Performance of Disparate-Bandwidth DS-SS Systems in Spectral Overlay Ad Hoc Networks

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Najeeb S. Al-Hashim
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This thesis titled
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Networks

by

NAJEEB S. AL-HASHIM

has been approved for
the School of Electrical Engineering and Computer Science
and the Russ College of Engineering and Technology by

________________________________________

David W. Matolak
Associate Professor of Electrical Engineering and Computer Science

________________________________________

Dennis Irwin
Dean, Russ College of Engineering and Technology
ABSTRACT

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Director of Thesis: David W. Matolak

In this thesis we investigate the performance of direct sequence spread spectrum (DS-SS) overlay ad hoc networks by performing computer simulations and numerical evaluations based upon mathematical analysis. Two such DS-SS systems, with different bandwidths, are studied. We investigate performance statistics for a terrestrial network model in a limited two-dimensional area, in which user (node) locations are random, and statistics are gathered over numerous realizations of these random node locations. For all users in both systems we collect statistics on performance in terms of signal-to-noise-plus-interference ratio (SNIR) and bit error probabilities, to illustrate aggregate behavior attainable in such systems. We first illustrate our technique for a specified reference system with a given set of parameters, then we vary several of these parameters to assess the effects on performance. Parameters we vary include transmit power, data rates, processing gain, path loss exponent and shadowing standard deviation. We demonstrate that overlay of different-bandwidth DS-SS systems in an ad hoc network can be practical by specifying appropriate system design parameters.

Approved: _____________________________________________________________

David W. Matolak

Associate Professor of Electrical Engineering and Computer Science
DEDICATION

This thesis is dedicated to:

My father Matouq A. Al-abdullah
and

My mother Haifa A. Al-nazer
and

the members of my family
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I would like to start addressing my praise to Allah Lord of the worlds, and peace and blessings be upon Mohammed PBUH and his pure progeny Ahl AlBait.

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CHAPTER 1: INTRODUCTION

Growth of Digital Communications

Communication systems are primarily designed to convey, from one point to another, information represented by waveforms, which are unknown to the recipient until received. There are two main types of waveforms used to represent information: digital waveforms and analog waveforms. Digital waveforms take amplitude values only from discrete sets as a function of time, for example binary waveforms are permitted to have two values \{0, 1\} [1]. In contrast, analog waveforms are continuous functions of time and can in general take any real number value.

Up through the 1960’s, analog communication systems were the dominant type. Analog communication was also used for the so-called 1st generation of wireless cellular radio systems. Due to the tremendous advantages of digital communication systems (DCS), 2nd generation cellular systems employed digital techniques. An example advantage of digital communication systems is cheaper, faster, smaller, and less power-consuming circuitry than in analog systems. Digital techniques also provide data processing options, higher capacity, and more convenient messaging, email and imaging capabilities. Additionally, DCS are easy to implement and can often offer better performance than analog communication systems. Nowadays many radio systems transmit digital binary signals, either by digitizing an existing analog signal or by directly acquiring binary data signals. Figure 1.1 shows a block diagram of some of the main elements of a DCS.
Figure 1.1: Digital communication system

In Figure 1.1, the source of information can be either analog, such as voice, or digital. Continuous time analog signals are quantized and encoded to produce a sequence of binary values. Modulation converts the digital sequence to a sequence of waveforms suitable for transmission on the channel. In spread spectrum systems (the topic of this thesis), spectrum spreading is done as part of modulation.

The receiver on the other end of the channel receives the attenuated and potentially distorted waveforms in the presence of noise and possibly interference. There are many types of channels, and two ways of classifying them are wired and wireless. In general, channels are not perfect, and they can distort the signal. In this thesis we focus on wireless channels. Due to the attractive property of user mobility, which removes limits on user location, wireless communication systems are the fastest growing sector of the communications business throughout the world.
1.1.1. Cellular

Cellular systems are the “main leap forward” in the “wireless revolution” and they are considered this since they have in large part solved the problems of spectral congestion and user capacity [33]. They were initially designed to reach large coverage areas by using high-powered transmitters located in a high tower. However, it was unfeasible to reuse the same frequencies (spectrum) throughout the same system due to the interference caused by users in the same channel. As shown in Figure 1.2, to overcome the problem of having a single large “cell” with very high transmitted power, several smaller cells, each with small transmit power, were spatially separated to cover the whole region and to re-use the same spectrum. These first cells are now known as macrocells, and the reason the spectrum can be re-used is that signals are attenuated with distance, so at a sufficiently large distance away, the frequency band of one cell can be re-used locally in another cell. In recent years, smaller cells with even smaller transmission power have been used, and these have been termed microcells and picocells.
Figure 1.2: Cellular network diagram.

These cells have centralized base stations that control and allocate the available channels of their own cell, and they also coordinate with nearby base stations (through high-speed wireline connections) to assign different sets of channels from the nearest base stations [6, 33]. If the cells are sized correctly for a given area, this system with multiple cells can support more users and requires less transmission power per user than a system with only a few very large cells. The smaller cells do though have drawbacks; managing the location of each user can be complicated, for example.

1.1.2. WLANs

The most popular wireless LAN protocol at present is IEEE 802.11 standard, which was established by one of the foremost standards-making associations in the world, the Institute of Electrical and Electronics Engineers (IEEE). A wireless LAN is a wireless network that links several devices together using one of several different types
of modulations, including direct sequence spread-spectrum (DSSS) [1, 6, 23,32]. WLANs have been “booming” in recent years, and they can be used in multiple ways, for example to replace networking wires within homes, buildings, and offices. They can also allow users within their coverage area to have some mobility while connected to the network [6]. In the U.S. WLANs operate in unlicensed frequency bands, centered near 900 MHz, 2.4 GHz, and 5.8 GHz.

The 1st generation WLANs were not that popular due to their relatively high cost, and with moderate performance, users did not quickly and widely accept them. In contrast, the 2nd generation systems operated with 80 MHz of spectrum in the 2.4 GHz spectrum band, and quickly became popular. This 2nd generation WLAN standard is IEEE 802.11b, which was the first widely adopted standard. Since the 2.4 GHz band is an unlicensed band, IEEE 802.11b devices can incur interference from devices operating in the same band. The IEEE 802.11a standard, which operates in the 5 GHz bands with nearly 300 MHz of spectrum, and the IEEE 802.11g standard, which uses either the 2.4 GHz or the 5 GHz bands, were developed to support more users and higher data rates than IEEE 802.11b. Today, often single user devices have the ability to run all these different standards to allow the users to be as "highly connected" as possible.

1.1.3. Example Standards

Communication systems require standardization if they are to work together, and if devices from different manufacturers must inter-operate. The IEEE is the one of the major communication standards developers in the USA and internationally. The
The Telecommunication Industry Association (TIA) group in the U.S. and the European Telecommunications Standards Institute (ETSI) group in Europe also take part in developing standards.

The IEEE 802.11a standard, which operates in the 5 GHz bands, uses orthogonal frequency-division multiplexing (OFDM) as the modulation scheme. The IEEE 802.11b standard operates in the 2.4 GHz frequency band \([6,23]\) and uses DSSS modulation. Maximum specified data rates for 802.11b and 802.11a are 11 Mbps and 54 Mbps, respectively. WLAN standards development is ongoing, and several new standards such as IEEE 802.11n and IEEE 802.16 are being used for personal area and metropolitan area networks, respectively.

1.2. Use of Spread Spectrum

Spread spectrum (SS) is a technique that has been used since the second World War for military applications. In the past two decades it has also seen use in the commercial marketplace \([1,6]\). Spread spectrum works by increasing the transmitted signal bandwidth far beyond the value required for data communication. The main two types of SS are frequency hopped spread spectrum (FHSS) and direct-sequence spread-spectrum (DSSS). The DSSS approach essentially multiplies the data signal with a very high rate spreading waveform to spread the spectrum. In contrast, FHSS modulates the data signal with a varying (hopping) carrier signal, which results in centering the narrow band waveform spectrum at a large number of frequencies over time. SS has several
advantages over non-spread signaling, which includes its ability to resist a narrowband jamming and interference, as well as being hard-to-intercept and detect [1,3,6]. Therefore as noted, SS was widely used for many years in military applications [3]. The ability for DSSS to resolve and combine multipath components has helped make it attractive for commercial applications such as cordless phones, cellular systems and wireless LANs. DSSS-Code Division Multiple Access (CDMA) is also used by the Global Positioning System (GPS) because of the fine timing resolution available with a wide bandwidth signal. CDMA technique has the ability of spectrally overlaid narrowband and wideband systems to share common spectrum [4,5,10,20].

