1.8234
	18	5.4406		3.4242

The average BER curves obtained for d_{sr} = 0.1, d_{sr} = 0.5 and d_{sr} = 0.9 when the selective transfer algorithm is used at the relay are given in Figure 5.4, 5.5 and 5.6 respectively. When the relay is close to the source (d_{sr} = 0.1), the LAR techniques using VN at the destination and LAR techniques with MRC show almost the same performance for all values of the channel parameter (m) as in the previous simulation result without using selective transfer algorithm at the relay.

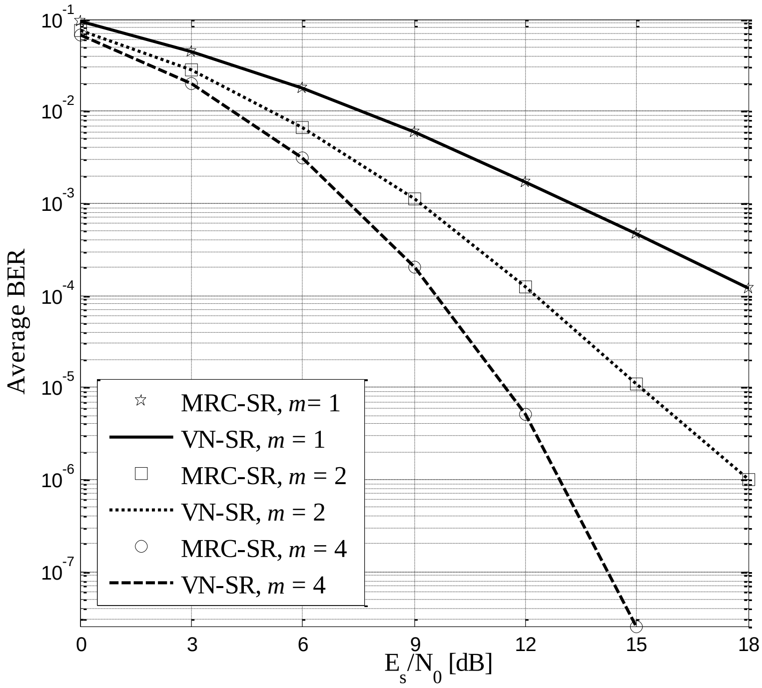

Figure 5. 4 Error performance curves when the selective relay is close to source

In Figure 5.5, when the relay is in the middle of source and destination (d_{sr} = 0.5), the LAR technique using VN at the destination shows better performance compared to LAR technique using MRC and this performance increases as the channel parameter value increases.

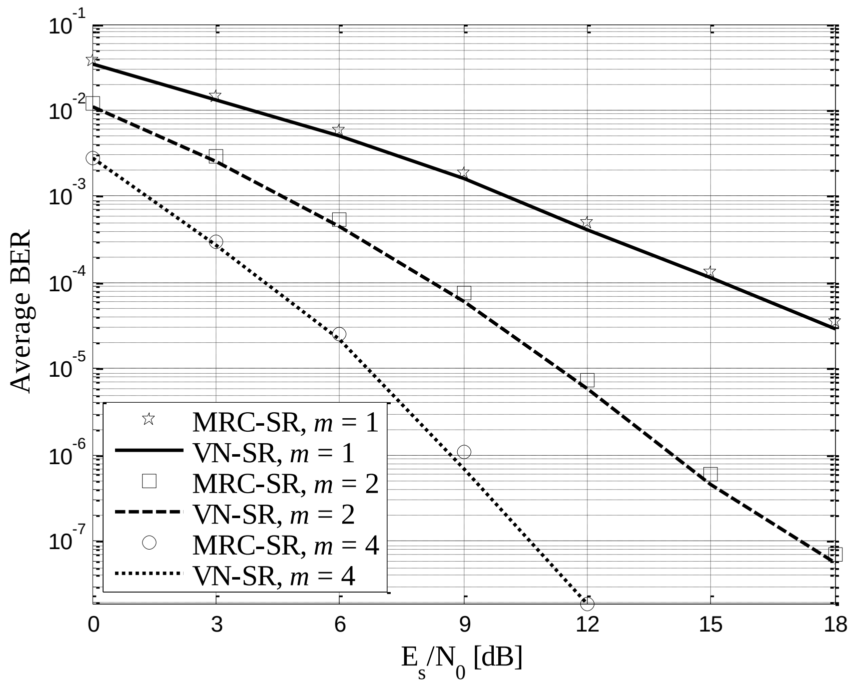

Figure 5. 5 Error performance curves when the selective relay is located in the middle

A similar situation is observed in Figure 5.6 when the relay is close to the destination.

