Energy Conservation of Co-operative Communication over Composite Channels

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Abstract

The studies about the effects of multipath fading and shadowing for wireless cooperative networks are insufficient. Almost all real wireless networks can be modelled by changing the parameters of the composite distribution which models both multipath and shadow fading. This composite distribution makes the analytical calculation of bit error rate (BER) difficult. In this thesis report, an approximation for this composite distribution has been introduced. A cooperative method, based on decode and forward (DF) for forwarding, is studied. For a required BER, for instance 10^{-2}, the gain in terms of power with using the cooperation with one relay is 4 dB in comparison to a case with same amount of energy to send a same message for a non cooperative network. The impact of parameters of composite distribution on the gain of cooperative communications (CC) in terms of power is discussed. In this work, the optimum value for power allocation in the relay and sender for a cooperative network is found in the simulations. The different position of a relay in a parallel line with respect to the line of sight (LOS) of the sender and the receiver; and its impact on the BER is investigated. The random deployment of the relays in the network is also investigated.

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Preface

Typically in a graduate program, students are encouraged at the very beginning to keep their minds open and look at any idea and any person as their prospective thesis subject and thesis adviser. Like most of my classmates I was planning to do very good on all my courses and to talk to all faculty members to be sure I make the right decision. The story of my academic career, however, happened to be totally different. I sharply remember that my first class in grad school was the course on Ad hoc Networks. I was deeply moved by the beauty of the ideas presented in the class. The thing I liked most about Cooperative Wireless Networks was the fact that simple ideas taken from our everyday life were taken to develop complex theoretical structures that created the technologies which are changing our lives every day in such a fascinating way, and I was seeing this whole cycle for the first time. I took many other courses in the first two semesters, and needles to say they were all interesting topics taught by people who were world class experts in those fields, but none of them inspired me in the same way that the first class did. A big part of that, for sure, was for the personal and professional characteristics of Dr. Onur. Now looking back I think choosing this topic has been one of the best decisions I have made in my life, and also having the honour to be supervised by Dr. Onur has been a wonderful experience for me during the time. I think what I have learned from him has had a profound effect on my life and it is going to continue guiding my professional life as a researcher in future.

Acknowledgements

I would like to thank Dr. Onur and Rizvi for their helpful assistance during the writing of this thesis.

"I want to dedicate this work to my parents because of their support and understanding when I was far away from home."

— *Khashayar Kotobi*

Chapter 1

Introduction

In this chapter we present an overview of wireless communication, its application and limits. After that, an introduction of cooperative communication which is quite a new field in the telecommunication industry is introduced. The third section is about the mathematical description of the topics in the report. In the last part, an overview of the subjects which are presented in this report is introduced.

1-1 Overview

Wireless communications is the fastest growing part of the telecommunication industry [1]. This method of communication is an answer to the need of users to connect anywhere, any time, with any desired speed and quality of service. The communications with any desired speed is not possible yet. This service must be as cheap as possible. With respect to these properties for a desired communication system, it is obvious that there are lots of trade-offs and as a result of this fact many improvements can be made based on the users needs. With change of wired communication to wireless communication; connecting from anywhere is more feasible.

With this change from wired to wireless, the amount of noise and other undesired signals will be more in the receiver side. This will lead to a higher bit error rate (BER) in the system. Another drawback in wireless systems is the fact that the state of a wireless channel is not stable and constant. With a simple movement of an object in the network area; the channel is going to be blocked for a transmission. In this case the distribution of the variables, which mathematically describe the system is important for us to evaluate the performance of system. In this case, the measurements and the science of probability is going to help researchers better describe the channel. For this mathematical description, we used [2] in this work. The instructions in [2] give a very thoughtful and understanding mathematical description of wireless channels with the effect of undesired signals and fading channels. This thesis work is an extension of [3].
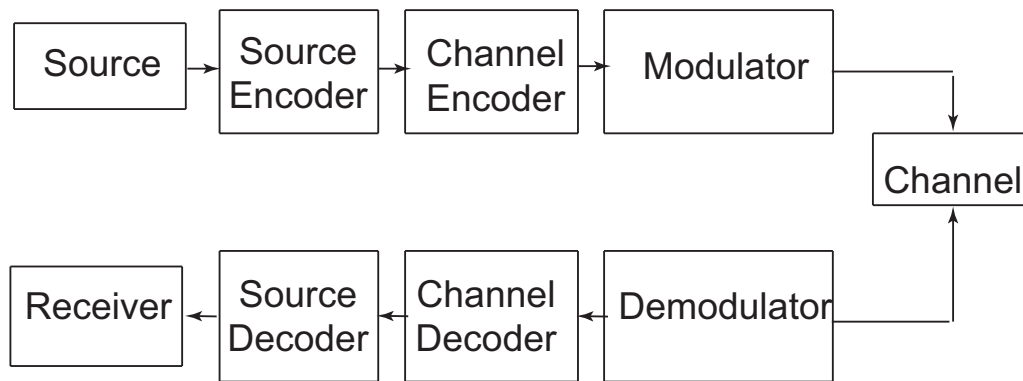
Figure 1-1: Representation of a communication system

New aspects of cooperative communications, like the performance of network in the multipath fading and shadowing is a new problem to overcome. These new problems are imposed to a telecommunication system with the change from wired systems to wireless systems.

1-2 Wireless Communication

1-2-1 Background

In 1901, physics Nobel Prize winner, Guglielmo Marconi first introduced the modern wireless communication by transmitting the three-dot Morse code of 'S' through a three kilometres distance [4]. In the wireless telecommunication system, information is transmitted without usage of any wire between the sender and receiver. Information is sent similarly to a typical communication system, like the one illustrated in Figure 1-1. In Figure 1-1, the procedure to send a message form a sender to receiver is illustrated. First the source encoder block, encodes the message, which is sent from a sender to a receiver, and removes redundant information. Then, the channel encoder encodes the message based on the channel performance to get a desired value for BER or symbol error rate (SER). This is for the systems that have channel state information (CSI) at the transmitter. The last block before giving the message to the channel is the modulator which makes the signal appropriate based on the specific channel after the channel encoder. The main difference between wired and wireless communication systems which has an effect on the performance of the whole system, is the channel. The channel's properties will make a relation between the amount of BER and the data rate. This block(channel) in Figure 1-1 will force the processing on the other blocks to be different from a wired network to a wireless network.

The main point of this study, is the fact that the multipath fading and shadowing will degrade the quality of the channel in wireless communication; which in its turn will impose different constraints for users in comparison to the wired one. There are many applications which can be associated with wireless communications, like voice, Internet access, short messaging, file transferring, sensing, distributed

controls and so on. Systems which use this technology are different according to their performance and coverage. The examples are, wireless LAN, satellite systems, ad hoc networks and so on. The coverage regions of these systems can vary from a building to a city or even global. There are lots of standards and characteristics for a wireless network and this is due to the fact that different wireless applications have different constraints and requests. For instance, the important parameter for making a voice communication, is delay. This delay must be less than 100 ms; but it is relaxed in respect to BER. For data transmission as another application of wireless communication, the delay and it's variance is not as critical as for the voice communication; and the important factor here is the fact that BER must be in order of 10^{-8}. Some applications even have more constraints. For real time applications like video conferencing or videos in internet the amount of delay and also data rate is important; and must be in a certain range. In the case of wired networks, the data rate is in order of Gbps and the BER should be 10^{-12}. To meet the requirement of different applications; the protocol running in these networks must meet the highest requirement of all applications. This is not a case for wireless network with much lower data rate and much higher BER. This will lead to different protocols for wireless communication networks based on their application and coverage regions.

1-2-2   Telecommunication Layering Concept

According to the open system interconnect (OSI) which is proposed by the international standard organization (ISO), there are seven layers for a typical telecommunication network [5]. For wireless networks, not only the bigger amount of bit error rate and average delay in comparison to the wired networks; but also their bigger amount of variance in these variables, force the network designer to change the layering concept of wired networks to a more efficient one. The layering concept and abstraction is a de facto term for designers and it can be changed due to different requirements and constrains.

In this work, the physical layer and network layer are mixed to achieve better results than current wireless networks. This will help to mitigate the poor performance of wireless communication over noisy channels which have multipath fading and shadowing effects. Some novel approaches have been proposed by researchers to mitigate the bad performance of a wireless network; one of these new methods is the cross layer protocol design. The advantages are less amount of delay and BER; but the cost is destroying the homogeneity in the field which will result in a bigger price for the costumers.

1-2-3   Ad hoc Wireless Network Challenge

Ad hoc networks are decentralized wireless networks. This property makes it easy for these networks to scale and set up easily. Because of its nature, these networks are robust and flexible to different challenges. Based on distributed nature of these networks, all the processing and functionality of the network must be done in each node of the network in a distributed fashion. We can see that energy consumption

of each node in these networks is important; since each node must not be complex and also cheap. The nodes often must be designed in a way that have really long life time without the need for charging the batteries. This will lead to the challenge of saving energy for different applications and also keep the desired performance. In this work, we try to achieve an energy saving gain by usage of cooperative communications (CC) for transmitting information. Using this method along with the cross layer approach which was introduced in 1-2-2; a more complex node and protocol is defined to achieve a same BER by less amount of energy to send a certain message.

Energy considerations are not the only challenges one faces in designing ad hoc networks. Additional measures should also be taken into account including, the reliability. The channel block in the Figure 1-1 for wireless networks are unpredictable and it's nature only can be described by random variables with specific statistical characteristics. The spectrum for wireless communication is a scarce resource; as a result, the higher frequencies are assigned for usage in ad hoc networks. In these high frequencies the effect of path loss is dominant and in this work, path loss is considered for calculation of the BER. The next challenge is how to make a correlation between lots of standards and protocols in this field.

In the next section, the mathematical base of this work to characterize the channel of the wireless network and its application in this case is investigated. The procedure to calculate the BER is also introduced.

1-3   Mathematical Background

In this section, first we introduce how to make a mathematical description of a channel; and then how to calculate the BER based on that.

1-3-1   Channel Description

The common way to evaluate a channel in a wireless network is measuring the average signal to noise ratio (SNR). SNR is the division of signal power and the thermal noise in the receiver. We use the average value for this property due the fact that there are shadowing and multipath fading in the channel which will result in various amount of power for received signal. This variation in the amount of received signal's power or amplitude which can be expressed by usage of a probability density function (PDF). With this PDF the amount of average SNR can be found based on the following equation:

$$\bar{\gamma} \hat{=} \int_0^\infty \gamma p_\gamma(\gamma)\, d\gamma. \tag{1-1}$$

Where $\bar{\gamma}$ is the average SNR and $p_\gamma(\gamma)$ is the PDF which represents the random distribution of the SNR. It is not possible to calculate this integral analytically.

The reason is that there exists no close form for a pdf which accounts for the real life situations.

For a simple PDF, the moment generating function (MGF) approach which is introduced in [2] can be used to calculate the BER or SER. The PDF used to describe the channel here is more difficult to handle and MGF is hard to find analytically. The thermal noise in the receiver with also shadowing and multipath fading together; are included as the undesired signals which will add to our desired signal. To the best of our knowledge, it is the first time that all of these effects together are used to evaluate the CC in wireless networks. This will lead to calculations based on the PDF only, and usage of 1-1.

Another step to calculate the average SNR is to calculate the composite PDF. This composition is result of the multipath fading and shadowing. The composite PDF can be found by usage of Nakagami-m and Log Normal distributions. This PDF and a novel approach to approximate it, are presented in this work.

1-3-2   Bit Error Rate Calculation

For better evaluating our proposed CC wireless networks the BER must be calculated, with respect to SNR according to the Section 1-3-1. The reason behind this is that most work in this field are using this measure to evaluate their networks. BER is a non-linear function of SNR and in this work this function is found.

Like similar cases for calculating the BER, this function is based on the Q-function. The most important factor that make finding the BER difficult, is the fact that fading parameter is also a function with an integral. By adding the relays and as a result of this new path for signal to receive the complexity of calculation will increase. We do not have an MGF, so we need to calculate the BER directly.

Another important factor to calculate the BER function, is the usage of RAKE receiver in this work. RAKE receiver has different branches which correspond to different multipath component of the received signal. In each branch, there are several components. First the whole signal is going to be multiplied by a signal which is orthogonal to the corresponding multipath component. After this, the output will be the corresponding multipath component. This will be input to a coherent demodulator. The result of all the coherent demodulators of all branches will be the input signals of the diversity combiner component of the RAKE receiver. Based on these signals the output will be calculated. In the simulation procedure, a RAKE receiver is assumed in our network.

Thermal noise also affects the BER. It's influence is at the input of receiver. In a CC wireless network, we assume all the nodes have almost same receiver antenna and as a result of this, we can conclude that the thermal noise is same for all nodes in the CC wireless network. When we have more than one path to receive a signal, for instance when a relay successfully decodes the message from the sender in decode and forward (DF) approach, the thermal noise will only be added to the received signal from the path between the relay and the receiver. This is another advantage in our analysis of CC in wireless networks.

After finding the composite PDF according to Section 1-3-1, there would be another integration with Q-function and this PDF to calculate the BER. In conclusion, the sender is broadcasting a message in the air as a channel, there would be a relay in the CC case to overhear it without more energy necessary from the sender. The amount of energy used to send the message is going to determine the amplitude of the received signal in ideal case without any shadowing or multipath fading and noise. However, the multipath fading and shadowing effects will impact the received signal as the channel coefficients. The thermal noise is going to be added to this received signal both in the relay (CC case) and also the receiver. Based on these variables and their statistical characteristics, the BER is calculated. The result of this calculation will help us to compare an ordinary wireless network to a wireless network with CC from the energy consumption point of view, and with respect to this new metric (BER).

1-4 Cooperative Communication

In this section, the concept of CC in our work is introduced. The concept of CC in wireless communication was introduced in [6]. The main point is the usage of diversity. Due to nature of wireless communications; signals broadcast, so other nodes can also receive it. The channel is not only unreliable but also it's properties varies over time.

1-4-1 Multipath Fading

A radio frequency (RF) signal carrying information may face objects while being transmitted form a sender to a receiver. These objects reflect, refract, diffract or interfere with the signal according to their physical properties. Based on the interactions with these encountered objects in its way; duplicates of the signal may originate. They may reach the receiver; but it is not going to be in the same time, amplitude and phase; as the main signal.

This phenomena can have both positive and negative influence on detection of the message in the receiver. If the duplicate signals are going to add with different phase shifts, they can cancel out the main signal. Therefore the total received signal may be lost in the thermal noise in the receiver. Another negative effect can be receiving a multipath signal in the time slot of other message for the same or another receiver. This signal will be considered as undesired signal at this time.

Assume a case of communication between a sender and a receiver as shown in Figure 1-2. There is a direct line which is indicated as line of sight (LOS) in the 1-2. This channel is responsible for the main received signal. As it can be seen in the figure, there are two other objects which can reflect the signal sent by the receiver. They reflect the signal to the receiver and these components will make the multipath component of our received signal.

With careful design of a wireless network, this multipath fading can be regarded as an effect to improve the performance of our network. As it mentioned before, the
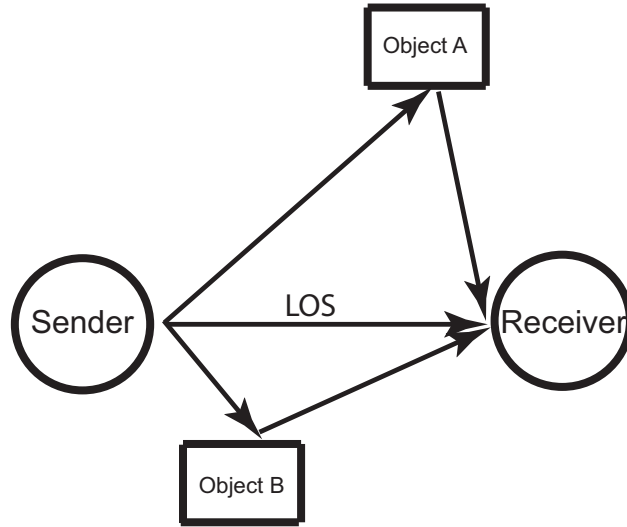
Figure 1-2: Multipath effect in a wireless communication

channel properties in wireless network are varying. If a main signal and it's channel are blocked by an object or it's performance is not good enough, other multipath components can be used to retrieve the sent information.

To make this possible, first the interval time between any two source symbols must be more than the maximum difference between arrival time of a multipath signal and the signal from LOS. This will help to make the inter symbol interference (ISI) minimum. Another important factor for the receiver to use diversity is its ability to add all the signals in a same phase shift. This can address the mentioned problem of destructive addition of multipath components.

1-4-2   Path Loss

As the spectrum for wireless communication is a scarce resource, there is a need to search for alternative frequency bands. In the 60 GHz band there is an unlicensed bandwidth of 5 GHz. One of the important factor for communicating in this bandwidth is the large amount of path loss. This large amount of path loss can be formulated in the modified Friis equation:

$$\frac{P_r}{P_t} \propto G_t G_r \left(\frac{\lambda}{R}\right)^n, \tag{1-2}$$

Where P_r and P_t represent the power of received and sent signals respectively, G_t and G_r are representing the antenna gain of the receiver and the sender, λ is the wavelength of the signal and R is the distance between the receiver and sender's antennas.

Even a simple blockage of a channel by a moving object will cause to reduce the signal to a level that the signal will be lost in the thermal noise in the receiver; due to this large amount of path loss. When a channel in this frequency band is blocked;

other multipath components of received signal will help the receiver to decode the message. But we need to consider the fact that the reflection loss is also really high in this frequency band. Therefore, a network which is deploying a good receiver, and a protocol that can employ both the LOS and multipath signals is desired. To compare new method; a simple scenario which only use LOS is going to be used in this work. The difference between BER for the same amount of power in two cases; will show the gain of our proposed method.

One of the new factors in this work is adding both path loss and multipath fading together in to the consideration for calculation of BER. The effect of path loss is presented in this work by usage of Log-normal distribution. The parameter of this distribution is the same for all the scenarios in this work.

1-4-3 Cooperation Concept

Cooperation in this work is adding new channels to the direct channel by employing the relay. The relay like the receiver can overhear the message and there is no need for more energy to retransmit the message to the relay again. So in a case that the LOS is blocked, the message can be retrieved from received signal sent by relay. The relay has same functionality as the sender and the receiver. So a sender or a receiver in a transmission, can be a relay for another transmission. The total amount of energy relay and sender use to send a message must be same to amount of energy a sender uses to send the same message in a simple case; so the comparison and gain in BER can be found.

1-5 Problem Definition

The use of the spatial diversity using cooperative communication in wireless networks will lead to decrease power consumption. Relay nodes use different methods for forwarding the message; but in this work we assume the DF as the forwarding method. In the receiver we assumed the maximal ratio combining as our space diversity combining scheme. For the channel, we assumed a composite distribution which can model both shadowing and multipath fading effects.

Since most work in this field only assume multipath fading or shadowing, with this composite distribution; we can nearly model most wireless channels.

In this work we want to calculate the gain of CC in comparison to the case of direct transmission between the sender and the receiver. This gain is in power to achieve a required BER. The impact of composite distribution and power allocation to relay is investigated.

After finding the gain in power for the CC, we investigate the impact of the position of relay in gain. Then for different network scenario, the gain of CC in comparison to direct transmission between receiver and sender is studied.

More detailed problem definition and assumptions can be found in each chapter.

1-6 Organization of The Report

In this section the organization of this report is presented.

- First, in the literature survey, a summary of the most recent works in the field of CC is presented. The concept of CC is a rather new concept and there is not a homogeneous protocol which can be used as an standard. This is due the facts explained in Section 1-2. To the best of our knowledge the impact of both multipath fading and also shadowing on the energy conservation is not adequately studied. As a result lots of improvements can be made in the performance of CC in the real life wireless networks.