1.3. Ad Hoc Networks

A mobile ad hoc network (MANET) is a communication network without the support of fixed infrastructure, in which wireless nodes are dynamically free to move and connect themselves randomly [23]. Wireless ad hoc or “on-the-fly” networks have an elementary feature that lets them organize themselves and form a temporary network without the involvement of centralized administration. Moreover, MANETs can be “multi-hop” networks, which means that any terminal (also called a “node”) can not only send and receive information directed from/to itself, but can also send information from other nodes by acting as a relay between the end nodes [22]. Ad hoc wireless networking is a progressively growing research topic in wireless communication. Researchers inquiring beyond third generation (3G) systems of telecommunication standards and networking ,are focusing on providing a higher transmission rate and lower system cost
Many envisioned systems are aiming at using a frequency band above 3 GHz due to the widespread use of the lower frequency bands, and the wider bandwidths available at higher carrier frequencies. In using these bands, channel propagation conditions (range, etc.) must be taken into account in system design.

Despite their convenience, MANETs face various types of challenges, such as imperfect wireless transmission range, the “hidden terminal” problem, potential security problems and power restrictions.

1.3.1. Traditionally Military Use of Ad Hoc Networks

With the lack of infrastructure that MANETs imply, this kind of network was used by the military in the battlefield where military maneuvers are regularly unstructured. Soldiers, for instance, are capable of using an ad hoc network communication system to form a network anywhere and anytime desired. Ad hoc networks can use GPS for determining geographical locations, or they can use network-internal means such as time difference of arrival. Ad hoc networks must use special medium access control (MAC) techniques to share the channel resources for finding a route between the source and the destination nodes. A “dense” MANET can increase interconnections between communication and computing devices in which information can be accessed all the time, everywhere, instead of anytime, anywhere [23]. For instance the U.S. Air Force and Navy use ad hoc networks to maintain a communication network between ground stations, airplanes and ships. Ad hoc sensors recently have been the
focus of research not only for commercial applications but also to advance the military communications, as for self-protection systems and surveillance.

1.3.2. Numerous Emerging Applications

Up-to-date applications of wireless ad hoc networks have increased to not only involve traditional military applications, but also to embrace wireless sensors networks, as well as a numerous other interesting and commercially feasible applications. For instance, some applications are relevant to emergency circumstances, health care, home networking, and catastrophe procedures. It is useful to exchange digital information such as video, music, etc., through devices such as laptops, between people within a local area, and MANETs can do this effectively. MANETs are also capable of “becoming the solution” to increasing radio coverage of wireless systems. In addition, MANETs are ideally self-organizing and could strengthen and provide wireless connectivity in an area with poor or no coverage [23].
1.4. Thesis Scope

The objective of this thesis is to perform computer simulations, numerical evaluations, and mathematical analysis, carried out in MATLAB®, to evaluate various characteristics of DS-SS overlay and Ad Hoc DS-SS overlay systems. We consider a simple channel model with just path loss and lognormal shadowing, with a frequency-flat (non-selective) transfer function. We generate random network node locations in a specific 2D terrestrial area and collect statistics on performance in terms of signal-to-noise-plus-interference ratio (SNIR) and bit error probabilities for all users in two distinct DSSS systems. We vary transmit power, data rates, noise figure, processing gain, path loss exponent and shadowing standard deviation, and collect statistics on performance of the ad hoc DS-SS overlay systems.
CHAPTER 2: DS-SS OVERLAY SYSTEM

In this chapter we discuss Direct Sequence Spread Spectrum (DS-SS) overlay systems sharing a common spectrum. First, we provide a general description of DS-SS systems. Second, we review the literature on related work on DS-SS overlay. Finally, we provide a simulation model for this type of system, and show example results for performance on AWGN and Rayleigh fading channels.

2.1 General Description

Initially, spread spectrum modulation systems were used by the military mainly to avoid jamming and prevent detection. Over the years spread spectrum has been embraced by various personal communication systems, including cell phones, wireless LANs, several military systems, and the global positioning systems (GPS), for its enhanced performance in resisting interference, jamming and fading [2]. Spread spectrum is accomplished when the transmitted signal occupies a much larger bandwidth than the minimum bandwidth required to send the information signal [1], as illustrated in Figure 2.1. Also, spread spectrum can be used for multiple access by allowing different numbers of users to simultaneously employ the same bandwidth without extensively interfering with one another [6]—this is termed code division multiple access (CDMA). A popular type of spreading is direct sequence (DS), in which a high rate signal directly multiplies the data signal. This type of spread spectrum signal is often termed “noise-like” in that it has a
lower power spectral density than a non-spread (narrow band) signal. The high rate DS signal is characterized by a digital sequence. One commonly used type of sequence is the pseudo-noise (PN) sequence, which is a binary pseudo-random sequence with several desirable properties [6]. To demodulate and de-spread the spread spectrum signals we use the cross-correlation operation with the identical PN sequence at the receiver [6].

**Figure 2.1:** A spread-spectrum system-signals are spread across a wide bandwidth.

Figure 2.2 shows the direct sequence spreading procedure, which is achieved by multiplying the data signal \( x(t) \) by a wideband spreading signal \( c(t) \)[1]. For nearly all applications, the resultant signal is then multiplied by a carrier sinusoid.
The transmitted spread spectrum signal can be represented as

\[ S_{ss}(t) = \sqrt{\frac{2\, E}{T_s}} d(t) c(t) \cos\left(2\pi f_c t + \theta\right) \]  \hspace{1cm} (2.1)  

where \( d(t) \) is the data waveform, representing a sequence of data symbols, each with duration \( T_s \), \( c(t) \) is the spreading waveform, representing a sequence of “chips,” each with duration \( T_c < T_s \) (typically \( T_c << T_s \)), \( f_c \) is the carrier frequency, and \( \theta \) is the carrier phase angle.

The chipping code (also known as the spreading code) usually consists of a sequence of bits. The processing gain \( PG \) (also known as the spreading factor) is the number of chips in each information bit (Figure 2.3)
Referring to Figure 2.3, the processing gain $PG$ of DS-SS is defined as [6]:

$$PG = \frac{T_s}{T_c} = \frac{R_c}{R_s} \quad (2.2)$$

where $PG$ is the processing gain, $T_s$ is the data symbol duration, equal to $1/R_s$ with $R_s$ the data rate, and $T_c$ is the chip duration, equal to $1/R_c$ with $R_c$ the code chip rate. For a given value of data rate, the larger the value of $PG$, the larger the resulting signal bandwidth, and the larger the number of possible allocated codes.
As noted, DS-SS can be used for multiple access via CDMA. This is illustrated conceptually in Figure 2.4. All users in a CDMA system are distinguished by a unique spreading code that is ideally orthogonal to all other spreading codes for other users. Since each user of the spread spectrum system employs a unique code, it is difficult for an unauthorized user to eavesdrop on the communication between authorized users.

![CDMA diagram](image)

**Figure 2.4:** Illustration of resource allocation in code division multiple access.

With a limited total amount of spectrum and with the need to support higher data rates and/or more users, the concept of spectral overlay has been proposed to 1) increase the system capacity and, 2) increase the spectral efficiency. Figure 2.5 illustrates spectral overlay of several systems with different values of bandwidth. For the reasons cited, spectrally overlaid CDMA systems of different bandwidths have been the focus of recent research. These systems can provide both low rate services via narrower band CDMA and the advanced high rate services via wider band CDMA.
2.2 Literature Review

Wireless communication has become a major facet of modern life, with prevalent use of mobile communication, global positioning systems (GPS), and wireless connection to the Internet as a few examples. In the continued quest for improved efficacy, code division multiple access (CDMA) stands as a promising candidate for new multiple access techniques [2]. CDMA techniques are “unlike traditional time or frequency-division multiple access – there is no requirement for precise time or frequency coordination between transmitters in the system” [2]. CDMA’s most common form is spread spectrum multiple access (SSMA). SSMA is divided into two main kinds: direct sequence (DS) and frequency hopped (FH) [2]. DS was described previously: a high-rate spreading waveform (code) multiplies the data waveform to spread the bandwidth of the signal to a wider value than the bandwidth of the original signal [3]. FH is a SS-CDMA technique in which the center
(carrier) frequency of the signal is shifted or "hopped" to a number of different frequencies in time, in accordance with a designed spreading (hopping) code [1]. In the present thesis, we address only DS-SS.