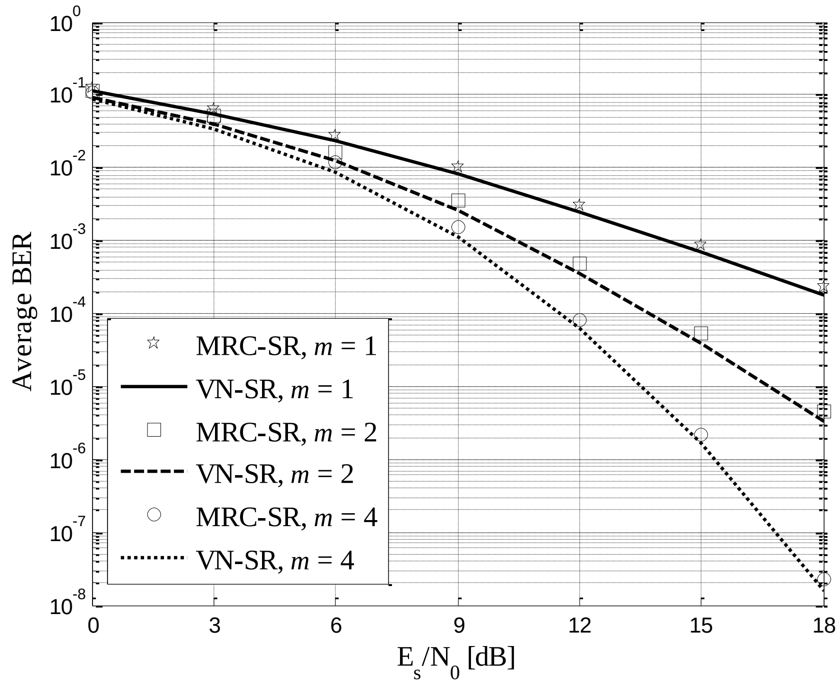

Figure 5. 6 Error performance curves when the selective relay is close to destination

In Table 5.2, average BER gain values of the proposed approach (LAR with VN) compared to the classical approach (LAR with MRC) for various SNR values are given when the selective transfer algorithm is used at relay.

Table 5. 2 Average BER gain of proposed combined technique compared to the classical technique (LAR with MRC) when selective transfer algorithm is used at relay

Channel Structure	SNR [dB]	$d_{sr}(0.9)$ $d_{rd}(0.1)$	$d_{sr}(0.1)$ $d_{rd}(0.9)$	$d_{sr}(0.5)$ $d_{rd}(0.5)$
Nakagami m = 1	0	0.5317	0	0.2833
	6	0.8782		0.5574
	12	1.0024		0.6583
	18	1.0028		0.6921
Nakagami m = 2	0	0.8505	0	0.3024
	6	1.3060		0.8195
	12	1.3666		1.1592
	18	1.5029		1.0266
Nakagami m = 4	0	1.0851	0	0.1724
	6	1.4771		0.8842
	12	1.1127		1.2493
	18	1.4612		NaN

Figure 5.7 and 5.8 show the BER performance of DF relaying cooperative system over Rician fading channel. Here, we haven't considered relay positioning.

In Figure 5.7, average BER curves obtained for Rician channel is given. The BER curves obtained for two different Rician factor (K = 5 and K = 10) and the LAR technique using VN at the destination shows better performance compared to classical LAR technique with MRC.