- Chapter 2 is dedicated to the mathematical background which is needed to calculate the BER. MATLAB and MATHEMATICA are used for simulations and analytical modeling respectively. In this section, first different statistical distributions which are used in this work is examined. Then, the calculation of BER is presented. The calculation is going to be implemented in MATHEMATICA. The simulation results from MATLAB is going to be used to compare the result in different scenarios.

- Chapter 3 is about presenting the results and improvements. It is going to be shown that the MATLAB results for simulations are in perfect match with the analytical results of MATHEMATICA. So the simulation procedure can be used for better understanding of CC properties in the fourth chapter.

- In Chapter 4, there is an investigation about the proposed method. Different position of the relay and it's impact on the BER and the energy usage is presented. In other parts, the random deployment of the nodes are investigated.

- In the last chapter, conclusions of this work are presented. There is also a proposal for better exploiting the CC properties for future home networks and also the improvements for this work, is presented as future work in the last chapter.

- In the appendix, the statistical properties of distributions in this work for different environment in the real life is presented.

Chapter 2

Literature Review

In this chapter, a literature survey about the cooperative communications (CC) in wireless networks and the motivation which lead to this concept is presented. The concept of multiple-input and multiple-output (MIMO) and its properties as one of the motivation for CC in wireless communications is discussed. The focus is on the physical layer; but a quick look to other layers is also provided. This is due the importance of cross layer design in CC in wireless networks. There is also a section about the literature work on the mathematical basis of this work.

2-1   Overview

The CC first introduced by "Laneman" [6]. In the [6] some CC protocols introduced to exploit spatial diversity, which was mentioned in Chapter 1 as a method to improve the performance of wireless networks. The relay nodes in these protocol use amplify and forward (AF) and decode and forward (DF) as their forwarding scheme. These concepts will be introduced later in this chapter. Authors in [6] used half-duplex operation which requires twice the bandwidth in comparison to a simple line of sight (LOS) case. They showed how CC will improve the the outage probability for the same amount of signal to noise ratio (SNR) for these different protocols.

There is much more research to do about the better and optimum spectral efficiency [6]. Which is due to fact that the proposed protocols are simple and their proposal was not to make this spectral efficiency optimum. Their goal was to decrease transmit power for the same reliability, or for the same amount of transmit power, better reliability for the network's performance. Here in this report the measure for reliability is bit error rate (BER).

The channel model used in most works, are not representing the complete image of real life; so more work must be done about the different types of channels. Which is the case for this report [6].

The last proposed future work in [6] is about the number of relays. They only investigate the impact of two relays on outage probability based on SNR.

With respect to Chapter 1, one of the goals in wireless communications is the data rate and the reliability. With introduction of MIMO, this goal can be achieved. An overview about how a giga bit per second wireless communication is possible can be found in [7]. This overview covers channel models, capacity, coding and performance design. They suggest that only hardware for multichannel radio frequency (RF) and digital signal processors must be in reasonable price to make this giga bit per second rate in wireless networks possible.

The basic idea behind the CC in wireless network, is derived from MIMO technology. In [8], a review about the capacity of MIMO network is investigated. This capacity can be achieved from a CC in wireless networks by sufficient amount of relays. Based on the fact that each new relay can make a new channel from the sender's antenna to the receiver's antenna.

After this understanding about MIMO, a tutorial about an overview on how a cooperative network can be made to get some benefits of a MIMO system, is presented in [9]. Several signalling schemes for CC in wireless networks also introduced.

After this proposal, the usage of CC in the field of telecommunications evolved rapidly. For instance, authors used cognitive radio (CR) approach to enhance the spectrum sensing and sharing in the case of CC in [10]. They also concluded that cooperative spectrum sensing can handle the hidden node problem. They also proposed some solutions for channels with multipath and shadowing effects. They also shown that dynamic spectrum can be used completely by adding CR relays.

The advantages of CC are not questionable in a wireless networks which have resource constrains, like wireless sensor networks. In these networks, power allocation is important since the power is a scarce resource and when a battery dies in a node, the node is also dead. One of the works which covers the power allocation for various scenarios can be found in [11]. Various power allocation plans for CC in wireless network has been evaluated [11]. But they used channel state information (CSI) for their protocols which cannot be always be estimated or sent by relays. Their studies also focused on one relay rather than multi relays.

As it mentioned in the Chapter 1, the concept of CC will lead to cross layer design. Authors in [12] exploit this opportunity to make improvements in throughput, delay, robustness, reduction in interference and also coverage region. In [12], with a study of cooperation in layer one and two according to open system interconnect (OSI), they showed the importance of cross layer design for CC case in wireless networks. With a study of media access control (MAC) protocols in the field, there is a proposal for new MAC in [12]. They called it CoopMAC.

This cross layer design can help the cooperation in physical layer by means of new and optimized routing. An example of this can be found in [13]. In [13] they used DF as forwarding method for cooperation in the relay nodes and with their proposed method for routing they gained a better outage probability in comparison to a given number of relays in the network. They also showed for their scenario the number

of nodes in the route path has a little influence on the outage probability. They also introduced the optimum transmission power when each node in the path has a same outage probability as their future work.

Different strategies for forwarding a message in the relays have been discussed in [14]. They studied DF and compress and forward (CF) as forwarding methods in CC in wireless networks. After calculating the capacity of the channel and comparing the results for DF and CF, they concluded that DF is better for networks in which the relays are close to the source node; and CF gives better results when the relays are closer to the destination. They proposed finding the capacity of channels for CC in wireless networks not only for one relay network, but also for multiple ones as a future work in this field. Since even capacity for a case of one relay network is not understood well.

The CoopMAC protocol is using two versions of the same data for decoding the message at the receiver; which is similar to the decoding procedure presented in this work for one relay scenario. With simulation results, authors in [12] showed improvements on the system's performance.

In [15] two protocols introduced to address the problem of power consumption in large wireless ad hoc networks. They compared these protocols by the number of deployed nodes for cooperation with respect to the power consumption. Their protocols are distributed and localized which can be applied to strongly connected networks.

Despite the fact that cross layer design can really help the CC in wireless networks, there is not enough work in this topic. In [16] a higher layer research has been done for CC in wireless networks. In [16], authors tried to investigate the impact of control signals and also overhead in total performance of a wireless networks in contrast to all idealized scenarios which can be found in the literature. In this article, they compared different scenarios with respect to overhead informations.

The concept of CC in wireless networks also lead to new ideas like network coding and coded cooperation. An example of this coded cooperation can be found in [17]. These new techniques make a fairly good improvements for channel capacity in wireless networks, based on the fact of overhearing a message. In [17], they proposed a coded cooperation which can improve the BER for a given SNR in the system. They showed that improvement both analytically and also in the simulations.

In CC, the problem of power allocation is another field of study. In [18], there is a proposal for distributed beam forming and power allocation algorithm so the diversity of network will improve. They used outage probability as their metric in comparison to SNR to show the improvements.

There are various cases for CC in wireless networks, and one relay scenario is the most common one in this field. In [19], for a one relay scenario authors investigated optimum power allocations based on BER. In their study, they assumed AF for the forwarding method for relay nodes. Based on these two cases, when one relay is close to the sender and when it is closer to the receiver, they showed how much their proposal for power allocation will improve the system performance based on BER.

After this overview, in the next section the focus is on MIMO technology and it's advantage. Since the basic idea behind the MIMO is used in CC in wireless networks.

2-2   MIMO

The basic fundamentals of CC can be understood by studying the MIMO technology. According to a review of the MIMO based technologies proposed for satellite communications in [20], the advantages and degree of freedom (DoF) of MIMO can be categorized in the following items:

- Diversity gain

- Spatial multiplexing gain

- Coding and array gain

- Reduction in interference

There is a good literature survey on this topic in [21]. In the following sections, these properties of MIMO systems in the literature are studied.

2-2-1   Diversity gain

The main point of diversity gain in MIMO can be achieved when there are different channels between the receiver and the transmitter. It means when a channel is blocked or experiencing fading; other channels which are good enough for a message to be sent can be used.

In [22], this property of a MIMO system is used to calculate the capacity of a system in an urban area. With an urban propagation model in [22], authors calculated the channel capacity characteristics of an urban area in the case of multi-user MIMO (MU-MIMO) in contrast to their previous work in [23] about single-user MIMO (SU-MIMO).

As it is the case for CC, spatial diversity can best exploit the property of a MIMO system rather than diversity in time or frequency [7]. The receiver in CC wireless network and also MIMO, will combine the arriving signals so the resultant signal has a less variability than a LOS link.

2-2-2   Spatial Multiplexing Gain

By correct scheduling of multiple users to share a spatial channel, we can enhance the overall system capacity [8]. But the cost of this will be an extra hardware cost, such as new antennas and filters (to detect a desired a signal from received signal). This technique unlike time division multiple access (TDMA) and code division multiple access (CDMA), need more bandwidth allocation does not.
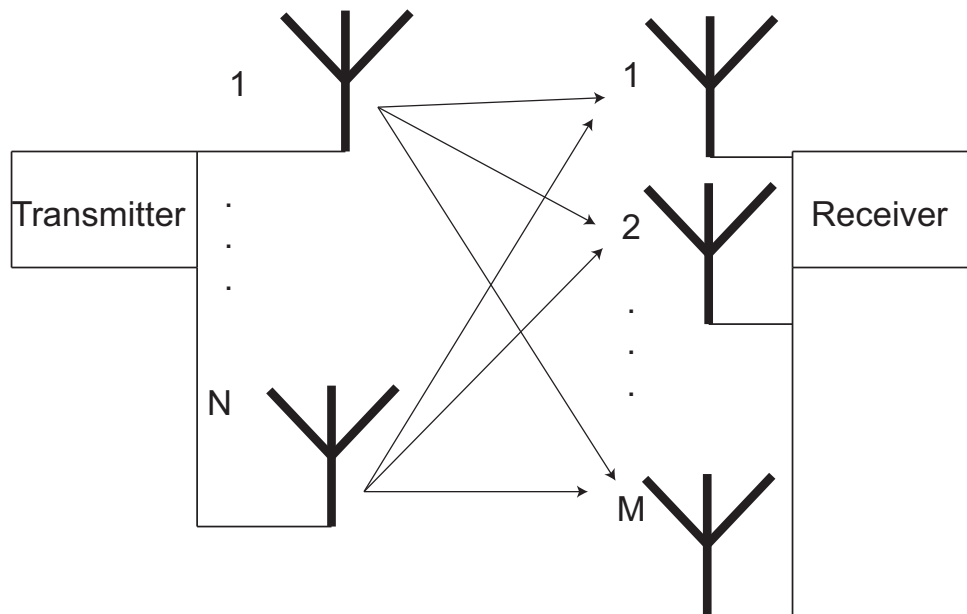
Figure 2-1: Representation of a MIMO system

In the Figure 2-1, a transmitter is communicating with N antennas to a receiver with M antennas. So there are N times M channel to communicate, which increase total systems capacity and also gives diversity gain to users.

In [24], a survey about the information theory point of view of MIMO and a measure to calculate the capacity of these networks has been presented.

2-2-3   Coding

For better error performance of a system, most schemes use a coding structure which is composed of one dimensional encoders and decoders. But usage of orthogonal codes is also growing in the MIMO technology. This will make different dimensions like time and frequency in TDMA and frequency division multiple access (FDMA). Which in their turn can also increase the capacity of a MIMO system.

Performance of a MIMO system with multi carrier code division multiple access (MC-CDMA) and orthogonal frequency division multiple access (OFDMA) based on BER is investigated [25]. They concluded that when the load of system is low, MIMO with MC-CDMA's performance is better than OFDMA case. But when the load increases, the performance of MC-CDMA is worse. The simulation results are also one of the first attempt to calculate and compare the BER for MC-CDMA and OFDMA in this field [25] .

2-2-4   Interference and Inter symbol Interference

As a result of channel reuse in wireless networks, other channel's interference will degrade the overall performance of system. In the case of MIMO with knowledge of

the desired channel, the spatial signatures of that channel can be used to reduce interference [7]. This interference reduction will result in aggressive frequency reuse which in turn lead to improve the capacity of system.

In contrast to previous idealized situations, we may encounter inter symbol interference (ISI). One suggestion to mitigate this effect according to [21] is the usage of a multi carrier transmission scheme. Then we can multiplex data symbols to parallel narrow bands which are quasi flat.

2-2-5   New Ideas in MIMO

A new method for data detection in MIMO systems is proposed by [26]. In their switching detector based on different modulation scheme, they showed that there is a gain of about 52 to 72 percent in SNR.

As it mentioned in the Chapter 1, cross layer design is not only a good approach for better performance in CC wireless networks; but also in MIMO systems. In [27], a new MIMO scheme for a wireless sensor network (WSN) is proposed with a cross layer routing protocol. With a given reliability requirement, authors in [27] showed that, they proposal will lead to lower amount of SNR.

2-3   Cooperative Communication

After studying fundamental properties of a MIMO systems and the improvements they can make in wireless communications, in this section we investigate the properties of CC in wireless networks. As it will be shown later, most properties in MIMO can be found in CC; but since there is no need for multiple antennae in each node, CC can be used in more wireless networks.

When there are one or more relays to help a transmitter to send it's message to a receiver, we have a cooperative wireless network. The power is going to be distributed according to the following equation between the relays and the transmitters:

$$P_{tr} + \sum_{i=1}^{N_r} P_i = P_{total}. \tag{2-1}$$

In the above equation, P_{tr}, P_i, P_{total} are transmitter's power, relay's power, and total power allocated to send a certain message, respectively. N_r is the number of relays in the wireless network.

With a certain power allocation method in a network based on the desired performance and the requirement of system, these relays will help a sender in forwarding it's message toward the receiver. As a result, a receiver will receive several replicas of the message via independent channels [28].

These relays will help the network overcome multipath fading and shadowing by introducing spatial diversity. There is a trade-off between the number of relays,

amount of power, BER, delay and data rate, complexity and so on. Smart methods and protocols based on this trade off can be found in order to meet the desired performance.

With respect to the Chapter 1 and as the authors summarized in [12] we can include the following items as advantages of CC in wireless networks:

- More spatial diversity which leads to better performance against all kind of fading in a given wireless channel

- More throughput which is due to increase in the capacity of network as it was calculated by [6]

- Reduction in power for the same reliability

- Adaptability to network conditions which can be achieved by redistribution of the network

A good overview of CC in wireless networks is presented in [29]. The main concept and properties of a one relay cooperative wireless networks are also illustrated [29]. There are also simulation and analytical results to compare different protocols of CC regarding the case of LOS.

One of the recent work in CC, can be found in [30]. Authors in [30], assumed a wireless network with N relay (for network representation look at Figure 2-2). They assumed Nakagami fading channels for their wireless network. They come up with a closed form expression for outage probability. With their power optimization strategy, they made a gain in terms of SNR for a given outage probability requirement.

Another work that focused on the N number of relays is [31]. They used outage probability as their metrics to compare different protocols for forwarding in the relays.

In the case of study of a CC in wireless networks in higher layers, specially in MAC layer, it is important to investigate a network with N relays. In [32], a new study in N relay network is done.

In WSN with respect to the nature of nodes, battery lifetime is an important issue. The reason is that, as stated earlier, when a battery dies, a node also dies. Energy efficient protocols for WSN is studied in [33]. Sensors will cooperate in a deterministic way for communication in [33]. If we calculate the overhead imposed by cooperation strategies and protocols; and if the long-haul distance in clusters are large enough, authors in [33] showed that CC will reduce the total energy.

A simple relay selection strategy has been introduced for a network with N relays, in order to save energy. They also used some other schemes to make a comparison with this new proposal in [34].

As it mentioned in [35], a CC with a best selection of the relay among all N relays of network, is an effective communication scheme for networks like WSN, which are energy constrained networks.

For a higher layer point of view, [36] proposed the following properties as the advantages for CC:

- Reducing BER and increasing reliability for wireless channels with time varying channel

- Decreasing delay and increasing the data rate

- Saving energy, improving spatial frequency reuse and reduction in interference

- Expanding the coverage and reducing outage probability

A proposal for future home networks is proposed in [3]. Authors in [3] studied the impact of cooperation in a network connectivity of 60 GHz using a realistic indoor environment model.

After an overview in the field, there is section in [3] to analytically calculate the BER according to moment generating function (MGF) approach as it is discussed in [2]. They assumed channels with Nakagami-m fading and with additive white Gaussian noise (AWGN). For their simulations and analytical calculations they assumed binary phase shift keying (BPSK) for modulation of data in the channel.

2-4   Multipath fading and Shadowing

In this section we focus on the problem of channel modelling in the literature. This is the reason behind the fact that the results of most works in this field cannot be compared. This also will lead to less coherence between the real life situations and the results obtained by research.

There is a proposal for a distributed cooperative routing algorithm in [37]. Most of the wireless device used in an ad hoc networks use batteries for their power consumption and as a result, that power is one of the most important factors to evaluate the performance of a certain network. In [37], authors proposed a routing method which can improve the performance of current routing methods up to 21.22 per cent.

Correct simulation of the real life channels is one of the most important factors which can make a correlation between the research in the field of CC in wireless networks and generally the communication theory with the real life. This can be done by modelling both the shadowing which is the random blockage of the channel and the multipath fading. These issues are addressed in the next chapter completely. Unfortunately; most research works in this field only address one of them; and these are really few cases which take the shadowing and multipath fading into the consideration.

For instance in [38] authors only assumed path loss in the channel. They assumed that communication is taking place over a flat fading channel which lead to the fact that the phase only depends on the distance in [38].

In [37], a propagation model with consideration of path loss and Rayleigh fading is used. Rayleigh fading is a model for some cases of multipath fading; but it cannot cover all different wireless channels. As it can be seen, there are lots of work to be done in this field regarding the modelling of the propagation channel.

Here in this work, we try to introduce a composite distribution which can nearly simulate all the wireless channels. This composite distribution is composed of the Log-normal and Nakgami distributions.

In [39], authors assume a channel model which incorporates both path loss and Rayleigh fading. They also mention that the power consumption of CC is not only affected by the quality of service (QoS) factors; but also the relative distance between the relay and the source and destination pairs. This conclude the study in [39].

Most important result of the work in [39], is the calculation of the total gain based on the position of the relay in the network. They plot the result in a three dimensional graph in their report.

2-5   The Number of Relays in CC Networks

The study of a CC in wireless networks, can be categorized in three topics:

- a network with only sender and receiver to make a metric for comparing the following cases
- a network with one relay
- a network with multiple relay

In the Figure 2-2, N is the number of relays in the network and the sender and the receiver's direct channel is represented by LOS.

As in the literatures, most works focus on the case of a one relay and they do the performance analysis by comparing it with the case of a network with only a sender and a receiver. For instance in [29], authors use symbol error rate (SER) as their metric for this comparison. Another example in this category can be found in [40].

There are also some works in which they assumed a network with N relays; but they propose some relay selection schemes to simplify the problem to a network with only one relay for cooperation. The examples are [34] and [35].

An investigation is conducted about the system performance by changing the N from one relay to five in [3]. The metric for performance evaluation in [3], is the average BER.

As it mentioned in [36] when many relays are considered for a communication, two problem may arise. First is the increase in the interference, and second more overhead control is needed.