In our research, we address the benefits of utilizing spread spectrum overlay in improving the performance and capacity of DS-SS systems. Within this approach, there has been some published work relevant to our research topic. In [4], the author found that spectral overlay could increase the system capacity when a DS-SS and non-spread system share a common band; specifically, the narrowband system (GSM) was shown to be able to coexist with the wideband (WCDMA) system as long as certain parameters were properly set.

In [5], the authors investigated the capacity of two different types of CDMA systems. These two types of systems were termed narrowband CDMA (NCDMA) and wideband CDMA (WCDMA). The authors analyzed the performance and the capacity tradeoffs of spectrally overlaid NCDMA and WCDMA systems [5]. They used a 1.25 MHz spreading bandwidth for NCDMA and a 5 MHz spreading bandwidth for WCDMA with different values of data rates (9.6 kb/s) and (2 Mb/s). With spectral overlay, network operators can provide existing and advanced services through these two spectrally overlaid NCDMA and WCDMA systems [5]. These authors derived an approximation for performance, in terms of bit error probability, of each system in the presence of the author. This approximation uses the Gaussian multi-user interference (MUI) assumption [5].
Reference [8] studied the spectral overlay of multi-carrier CDMA (MC-CDMA) on existing CDMA mobile systems. The authors provided results for two studies, one on spectrally overlaid NCDMA to wide-band single-carrier CDMA (WS-CDMA), and one on spectrally overlaid NCDMA to wide-band multicarrier CDMA (WM-CDMA). In addition, they noted that with the limited radio spectrum, spectral overlay could ease the migration of an existing system to a new system while employing the same radio spectrum. They also showed that the capacity of N/WM-CDMA is larger than that of N/WS-CDMA.

In [9], the authors address the question of whether or not to use spectrum spreading in ad hoc networks. They explore some recent research to illustrate the advantages and disadvantages of CDMA design in ad hoc networks. The advantages of CDMA in ad hoc networks are that it allows longer hops, reduces the delay of end-to-end messages, and consumes less energy. In addition to allowing longer hops, CDMA can enhance the capacity and network efficiency by operating in a low signal-to-interference-plus-noise ratio (SINR) condition. Additionally, CDMA can enhance network security. In contrast, the disadvantages of CDMA in ad hoc networks are its inability to effectively average interference via power control at the receiver, and the high “cost” to setup transmitters and receivers for CDMA, which for packet transmissions could frequently require spreading code acquisition and synchronization. This arises because both CDMA transmitters and receivers in ad hoc networks lack knowledge of position or delay for achieving this
synchronization, and can't rely on a single “beacon” as in a cellular system with base stations.

In [10], the authors discuss and estimate CDMA capacity and how to attain the most favorable frequency and power allocations for sub systems of spectrally overlaid multiband CDMA mobile networks (SOM-CDMA). Assuming limited spectrum resources and the increased need for capacity, the authors discuss the design of a radio network of SOM-CDMA systems. The authors employed wideband CDMA as their radio-access technique due to its capability to provide higher data rates. In their study they focused on the reverse link (mobile to base) capacity, in which they suggest that third generation mobile communications systems should utilize three different spreading bandwidths: 1 MHz Narrowband frequency allocations (FA's), 5 MHz Medium band FA's and 20 MHz Wideband CDMA FA's. They consider two cases: first, when Narrowband FA's and Medium band FA's are fully overlaid; second, when N-, M- and W- FA's are not fully overlaid. They conclude that full spectral overlay is the best way to enlarge the system capacity.

In another paper [7], the authors state that “spread-spectrum overlay would not cause excessive interference to co-located fixed-service microwave signals [7]”. This is another example of DS-SS and non-SS overlay, wherein spectral efficiency is increased via careful control of system parameters.

In [18,21,22,25], several studies of ad hoc networks demonstrate, either through analysis or simulations, the benefits of using spread spectrum to improve the ad hoc networks spectral efficiency. They prove that controlling the transmit
power level could limit interference and reduce energy consumption to deliver data packets. For instance, authors in reference [25], prove through simulations this method of controlling the power shows a considerable increase in network throughput. In [30], joint scheduling and power control for wireless ad hoc networks were considered to attain the best spatial reuse. The authors showed that a well-designed scheduling algorithm could aid transmissions in terms of the number of simultaneous successful transmissions and reduced power consumption. With these techniques, they were able to obtain close to the best possible performance by eliminating strong interference that cannot be defeated by power control alone.

In [25, 26, 29], the authors analyzed the well-known near-far problem in ad hoc networks, which is the main contributing factor to the poor performance of DS-SS in ad hoc settings. Their main intention was to identify the methods of restraining strong interference at receivers, without compromising system capacity. As the system load increases, the near-far resistance diminishes. Consequently, extra users lead to extra MUI and near-far problems. To avoid the near-far problem in ad hoc DS-SS, all mobile units have to control their transmitted power; therefore that same power is received at the intended receiver by estimating the path loss between the receivers and transmitters [26]. This control requires some overhead in terms of this path loss estimation.

Prior to data transmission, additional spreading code protocols in an intense network open with a unique code to transmit data packets is suggested, to keep
away from disruptions of any continuing transmission [31]. The main goal of this is elimination of certain opposing transmitters if all transmit concurrently, which will cause excessive interference and probable outage to other receivers.

Reference [24] discusses some assumptions of propagation models in ad hoc wireless networks. Due to the complexity of ad hoc networks, the authors recommended simple models that adapt to environmental conditions. Also, they suggested the utilization of real data for the input to any simulators, so researchers could confirm whether their protocols shape networks as predicted. In [13] the authors showed the impact of several topology control plans on the transmit power of randomly distributed nodes over a large area according to a homogeneous Poisson process. The radio propagation model was also discussed in [13] with different assumptions concerning parameters. As mentioned earlier the main goal of any topology control algorithms is to lower the energy consumed through the system.

The lack of attention to using DS-SS overlay in ad hoc networks has resulted in few studies evaluating this type system. The main motivation of our work is thus to investigate the use of SS overlay in an ad hoc network and characterize some features of performance and capacity.
2.3 Thesis Objectives

In this thesis, we analyze the performance of DS CDMA systems in spectral overlay ad hoc networks. We limit our study to two distinct systems, with two distinct values of bandwidth. For this, we simulate an ad hoc network with an arbitrary number of users (also called nodes) and we employ different values of processing gain (and hence bandwidth). Our goal is to investigate the performance of this type of system in multi-user asynchronous conditions over AWGN and Rayleigh fading channels. We estimate signal to noise plus interference ratio (SNIR) and bit error probability for each user, as a function of processing gains, data rates, numbers of users, and channel model parameters. The channel model parameters we vary are path loss exponents and shadowing standard deviations.

To achieve our thesis objectives, we employ numerical evaluation using Matlab®. We develop routines to place users in arbitrary positions, and based upon path loss and fading models, estimate received signal and interference energies. This enables us to estimate SNIR and approximate values of probability of bit error ($P_b$). We use short random spreading codes in an asynchronous system, with both binary data and code chip values [2].
2.4 Simulation and Example Results

2.4.1 System Model

2.4.1.1 DS-SS System Model

DS-SS system transmitter and receiver block diagrams are illustrated in Figure 2.6.

![DS-SS Transmitter and Receiver Block Diagrams](image)

**Figure 2.6:** DS-SS transmitter and receiver block diagrams.
In general, this system spreads the baseband data by multiplying each bit with a sequence of spreading chips. The transmitted signals are binary modulated with user-\(k\)’s baseband signal defined in (2.3)

\[
u_k(t) = A_k \sum_{n=-\infty}^{\infty} b_k(n)s_k(t - nT)
\]

(2.3)

where \(b_k(n)\) is the \(n\)th binary data symbol in the set \(\{\pm 1\}\), \(s_k(t)\) is the spreading signal, and \(A_k\) is the amplitude. The amplitude \(A_k\) equals the square root of twice the bit energy \(E_b\). In general, the spreading signal can be represented as

\[
S_k(t) = \sum_{m=0}^{N-1} c_k(m)p(t - mT_c)/\sqrt{PG}
\]

(2.4)

where the \(m\)th chip code \(c_k(m)\) equals either +1 or -1, and the chip pulse shape \(p(t)\) is rectangular over the chip time \(T_c\). As previously mentioned, \(PG = T/T_c\) is the processing gain, which is equal to the code period \(N\) for short codes, and is less than \(N\) for long codes. The transmitted DS-SS signal is \(x_k(t) = u_k(t)\cos(\omega_c t)\) where \(\omega_c\) is the radian carrier frequency.