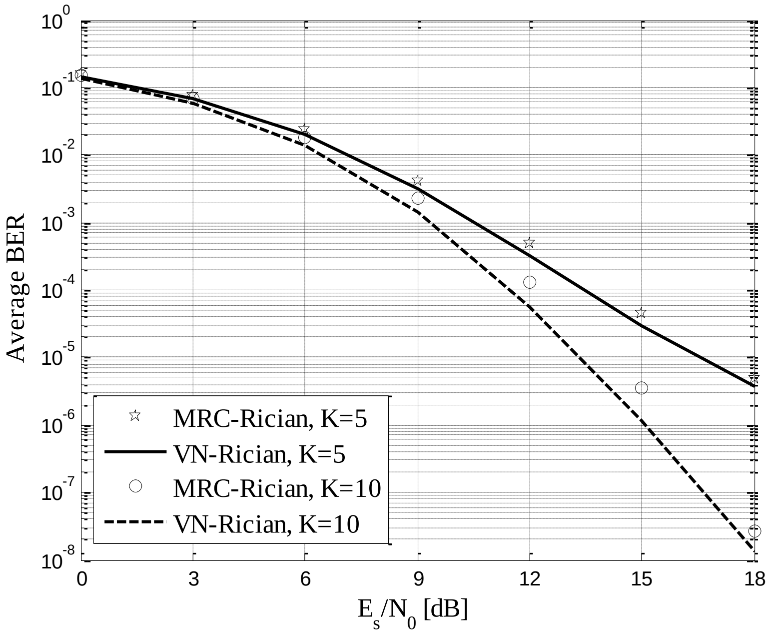

Figure 5. 7 Error performance curves for Rician fading channels

In Figure 5.8, average BER curves obtained for Rician fading channel is given when the selective transfer algorithm is used at the relay. The BER curves obtained again for two different Rician factor (K = 5 and K = 10) and the LAR technique using VN at the destination shows better performance compared to classical LAR technique.

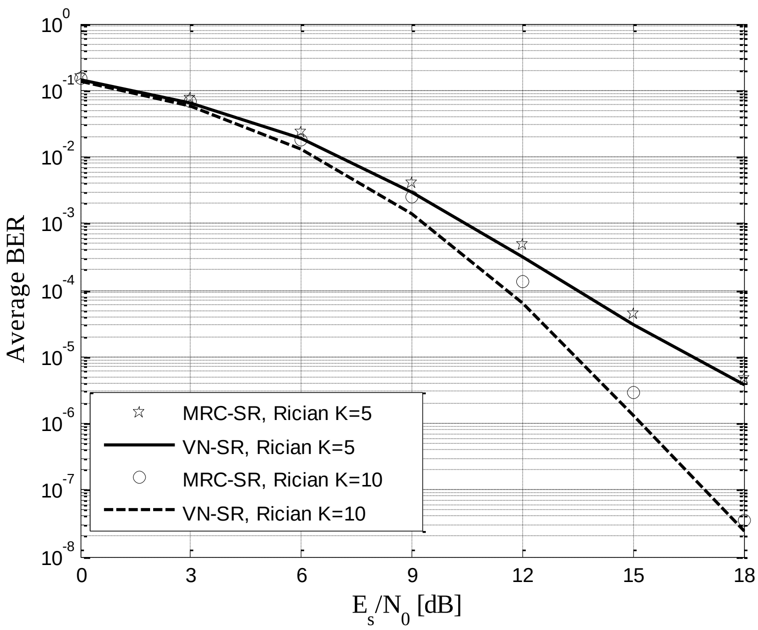

Figure 5. 8 Error performance curves for Rician fading channels when the selective transfer is used at relay

In Table 5.3, the BER gain values obtained by proposed approach (LAR with VN) compared to the classical approach (LAR with MRC) for various SNR values are given for both relay situation.

Table 5. 3 Average BER gain of proposed technique (LAR with VN) compared with classical technique (LAR with MRC) for Rician fading channels

Channel Structure	SNR [dB]	Selective Relay	Not Selective Relay
Rician K = 5	0	0.3546	0.3025
	6	1.0578	0.7358
	12	1.8771	1.6617
	18	0.9033	1.1860
Rician K = 10	0	0.4169	0.3955
	6	1.4911	1.1128
	12	3.4202	3.8047
	18	1.5490	3.9794

These numerical results show that the proposed LAR technique using VN at the destination shows better performance compared to LAR technique with MRC.

The average BER performances of proposed DF relaying cooperative system are also obtained for the ML technique over both Nakagami-m and Rician fading channels and these BER curves obtained without using the selective transfer algorithm at relay. In Figure 5.9, 5.10 and 5.11, average BER curves obtained for d_{sr} = 0.1, d_{sr} = 0.5 and d_{sr} = 0.9 in Nakagami-m fading channels are given respectively.

In Figure 5.9, the relay is close to the source (d_{sr} = 0.1) in all values of the channel parameter (m) and the LAR techniques using VN at the destination, LAR techniques with MRC and the LAR techniques with ML show almost the same performance.