A delay for different protocols for forwarding based on the number of relays is presented in [31]. A calculation for a channel capacity based on the number of relays can be found there too.
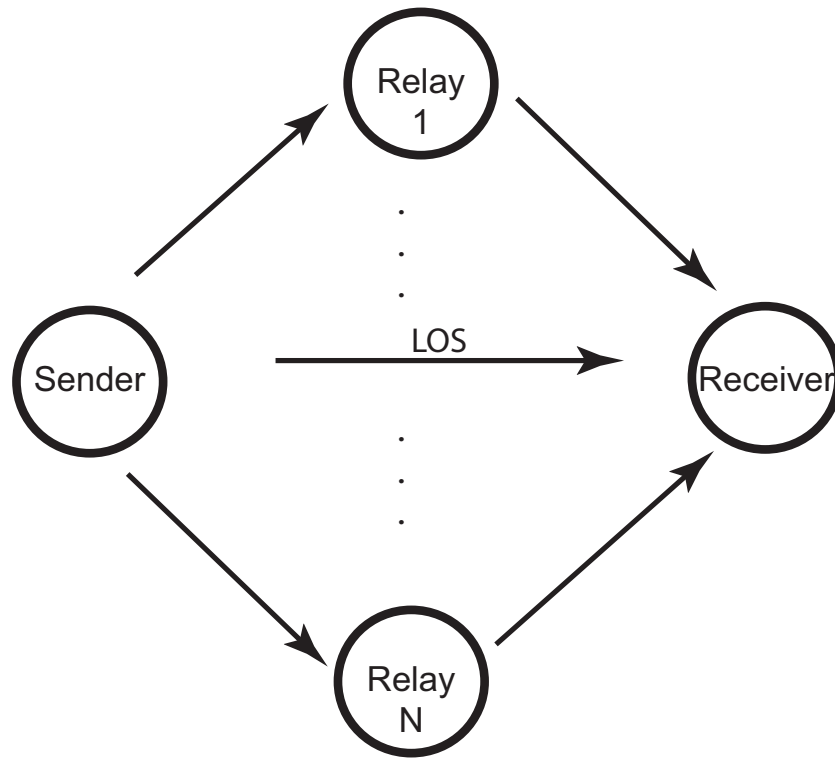
Figure 2-2: Representation of a Cooperative Network

2-6   Distribution of Relays

Most of the work in the field of CC assumes there is a fixed position for relays and assume the relays will stay in their position in the transmission. In cellular networks for instance, these assumptions are not correct. Even in some WSN, most sensors may move or be moved by external forces in the nature, so even Doppler effect must be considered.

For the first assumption about fix position of relays, some counter examples can be found. For instance, when a sensor wants to send it's data to the data base in WSN, may have no clue about the spatial positions of the relays. Another example can be a mobile user in a cellular wireless network.

Randomness of the position of users is modelled as a Bernoulli process in [41].

In [42], a CC system with spatially random relays is studied.

Authors assumed a randomly distributed nodes in a network which can be regarded as a source, destination or a relay in [38]. This model is similar to the case of real life.

Here in this work a random node distribution is also studied. The results can be found in the last chapter.

2-7   Relay Functionality

There are different protocols for forwarding the received message in the relays toward the receiver or other relays. In this section AF, DF, CF and the new ideas in this field is studied.

2-7-1   Amplify and Forward

In the CC systems which use AF as their forwarding protocol, a relay node forwards the message in a non regenerative way and can only amplify the received signal according to the power allocated to it.

An example for this protocol can be found in [40]. Authors in [40], used a network with only one relay and calculated BER in a closed form assuming Rayleigh fading channel and AWGN signals.

In [43], authors proposed a modified AF. This new differential AF with a proposed power allocation make a gain of 4 dB for BER of 10^{-3} in comparison to the direct transmission.

2-7-2   Decode and Forward

When a relay in the wireless network helps cooperation by decoding a message and then forwarding it, we have DF protocol in the CC. In this case, the relay only forward a message when it can decode it without any error. Then the relay will regenerate the original signal and retransmit it. Even if a signal is decoded without error, there is a chance that decoded signal is not the original one. It may happen when errors in the channel between the sender and the relay is changing a codeword to another codeword.

In [44], DF is used for forwarding protocol. They found a close form for SER for systems with quadrature amplitude modulation (QAM) and phase shift keying (PSK).

In [30], authors use DF for their relaying strategy and compare their proposed scenarios. Another work in CC which used DF as its forwarding strategy can be found in [35].

A case of modified DF can be found in [39]. They compare the performance of the simple DF and their proposed modified version of DF and calculate the gain.

For the case of AWGN and Rayleigh fading channels, a game theoretic analysis of DF is presented in [45]. In these two cases, authors showed how relays can be selfish to cooperate and how with this game theoretic approach; they need to participate in cooperation to improve their own performance.

2-7-3   Compress and Forward

The concept of CF first introduced in [46] in Theorem 6. In CF, anything received by a relay will be coded again and retransmit toward the receiver as a new codeword.

In [47], with full knowledge of a channel and in the case of Gaussian MIMO, CF will outperform DF.

Based on regular encoding and backward decoding, a new generalization of CF is proposed in [48]. They demonstrate the achievable data rate for CC with CF.

2-7-4   Selection of Relays and New Protocols

There are also some improved and combined versions of mentioned methods in the literature. For instance in [31], there are some modification in respect to orthodox AF and DF. They assumed two phases for data transmission; first a sender is broadcasting and the relays and/or the receiver will try to decode or receive it. In the second step, the relays are forwarding the message to the receiver. They also divide the mentioned strategies to two different categories. If the sender continues to transmit during the cooperation phase or not, we have different new protocols which are orthogonal amplify and forward (OAF), orthogonal selection decode and forward (OSDF) and non-orthogonal selection decode and forward (NSDF). They compared these new protocols with the metric of outage probability and calculated the gain in terms of SNR.

2-8   Cross Layer Design

As it mentioned in the Chapter 1, a way to better optimize total performance of a CC in wireless network is a cross layer design. This will help to better understand the total cost of a CC. For instance, when a relay wants to forward a message toward the destination in a cooperation phase, there is a delay for a processing time and also retransmission. This measurements will help for better evaluating the performance of a system.

2-8-1   Introduction

There is an investigation about how CC in physical layer can be integrated and influence a MAC layer for more reliable and efficient networks in [36]. As it is introduced in [36], there are some issues which are valid for ordinary wireless networks and also new ones that are closely related to CC in wireless networks:

- Choice of cooperation for a node

- Selection of relay

- Solution of the new problem of hidden and exposed terminals in CC

- Optimum value for rate and interference

The Choice of Cooperation for a Node

As it is discussed before, CC has some advantages, but if the overhead information which is used by higher layer protocols are considered, this cooperation may not be useful. In [49], CoopMAC a MAC protocol for CC is proposed. Another MAC protocol to address this problem is rDCF which is suggested by [50]. In these protocols, when a decision is made on weather a cooperation is useful or not, then the nodes can only choose to participate in cooperation or not. A MAC which uses instantaneous throughput maximization to decide about cooperation, can be found in [51]. The name of this proposed MAC is CTBTMA.

These new MAC protocols send enquiries to a selected relay and check if the cooperation with this relay will improve the performance or not. The relay selection is not optional in this case.

Selection of Relay

When the number of relays increases, from the perspective of the information theory, we will have more diversity. But as this number increases, as it mentioned before, interference will also increases. So there is a trade off here.

Hidden and Exposed Terminals in CC

The hidden and exposed terminal problem in CC is different from that in an ordinary wireless network. When a relay is cooperating; it is receiving a message not only from the sender; but also from the neighbouring nodes. Also the receiver is going to get the message form not only the sender but also from the relays. So a careful scheduling is needed to avoid collisions. This new overheads must be calculated in overall performance of a wireless network with CC.

Optimum Value for Rate and Interference

As it is stated in the Chapter 1, diversity gain in CC in wireless networks will cause a trade off between rate maximization and interference reduction. In [52] and [53], rate maximization is done without any effort for reduction in interference.

2-8-2   MAC Protocols

In [35], authors proposed three phases for data communication in a CC network. First we have relay selection phase, based on exchanging request to send (RTS) and clear to send (CTS) messages between relays and the sender. Each relay will calculate transmission energy per symbol for itself E_{Relay} and transmission energy per symbol for sender E_{Sender}. With these data and also based on predefined source to destination data rate R, source node is going to choose an appropriate relay.

In the second phase source starts sending the message with E_{Sender} per symbol. In this phase, the selected relay according to the previous phase will save the data and will do the decoding in the next phase.

In the last phase, if a relay is successful in decoding the message, it will retransmit it with E_{Relay} per symbol toward the final destination. In the destination, a joint decoding is performed based on the signal received in the second phase and the third one. If the message is decoded successfully and an acknowledgement (ACK) will be sent to only the source from the receiver node.

In summary, authors in [35], proposed a MAC based on a power control information from the physical layer. For more information about layering concept and cross layer design the reader can look at Chapter 1. They evaluate their energy-efficient with single relay selection in a CC by outage probability and also network life time in [35].

2-8-3   Routing Dilemma

Most of the work in field of CC propose a routing based on shortest path problem [5] and then they try to improve it based on cooperation properties. But the optimal cooperative route is not necessary same as a rout found by the shortest path problem. There are other metrics in a CC case which shortest path problem is not answering them. In [28], a distributed cooperative routing is proposed.

Authors in [32], investigate the problem of routing selection in a wireless network with N relays. They introduced new concepts like virtual node and link and virtual link based contention graph, for finding an optimal cooperative routing. According to their simulations, they achieved 20 percent energy saving.

In [54] authors with the usage of outage probability as their metrics, propose an algorithm to find the most reliable route with respect to power constraints as well as the minimum energy route regarding a reliability constraint. They also study trade off between outage probability and the transmission power, with and without route diversity.

One of the works about the cross layer design which is focusing on efficient routing can be found in [37]. The authors in [37] use Monte-Carlo simulations to evaluate the performance of their proposed routing protocol.

In [38] a novel routing method is proposed.

2-9   Mathematical Representation

In this section the research works concerning the mathematical bases of this research is presented. The mathematical approach of this work is done in a similar way.

Basic source for the mathematical parts of this work is done based on [2]. [2] is a best and complete reference for studying the fading channels in a wireless network. For other calculation of this work, a description in these books also used [55] and [56].

One of the good works about the calculation of the SER can be found in [57]. Authors tried to introduce an approach to calculate the SER for the generalized fading channels. They found simpler expressions for calculation of SER in comparison to previous results.

In [58], authors proposed average level crossing rate (LCR) and average time fade duration (AFD) as new metrics for their performance evaluation. They assumed a simplified distributions for their channel representation of multipath fading and shadowing effects.

There can be found lots of works about the mathematical description of the channel when only multipath fading is considered. In [59], authors tried to describe a channel with the Nakagami fading. They also considered the shadowing as another parameter to effect the channel performance. In their calculation; they assumed that the m parameter in the Nakagami distribution can also be a non integer value. They used outage probability as their metric.

Another recent work about the performance analysis of the composite channels which both consider the multipath fading and shadowing effects, can be found in [60]. They mentioned that the resulting probability density function (PDF) is not available in the closed form. They used G distributions to model this composite channel in [60].

In [61], a study about this composite distribution can be found. They proposed a new form of distribution which can represent both the shadowing and multipath fading effects. They measured the accuracy of their proposal.

In the last chapter, the main focus of this work is about the position of the relay and random deployments of nodes in the network. For this random deployment, research works like the one in [62] is used.

2-10   Summary

In this chapter a brief review about the research work in CC presented. The literature can be compared in this field via several criteria. For the summary of this chapter, another brief look to some of more relevant research to this work is presented here.

MIMO technology is introduced to improve communication performance in wireless systems. According to the definition and functionality of MIMO systems, there is a need for more antennae both in the receiver and the transmitter to achieve more diversity and more capacity. In cooperative wireless communication on the other hand, these features can be reached without need for installing new antennas. Because of the nature of these networks, even better spatial diversity can be achieved. This is due the fact that nodes in an cooperative network can form an array and a diversity combining can be used in the receiver side. This is done by relaying the information by nodes which have diverse channel qualities [6, 11].

Higher spatial diversity is achieved in two ways depending on the algorithm of the network. First, message can be transported to the destination in different paths; so

if there is a small scale fading or shadowing in a path from source to destination, the message can be sent through other path only. Second, if destination can combine the signal from different relays and source (if it is in its coverage range), it makes network robust due to fading in channel, and this diversity helps the system to outperform [12,15]. Even if a signal to noise ratio of one of those paths is below the threshold for detection, other received signals can be used for better performance of the network. This can also help to achieve a better data rate. Even if there is a multipath fading, with the use of a RAKE receiver at destination node the spatial diversity can be achieved; but at the cost of complexity at the receiver which is not a good choice for wireless sensor networks. There are some methods to overcome this problem [10].

Cooperative communications can increase the data rate. If a direct path between the source and destination has a low data rate due to some blocking or shadowing compared to the data rate between the source and a relay and that relay to the destination for a certain BER. In this case, the total delay for sending a packet through indirect path is less than direct one. Another advantage can be the frequency reuse. The unlicensed frequency band is a scarce resource. So each frequency band must be reused in other cells. For instance, in a cellular network there is a pattern to allow frequency reuse. With the help of cooperative communications and proper power allocation, the signal strength of a single in a certain path is much less than the traditional method. So the signal to interference ratio will decrease and this can help the system performance [11].

Cooperative networks can be studied on three different groups; three node cooperative, dual hop cooperative and multi hop relay networks [11]. A three-node cooperative network is a simple case that illustrates basic principles. The power allocation is based on the available CSI. For instance, if the direct link in a three-node cooperative network is experiencing shadowing according to its CSI, all the power can be allocated to the indirect link. For these groups different scenarios based on the relay nodes and destination awareness about CSI are investigated in [11]. Various methods have been proposed for relaying. AF and DF are the most common ones [14]. In the DF, each relay node decodes the message and if this procedure is successful; it retransmits the message. Some other methods are coded cooperation [17] and CF in [14].

Surprisingly, not sufficient amount of research have been done regarding the power allocation. In most cases equal power sharing for relays are assumed. On the other hand, most performance evaluations do not consider hidden power consumptions. There is power consumption for sending the CSI and synchronization between relays. If the RAKE receiver is not used in the receiver, there should be some symbols for synchronizing the receiver for frequency (due to Doppler frequency shift) and time offset. These hidden power consumption problems and a new protocol for MAC have been addressed in [16]. Some of the recent works regarding power allocation is based on the equal power allocation for the relays with shortest path problem. A heuristic algorithm is proposed to minimize the end to end outage probability, compared to equal power allocation in [13]. A distributed algorithm is proposed in order to improve the quality of the combined signal at the destination in [18].

The links are assumed as flat Rayleigh fading. In the recent works, there are few channel models that consider both small and long scale fading. A channel model which takes into account both long and small scale fading is assumed in [19]. The method for forwarding the message for relays in [19] is AF.

There is still a need for research regarding power allocation in order to lower BER and obey the power and bandwidth constrains. The model that is used for channels of cooperative networks is also important. In indoor environment there is always shadowing and small scale fading that degrades the performance of network due to fast movements of objects. In outdoor environment in other hand, for instance in big cities, multi path fading which causes different delays for a single symbols is the main problem that needs to be encountered.

Chapter 3

Composite Channel Model

In this chapter the analytical method of the wireless channel and a method to calculate the bit error rate (BER) is presented [2], [55] and [56]. The cumulative distribution function (CDF) and probability density function (PDF) of the distributions which represents the multipath fading and shadowing are going to be explained.

Analytical and simulation results for the channel characteristics are presented. First log-normal distribution is presented as a representative of shadowing [63], [64]. The Nakagami-m distribution is introduced to model the multipath fading effect [65], [66]. In the next step a composite PDF based on the mentioned distributions is presented [67], [68].

This channel modeling will be used as a base for the analytical calculation of the gain of cooperative communications (CC) in term of power and also simulations of the next chapters.

In this chapter first the problem definition of this work is introduced. This scheme is an introduction to analytical calculations and simulations which are done in this report.

The distributions which construct our composite distribution are introduced. This distributions will model nearly most wireless channels. Then the analytical procedure to find the PDF of this composite distribution is shown.

After this, an approximation for this PDF is proposed. This approximation can be used to simplify the analytical calculations of BER. Then each node in a network can do the calculations required for its participation in CC.

In the last part the analytical procedure to calculate the BER of a wireless channel with multipath fading and shadowing effects is shown. This equation will be used for the following chapters scenarios and evaluations.

3-1 Problem Definition

In this thesis work, we work with a channel model which can nearly model all the real wireless channels. This is due to the fact that this channel model is taking multipath fading, shadowing and thermal noise as the undesired signals, into the account. As it was mentioned before, most works in this field are not taking both multipath and shadowing effects into the account.

This channel model is going to be used to calculate the gain of CC in wireless networks, in comparison to a case when the transmitter and the receiver are communicating directly. In this work, by CC in wireless networks, we mean that there is a relay beside the sender and the receiver which will help the communication. The total power for transmission is going to be divided between the relay and the sender. Then, the sender is going to send the message with its allocated power. Since transmitter is broadcasting its message in the air, both relay and receiver can receive it.

In this work, decode and forward (DF) is used as a forwarding method in relays. In this method, as it was mentioned before, the relay is forwarding the message if it can correctly decode the message. The modulation scheme in this work is binary phase shift keying (BPSK) due to its simplicity. In the receiver, we assume that we have a RAKE receiver which can coherently demodulate the received signals from the sender and the relay. The method used in there is maximum ratio combining (MRC).

The gain of CC with respect to the direct communication is calculated analytically and through the simulations in terms of reduction in required signal to noise ratio (SNR) for a specific BER. This procedure must be repeated in different wireless channels to make the results general.

There are various statistical parameters in the PDF of the composite distributions which represent the wireless channel. The impact of these parameters in the gain in power for CC case in comparison to direct case is investigated.

Next step is finding the optimum value for the power allocation between the sender and the relay. This will help us to find the optimum value for gain of power. This problem is investigated in various cases.

Then the impact of position of the relay in the gain of power is investigated. This will help the network designer to increase the gain by putting the relay in best position in a deterministic way.

In the last task, the case of CC is studied in two different networks. In these networks, there are a number of nodes which are randomly deployed. Based on the number of these nodes the gain in power for CC with respect to direct transmission is calculated.

3-2 Distributions of Channel Coefficients

In this section two distributions which are used for representing the shadowing and multipath fading in CC are presented. After this, the procedure to calculate

the composite PDF which represent both multipath fading and shadowing effects is shown.

In each section, the results of Monte Carlo simulations are presented in the figures to validate the accuracy of the method. These random generators will be used in future simulations of our wireless network. The results will be compared to the analytical calculations in MATHEMATICA.

First two different distributions with their corresponding PDFs based on their properties are presented; there distributions will represent the shadowing and the multipath fading effects of the channel. After this, a composition of these distributions is presented. These distributions are plotted to show the variety of wireless channels they can present. Formulation for their PDF and CDF is presented. Then a summary about where and when these distributions are used is introduced.

In the last section, the method to calculate the composite PDF from two mentioned PDFs is shown. Then in a plot, three distribution for different parameters is presented.

3-2-1   Log-normal Distribution

shadowing is the decrease in signal power created by objects in the propagation path between transmitter and receiver. It is an experimentally verified fact that, the received power varies with a log-normal distribution about the mean power. Log Normal is a probability distribution in which a logarithm of a random variable (RV) has a normal distribution.

The PDF of log-normal distribution is:

$$P_\Omega\left(\Omega, \mu, \sigma\right) = \frac{1}{\Omega\sigma\sqrt{2\pi}} \exp\left(-\frac{\left(\lg\Omega - \mu\right)^2}{2\sigma^2}\right),\qquad(3\text{-}1)$$

where Ω is the variable of distribution. μ and σ are the mean and standard deviation of the variable's logarithm respectively. Then, the CDF of log-normal is:

$$F_\Omega\left(\Omega, \mu, \sigma\right) = \frac{1}{2}erfc\left(-\frac{\left(\lg\Omega - \mu\right)}{\sigma\sqrt{2}}\right),\qquad(3\text{-}2)$$

where $erfc$ is the complementary error function.

In Figure 3-1, log-normal distributions for three different parameter sets are shown. The simulation results are based on a random generator in MATLAB. The parameters for the distributions are $\mu = 0$ and $\sigma = 0.25$, $\mu = 1$ and $\sigma = 0.25$, and $\mu = 1$ and $\sigma = 0.5$ for three different lines. Analytical lines which represents (3-1) can be seen. As it is obvious, they are in a perfect match.