The DS-SS received band pass signal is

\[
r(t) = x_k(t) + n(t)
\]

(2.5)

where \(n(t)\) is additive white Gaussian noise (AWGN) of spectral density \(N_0/2\). The RF carrier signal of the \(k^{th}\) user is generally \(\cos(\omega_c t + \Theta)\), in which \(\Theta\) is the transmitter phase [19]. We also study performance over a flat fading Rayleigh channel, in which the communication channel causes the magnitude of the transmitted signal to vary randomly with Rayleigh amplitude statistics.
2.4.1.2 DS-SS Systems in Spectral Overlay

Ideally, the concept of DS-SS overlay is to allow wideband CDMA waveforms and narrowband waveforms to share a common region of spectrum without causing significant degradation of either system’s performance [5], [20]. For our two-system study, we sometimes refer to the different systems as NCDMA and WCDMA for brevity. In this study we allow for different values of data rate, processing gain, and numbers of users within each system. The total interference consists of intra system and outside system interference for our “single-cell” ad hoc network. In [5], [10] the bit energy-to-interference ratio is given as

\[
\gamma = \frac{E_b}{I_0} = \frac{(C/I)(B/R) = (C/I)PG}{PG}\]

(2.6)

where \(C\) is the desired signal power, \(I\) the interfering power, \(R\) is the data rate, \(B\) is the spreading bandwidth, and \(PG\) is the processing gain of the system. This expression ignores thermal noise. The total interference at the N-CDMA receiver is defined as

\[
I_0^n \approx (1 + \gamma)(\frac{\alpha_n}{PG_n}K_nE_b^n + \frac{\alpha_w}{PG_w}K_wE_b^w)\]

(2.7)

where \(\alpha_n\) and \(\alpha_w\) are the voice activity factors for the narrow and wide band systems, and assuming transmission of data not voice, these equal one--a user generates and transmits traffic 100% of the time [5]. Likewise, the total interference at the W-CDMA receiver is defined in (2.8)

\[
I_0^w \approx (1 + \gamma)(\frac{\alpha_n}{PG_n}fK_nE_b^w + \frac{\alpha_w}{PG_w}K_wE_b^w)\]

(2.8)
where \( f = 1/(B_n^{B_w}) \) is the relative fraction of N-CDMA bandwidth within the W-CDMA spectrum.

2.4.2 System Performance

We use the probability of bit error (often termed the bit error ratio, BER), and the number of users to assess system performance. The BER for BPSK in an AWGN channel with synchronous orthogonal DS-SS signals is the same as that for single-user BPSK,

\[
BER = P_b = Q\left(\frac{2E_b}{N_0}\right)
\]  

(2.9)

where \( Q(x) \) is the tail integral of the zero-mean, unit variance Gaussian pdf [1].

The BER of asynchronous DS-SS BPSK in the AWGN can be expressed as

\[
BER = Q\left(\sqrt{\frac{E_b}{N_0}}\right)
\]  

(2.10)

where the “effective” bit energy to noise density ratio is, for a single system (no overlay)

\[
\frac{E_b}{N_0/2 + I_0} = \frac{E_b}{N_0})_{\text{eff}} = \frac{2E_b}{N_0} \left( \frac{N_0}{N_0 + (M - 1)E_b/(\alpha N)} \right) / N_0
\]  

(2.11)

In (2.11), the parameter \( \alpha \), which depends upon chip and carrier phase synchronism among signals, is equal to 3 for random chip timing and random phases. For the overlaid systems we use (2.7) or (2.8) for \( I_0 \) in (2.11).

The synchronous orthogonal CDMA (or single-user) BER on the Rayleigh flat fading channel is obtained by averaging the BER given a channel fading amplitude \( a \), over the amplitude pdf \( p(a) \).
\[ BER = P_b = \int_0^\infty O\left(\sqrt{\frac{2a^2E_b}{N_0}}\right) p(a) da \] (2.12)

\[ P_b = \frac{1}{2} \left[ 1 - \frac{\gamma_b}{1 + \gamma_b} \right] \] (2.13)

where \( \gamma_b \) is the average \( E_b/N_0 \). This serves as a lower bound to asynchronous DS-SS CDMA performance.

### 2.4.3 Numerical Results

Here we support our analysis of a DS-SS system performance with computer simulations conducted in Matlab. This simulation model could be used as a foundation to generate DS-SS overlay systems, but in our case, for simplicity, we simulate only a centralized system (as in cellular), where all transmitters send signals to a common receiver (base station), and hence can be power controlled. Figure 2.7 shows a schematic representation of our DS-SS simulation. There are different selectable parameters in our simulations:

- \( K \): Number of users
- \( PG \): Processing gain
- \( N_b \): Number of bits transmitted
- \( E_b/N_0 \): Energy per bit to the noise density ratio
- Type of channel: AWGN/Rayleigh
- Received signal timing: Synchronous/ Asynchronous
At the DS-SS CDMA transmitter, there are different random binary data bit generators, and different spreading code generators. The spreading code $c_k$ and the random binary $b_k$ multiply to generate a vector $v_k$. Then, all the generated vectors (which represent samples of continuous wavefores) add together to form $s$, the transmitted waveform. Either the AWGN or Rayleigh fading channel is used in the channel block to obtain $r$, the received signal. At the DS-SS CDMA receiver, the received signal and the locally generated spreading code signals are correlated to produce data bit estimates, which are compared with the transmitted bits to estimate $P_b$. The simulated error probability is then compared with the theoretical value of BER.
Figure 2.7: Schematic representation of DS-SS simulation procedure.
In Figure 2.8, example BER results for our multiple user, two-system, asynchronous DS-SS overlay simulations for the AWGN channel. System one uses processing gain $PG_1 = 32$, has $K_1 = 6$ users, and received SNR equal to $E_b/N_01 = 8$ dB, whereas system two has $PG_2 = 16$, $K_2 = 4$, and $E_b/N_0 = 4$ dB. In this simulation we transmitted $N_b = 1000$ bits. The plots of our simulation concur with the analytical values for both systems. The analytical values are obtained using (2.10) and (2.11) with (2.7) or (2.8) for the $I_0$ term. As expected, with larger values of $E_b/N_0$ and $PG$, the system one has better performance than system two. Agreement with analysis is good, and the effects of MUI appear as the degradation to BER beyond the single-user values.

**Figure 2.8:** $P_b$ vs. user index in DS-SS overlay system in AWGN channel, for $K_1 = 6$, $K_2 = 4$, $PG_1 = 32$, $PG_2 = 16$, $E_b/N_01 = 8$ dB, and $E_b/N_02 = 4$ dB.
In Figure 2.9, we show another plot of $P_b$ vs user index for two asynchronous DS-SS overlaid systems in the AWGN channel with centralized power control. In this plot, $PG_1=128$, $PG_2=64$, $K_1=6$, $K_2=4$, $E_b/N_0_1=4$ dB, $E_b/N_0_2=2$ dB and $N_b=10000$ bits. Once again, system one with higher processing gain and bit energy has better performance than system two.

Figure 2.9: $P_b$ vs. User index in DS-SS overlay system in AWGN channel, for $K_1=6$, $K_2=4$, $PG_1=128$, $PG_2=64$, $E_b/N_0_1=4$ dB, and $E_b/N_0_2=2$ dB.
Figure 2.10 shows another set of example results for our overlaid networks in the AWGN channel. The parameters are the same as those for Figure 2.9, except $E_b/N_0_1 = 4$ dB, $E_b/N_0_2 = 8$ dB. It can be observed that as the SNR value increases, with the same processing gain, system two performance improves, as expected.

Figure 2.10: $P_b$ vs. User index in DS-SS overlay system in AWGN channel, for $K_1 = 6$, $K_2 = 4$, $PG_1 = 128$, $PG_2 = 64$, $E_b/N_0_1 = 4$ dB, and $E_b/N_0_2 = 8$ dB.

Figure 2.11 shows BER versus user index for two overlaid systems in the Rayleigh fading channel, with $PG_1 = 128$, $PG_2 = 64$, $K_1 = 6$, $K_2 = 4$, $E_b/N_0_1 = 4$ dB, $E_b/N_0_2 = 8$ dB and $N_0 = 10000$, the same parameters as in Figure 2.10. As expected, performance on the Rayleigh fading is worse than on the AWGN channel. Agreement between simulations and analytical results is again good.
Figure 2.11: $P_b$ vs. User index in DS-SS overlay system in Rayleigh Fading channel, for $K_1=6$, $K_2=4$, $PG_1=128$, $PG_2=64$, $Eb/No_1=4$ dB, and $Eb/No_2=8$ dB.