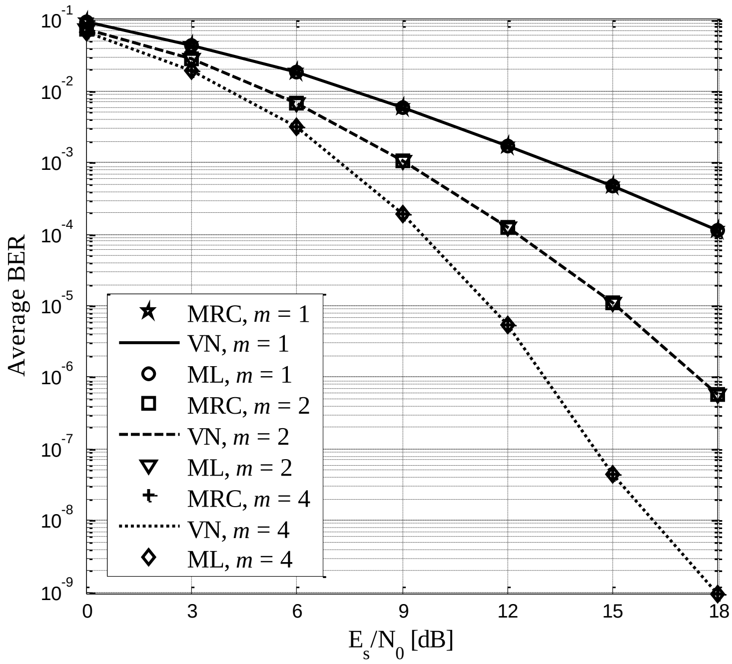

Figure 5. 9 Error performance curves when the relay is close to source

When the relay is located in the middle of source and destination (d_{sr} = 0.5), the LAR technique using ML at the destination shows the best performance compared to the LAR technique with MRC and the LAR technique with VN at destination, as shown in Figure 5.10.

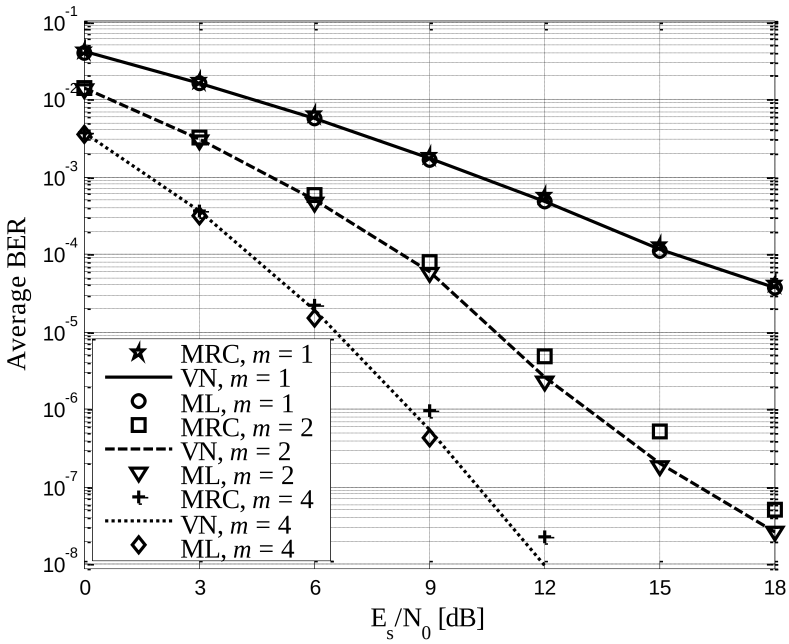

Figure 5. 10 Error performance curves when the relay is located in the middle

In Figure 5.11, a similar situation is observed when the relay is close to the destination.