In Figure 3-2, error bars in the confidence interval of 95 percent are shown. It can be seen that the simulations are validated by the analytical results. In simulations, a random generator is used to generate the RVs according to the log-normal distribution.
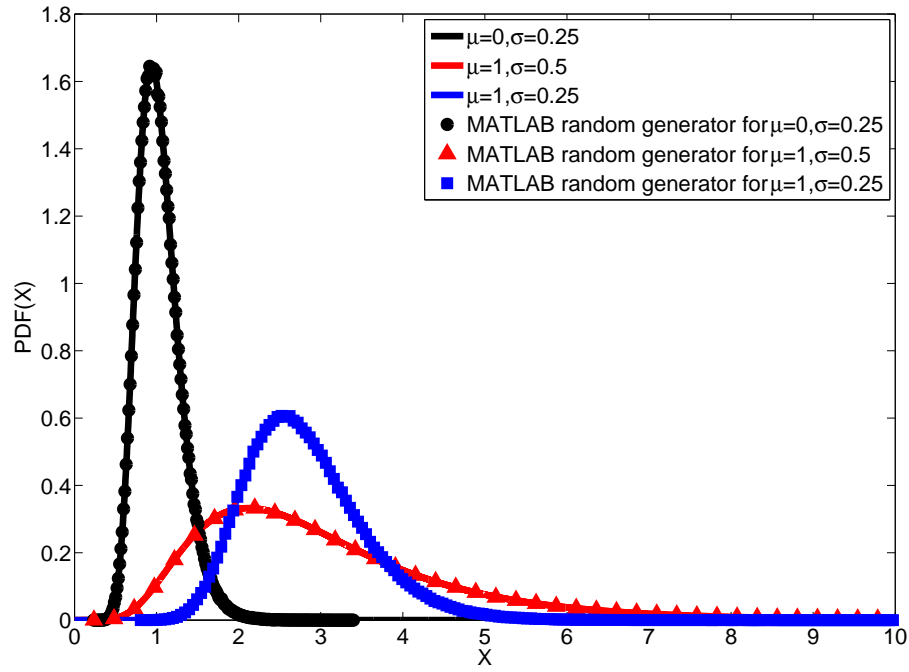
Figure 3-1: Log-normal Distributions for $\mu = 0$ and $\sigma = 0.25, \mu = 1$ and $\sigma = 0.25$, and $\mu = 1$ and $\sigma = 0.5$
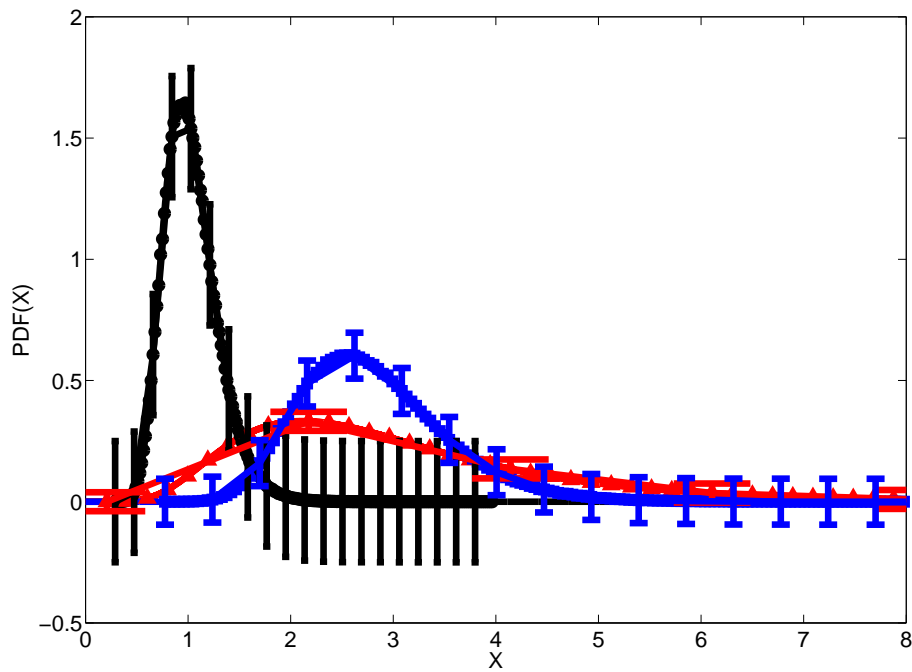
Figure 3-2: Log-normal Distributions with Error Bars for $\mu = 0$ and $\sigma = 0.25, \mu = 1$ and $\sigma = 0.25$, and $\mu = 1$ and $\sigma = 0.5$

3-2-2 Nakagami-m distribution

Nakagami-m distribution was first introduced in [69]. Nakagami fading occurs for multipath scattering with relatively large delay time spreads. It describes the amplitude of received signal after maximum ratio diversity combining [69]. The parameter of Nakagami-m distribution is shown by m.

The PDF of Nakagami-m distribution is [70]:

$$
P_\alpha \left(\alpha, \Omega, m\right) = \frac{2}{\Gamma \left(m\right)} \left(\frac{m}{\Omega}\right)^m \alpha^{2m-1} \exp \left(-\frac{m\alpha^2}{\Omega}\right),
\tag{3-3}
$$

where α is the variable of distribution. Ω is the mean of variable, and m is the factor of Nakagami-m distribution.

The CDF of Nakagami-m is [71] and [72]:

$$
F \left(\alpha, \Omega, m\right) = P \left(\Omega, \frac{\Omega}{m}\alpha^2\right),
\tag{3-4}
$$

where P is an incomplete gamma function, Ω is the mean of variable, and m is the factor of Nakagami-m distribution.

In Figure 3-3, Nakagami-m distributions for three different parameter sets can be seen. The simulation results are based on a random generator in MATLAB. The parameters for these three distributions are $m = 1$ and $\Omega = 1$, $m = 1$ and $\Omega = 3$, and $m = 3$ and $\Omega = 3$.

In Figure 3-4, Nakagami-m distributions of Figure 3-3 can be seen with error bars. As it can be seen, the error bars demonstrate the validation of the simulation results with the analytical equations in 3-3.
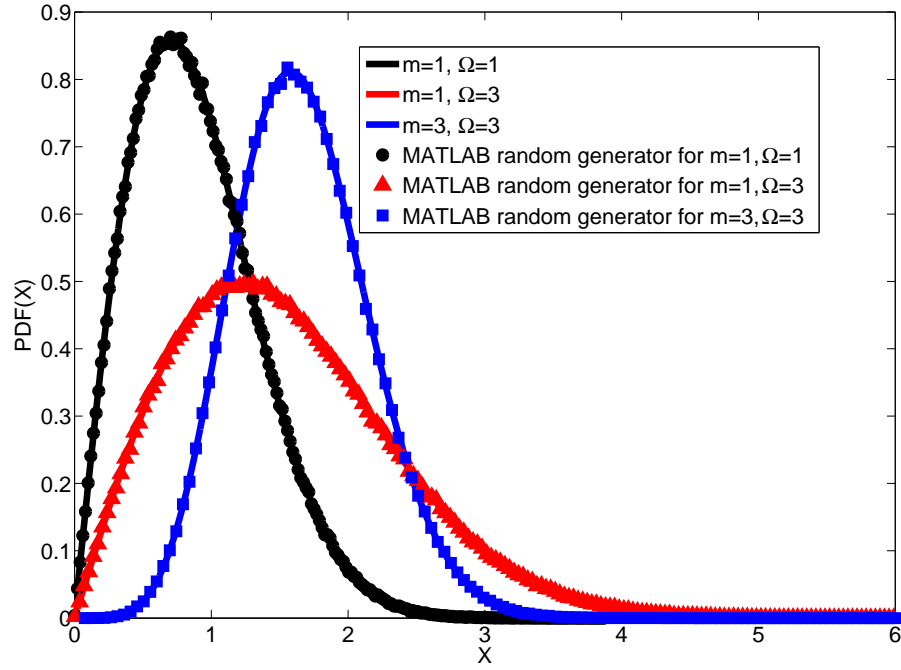
3-2-3 Composite distribution

In this section a composite distribution which is the base of the work in the next chapters is presented.

The composite distribution in this work is based on Nakagami-m and log-normal distributions. Using the PDF of these distributions in (3-1) and (3-3), we can have the following equation for the PDF of this composite distribution:

$$
P_\gamma \left(\gamma\right) = \int_0^\infty \frac{1}{\theta} P_\alpha \left(\frac{\gamma}{\theta}\right) P_\Omega \left(\theta\right) d\theta,
\tag{3-5}
$$

where P_Ω is the PDF of log normal distribution and P_α is the PDF of Nakagami-m distribution. Then we can have the following for the PDF of composite of Nakagami-m and log normal distribution [61]:
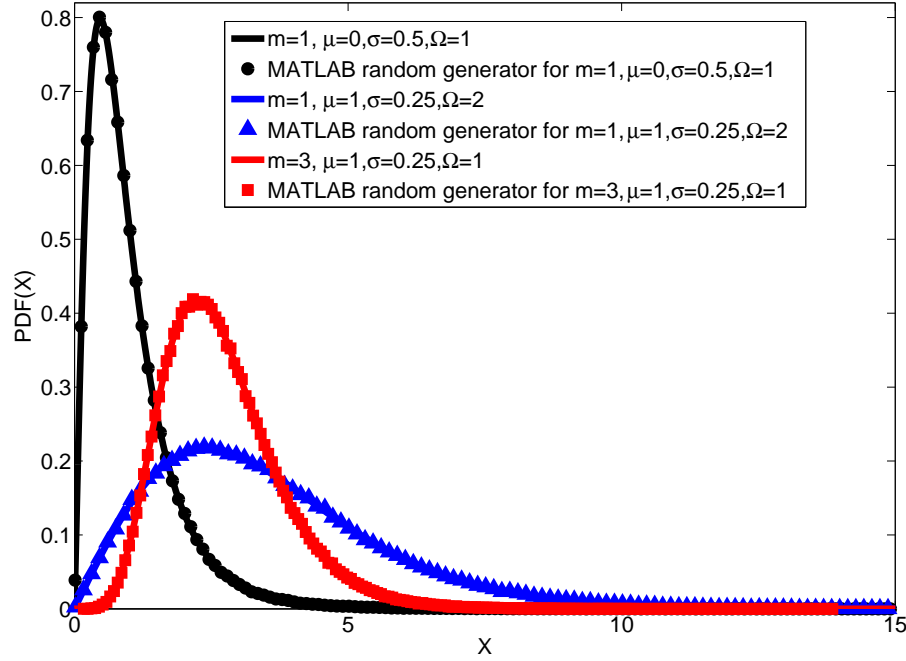
Figure 3-3: Nakagami-m Distribution for $m = 1$ and $\Omega = 1$, $m = 1$ and $\Omega = 3$, and $m = 3$ and $\Omega = 3$
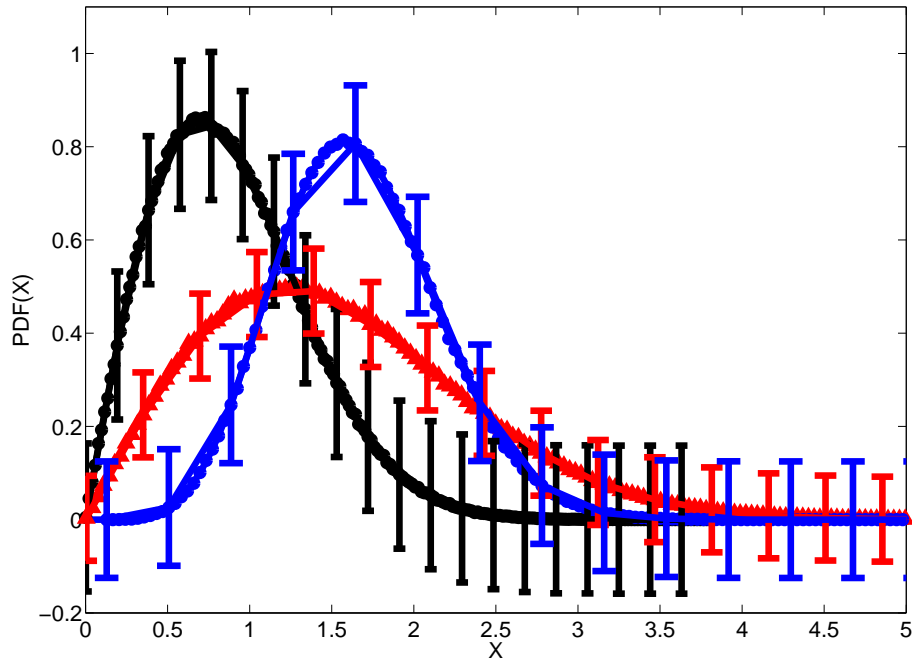
Figure 3-4: Nakagami-m Distributions with Error bars for $m = 1$ and $\Omega = 1$, $m = 1$ and $\Omega = 3$, and $m = 3$ and $\Omega = 3$

Figure 3-5: Composite Distributions for $m = 1$, $\Omega = 1$, $\mu = 0$ and $\sigma = 0.5$, $m = 3$, $\Omega = 1$, $\mu = 1$ and $\sigma = 0.25$, and $m = 1$, $\Omega = 2$, $\mu = 1$ and $\sigma = 0.25$

$$p_\gamma\left(\gamma; \mu, m, \sigma, \Omega\right) = \int_0^\infty \frac{2m^m \gamma^{2m-1}}{w^{2m}\Omega^m\Gamma(m)} \exp\left[-\frac{m\,\gamma^2}{w^2\Omega}\right]$$
$$\frac{1}{\sqrt{2\pi}\sigma w} \exp\left[-\frac{(\log w - \mu)^2}{2\sigma^2}\right] dw, \qquad (3\text{-}6)$$

where μ is the mean of the variable's logarithm, Ω and m are the variables of Nakagami-m distribution, and σ is standard deviation of the variable's logarithm. These variables can almost define all the wireless channels.

Based on (3-5), for three different set of variables the composite PDF is shown in Figure 3-5. The set of parameters for the composite distributions are $m = 1$, $\Omega = 1$, $\mu = 0$ and $\sigma = 0.5$, $m = 3$, $\Omega = 1$, $\mu = 1$ and $\sigma = 0.25$, and $m = 1$, $\Omega = 2$, $\mu = 1$ and $\sigma = 0.25$. As it can be seen the simulation random generator variables are in perfect harmony with the analytical values taken from Equation 3-5.

The composite distributions of Figure 3-5 with error bars can be seen in the Figure 3-6. This figure shows the validation of the results found in the Figure 3-5.

After calculation of the PDF for our composite distribution for the wireless channel; now in the next section an approximation for this closed form PDF is presented. Then in the section after that, we use this PDF to calculate the BER in a channel with multipath fading and shadowing effects.
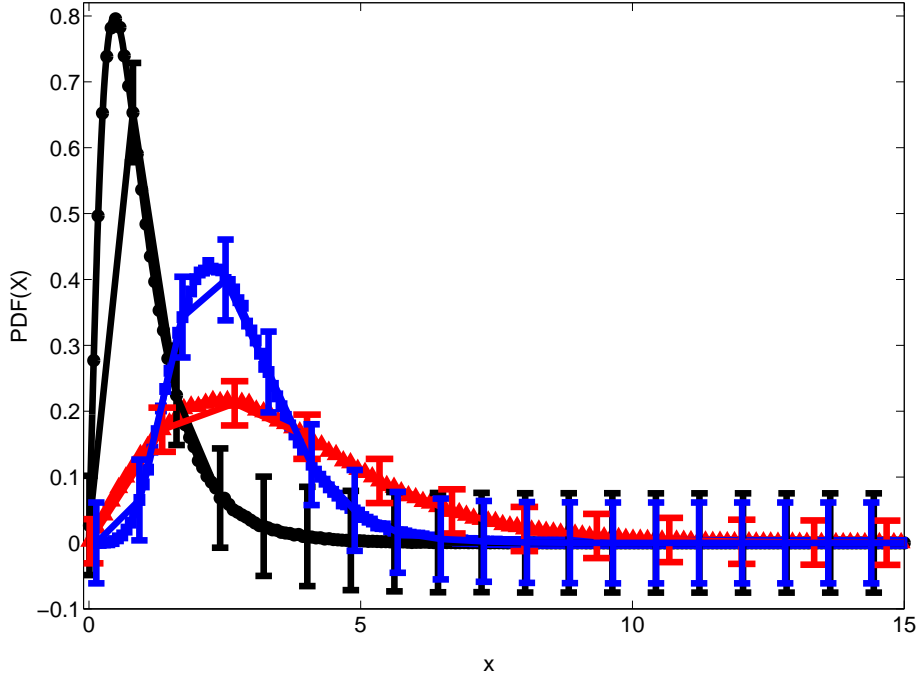
Figure 3-6: Composite Distributions with Error bars for $m = 1$, $\Omega = 1$, $\mu = 0$ and $\sigma = 0.5$, $m = 3$, $\Omega = 1$, $\mu = 1$ and $\sigma = 0.25$, and $m = 1$, $\Omega = 2$, $\mu = 1$ and $\sigma = 0.25$

3-3   Closed From Approach for BER Calculation

In this section in contrast to the previous section; our focus is on the PDF of the power of the signal. In the last section the PDF for the amplitude of a signal was presented.

First an approximation for the PDF of the power of the signal is introduced. This closed form is used in next part to calculate the BER.

3-3-1   Approximation

Since the analytical calculations with the PDF of the composite channel is difficult; we need to make an approximation. This approximation will help use to have a closed form equation for BER. This also important in a case that can be implemented in simple nodes for their calculations. Then each node in a wireless network can decide about the cooperation and best possible relay. These terms will be discussed in next chapters.

To put the composite PDF in an approximate form, we can simplify it to:

$$p_{\gamma_l}\left(\gamma_l; \mu_l, m_l, \sigma_l\right) = \frac{m_l^{m_l}\gamma_l^{m_l-1}\xi}{\sqrt{2\pi}\sigma_l\Gamma(m_l)}\int_0^\infty \frac{1}{w^{m_l+1}}$$

$$\exp\left[-\frac{m_l\,\gamma_l}{w}\right]\exp\left[-\frac{\left(10\log_{10}w - \mu_l\right)^2}{2\sigma_l^2}\right]dw. \tag{3-7}$$

After transforming the limits using the substitution $w = \frac{1+v}{1-v}$, we get:

$$p_{\gamma_l}\left(\gamma_l; \mu_l, m_l, \sigma_l\right) = \frac{m_l^{m_l}\gamma_l^{m_l-1}\xi}{\sqrt{2\pi}\sigma_l\Gamma(m_l)}\int_{-1}^1 \frac{1}{\left(\frac{1+v}{1-v}\right)^{m_l+1}}$$

$$\exp\left[-\frac{m_l\,\gamma_l}{\left(\frac{1+v}{1-v}\right)}\right]\exp\left[-\frac{\left(10\log_{10}\left(\frac{1+v}{1-v}\right) - \mu_l\right)^2}{2\sigma_l^2}\right]$$

$$\left(\frac{1}{1-v} + \frac{1+v}{(1-v)^2}\right)dv. \tag{3-8}$$

With the procedure explained in [73], now applying the Chebyshev Gauss (CG) quadrature the integral above can be approximated in closed form as:

$$p_{\gamma_l}\left(\gamma_l; \mu_l, m_l, \sigma_l\right) \approx \frac{m_l^{m_l}\gamma_l^{m_l-1}\pi\xi}{\sqrt{2\pi}N_g\sigma_l\Gamma(m_l)}\sum_{k=1}^{N_g}\frac{1}{\left(\frac{1+v_k}{1-v_k}\right)^{m_l+1}}$$

$$\exp\left[-\frac{m_l\,\gamma_l}{\left(\frac{1+v_k}{1-v_k}\right)}\right]\exp\left[-\frac{\left(10\log_{10}\left(\frac{1+v_k}{1-v_k}\right) - \mu_l\right)^2}{2\sigma_l^2}\right]$$

$$\left(\frac{1}{1-v_k} + \frac{1+v_k}{(1-v_k)^2}\right)\sqrt{1-v_k^2}. \tag{3-9}$$

Where v_k represents the roots of the N_gth order GC Polynomial and are given as:

$$v_k = \cos\left(\frac{\pi}{2N_g}(2k-1)\right).$$

Equation (3-9) can be used for calculation of PDF of composite distributions. This equation is simple and will let us use the moment generating function (MGF) approach to calculate the BER. Then, the network designer can implement this in simple nodes; and then we have a chance to have distributed algorithms for CC.