In Figure 2.12, we use the same parameters as in Figure 2.11 except that we decrease $Eb/No_2$ value from 8 dB to 2 dB; as expected, system two performance degrades. The simulation results in this figure are also in with analytical results.
Figure 2.12: $P_b$ vs. User index in DS-SS overlay system in Rayleigh Fading channel, for $K_1 = 6$, $K_2 = 4$, $PG_1 = 128$, $PG_2 = 64$, $Eb/No_1 = 4$ dB, and $Eb/No_2 = 2$ dB.

Finally, Figure 2.13 shows $P_b$ vs. user index again for the Rayleigh fading channel, with the same parameters as in Figure 2.12 but $PG_2$ reduced from 128 to 32. Performance degrades as expected.
Figure 2.13: \( P_b \) vs. User index in DS-SS overlay system in Rayleigh Fading channel, for 
\( K_1 = 6 \), \( K_2 = 4 \), \( PG_1 = 32 \), \( PG_2 = 64 \), \( Eb/No_1 = 4 \) dB, and \( Eb/No_2 = 2 \) dB.

These example simulation results for spectrally overlaid DS-SS systems have verified the expected trends as parameters change, in a centralized CDMA system. As noted, this simulation can form a platform for developing future ad hoc DS-SS CDMA simulations.
CHAPTER 3: AD HOC DS-SS OVERLAY

This chapter describes ad hoc DS-SS overlay systems and presents analytical results for system performance estimation. The analytical results employ the various DS-CDMA physical layer parameters mentioned previously. The ultimate aim in using DS-SS overlay is to achieve a larger ad hoc network capacity than a single system can attain; we do not assess this capacity increase here, but provide the initial results in such a study in terms of performance for each of the overlaid systems. We start by describing the terrestrial setting for our ad hoc network, then our propagation model, and then we define the selected ranges for data rate and transmit power. We describe our analysis and approximations of bit error probability for the AWGN and Rayleigh fading channels. Finally, we provide a large number of simulation results and interpretations.

3.1 Network Description

In this network, we consider randomly placed transmitters using fixed power levels, for simplicity. First we establish two different ad hoc DS-SS systems, which operate independently in the same geographic area in an overlay mode. We suppose nodes are randomly distributed (uniformly) in a 100 meter by 100 meter area. Each node consists of a transmitter and a receiver that works in only one system. In addition, we assume all transmitters are asynchronous, that is, they transmit at arbitrary times.
3.1.1 Terrestrial Network Area

As nodes in ad hoc networks may generally be unaware of their geographical locations, multiple signals (direct path, reflected path) could be received in terrestrial systems. For simplicity, when we model channel fading, we assume any channel dispersion results in frequency flat fading. Our node placement algorithm randomly selects node locations in two dimensions. One can think of our model as assuming the earth is flat (two-dimensional plane), although when we employ channel fading, this could be caused by rough terrain as well as multipath propagation. The AWGN (non-fading) case can be thought of as a setting where all nodes have a line of sight (LOS) to all others.

Figure 3.1 shows node locations for an example ad hoc DS-SS overlay system, with two sets of users. There are \( K_1 = 3 \) users in system 1 (with one processing gain, \( PG_1 \)) and \( K_2 = 4 \) users in system 2 (with a different processing gain, \( PG_2 \)). These node locations were obtained from a uniform 2D distribution in the square of side length \( D = 100 \) meters.
Figure 3.1: One realization of random node locations for reference system, with $K_1=3$, $K_2=4$ users.

3.1.2 Propagation and Link Model

In mobile communication, as shown in Figure 3.2, distance can change quickly from receiver A to transmitters B and C. Thus, since signal power attenuates with distance, path loss changes due to mobility can lead to a near-far power imbalance [26] between two signals received at a given node. In [13, 25, 26, 29, 30], it was shown that the near-far problem in DS-SS systems can be avoided by continually controlling the
received power at the nodes. In centralized systems such as cellular systems, this is feasible via control of transmit power, but in ad hoc systems where no centralized receiver exists, and link distances between multiple transmitters and any receiver are arbitrary, this is not possible.

**Figure 3.2**: Illustration of near-far effects.

In our research we employ path loss models to estimate the received signal power as a function of distance, and from the set of all received powers and the other DS-SS parameters, we can estimate the SNIR at each node. When the path between transmitter and receiver is free of obstacles, the free space propagation model is used as a basic reference model to calculate the strength of the received signals [1,6]. In terrestrial settings, where LOS paths may not exist, the free space model is inappropriate. The path loss model we employ describes attenuation as a function of distance [6]:

\[ L = L_0 + 10 \log \left( \frac{d}{d_0} \right) + X \]  

(3.1)
where path loss \( L \) is given in dB, \( L_0 \) is the average large-scale path loss at a reference distance \( d_0 \), \( n \) is the path loss exponent, \( d \) is the distance between transmitter and receiver, \( d_0 \) is a generally small reference distance (e.g., typically 1 m for indoor channels and 1 km for larger cells), and \( X \) is a zero-mean Gaussian random variable [1,6]. One model for the average large-scale path loss \( L_0 \) in (3.2) is the free space loss at the reference distance.

Free-space path loss requires we specify the wavelength \( \lambda \) of the signal in meters

\[
\lambda = \frac{c}{f_c}
\]  

(3.3)

where \( c \) is the speed of light \( \left( 3 \times 10^8 \text{ m/s} \right) \) in a vacuum, and we set the carrier frequency \( f_c \) of the transmitted signal equal to 900 MHz. The value we use for \( c \) is a commonly used estimate even though the propagation velocity throughout the earth’s atmosphere is less than \( 3 \times 10^8 \text{ m/s} \). Similarly, the carrier frequency is in the unlicensed band, which can be used for ad hoc networking.

The noise power at the receiver, in the signal bandwidth, is given by

\[
P_N = N_0 + n f + 10 \log R_b
\]  

(3.4)

where \( N_0 \) is the noise density, assumed to be -174 dBm/Hz at a room temperature 20\(^\circ\) Celsius, \( n f \) is the noise figure, assumed equal to 2 (3 dB), and \( R_b \) is the data rate in bps. We can “absorb” \( n f \) into the noise density, so that our “effective” \( N_0 = -171 \text{ dBm/Hz} \).

We obtain the received energy per bit \( E_b \) as

\[
E_b = P_t - L - 10 \log R_b
\]  

(3.5)
where \( P_t \) is the transmitted signal power and the received power \( P_r = P_t - L \). Using these equations we can calculate the received energy per bit to noise power spectral density ratio \( E_b/N_0 \) as

\[
\left( \frac{E_b}{N_0} \right)_{db} = P_t - L - 10 \log(R_b) - N_0 = P_t - L - P_N
\]

### 3.1.3 Data Rate and Transmit Power

As mentioned, date rate is the amount of data that is transferred from one place to another, usually measured in bits per second. In telecommunications, to receive digital information with higher data rates, more energy needs to be transmitted and consumed [1,6]. Link parameters such as power and data rate have major consequences in the reliability of sending and receiving packets to and from nodes. In an ad hoc network, as the transmitted data rate in a small area increases, the interference between nodes rises, since more nodes are transmitting. Generally, many nodes near each other transmitting signals with low power can produce less interference than fewer nodes far apart sending at high transmission power.

The relationship between bit energy, transmit power and data rate for any signal is

\[
P_t = E_b R_b
\]  

so the received energy per bit is equal to

\[
E_b = \frac{P_r}{R_b} \geq \frac{P_r}{C}
\]
where $Pr$ is the received power and $C$ is the Shannon capacity which for a bandlimited AWGN channel is equal to

$$C = B \log_2 \left( 1 + \frac{P}{N_0 B} \right) \tag{3.8}$$

In (3.8) $B$ is the channel bandwidth and $P$ is the received signal power. Bandwidth ultimately limits the number of signals of a given bandwidth that may coexist within a spectral band as well as the amount of information the band can accommodate. In our simulation we use a transmit power value equal to one Watt (30 dBm) as the reference transmit power value and 1 Mbits/sec as our reference data rate.

3.2 SNIR and $P_b$ Analysis

Different systems have been designed using various kinds of signal quality parameters. SNIR and $P_b$ are the most widely used physical layer signal quality parameters. The physical model of our ad hoc network allows us to compute values of SNIR. We assume BPSK modulation, and asynchronous DS-SS with short random codes. In chapter two we highlighted the ability of the DS-CDMA physical layer to diminish interference through spreading, and it is this interference reduction that enables overlay.