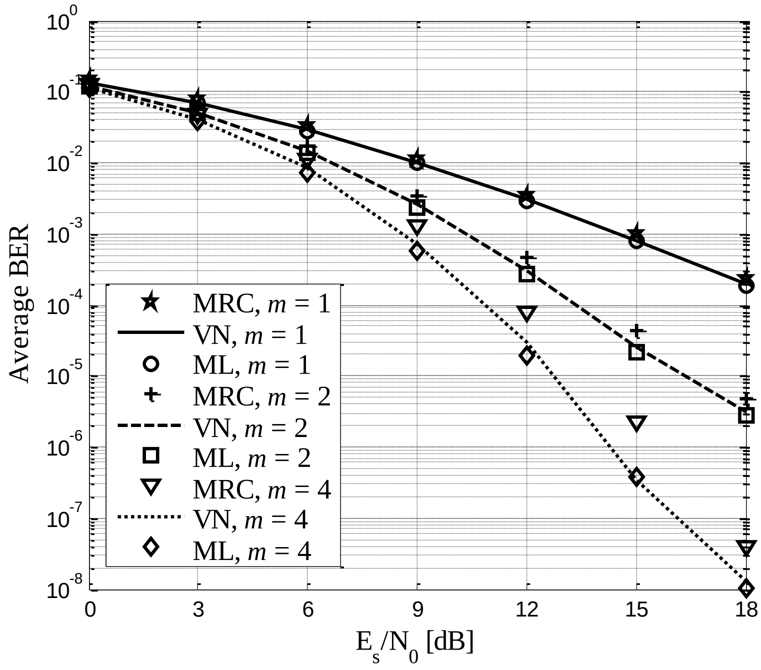

Figure 5. 11 Error performance curves when the relay is close to destination

In table 5.4, the BER gain values obtained by VN and ML technique compared to the LAR with MRC for various SNR values are given.

Table 5. 4 Average BER gain of VN and ML technique compared with classical LAR

Channel Structure	SNR [dB]	$d_{sr}(0.9)$ $d_{rd}(0.1)$		$d_{sr}(0.1)$ $d_{rd}(0.9)$		$d_{sr}(0.5)$ $d_{rd}(0.5)$	
		VN	ML	VN	ML	VN	ML
Nakagami m = 1	0	0.2577	0.2687	0	0	0.1075	0.1850
	6	0.4525	0.5350	0	0	0.2731	0.3550
	12	0.6078	0.7823	0	0	0.4458	0.5757
	18	0.6956	0.9150	0	0	0.4782	0.5504
Nakagami m = 2	0	0.3335	0.3445	0	0	0.1341	0.2437
	6	0.8025	1.0761	0	0	0.5628	0.8690
	12	1.8990	2.4650	0	0	2.4987	3.2330
	18	1.8054	2.3789	0	0	3.0103	3.0103
Nakagami m = 4	0	0.3994	0.4354	0	0	0.0504	0.1620
	6	1.2789	1.7821	0	0	0.6621	1.5365
	12	4.2313	6.0727	0	0	3.8021	6.0206
	18	4.7712	5.7403	0	0		

In Figure 5.12, average BER curves obtained for Rician channel is given. The BER curves obtained for two different Rician factor (K = 5 and K = 10) and the LAR technique using ML at the destination show the best performance compared to LAR technique with MRC and LAR technique using VN at receiver.

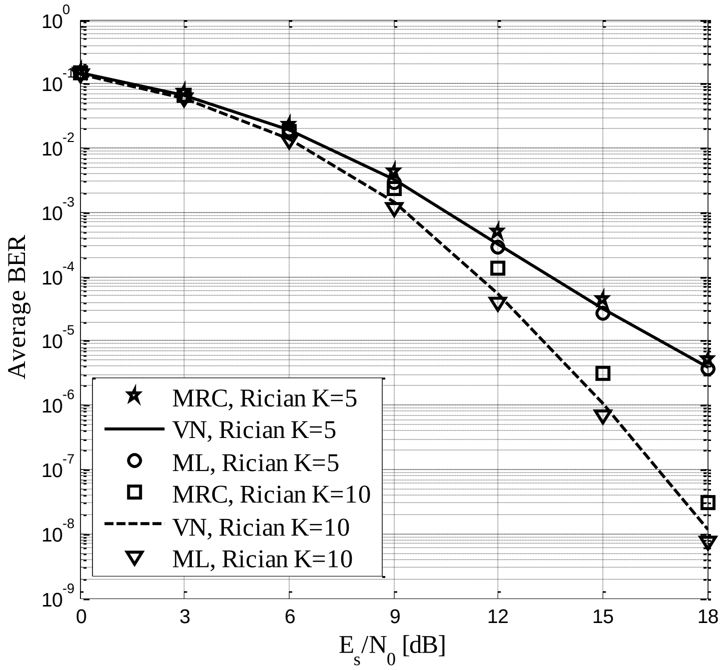

Figure 5. 12 Error performance curves for Rician channels

In Table 5.5, the BER gain values obtained by VN and ML technique compared to the LAR technique with MRC for various SNR values are given.