In next part an approach for BER calculation based on this PDF is introduced.

3-3-2 MGF Approach

It can be seen that the MGF of the RV which follows a gamma/log-normal distribution, can be found from the following equation [57]:

$$
M_{m\sigma}(w; \mu) \simeq \frac{1}{\sqrt{\pi}}
$$

$$
\sum_{n=1}^{N_p} H_{x_n} \left(1 - \frac{w 10^{\frac{(\sqrt{2}\sigma x_n + \mu)}{10}}}{m} \right)^{-m}.
\tag{3-10}
$$

Then, the error probability is calculated [57]:

$$
P^{R_i}\left(\varepsilon \mid P_t^S\right) = \frac{1}{\pi} \int_0^{\pi/2} M\left(-\frac{P_t^S}{\sin^2(\psi)}\right) d\psi.
\tag{3-11}
$$

Based on the simplicity of these calculations, each node can decide that if CC will improve its performance. The node can also calculate the best relay in its vicinity for the CC process.

In the other approach BER can be calculated directly. In the next section, we use this approach to calculate the BER. This analytical calculation is the base of other chapters for evaluation of the CC.

3-4 Channel Bit Error Rate Calculation

In this section, the analytical calculation of channel BER based on the PDF of proposed composite distribution is presented.

$$
r = \eta s + n.
\tag{3-12}
$$

The received signal is calculated based on the channel coefficients which are representing the multipath fading and shadowing; the transmitted signal and the additive white Gaussian noise (AWGN). In 3-12, r is the received signal, η is the channel coefficients, s is the transmitted signal and n is the AWGN.

In this work, we used BPSK as our modulation. So we have two symbols as the transmitted signals; s_i where i can be 0 or 1. Other modulations can be evaluated in a similar procedure. They will be regarded as a future work in the last chapter.

Based on these facts, the probability of error in the channel which is represented by (3-12), is:

$$P_E = P_r(s_0) \, P_r(\epsilon \mid s_0) + P_r(s_1) \, P_r(\epsilon \mid s_1). \tag{3-13}$$

In (3-13), P_E is representing the error probability in the channel. $P_r(s_i)$ is representing the probability of transmitting symbol s_i, where i can be 0 or 1. $P_r(\epsilon \mid s_i)$ is representing the probability of error given the symbol s_i is transmitted.

We can assume that:

$$P_r(s_0) = P_r(s_1). \tag{3-14}$$

Since the $P_r(s_i)$ is equal for both values of i and is 0.5 and with the fact that error in channel is not dependant to the symbol transmitted, we can see that:

$$P_r(\epsilon \mid s_0) = P_r(\epsilon \mid s_1). \tag{3-15}$$

With the Equations 3-13 and 3-15, we can find the following expression for the error probability of channel:

$$P_E = P_r(\epsilon \mid s_0) = P_r(\epsilon \mid s_1). \tag{3-16}$$

For the case of AWGN we know that the error probability can be found in the following form:

$$P_E = Q\left(\sqrt{\frac{2E_s}{N_0}}\right). \tag{3-17}$$

In (3-17), E_s is the energy per bit of transmitted signal, N_0 is the noise power spectral density and Q represents the Q function.

Based on (3-12) and (3-17), the error probability of a channel for a given multipath fading and shadowing parameters, is:

$$P_E \mid \eta = Q\left(\sqrt{\frac{2\eta^2 E_s}{N_0}}\right), \tag{3-18}$$

where η is the given fading/shadowing parameter. The PDF which can statistically model this RV variable is introduced in (3-6).

As it was mentioned before, η is a RV with a given PDF. To find the average error probability, we need to average the P_E over the PDF of η. So we have:

$$P_E = \int_0^\infty P_E \mid \eta P_\eta\left(\eta\right) d\eta. \tag{3-19}$$

In the Equation 3-19, $P_\eta\left(\eta\right)$ is the composite PDF which is introduced before.

So with the usage of the Equation 3-18 and 3-5 in the Equation 3-19, we can find the following equation for the average BER in the wireless channels which have both multipath fading and shadowing effects:

$$P_E = \int_0^\infty Q\left(\sqrt{\frac{2\eta^2 E_s}{N_0}}\right) P_\eta\left(\eta\right) d\eta. \tag{3-20}$$

In the next section a summary about the analytical and simulation results of this chapter can be found.

3-5 Summary

In this chapter the analytical foundation of this research work and the metric to calculate the energy conservation of CC is presented.

As it was mentioned in the literature survey, one of the problems of the research works in this field is the fact that the results cannot be compared. When researchers are using different channel models for their research, they cannot compare their gain to other works.

In this work, we introduced a composite PDF which can model nearly all wireless channels.

In the first section of this chapter, two different distributions which represent the multipath fading and shadowing effects are presented. Then in the figures the result of generation of RV's according to these distributions and the validation procedure is also presented.

Then an analytical way to calculate the composite PDF is introduced. The result of RV generation based on this procedure and it's validation is also presented in the next figures.

In the next section an approximation for the signal power is presented.

In the last section, the analytical calculation of the average BER for the direct path between a sender and a receiver can be found.

In the next chapter, a CC scheme for this wireless channel is presented. Then with the procedure introduced here, the gain of this CC is calculated both analytically and also in the simulations. This procedure is repeated for another wireless environment to show the generality of the results. The parameters of these two wireless networks can be found in (A-1).

The optimum power allocation between the sender and the relay is also investigated. Then in last section, the impact of different parameters of composite distribution on the gain of CC is discussed.

Chapter 4

Energy Conversation in One Relay Scenario for Cooperative Network

In this chapter a cooperative communications (CC) in wireless network with composite channel which was introduced in previous chapter is evaluated. The results are presented based on Monte Carlo methods.

In the first section the network set up and assumption for calculation of the gain in CC is explained.

In the second section the results of analytical calculations, the simulations and the confidence intervals to validate them is presented. Then for another network parameters, the procedure is repeated to make a comparison. The parameters used in these scenarios can be found in (A-1).

Then the power allocation for the relay and the sender in this network is investigated.

In the last part, the impact of different parameters of composite distribution on the gain of CC is discussed.

4-1 Problem Definition

Some scenarios can be defined in the case of wireless cooperative network. In this work we address two problem. In the first problem, we need to find the gain of CC in wireless networks. This is the main focus of this chapter. Secondly, it can be assumed that there is a power limitation in the network; and for a desired bit error rate (BER), finding the best relay in a number of nodes that is needed to achieve this goal; is the issue. This is done in the next chapter. In the next chapter the focus will be on the position of this relay.
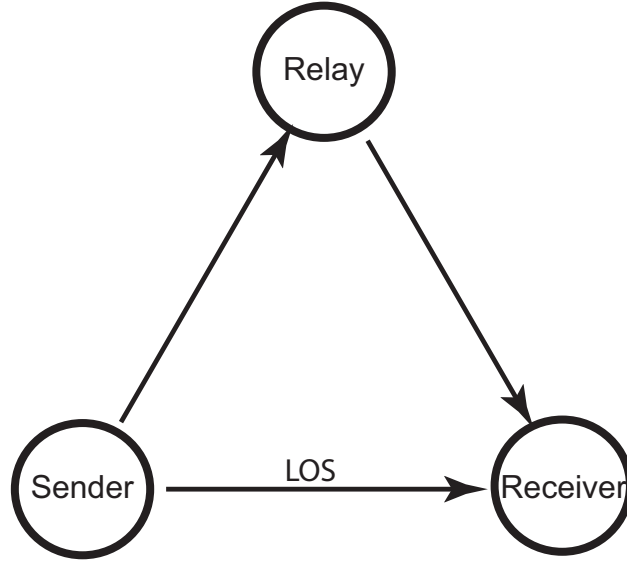
Figure 4-1: Network representation of one relay cooperative communication network

In this chapter, we assume that we have a relay in a deterministic position and we want to calculate the gain in the signal to noise ratio (SNR) value, when the relay is helping the sender and the receiver for their transmission.

The network representation of this simulation in this chapter can be seen in Figure 4-1. As it can be seen, the wireless network is consist of a relay, a receiver and a sender.

In this work, for different positions and different amount of power allocation of the relay, BER is going to be calculated by both analytical and simulation methods.

If a relay is successful to decode the received message from the sender; it is going to regenerate it and then retransmit it to the receiver. This method is decode and forward (DF), as it is mentioned in detail before. In a typical CC in wireless networks, there are N_r relays. Power is allocated to the sender and the relays according to the following equation:

$$\alpha + \sum_{i=1}^{N_r} \beta_i = 1, \qquad (4\text{-}1)$$

where α is the amount of energy allocated to sender, N_r is the number of relays in the cooperative network and β_i is the amount of energy allocated to i-th relay. In this chapter N_r is one. In a one relay scenario the probability of error depends on

the probability of decoding a message in the relay. It can be easily seen that the probability of error in this case is calculated from the equation below [3]:

$$
\begin{aligned}
P_E = P_E^R \left(\epsilon \mid P_t^S = \alpha P_c, P_t^{R_1} = 0 \right) P_E^{R_1} \left(\epsilon \mid P_t^S = \alpha P_c \right) \\
+ P_E^R \left(\epsilon \mid P_t^S = \alpha P_c, P_t^{R_1} = \beta P_c \right) \left(1 - P_E^{R_1} \left(\epsilon \mid P_t^S = \alpha P_c \right) \right),
\end{aligned} \tag{4-2}
$$

where P_E, P_E^R and $P_E^{R_1}$ are the total error probability of channel, the error probability in the receiver and the error probability in the relay, respectively, α and β are representing the power allocation of the sender and the relay respectively, P_c, P_t^S and $P_t^{R_1}$ are the total power for data transmission, the power allocated to the sender and the power allocated to the relay, respectively. The equation for more relays can be found in [3].

For calculation of the channel BER, first we need to understand what the received symbols consists of. In this work, it is assumed that maximum ratio combining (MRC) is employed in the receiver. The effect of path loss is taken into account by Friis equation. The received signal contains both the noise and the senders symbols which are multiplied by the channel coefficients.

$$
y_{sd} = h_{sd} \sqrt{P_t^S}\, s + z_{sd} \tag{4-3}
$$

$$
y_{sr} = h_{sr} \sqrt{P_t^S}\, s + z_{sr}, \tag{4-4}
$$

where, y_{sd} and y_{sr} are received baseband signals in the receiver and the relay, respectively. h_{sd} and h_{sr} are assumed to be independent and identically distributed (i.i.d.) with Nakagami(m)-Lognormal composite distribution. P_t^S is the power which is allocated for sender. In this paper, BPSK modulation is used and the signal s is a message which will be valued either 1 or -1. The additive white Gaussian noise (AWGN) with variance $N_0/2$ per dimension is represented by z_{sd} and z_{sd}. As shown in (4-3), the channel coefficients should be taken into account for calculation of the channel bit error rate. In the second stage, if the relays use the DF cooperative protocol as explained in the previous section; the relay's message received in the receiver follows same formula as in (4-5). On the other hand if the relays use the AF cooperative protocol, the received signal in the receiver which is sent by the relays will be an amplified version of received signal in a relay. Here the DF method is used, therefore:

$$
y_{r_i d} = h_{r_i d} \sqrt{P_t^{R_i}}\, s + z_{r_i d}, \tag{4-5}
$$

where, $y_{r_i d}$ is received signal to the ith relay, $h_{r_i d}$ has Nakagami(m)-Lognormal composite distribution, s is decoded message in the relay. $z_{r_i d}$ is the additive white Gaussian noise of the channel, $P_t^{R_i}$ is power allocated to the relay.

In the equations mentioned above the choice for the P values in the relays and the source nodes are in the main interest of this research. For the values of the P in the equation above, it should be mentioned that:

$$P = P_t^S + \sum_{i=1}^{N_R} P_t^{R_i}, \tag{4-6}$$

where the N_R is the number of relays.

The multipath fading always presents in the communication channels, and if its effect is not taken as an advantage for exploiting network as a virtual MIMO channel, it can degrade the systems performance. In this work, the multipath fading is assumed to have the Nakagami-m distribution. Considering the m parameter; this distribution can include the widest range of the fading in all distributions.

For calculating the gain of CC in this wireless network; first we calculate the BER for a situation when we do not use any relays for a specific range of SNR. Then we do the same procedure by deploying a node as a relay. Then for a desired amount of BER we calculate the gain in SNR.

Most works in this area do not consider the effect of shadowing. Shadowing can happen a lot in the indoor cooperative networks, mostly due to frequent change in the position of objects in the indoor network. In the simulations the channel is assumed to have the composite multipath shadowing effect. The signal to noise ratio of the received signal can be assumed to be a random variable with the following probability density function:

$$p_{\gamma_l}\left(\gamma_l; \mu_l, m_l, \sigma_l\right) = \int_0^\infty \frac{m_l^{m_l} \gamma_l^{m_l-1}}{w^{m_l} \Gamma(m_l)} \exp\left[-\frac{m_l\,\gamma_l}{w}\right]$$
$$\frac{10}{\ln 10 \sqrt{2\pi}\sigma_l w} \exp\left[-\frac{\left(10\log_{10} w - \mu_l\right)^2}{2\sigma_l^2}\right] dw, \tag{4-7}$$

where γ_l is the variable in which this pdf is explaining its distribution, μ_l is the mean of the variable's logarithm, m_l is the variable of Nakagami(m) distribution, and σ_l is standard deviation of the variable's logarithm.

We can predict that by increasing Ω and decreasing σ we can get a desired amount of BER with less SNR. The results of simulations can be found in next section.

4-2   Simulation

For simulating the scenarios mentioned in the problem definition, there is a need for a random generator which can generate the random variables according to the probability density function which has been mentioned before.

First for validation of one relay scenario, a relay is assumed to be in a 4 meters distance to sender and 3 meters distance to receiver. The distance between sender
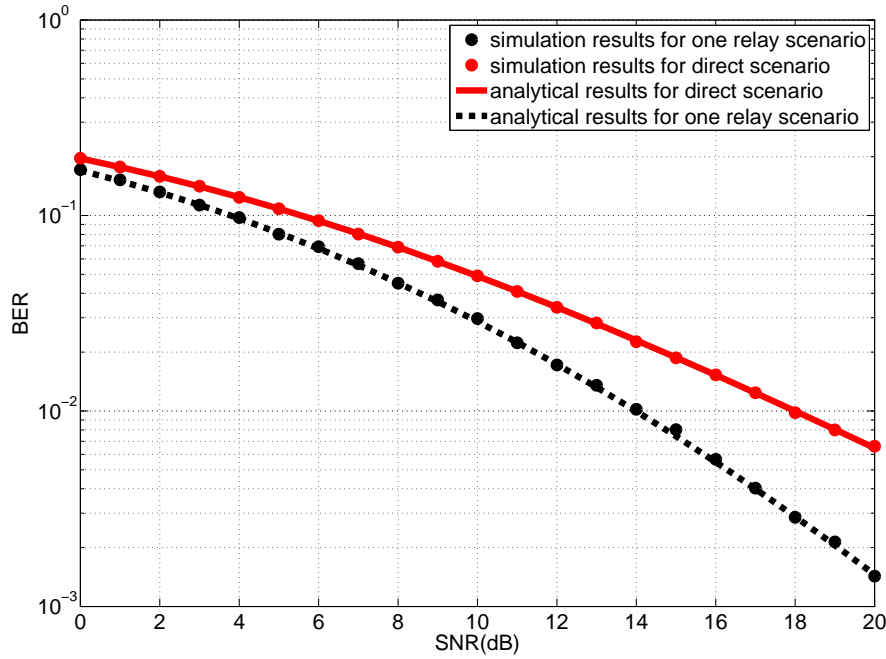
Figure 4-2: Comparison between one relay and the direct scenario without any relay, when μ is 0 for direct path, Ω is 1, m is 1 and σ is 0.5

and receiver is 5 meter. The analytical and simulation values of BER according to SNR values of signal is calculated. The result can be seen in Figure 4-2.

As it can be seen from in Figure 4-2, the simulation result which is shown as a dotted line match the values which are calculated analytically. Analytical calculation is based on (4-1), (4-2) and (4-7).

To investigate how much this cooperation can help to save power, a comparison between the case without any relay and a case with CC can be made. The difference between SNR for the same amount of BER in these two cases is an indicator for this gain. The comparison between these two scenarios can be seen in Figure 4-2.

According to Figure 4-2, the gain of this CC can be seen, if network is using this cooperation to send its messages. For $P_e = 10^{-2}$ the gain of using CC with one relay is 4 dB. In this scenario μ is 0 for direct path between the sender and the receiver, Ω is 1, m is 1 and σ is 0.5.

In Figure 4-3, the comparison between mentioned cases in Figure 4-2 can be seen with the confidence intervals of 90 percent.