3.2.1 AWGN Channel Analysis

Any receiver in our ad hoc network overlay system receives signals from different transmitters that arrive with different delays and power levels. Some of these signals are
in the same system (have the same bandwidth and processing gain), and some signals are from the other system (with different bandwidth and processing gain). To estimate $P_b$ (or BER), we employ the Gaussian approximation for multiuser interference (MUI) [5,8,11,27]. In this approximation, the MUI has zero mean and variance $I_0$. Assuming the MUI plus AWGN is Gaussian, we can use the SNIR to determine the BER for our ad hoc overlay network, in a closed form, by the use of standard functions. For finding the SNIR for a single DS-SS system we use equation (3.9).

$$SNIR = \frac{E_b}{N_0 + I_0} \quad (3.9)$$

where for user $k$ in system 1 we have

$$SNIR_{k,1} = \frac{E_{b,k1}}{N_0 + \frac{1}{aPG_1} \sum_{i \neq k} E_{b,i1} + \frac{1}{aPG_2} \sum_{j=1}^{K} E_{b,j2}} \quad (3.10)$$

where $E_{b,nv}$ is the received bit energy at user $k$’s receiver due to transmission by user $n$ in system $v$, and similarly for user $m$ in system 2 we have

$$SNIR_{m,2} = \frac{E_{b,m2}}{N_0 + \frac{1}{aPG_1} \sum_{i \neq m} E_{b,i1} + \frac{1}{aPG_2} \sum_{j \neq m} E_{b,j2}} \quad (3.11)$$

where in both these equations, the MUI $I_0$ is defined implicitly, and the constant $a$ depends on the conditions of carrier phase and spreading code chip synchronism or asynchronism.
In (3.10) and (3.11), $K_i$ is the number of users in system $i$, and $PG_i$ is the processing gain. In our AWGN channel with the Gaussian MUI assumption, the BER is given by

$$P_b = Q(\sqrt{SNIR})$$

(3.12)

where the Q-function is the tail integral of the zero-mean, unit variance Gaussian pdf [1,6].

### 3.2.2 Rayleigh Fading Channel Analysis

As mentioned, DS-SS has a variety of advantages such as the capability to suppress multipath interference [26,27,28]. As there are multiple reflected paths in many real terrestrial settings, if there is no dominant (often LOS) path between transmitter and receiver, the received signal envelope can often be modeled as having Rayleigh statistics [1,6]. As discussed in [27,28], some results are available for calculating BERs of DS-SS operating in Rayleigh fading channels with random sequences. We employ Jensen’s Inequality [34] to bound the BER of the Rayleigh fading channel. Jensen’s Inequality states that if $h(x)$ is convex, then

$$h(E(x)) \leq E(h(x))$$

In our case we have

$$h(x) = Q(\sqrt{x})$$

so our error probability can be bounded by

$$P_{b,k} \geq Q(\sqrt{E(SNR_k)}) \approx Q(\sqrt{SNR_E})$$

(3.13)
The “instantaneous” SNIR, using our Gaussian MUI approximation is

\[
SNIR_k = \frac{\alpha_k^2 E_{b,k}}{N_0 + \sum_{i \neq k} \alpha_i^2 E_{b,i} PG_1 E_{b,j} + \sum_{j=1}^{K} \alpha_j^2 E_{b,j} PG_2} \tag{3.14}
\]

where \(\alpha_k^2\) is the squared Rayleigh amplitude variable for received signal \(k\), which we assume has unity power, \(E(\alpha_k^2) = 1\). Then the expectation in (3.13) is given by

\[
S_k = E(SNIR_k) = \int \ldots \int SNIR_k(\alpha) d\alpha \tag{3.15}
\]

where \(p(\alpha)\) is the joint pdf of all the Rayleigh variables, and vector \(\alpha\) is given by \(\alpha = [\alpha_1 \ldots \alpha_k \alpha_{k+1} \ldots \alpha_{k+2}]\). Since this integral cannot be solved in closed form, we simply use the following as our estimate

\[
SNIR_E = \frac{E(\alpha_k^2) E_{b,k}}{N_0 + \sum \frac{E(\alpha_{i}^2) E_{b,i}}{PG_1} + \sum \frac{E(\alpha_{j}^2) E_{b,j}}{PG_2}} \tag{3.16}
\]

Then since we assume all Rayleigh mean-square values are one, the SNIR estimate becomes the AWGN channel value, and this value is an upper bound to the Rayleigh SNIR, so that the Rayleigh BER is lower bounded by the AWGN channel BER.
3.3 Simulation Results

Table 1 shows the parameter values of interest for our reference system with the specific distance realizations of Figure 3.1. Values \((X_i, Y_i)\) are the node locations of system one, and values \((X_j, Y_j)\) are the node locations of system two.

**Table 1**: Position values for reference system with realization of Figure 3.1

<table>
<thead>
<tr>
<th>User index</th>
<th>Node Location</th>
<th>User index</th>
<th>Node Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>i</td>
<td>(X_i)</td>
<td>j</td>
<td>(X_j)</td>
</tr>
<tr>
<td>1</td>
<td>54.72</td>
<td>1</td>
<td>25.75</td>
</tr>
<tr>
<td></td>
<td>35.17</td>
<td></td>
<td>54.97</td>
</tr>
<tr>
<td>2</td>
<td>13.86</td>
<td>2</td>
<td>84.07</td>
</tr>
<tr>
<td></td>
<td>83.08</td>
<td></td>
<td>91.72</td>
</tr>
<tr>
<td>3</td>
<td>14.93</td>
<td>3</td>
<td>25.42</td>
</tr>
<tr>
<td></td>
<td>58.53</td>
<td></td>
<td>28.58</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>4</td>
<td>81.42</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>75.72</td>
</tr>
</tbody>
</table>

Table 2 shows the parameters \(D_{ik}\) and \(D_{jk}\), which are defined as the distances between nodes within the same system.
Table 2: Intra-System Distances

<table>
<thead>
<tr>
<th>System 1 nodes</th>
<th>$D_{ik}$ (m)</th>
<th>System 2 nodes</th>
<th>$D_{jk}$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,2</td>
<td>62.97</td>
<td>1,2</td>
<td>68.93</td>
</tr>
<tr>
<td>1,3</td>
<td>46.14</td>
<td>1,3</td>
<td>26.39</td>
</tr>
<tr>
<td>2,3</td>
<td>24.58</td>
<td>1,4</td>
<td>59.41</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2,3</td>
<td>86.17</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2,4</td>
<td>16.22</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3,4</td>
<td>73.19</td>
</tr>
</tbody>
</table>

Table 3 provides the distances $D_{ij}$ from node locations in system one to node locations in system two. These distances represent path lengths for inter-system interference.
Using these distances in our path loss model allows computation of all $E_b$ values in the SNIR equations, which then enables computation of SNIR and $P_b$. We illustrate this in the next section.
3.3.1 Reference System Parameters

Table 4 shows the reference system parameter values. Variables are defined as follows: $P_t =$ node transmit power, $n =$ propagation path loss exponent, $X =$ standard deviation of the lognormal shadowing (Gaussian) random variable, $PG_i =$ processing gain for system one and similarly for system two, $f_c =$ carrier frequency, $R_b =$ data rate, $N_0 =$ thermal noise density, $K_i =$ number of users in system one, and likewise for $K_2$. We have chosen the reference transmit power level of 30 dBm because it is at the upper range of that used for cellular phones. The propagation path loss value is also a typical one for terrestrial propagation, as is the lognormal shadowing standard deviation. The carrier frequency represents an unlicensed band which could be employed for ad hoc networking. The thermal noise density assumes a “room temperature” of 290K, and a 3 dB receiver noise figure. The processing gains are arbitrary, but represent practical values at present, as does the data rate. The small numbers of users were chosen to enable a clear illustration of the SNIR and $P_b$ computation and, of course, these numbers yield reasonably good BER performance since the multiuser interference is small with these processing gains.