Table 5. 5 Average BER gain of VN and ML technique compared with LAR with MRC for Rician channel

Channel Structure	SNR [dB]	VN	ML
Rician K = 5	0	0.3025	0.2666
	6	0.7296	0.9194
	12	1.7142	2.3127
	18	1.1916	1.3901
Rician K = 10	0	0.3955	0.3538
	6	1.1025	1.4293
	12	3.8982	5.3237
	18	4.2596	6.0206

The increasing BER gain values as the relay get closer to the destination is the result of the decrease of the effective noise effect at the destination and the increase in the probability of error between source and relay. Since the probability of error between source and relay is not too much when the relay is located too close to the source, all of the techniques give nearly the same results.

Table 5.6 shows the SNR gains of the all detection techniques for a target BER of 10^{-5} when the relay is closed to destination.

Table 5. 6 SNR gains of the detection techniques at a BER of 10^{-5}

Detection Techniques	Nakagami m = 2	Nakagami m = 4	Rician K = 10
ML - MRC	0.87 dB	1.25 dB	1.20 dB
VN - MRC	0.6 dB	0.98 dB	0.85 dB
ML - VN	0.27 dB	0.27 dB	0.35 dB
VN(SR) - MRC(SR)	0.58 dB	0.27 dB	0.56 dB

These numerical results show that the same average BER values can be obtained with the VN and ML detection techniques in lower SNR values compared to classical LAR technique.

CHAPTER 6

RESULTS

In this thesis, a cooperative communication system where the source transmits its data to the destination with the help of a relay has been examined. At the relay node, selective relaying where the source signal is either forwarded or the relay remains silent and LAR approach, which is based on the idea of scaling the relay power with a coefficient depending on the link SNRs of the source-relay and relay-destination links, are used to reduce the error propagation. At the destination, three different detection algorithms VN (Virtual Noise), MRC (Maximal Ratio Combining) and ML (Maximum Likelihood) has been employed. The performances of these detection algorithms have been examined for different channel structures and the different positions of relay with respect to destination and source locations. The channel structure is obtained by assuming that source, relay and destination are placed linearly on the same axis and the distance between source and destination normalized to one. In this model, the relay is placed in different positions between source and destination and the performance of considered systems are obtained for both Nakagami-m and Rician fading channels. It has been shown by numerical results that VN technique provides better average BER performance than the MRC technique in most of the situations and this performance gain increases as the channel parameter value increases. When the relay is located very close to the source, all of the techniques give nearly the same results since the probability of error to be corrected by the relay between source and relay is not very high.

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CURRICULUM VITAE

PERSONAL INFORMATION

Name Surname : AHMET BOZDAĞ

Date of birth and place : 16.04.1988 Malatya

Foreign Languages : English

E-mail : ahmetbozdag44@gmail.com

EDUCATION

Degree	Department	University	Date of Graduation
Master	Communication	Yıldız Technical University	-
Undergraduate	Electronics	Isık University	2010
High School		Rahime Batu Collage (Science High School)	2005

WORK EXPERIENCE

Year	Corporation/Institute	Enrollment
2010-present	Netaş	Global Product Support
2008-2010	Işık University	Assistant
2009	Alcatel Lucent	Intern

2008	Bilgi Teknolojileri ve İletişim Kurumu (BTK)	İntern

PUBLISHMENTS

Conference Papers

1.A. Bozdag, H. Ilhan, Ö. Özdemir, İşbirlikli Telsiz Ağlarda Sanal Gürültüye Dayalı Sezim ile Link Uyarlamalı İletim , IEEE SIU, (2013)

2.A. Bozdag, H. Ilhan, Ö. Özdemir, Link Adaptive Relaying with Virtual Noise Based Detection in Cooperative Wireless Networks (will be submitted)

Projects

1. Simulation of error correction codes in the IEEE 802.16e Standard and their performance. (B.S Thesis-2010)

AWARDS

1. Superior Achievement Scholarship (Işık University 2005-2010)

2.Superior Achievement Scholarship (Rahime Batu Collage 2002-2005)