In another channel environment the procedure mentioned for Figure 4-2 is done. In this new environment, μ is 0 for the direct path between the sender and the receiver, Ω is 2, m is 1 and σ is 0.25. According to Figure 4-4, we can find a gain in SNR, if network is using this cooperation to send its messages. For $P_e = 10^{-2}$ the gain of using CC with one relay is 3.5 dB.
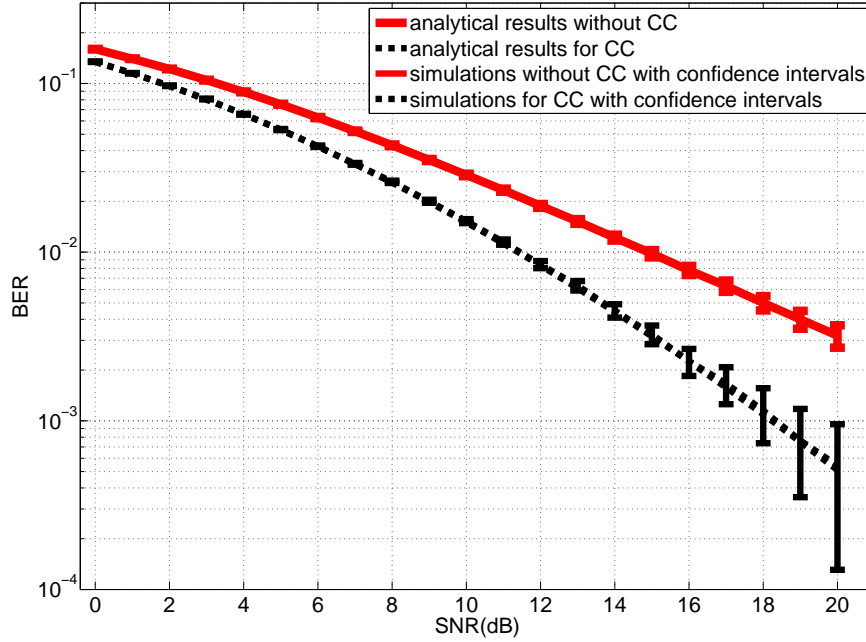
In Figure 4-3, the comparison between two cases mentioned for Figure 4-4 can be
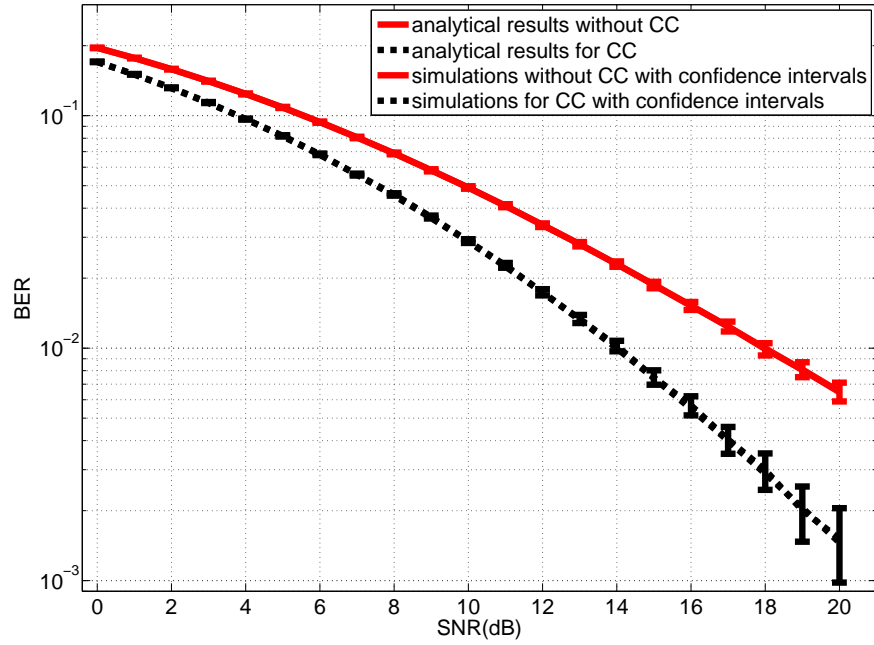
Figure 4-3: Comparison between one relay and the direct scenario without any relay; and with confidence intervals of 90 percent, when μ is 0 for direct path between the sender and the receiver, Ω is 1, m is 1 and σ is 0.5
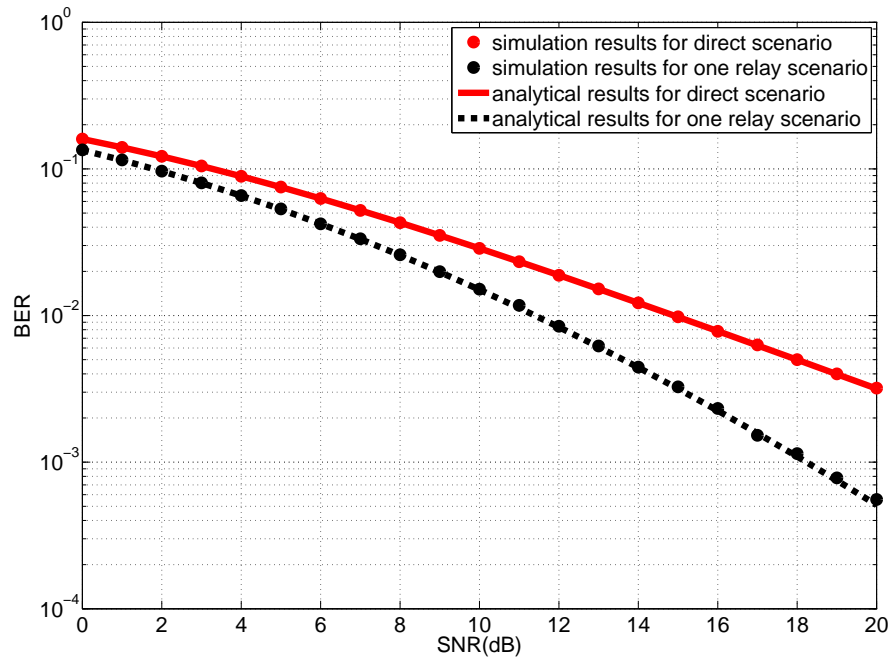
Figure 4-4: Comparison between one relay and direct scenario without any relay, when μ is 0 for the direct path between the sender and the receiver, Ω is 2, m is 1 and σ is 0.25

Figure 4-5: Comparison between one relay and the direct scenario without any relay; and with confidence intervals of 90 percent, when μ is 0 for the direct path, Ω is 2, m is 1 and σ is 0.25

seen with the confidence intervals of 90 percent.

As it was predicted in previous section, by increasing Ω and decreasing σ we can find a gain in SNR for a desired value of BER. Of course if we have a specific wireless channel, we cannot change the multipath fading and shadowing; but now we know the impact of each parameter on system performance.

In next section, we try to find the optimum values for α and β which are representing the power of sender and relay.

4-3   Power Allocation

In this section, the optimum value for power allocation of sender and relay in a case of one relay in CC is found. The calculation of α, which is the power allocated to the sender, is not an easy task analytically. So here, based on simulation, by changing α, optimum value can be found. These simulations are done in two different wireless environments.

First we assume a wireless network with μ is 0 for the direct path between the sender and the receiver, Ω is 1, m is 1 and σ is 0.5. Then by changing α; BER is calculated. The least amount of BER will correspond to the optimum α. Then the optimum α will lead to gain in SNR. In Figure 4-6, the optimum value for α is 0.9, this value is corresponded for SNR of 6 dB.
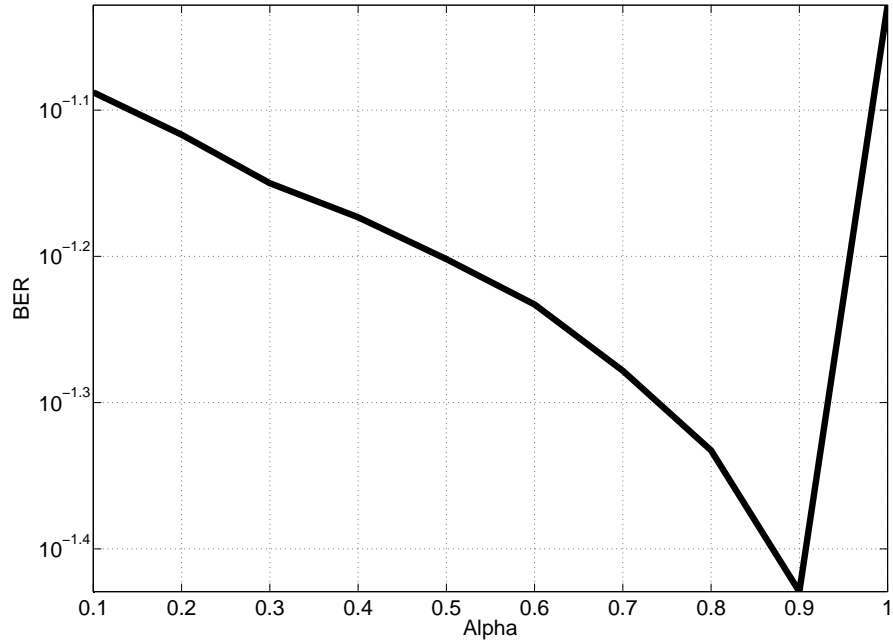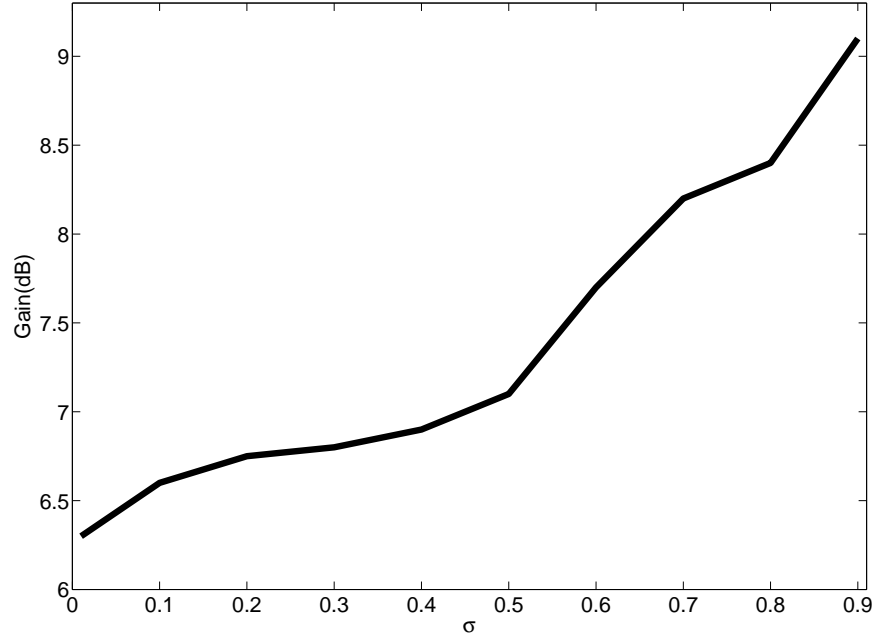
Figure 4-6: Alpha range for SNR = 6 dB, when μ is 0 for the direct path between the sender and the receiver, Ω is 1, m is 1 and σ is 0.5
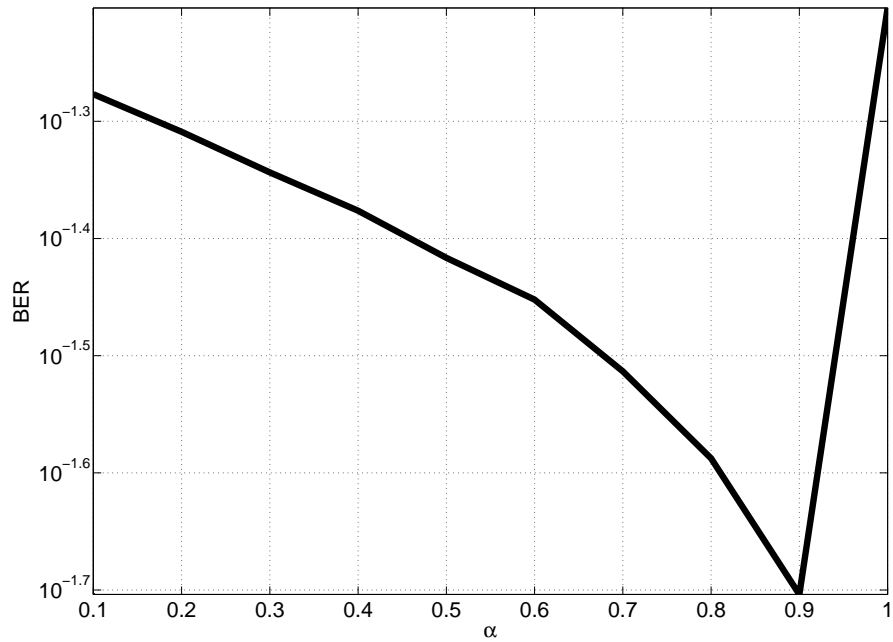
Figure 4-7: Alpha range for SNR = 6 dB, when μ is 0 for the direct path, Ω is 2, m is 1 and σ is 0.25

Figure 4-8: Impact of σ on gain, when μ is 0 for the direct path, Ω is 1 and m is 1

In the second wireless environment, μ is 0 for the direct path between the sender and the receiver, Ω is 2, m is 1 and σ is 0.25. It can be seen in Figure 4-7, that the optimum value for α is 0.9. The result is same as previous case.

4-4   Impact of Composite Distributions Parameters on Gain

In this section, the impact of different parameters of the composite distribution which is used to model our wireless channel is investigated. These factors are σ, m and Ω which are introduced in previous chapter.

In Figure 4-8, the impact of σ on gain of CC when μ is 0 for the direct path, Ω is 1 and m is 1 can be seen. σ is the standard deviation of the variable's logarithm. Since in the case of CC we have another chance to receive a signal when the variation of the signal is a lot; by increasing σ the gain of CC will increase.

In Figure 4-9, the impact of m on gain of CC, when μ is 0 for the direct path, Ω is 1 and σ is 0.25 in comparison with direct transmission can be seen. The m parameter of Nakagami distribution can be studied in the references mentioned in the previous chapter. This decrease in gain with respect to m is according to the property of m.

In Figure 4-10, the impact of Ω on gain of CC, when μ is 0 for the direct path, m is 1 and σ is 0.25 in comparison with direct transmission can be seen. Ω is the mean of the variable which has Nakagami distribution. As we compare both cases with almost same mean, we can expect that the gain is not changing with respect to Ω.
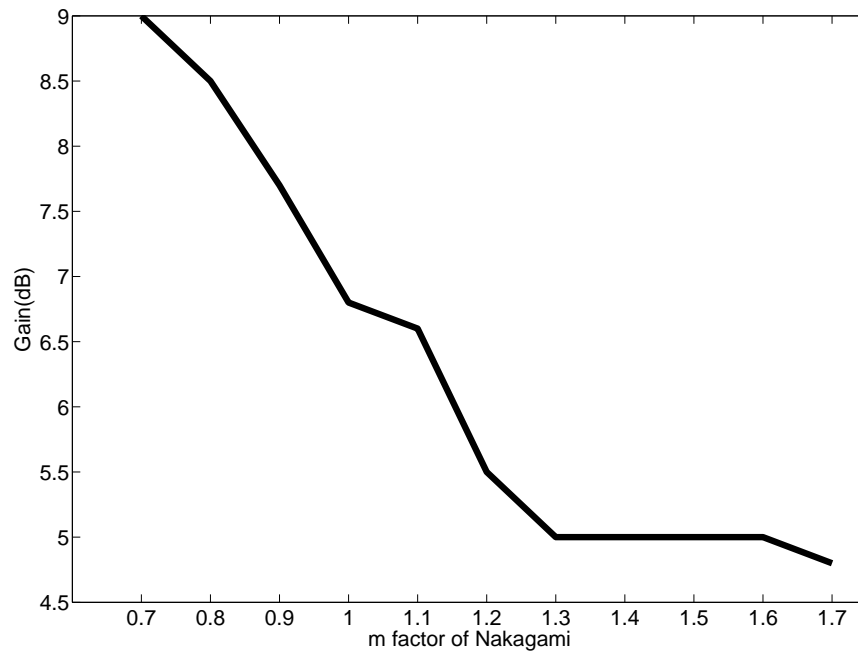
Figure 4-9: Impact of m on gain, when μ is 0 for the direct path, Ω is 1 and σ is 0.25
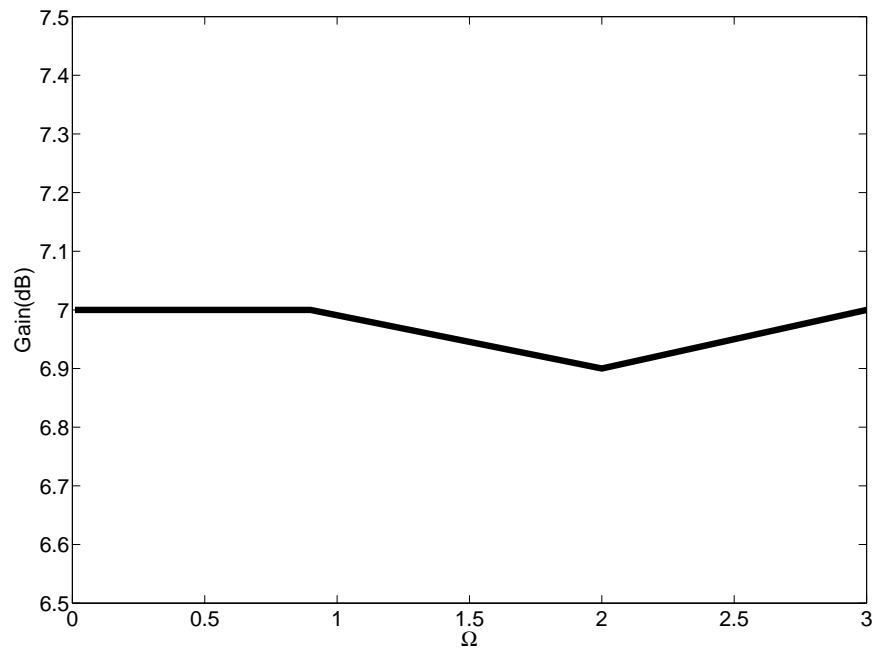
Figure 4-10: Impact of Ω on gain, when μ is 0 for the direct path, m is 1 and σ is 0.25

4-5   Summary

In this chapter, first the procedure to calculate the BER in a case of CC is introduced. Then the gain of CC in comparison to the case of direct data transmission between sender and receiver without usage of relay in terms of SNR is calculated. This procedure repeated for different parameters of wireless channel.

In the last section, the optimum value for power allocation of sender and relay to get the minimum BER is found through simulations.

Chapter 5

# Energy Conservation in Random Deployment

After calculating the gain of cooperative communications (CC) in wireless networks to satisfy the bit error rate (BER) requirement; in this chapter different position of a relay in a one relay cooperative network is studied through simulations. Then for two cases of random deployment of nodes in an area, the gain of CC in wireless networks is calculated in term of save in the required value of signal to noise ratio (SNR) for a required amount of BER.

Fist, different positions of the relay with respect to the position of the sender and receiver is investigated. This will lead to finding the optimum position of the relay in a typical wireless network. This is going to help us in the next sections.

The amount of power allocated to the relay is based on the calculations and the simulations in the previous chapter.

In the second section, a network with a rectangular shape is discussed. Some nodes are randomly distributed in the network. In each simulation experiments; the number of nodes are increasing with the step of 10. The result is based on the required amount of BER for the performance of network. The measure here for the evaluation is the gain in the SNR in the case of using the best relay according to the result of first section and the case of the direct communication between the sender and the receiver without any relay.

In the third section, a network with a wireless access point (WAP) is investigated. In this case, the receiver is assumed to be a WAP and a sender wants to send its message to it. In the case of CC in our wireless network, the best relay is going to be chosen from all random nodes to help the sender for transmitting its message. This choice is based on the result of first section. The gain of CC is calculated in this section in terms of improvement in SNR in comparison with the transmission without any relay.

Direction of change in position of relay
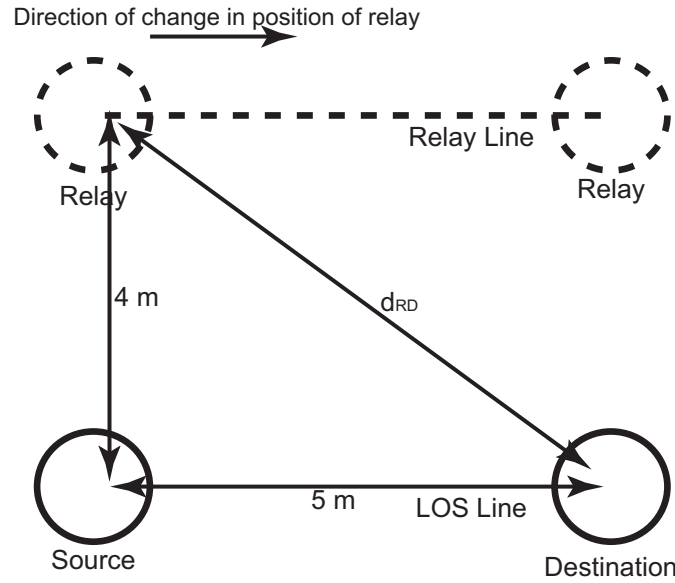
Figure 5-1: Network representation of one relay moving in a cooperative communication network

5-1   The Optimum Position of Relay

5-1-1   Problem Definition

Here, the distance between sender and receiver is 5 meters. This distance is chosen in a way that the value for μ which is introduced before, is 0. This distance can be changed according to the antennas gain, frequency according to (1-2) to make the μ zero. Based on this fact and typical values of antenna gain's this distance is different. In a parallel line to the line between sender and receiver, the position of the relay is changing. The distance between these lines are 4 meters. From an engineering perspective, we try to find the optimal position of the relay, assuming that the network designer has freedom to position the relay deterministically. Figure 5-1 is representing the scenario for this simulations.