Table 4: Reference System Parameters

<table>
<thead>
<tr>
<th>$P_t$</th>
<th>$n$</th>
<th>$X$</th>
<th>$PG_1$</th>
<th>$PG_2$</th>
<th>$f_c$</th>
<th>$R_b$</th>
<th>$N_0$</th>
<th>$K_1$</th>
<th>$K_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 dBm</td>
<td>3</td>
<td>7 dB</td>
<td>512</td>
<td>256</td>
<td>900 MHz</td>
<td>10 kbits/s</td>
<td>-171 dBm/Hz</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>
We illustrate the computation of SNIR for our 7-user reference system. All distances are found using standard plane Euclidean geometry since we assume a 2D area. For example, for users 1 and 2 in system one, the two X values are (54.72, 13.86) and the two Y values are (35.17, 83.08), the distance is

$$D_{12}^{(1)} = \sqrt{(54.72 - 13.86)^2 + (35.17, -83.08)^2} = 62.97 \text{ m}$$

and for user 1 in system 2, with X=25.75 and Y=54.97, the distance from user 1 in system 1 to user 1 in system 2 is

$$D_{12}^{(2)} = \sqrt{(54.72 - 25.75)^2 + (35.17 - 54.97)^2} = 35.1 \text{ m}$$

To calculate the average large-scale path loss between user one in system one and user two in system one, we use equation (3.2) and find $L_f s = 31.526 \text{ dB}$ when $d_0=1 \text{ m}$. Using the free space path loss for $L_0$, our path loss exponent of 3, and shadowing standard deviation of 7 dB, we can obtain the losses between all nodes for the realization of the reference system in Figure 1. These path losses are as follows

$$L_1 = [92.50, 88.44, 80.24]$$

$$L_2 = [93.67, 81.17, 91.74, 96.58, 74.82, 94.46]$$

where $L_1$ and $L_2$ represent the path loss vectors for the intra-system distances (same system nodes), and

$$L_{12} = [84.88, 83.06, 70.22, 92.65, 94.01, 95.07, 82.85, 90.90, 83.57, 89.11, 93.49, 93.63]$$

represents the path losses for the inter-system distances (different systems nodes).

The received power levels can be found by using equation (3.6)
\[ P_{r1} = [-62.50, -58.45, -50.24] \text{ dBm} \]

\[ P_{r2} = [-63.67, -51.17, -61.74, -66.59, -44.83, -64.46] \text{ dBm} \]

where \( P_{r1} \) represents the received powers in system one, and the same applies for \( P_{r2} \), which represents the received power levels in system two.

The noise power is equal to (3.4) \( P_N = -131 \text{ dBm} \) By using equation (3.7) the energy per bit to noise density ratios are given by the following vectors:

\[ \frac{E_{b1}}{N_0} = [71.49, 75.55, 83.76, 71.49, 75.55, 83.76] \text{ dB} \]

\[ \frac{E_{b2}}{N_0} = [70.32, 82.83, 72.26, 67.41, 89.17, 69.52] \text{ dB} \]

Finally, the error probability estimate is then obtained from the SNIR equations (3.13)-(3.15) as

\[ SNIR_{1,2}^{(1)} = \frac{0.07081 \times 10^8}{1 + 0.18 \times 10^8 + 0.129 \times 10^8} = 13.13 = 11.18 \text{ dB} \]

where \( SNIR_{1,2}^{(1)} \) is the value of signal-to-noise-plus-interference ratio for the link between nodes one and two in system one. For this SNIR, we find \( P_b = Q(\sqrt{13.13}) = 1.45 \times 10^{-4} \).

Table 5 shows error probabilities \( P_{b1} \) and signal-to-noise-plus-interference ratio \( SNIR_1 \) for links in system one, in the presence of the spectrally overlaid interferers in system two.
Table 5: Analytical SNIR and $P_b$ reference system values for links in system 1

<table>
<thead>
<tr>
<th>System 1 nodes j,k</th>
<th>SNIR$_1$ (dB)</th>
<th>$P_b$$_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,2</td>
<td>11.20</td>
<td>1.4×10$^{-4}$</td>
</tr>
<tr>
<td>1,3</td>
<td>9.84</td>
<td>9.5×10$^{-4}$</td>
</tr>
<tr>
<td>2,1</td>
<td>17.26</td>
<td>“0”</td>
</tr>
<tr>
<td>2,3</td>
<td>15.09</td>
<td>“0”</td>
</tr>
<tr>
<td>3,1</td>
<td>13.82</td>
<td>4.6×10$^{-7}$</td>
</tr>
<tr>
<td>3,2</td>
<td>13.80</td>
<td>4.9×10$^{-7}$</td>
</tr>
</tbody>
</table>

Similarly, Table 6 shows error probabilities $P_b2$ and signal-to-noise-plus-interference ratio SNIR$_2$ for links in system two. Clearly, based upon these SNIRs in comparison to the $E_b/N_0$ values, our DS-SS CDMA system performance is dominated by MUI.
Table 6: Analytical SNIR and $P_b$ reference system values for links in system 2

<table>
<thead>
<tr>
<th>System 2 nodes j,k</th>
<th>SNIR₂ (dB)</th>
<th>$P_b$₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,2</td>
<td>2.63</td>
<td>8.8×10⁻²</td>
</tr>
<tr>
<td>1,3</td>
<td>15.7</td>
<td>“0”</td>
</tr>
<tr>
<td>1,4</td>
<td>4.58</td>
<td>4.5×10⁻²</td>
</tr>
<tr>
<td>2,1</td>
<td>2.18</td>
<td>1×10⁻¹</td>
</tr>
<tr>
<td>2,3</td>
<td>38.2</td>
<td>0.00</td>
</tr>
<tr>
<td>2,4</td>
<td>5.12</td>
<td>3.6×10⁻²</td>
</tr>
<tr>
<td>3,1</td>
<td>8.46</td>
<td>4×10⁻³</td>
</tr>
<tr>
<td>3,2</td>
<td>25.3</td>
<td>“0”</td>
</tr>
<tr>
<td>3,4</td>
<td>6.29</td>
<td>1.9×10⁻²</td>
</tr>
<tr>
<td>4,1</td>
<td>6.98</td>
<td>1.2×10⁻²</td>
</tr>
<tr>
<td>4,2</td>
<td>36.1</td>
<td>0.00</td>
</tr>
<tr>
<td>4,3</td>
<td>4.20</td>
<td>5.2×10⁻²</td>
</tr>
</tbody>
</table>

Figure 3.3 shows histograms of SNIR for systems one and two in our reference case, computed numerically. Note the agreement with the values in Tables 5 and 6. We have limited all SNIR values to a maximum of 50 dB, so that if any SNIR is greater than this value, we artificially assign it a value of 50 dB. This primarily for simplicity: in our
simulations we will be distributing nodes randomly in two dimensions, and in some cases, inter-node distances will be extremely small (smaller than practical). With fixed transmit power, the received SNIR will generally be large for these “very near” cases. Rather than remove these nodes, which requires we check all inter-node distances, we just allow these “very near” cases and compute all SNIRs as previously described. The value 50 dB is arbitrary, and for this value, the error probability estimate is essentially zero.

![Figure 3.3: SNIR histogram for reference system with distances of Figure 3.1.](image)

Figure 3.4 shows numerically computed $P_b$ values in histograms for the reference system. As with SNIR, $P_b$ values are also limited (on the low end) to a minimum of $10^{-8}$ by setting all values less than $10^{-8}$ equal to this minimum. These $P_b$ values also agree with those previously specified in Tables 5 and 6. Figure 3.5 shows $\log_{10}(P_b)$ for the reference system for clarity; henceforth we will display all BER results in this manner.
**Figure 3.4:** Error probability histogram for reference system with distances of Figure 3.1.

**Figure 3.5:** Histogram of $\log_{10}(P_b)$ for reference system with distances of Figure 3.1.
Figures 3.6 to 3.8 show probability density function (PDF) and cumulative distribution function (CDF) plots for SNIR and BER for our illustrative reference system, using two different analytical fits, lognormal and exponential. The pdf figures appear different from the histograms in prior plots because of the different numbers of bins employed by the Matlab distribution-fitting tool, which we used to generate the analytical plots. The best fits for the SNIR are the lognormals; this is clearest on the CDF plot. For the log(BER), a Gaussian fit was employed.

**Figure 3.6**: SNIR CDF plots for reference system with distances of Figure 3.1.
Figure 3.7: SNIR PDF plots for reference system with distances of Figure 3.1.

Figure 3.8: BER CDF plots for reference system with distances of Figure 3.1.
3.3.2 Statistical Ad Hoc Network Performance Results

Figure 3.9 shows histograms of SNIR for systems one and two in our reference system with parameters of Table 4, but where we have run 100 trials, with each trial creating a completely new set of node locations. We have again limited all SNIR values to a maximum of 50 dB and to a minimum of -10 dB. It can be seen that approximately 2.8% (34/1200) of the system 2 SNIRs and 3% (18/600) of the system 1 SNIRs are less than -10 dB, and even smaller percentages are above our 50 dB threshold.