In Figure 5-1, the source and destination are shown. The direct path between them is chosen in a way that the amount of μ is zero. Based on this, a comparison with the results of previous chapter can be made. Different positions of the relay can be found in (5-1).

In these simulations, we assumed that μ is 0 for direct path between the sender and the receiver, Ω is 1, m is 1 and σ is 0.5. The results can be seen in the next section.

5-1-2   Results

In first case when the distance between the line in which the relay is changing it's position and line of sight (LOS) is 4 meters, the SNR is 5 dB and 7 dB for first and second case respectively. The result can be seen in the Figure **??**.
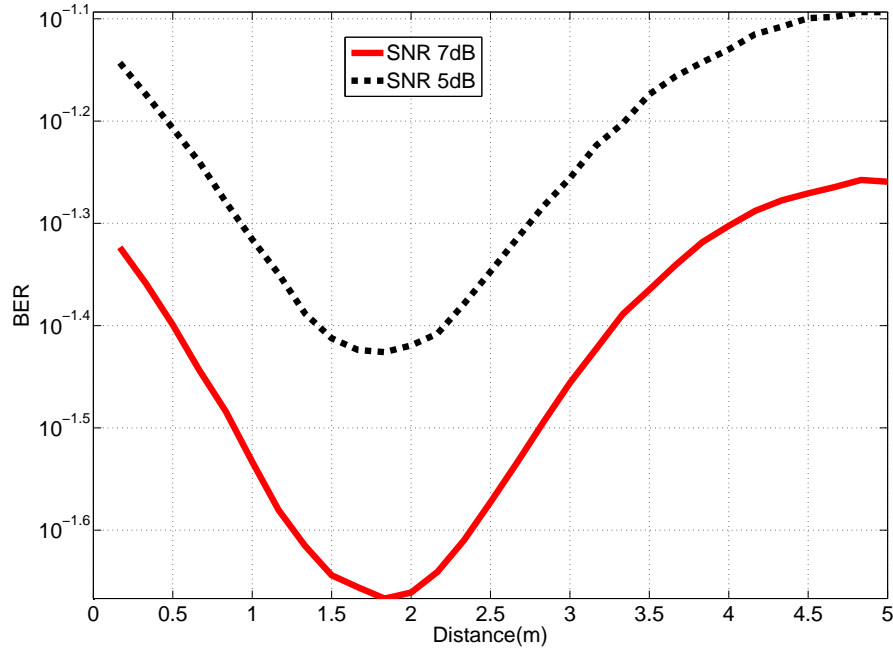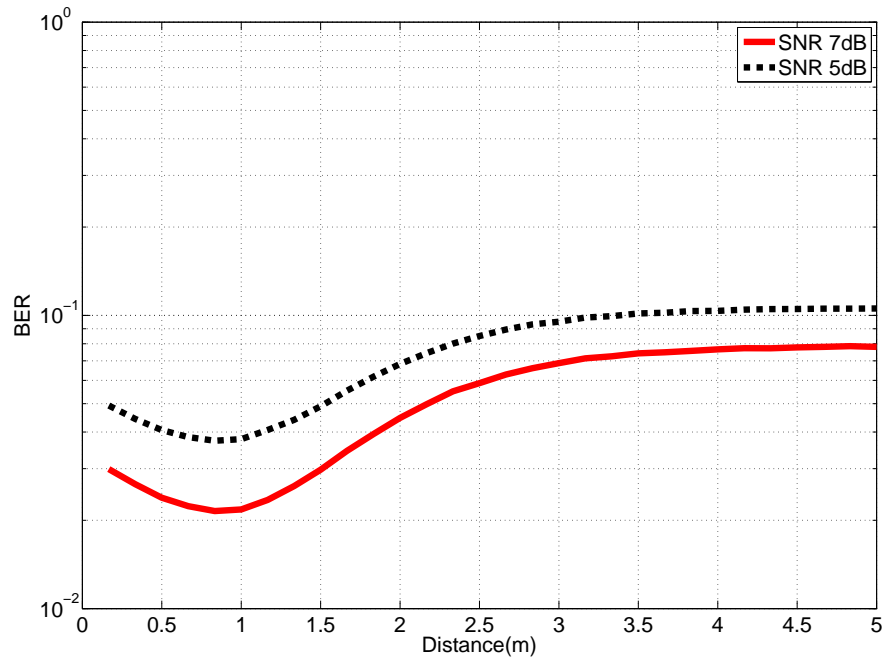
Figure 5-2: Movement of Relay with SNR of 7 and 5 dB in a path with distance of 4 meters to the direct line

As it can be seen in Figure 5-2, the optimum value for BER can be obtained when the relay is in 2 meters of the beginning of the parallel line to the LOS. For the case of 5 and 7 dB, we have the gain of 3.5 and 4 dB gain. In this scenario the parallel line distance to LOS is 4 meters.

As it can be seen in Figure 5-3, the optimum value for BER can be obtained when the relay is in 1 meters of the beginning of the parallel line to the LOS. For the case of 5 and 7 dB, we have the gain of 6 and 5 dB gain respectively. The reason for the change in the shape of the graph in comparison to (5-2) is the fact that theses two lines are closer to each other; and therefore for getting the optimum value for gain the relay must be closer to both sender and receiver. In this scenario the parallel line distance to LOS is 3 meters.

In Figure 5-4, the optimum value for BER can be obtained when the relay is in half a meter of the beginning of the parallel line to the LOS. For the case of 5 and 7 dB, we have the gain of 6 and 5 dB gain respectively. In this scenario the parallel line distance to LOS is 2 meters. Same reasoning can be used to explain the change in the shape of the graph as it is mentioned for (5-3).

In Figure 5-5, the optimum value for BER can be obtained when the relay is in 2 meters of the beginning of the parallel line to the LOS. For the case of 5 and 7 dB, we have the gain of 6 and 5 dB gain respectively. In this scenario the parallel line and LOS are the same.
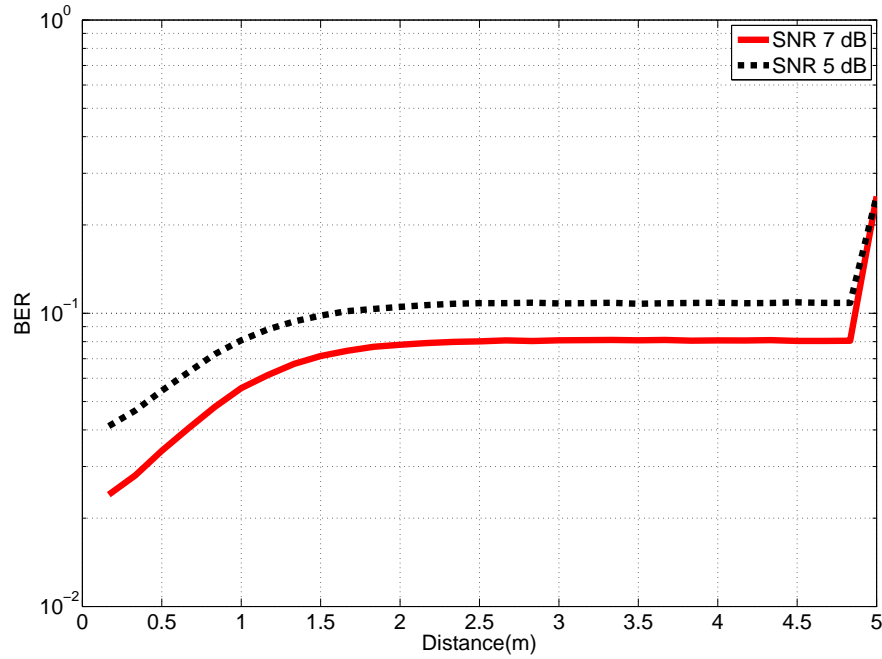
Figure 5-3: Movement of Relay with SNR of 7 and 5 dB in a path with distance of 3 meters to the direct line
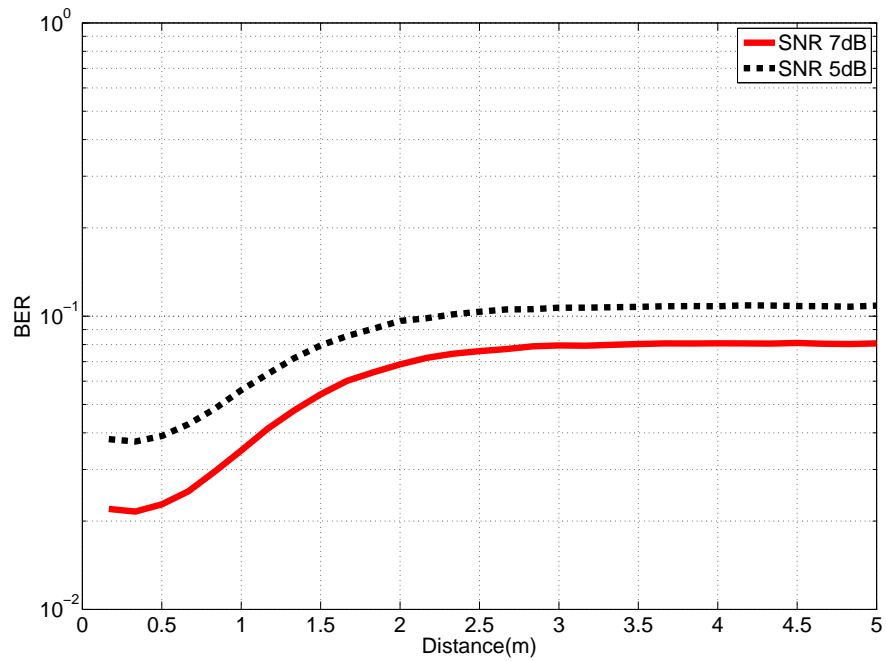
Figure 5-4: Movement of Relay with SNR of 7 and 5 dB in a path with distance of 2 meters to the direct line

Figure 5-5: Movement of Relay with SNR of 7 and 5 dB in the direct line between the sender and the receiver

5-2   Random Deployment of Nodes in a Rectangular Area

In this section, a random deployment of a number of nodes in a rectangular area is investigated.

5-2-1   Problem Definition

For the case of random deployment; we assume that sender and the receiver are in a rectangular area; and they have a distance of 5 meters. There will be some relays which are randomly deployed in the field.

Network representation can be seen in Figure 5-6. In this figure, 20 nodes are randomly deployed in a normalized size and rectangular shape network. Three nodes are chosen randomly as a transmitter, a receiver and a relay. Then the transmission with the help of the relay will take place.

The method to evaluate if the usage of a random node as a relay, is comparing the required amount of power for a required value of BER to the case of the direct transmission without any relays.

In this process, the best node is going to be selected as a relay based on the results of previous section. In these simulations, we assumed that μ is 0 for direct path between the sender and the receiver, Ω is 1, m is 1 and σ is 0.5. The results can be seen in the next section.
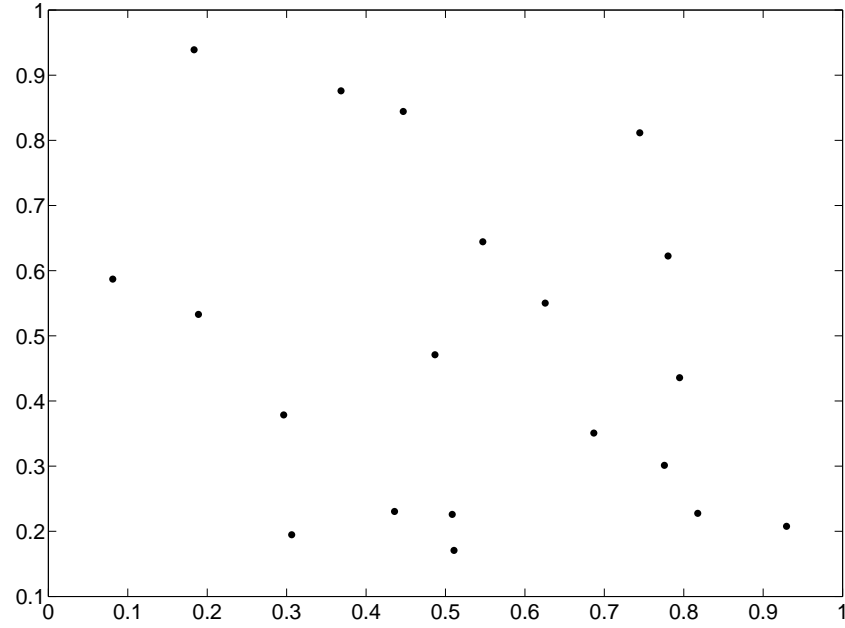
Figure 5-6: Network representation of a rectangular network with 20 random nodes

5-2-2   Results

In this section, the simulation results of the random deployment of nodes in this rectangular network is presented.

As it can be seen from Figure 5-7, the performance of the network with only 10 random nodes is worse than the case without CC. The reason behind this is the fact that the number of random nodes are not enough to make it probable enough that one of the node is in the best position for the CC according to the previous section. So the overall performance of CC with this number of random nodes are worse than direct communication between the sender and the receiver without any relay.

In Figure 5-8, the performance of a wireless network with 20 random relays is shown. The performance is almost the same as the case of direct communication between the sender and the receiver. So in this network and with the parameters mentioned in the problem definition, the critical number of nodes to deploy in this network is 20.

In Figure 5-9, the performance of a wireless network with 110 random nodes is shown. Since the number of nodes is enough, the gain is almost same as the case of a relay in an optimum position.

After these observations, in next figure a conclusion about the gain of cooperation in such a network is presented.

In Figure 5-10, the performance of a wireless network with random relays in a rectangular shape network is shown. As it can be seen, the gain would stay constant

Figure 5-7: Random deployment of 10 nodes in a rectangular shape network when α is 0.9

Figure 5-8: Random deployment of 20 nodes in a rectangular shape network when α is 0.9
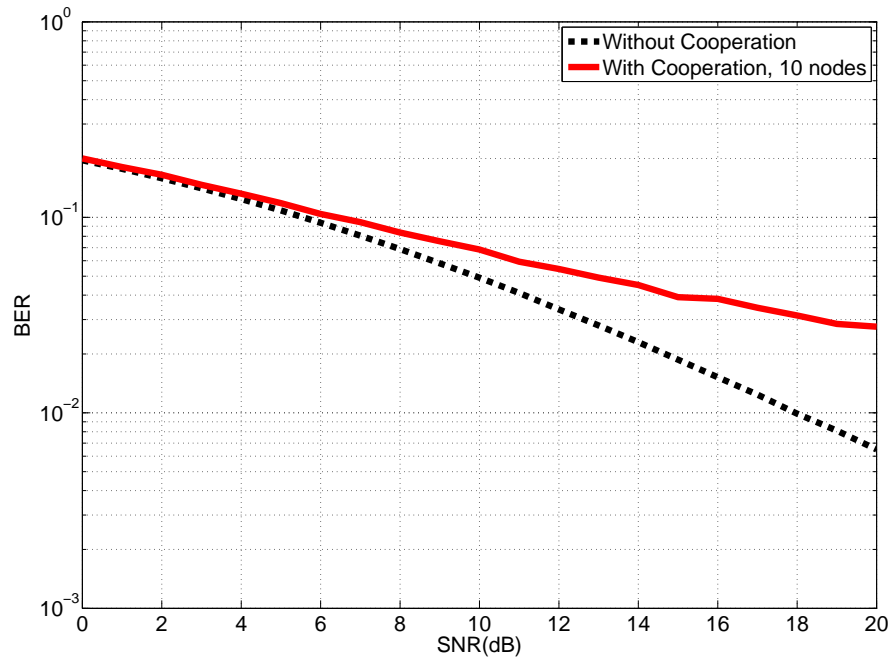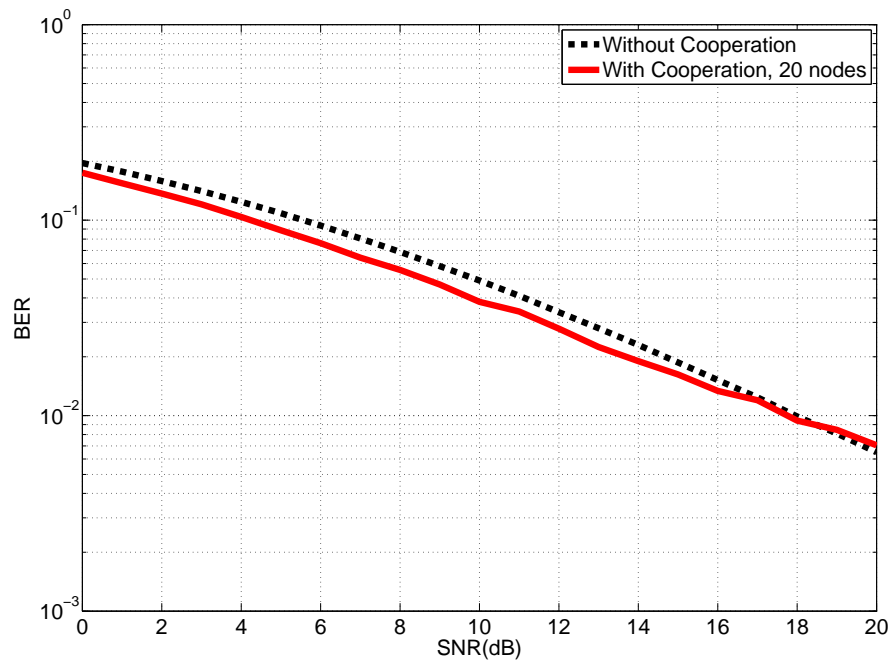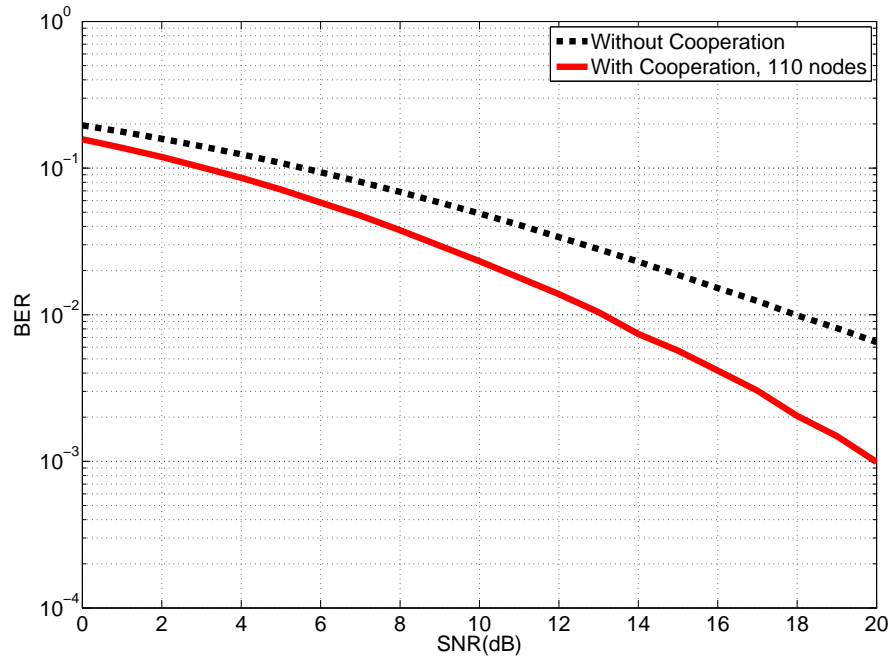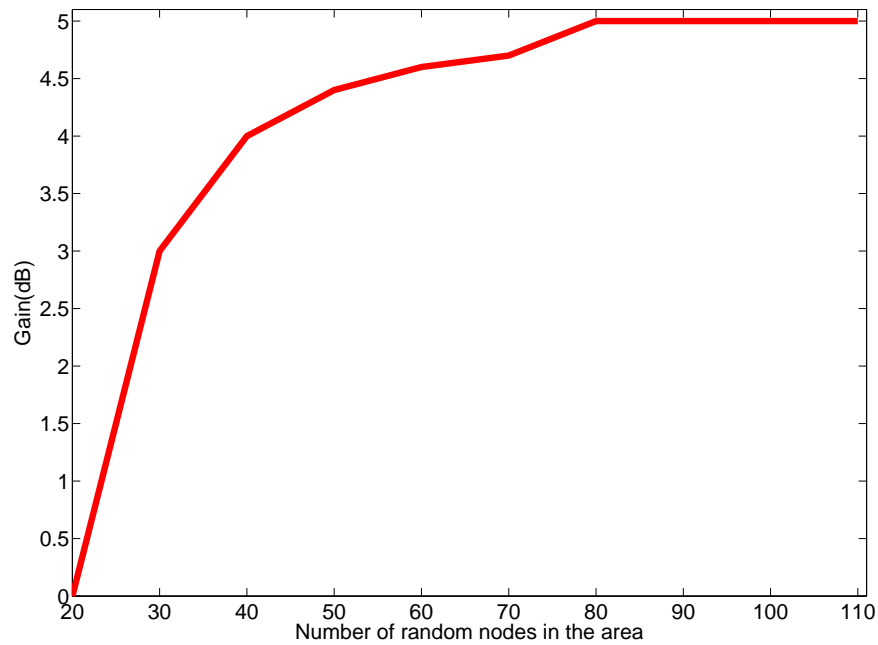
Figure 5-9: Random deployment of 110 nodes in a rectangular shape network when α is 0.9

Figure 5-10: Gain of using one relay in a rectangular shape network when α is 0.9 and various number of random nodes
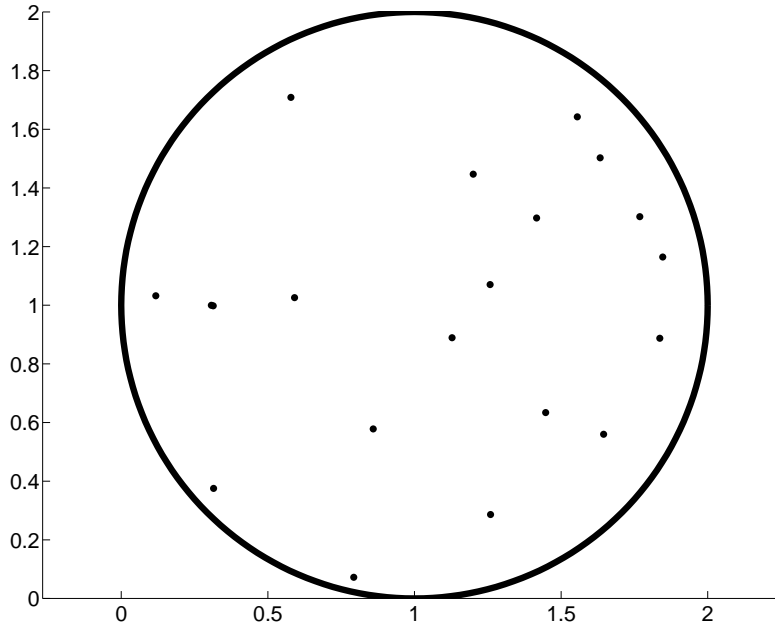
Figure 5-11: Network representation of a circle shape network with 20 random nodes

after a certain point. This is due to fact that, after some point there are enough random nodes; and then the optimum position for the relay is similar to atleast one of the random nodes. Then after this point, the increase in the number of random deployed nodes are not important for the gain in SNR.

5-3 Random Deployment of Nodes in Cellular Networks

In this section, a circle shape wireless network and some random deployed nodes inside it is investigated.

5-3-1 Problem Definition

In this scenario we assume that the receiver is a WAP. Position of the sender and the relays is assumed to be random in a circle area which has the WAP as its center. In the case of CC, the best node is going to be selected as a relay with respect to the results of 5-1. To calculate the gain the average amount of BER in CC is going to be compared with the direct transmission between the sender and the receiver. The network representation can be seen in following figure:
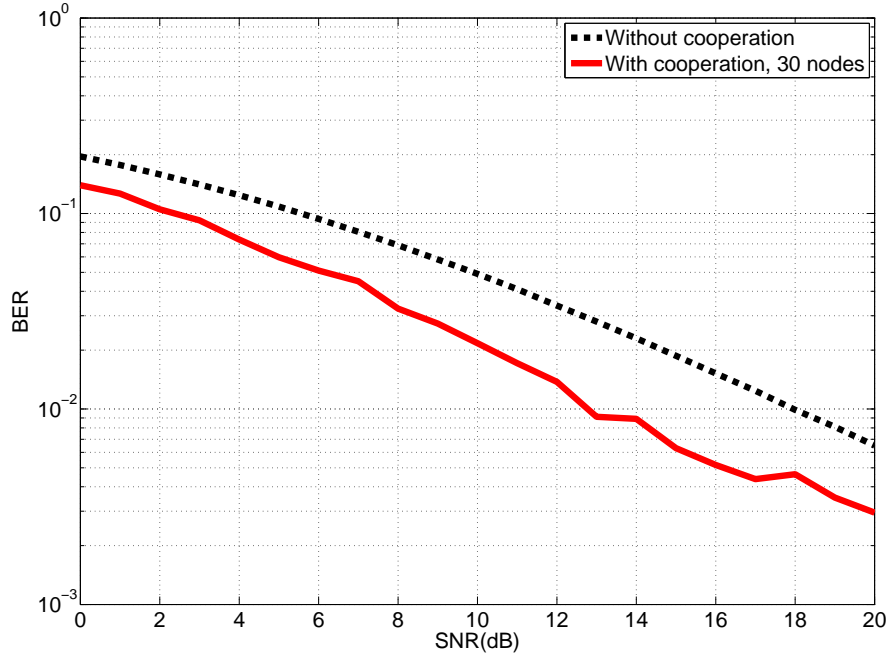
Figure 5-12: Random deployment of 30 relays in a circle shape network when α is 0.9

5-3-2 Results

In this section, results of simulations for various numbers of random nodes in a certain network is presented.

In Figure 5-12, 30 random nodes are deployed in our circle shaped network. The shape of graph is not smooth. The reason behind this is that the number of simulations are enough for the Monte Carlo simulations of the last works; here by imposing new parameter this number is not enough. The number of simulations here is 10^6 and it was good for the previous results.

In Figure 5-13, the graph is smoother than (5-12). This is due the fact that by increasing the number of random nodes, the chance that the method can find the a node in an optimum position is more.

In Figure 5-14, the maximum gain of random deployment of nodes in a circle shape network can be found. The gain is 6.5 dB in comparison to the direct transmission between the sender and the receiver, which is same as the theoretical value. In another comparison, we can compare the results in (5-9) and (5-14). As it can be seen the gain in both graphs for 10^{-2} as BER is same; and it is 6.5 dB. In this case α which is the power allocated to the sender is 0.9. We can conclude that when the number of random nodes are high enough; the gain will merge to the theoretical value.

In Figure 5-15, the gain of CC in comparison with the number of random deployed nodes in a circle shape network can be seen. After some critical value, which is
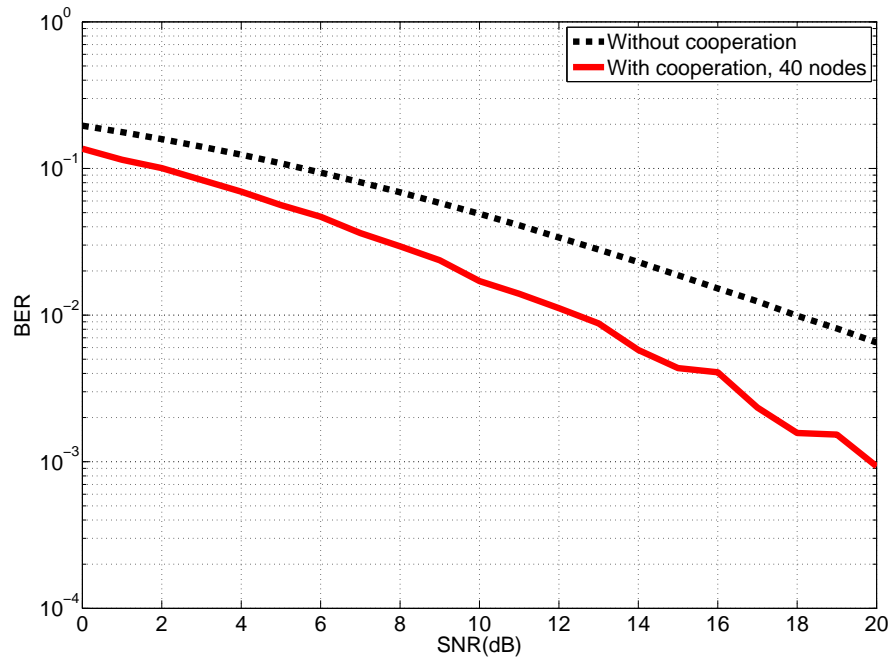
Figure 5-13: Random deployment of 40 relays in a circle shape network when α is 0.9
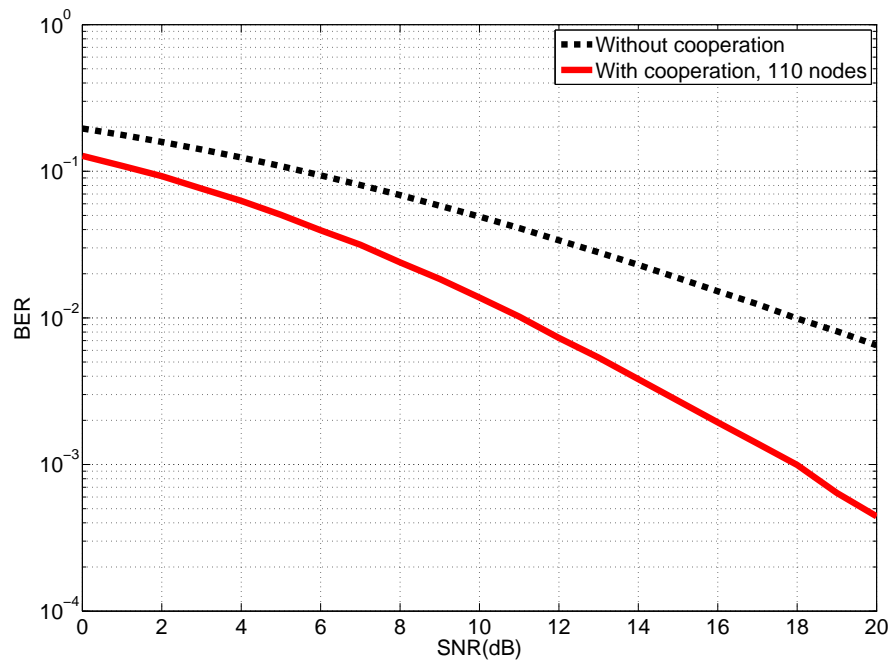
Figure 5-14: Random deployment of 110 relays in a circle shape network when α is 0.9
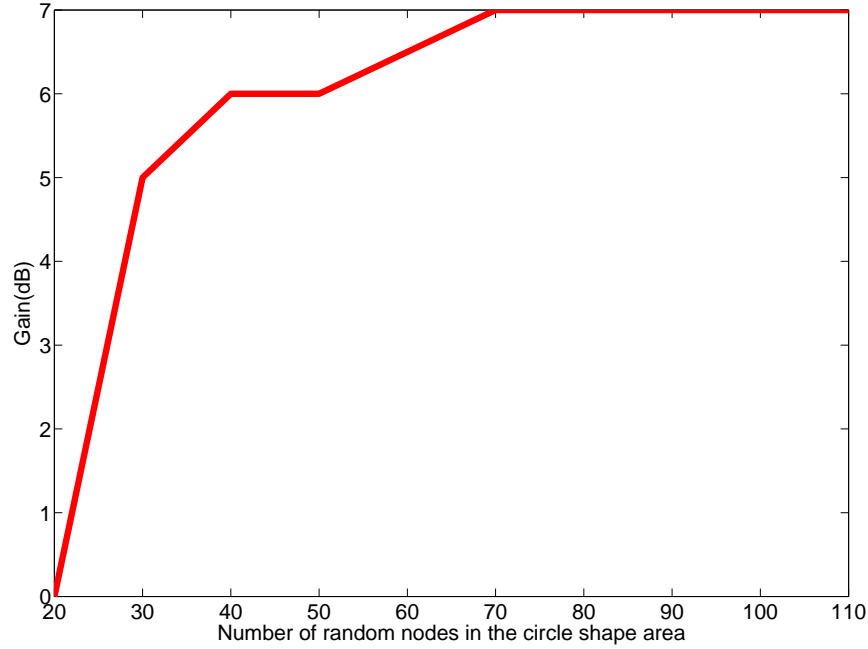
Figure 5-15: Gain of using one relay in a circle shape network when α is 0.9 and various number of random nodes

almost 30 in this case, the gain of CC will remain constant. The step of change in the number of nodes here is 10; therefore the exact value for this critical value is near 30. In these simulations, each point is calculated based on 10^6 times of simulations.

In next section a conclusion of this chapter is presented.

5-4   Conclusion

In this chapter, with the understanding of CC from last chapters, the optimum performance of this network is studied.

First, best position of a relay in a plane of the transmitter and receiver is found. This optimum is based on the gain in SNR to satisfy the required value of BER. Since the sender and the receiver are in two point of a line; and if we assume that we have omni directional antennas in both transmitter and receiver; we can conclude that we have the best position of the relay in a three dimensional area around the sender and the receiver in a composite Nakagami-m and log-normal wireless channel.

Second, for a rectangular shape network, the impact of CC is studied. If a number of random nodes in area is more than a critical value, the is high chance that one node have almost similar position as the position of the relay which will lead to optimum value for SNR for a required BER.

In last part, for a case in which the receiver is assumed to be a WAP is studied. Similar to previous case, if the number of random nodes are high enough; the optimal value for SNR for a required BER is similar with the theoretical results.

Chapter 6

Conclusion and Future Work

6-1 Conclusion

First an overview of current research in the field of cooperative communications (CC) in wireless networks is discussed.

Then with the help of Nakgami-m and log-normal distributions, a probability density function (PDF) for a composite distribution which can nearly model all wireless channels is presented. An approximation is introduced for analytical calculation of PDF of the composite distribution.

The cooperation in a wireless network which its channel coefficients follow Nakagami-m and log-normal distributions is studied. The results are compared to a case of direct transmission between a transmitter and a receiver. Then for a required bit error rate (BER), the gain of this CC in comparison with the direct transmission in term of power has been shown. When the required BER is 10^{-2} the gain in signal to noise ratio (SNR) is 4 dB in comparison to the direct case. The distribution parameters for this scenario can be found in (A-1).

This gain in SNR is investigated for different wireless channels. Then the impact of m, σ, and Ω on the gain of CC is studied. By increase in σ the gain will increase. This is the result of increase in variations of channel coefficients. This will lead more fluctuations in channel; and when a channel is blocked or the performance is not good enough; the CC will improve the system performance. By increase in m the gain will decrease. The correlation between the gain of CC and Ω is negligible.

The power allocation between the sender and the relay is investigated. The optimum value for α depends on the the position of the relay, which varies around 0.9.

In the network area between the sender and the receiver, best position of the relay in CC is also found. This optimum position will lead to a gain in terms of power.

For two different wireless networks, the random deployments of nodes is investigated. In these networks, a random number of nodes are deployed in a certain area.

Then based on the results of best positions of the relay for a CC network; best node is selected as a relay. Then the BER performance is compared to the case of direct transmission. The gain in power for the case of CC has been shown with respect to the number of random nodes in the network.

6-2   Future Work

In this section, some suggestions for future work in this field is presented.

- Multi-level modulation: In this work, the modulation scheme is binary phase shift keying (BPSK). For future studies in this field, other modulation schemes which are more popular in wireless communications must be investigated. The gain of power in CC in these modulations most be found.

- Multiple relays: The impact of one relay in CC studied in this work. The gain is obviously larger if more relays are deployed. The cost will be complexity of methods for CC. The amount of overhead will also increase when there more relays are used. These trade-offs with this composite channel as the wireless model can be future research in this field.

- Discrete simulations: To better evaluate this CC network; a higher layer investigation is required. For this research discrete simulations are needed to model the layering concept of CC network. The CC requires a cross layering design. New protocols must be introduced. These new protocols will lead to more overhead in the message; then the efficiency of this new protocols must be compared with current protocols.

- Cooperative media access control (MAC): New MAC protocols must be defined to address new issues in CC network. The procedure of choosing the relay needs new signalling. The decode and forward (DF) in the relays will impose delay in transmission. This delay needs to be considered for the evaluation of the whole network.

- Routing: The current routing algorithms in wireless networks are not based on CC. Some modifications must be done to make them suitable in case of CC.

- Multi hop networks: The gain of CC must be compared to a case of a multi hop network. In this network, instead of a direct transmission between sender and receiver, they communicate via nodes in between them to forward they message. When a path is not performing well, another path can be chosen based on a proper routing protocol. The multi hop network can also increase the diversity, which will lead to better performance.

- Security issues: When a node is using another node as its relay for improving the performance or energy savings, they need to start a secure protocol to trust each other. Some malicious or intruder nodes may pretend to be a relay to get the message.

- Cooperation problems: Some nodes may use the CC for their benefits but they are not helping others. In this channel model this issues can be investigated in more realistic situations.

Appendix A

Wireless Network Parameters

A-1   Parameters for One Relay CC Results

In Table A-1, the parameters used for our analytical calculations and simulation results can be found.

Table A-1: Parameters for One Relay CC Results

Environment	μ	Ω	σ	m	α
First	0	1	0.50	1	0.9
Second	0	2	0.25	1	0.9

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Glossary

List of Acronyms

CC	cooperative communications
BER	bit error rate
OSI	open system interconnect
ISO	international standard organization
SNR	signal to noise ratio
PDF	probability density function
MGF	moment generating function
DF	decode and forward
RF	radio frequency
LOS	line of sight
ISI	inter symbol interference
MIMO	multiple-input and multiple-output
AF	amplify and forward
CR	cognitive radio
CSI	channel state information
MAC	media access control
CF	compress and forward
DoF	degree of freedom
TDMA	time division multiple access
CDMA	code division multiple access

MU-MIMO	multi-user MIMO
SU-MIMO	single-user MIMO
FDMA	frequency division multiple access
OFDMA	orthogonal frequency division multiple access
MC-CDMA	multi carrier code division multiple access
WSN	wireless sensor network
SER	symbol error rate
OAF	orthogonal amplify and forward
OSDF	orthogonal selection decode and forward
NSDF	non-orthogonal selection decode and forward
RTS	request to send
CTS	clear to send
ACK	acknowledgement
CSI	channel state information
AWGN	additive white Gaussian noise
QAM	quadrature amplitude modulation
PSK	phase shift keying
BPSK	binary phase shift keying
CDF	cumulative distribution function
RV	random variable
CG	Chebyshev Gauss
WAP	wireless access point
QoS	quality of service
LCR	average level crossing rate
AFD	average time fade duration
MRC	maximum ratio combining

List of Symbols

$\bar{\gamma}$	Average SNR
λ	Wavelength
E_{Relay}	Transmission Energy per Symbol for Relay
E_{Sender}	Transmission Energy per Symbol for Sender
G_r	Receiver Antenna Gain
G_t	Transmitter Antenna Gain
m	Parameter of Nakagami distribution
N_r	Number of Relays
P_i	Relay's power
P_r	Received Power
P_{total}	Total power
P_{tr}	Transmitter's power
P_t	Transmitted Power
R	Data Rate
μ	Mean of the variable's logarithm
σ	Standard deviation of the variable's logarithm