![SNIR histogram for reference system over 100 node location trials.](image)

Figure 3.9 SNIR histogram for reference system over 100 node location trials.

Figure 3.10 shows the corresponding $P_b$ histograms for the reference systems when collected over the same 100 runs. As noted, $P_b$ values are limited on the low end to
a minimum of $10^{-8}$. It can be seen that approximately 66.75% (801/1200) of the system two BERs and 62.5% (375/600) of the system one BERs have values less than $2 \times 10^{-3}$, and 42.8% (514/1200) of the $P_{b2}$’s and 38.3% (230/600) of the $P_{b1}$’s have values less than $10^{-8}$.

Figure 3.10: $\log_{10}(P_b)$ histogram for the reference system.

Figure 3.11 depicts the PDF fits for SNIR for the reference system for the collected results over 100 node location trials. The Gaussian fits with means $m_1=12.3$ dB and $m_2=13.71$ dB, and standard deviations $s_1=10$ dB and $s_2=10.7$ dB, were found for the SNIRs of systems one and two, respectively.
Figure 3.11: SNIR PDF plots for reference system.

In Figures 3.12-3.13, we show CDFs for SNIR and $\log_{10}(P_b)$ along with the fits. The SNIR fit is quite good, whereas the BER fit is coarse.
Figure 3.12: SNIR CDF plots for reference system over 100 node location realizations.

Figure 3.13: Error probability CDF plots for reference system over 100 node location realizations.
3.3.3 Statistical Results for Ad Hoc Network Performance; Varied Parameter Settings

In this section we investigate the changes in SNIR and BER performance when we vary parameter values from those in the reference system. For clarity, we vary only one parameter at a time. We again use multiple trials (100 trials) where each trial establishes new node locations.

Figure 3.14 shows SNIR histograms for two different sets of users when transmit power is reduced to $P_t=10$ dBm. All other system parameters are the same as in Table 4. As can be seen from the plot, approximately 3.91% of the SNIR$_2$’s and 4% of the SNIR$_1$’s are less than -10 dB. Compared with Figure 3.9 for transmit power $P_t=30$ dBm, this figure has a larger number of users with SNIR below our threshold of -10dB. This is expected since as the transmit power decreases, desired signal power also decreases.

![Figure 3.14: SNIR histogram for $P_t=10$ dBm.](image)
Figure 3.15 depicts $P_b$ histograms when the transmit power $P_t=10$ dBm. It can be seen that 69.75% of the system two BERs and 61.83% of the system one BERs are less than $2 \times 10^{-3}$, and 45% of the system two BERs and 39% of the system one BERs are less than $10^{-8}$.

![Histogram of log$_{10}(P_b)$ for $P_t=10$ dBm.](image)

**Figure 3.15**: Histogram of log$_{10}(P_b)$ for $P_t=10$ dBm.

Figures 3.16 to 3.18 show PDF and CDF fits for SNIR and BER. The Gaussian fits for the SNIRs have means and standard deviations given by $m_1=12.7$ dB, $m_2=13.5$ dB, $s_1=11.2$ dB and $s_2=10.9$ dB. The reference system results of Figure 3.11 showed
smaller standard deviation values and almost the same mean values compared to this reduced-transmit-power case.

**Figure 3.16**: SNIR PDF plots when $P_t=10$ dBm

**Figure 3.17**: SNIR CDF plots when $P_t=10$ dBm
Next we show in Figure 3.19 an SNIR histogram when the transmit power is even lower, 0 dBm. All other parameters are the same as in Table 4. These plots show that 3/1200 SNIR$_2$’s and 2/600 SNIR$_1$’s are larger than 50 dB. Comparing the plots of this figure with the plot of Figure 3.9, fewer users have SNIR $\geq$ 50dB, as expected.
Figure 3.19: SNIR histogram for $P_t = 0$ dBm.

Figure 3.20 shows that a larger number of users has BER greater than or equal to 0.002 when $P_t = 0$ dBm than when $P_t = 30$ dBm. It can be seen that 45% of the system two BERs and 37.6% of the system one BERs are less than $10^{-8}$, similar to the case for the 10 dBm transmit power, but only 15.16% of the system two BERs and 17.5% of the system one BERs are less than $2 \times 10^{-3}$. 
Figure 3.20: Histogram of log_{10}(P_b) for P_r=0 dBm.

Figure 3.21 presents PDF plots for averaged SNIR with Gaussian fits. Comparing the curves of the reference values Figure 3.11 when P_r=30 dBm and the curves of Figure 3.21 when P_r=0 dBm, when the mean of SNIR is equal to 14 dB and sigma of SNIR is equal to 10 dB for both figures.
Figure 3.21: SNIR PDF plots when $P_r = 0$ dBm

Figure 3.22 shows CDF plots and Gaussian fits. Comparing the plots of this figure with the plot of Figure 3.12, both have 90% of SNIR values below 30 dB.
Figure 3.22: SNIR CDF plots when $P_t=0$ dBm.

Figure 3.23 shows BER CDFs. As can be seen, comparing this figure with those for larger values of transmit power, when BER value is equal to $10^{-5}$, plots in Figure 3.13 have fewer BER than Figure 3.23. For instance, for $P_t=30$ dBm transmit power, 49% of BERs are below $10^{-5}$, whereas for 0 dBm transmit power, 55% of BERs are below this level.
Next we vary the path loss exponent to see the effects of this parameter. Figure 3.24 shows the histogram of SNIR for two different sets of users when path loss exponent \( n = 4 \), and all other system parameters are the same as in Table 4. It can be seen that 11.3\% of the system 2 SNIRs and 10.5\% of the system one SNIRs are less than -10 dB. Also, approximately 1\% of the SNIR\(_2\)'s and 1\% of the SNIR\(_1\)'s are more than 50 dB.

Comparing the plots of this histogram figure with the plot of Figure 3.9, fewer users have SNIR less than -10 dB when path loss exponent \( n = 4 \) than when \( n = 3 \) in Figure 3.9, thus showing that attenuation of interference is more significant than attenuation of the desired signal in our interference-dominated ad hoc network.
Figure 3.24: SNIR histogram for $n=4$.

Figure 3.25 shows though that a larger percentage of users has BER greater than or equal to 0.002 when $n=3$ than when $n=4$. It can be seen that 37.5% of the system two BERs and 32.8% of the system one BERs are less than $10^{-8}$ and 27.8% of the system two BERs and 32% of the system one BERs are less than $2 \times 10^{-3}$. Thus, although a larger path loss exponent reduces the percentage of users with very low SNIR, the distribution of SNIRs is less concentrated around a mode than for the $n=3$ path loss exponent case.
Figure 3.25: Error probability $\log_{10}(P_b)$ histogram for n=4.

Figure 3.26 depicts the PDF fits for SNIR for when path loss exponent $n=4$, and all other system parameters are the same as in Table 4. The Gaussian fits with means $m_1=9.9$ and $m_2=11.4$, and standard deviations $s_1=13.9$ and $s_2=12.9$ illustrate the “more even” distribution than in the case with a smaller path loss exponent.
Figure 3.26: SNIR PDF plots when n=4.

In Figures 3.27, we show CDFs for SNIR along with the fits. Comparing the plots of this figure with the plot of Figure 3.12, we show this has 50% of SNIR’s below 10 dB compared to 40% in Figure 3.12. Figure 3.28 shows BER CDFs. If we compare this figure to the corresponding figure with path loss exponent $n=3$, Figure 3.13, for a BER value of $10^{-5}$, the $n=4$ system has approximately only 40% of users below this BER, whereas the $n=3$ system has approximately 50% of users below this BER.
Figure 3.27: SNIR CDF plots when n=4.

Figure 3.28: Error probability CDF when n=4.
Next we show in Figure 3.29 an SNIR histogram when the processing gain of system one is increased to PG$_1$=1024. All other parameters are the same as in Table 4. This thus represents a signal with larger bandwidth. These SNIR histograms show that 6/1200 SNIR$_2$’s and 4/600 SNIR$_1$’s users are larger than 50 dB. Comparing the plots of this figure with the plot of Figure 3.9, a larger fraction of users has SNIR $\geq$ 50dB. This is expected since increasing PG decreases MUI and hence increases the effective $E_b/N_0$.

![Figure 3.29: SNIR histogram when PG$_1$=1024.](image)

Figure 3.30 shows the P$_b$ histogram when PG$_1$=1024. It can be seen that that 11.6% of the system two BERs and 17.3% of the system one BERs are less than $2 \times 10^{-3}$.
and 47.6% of the system two BERs and 37.3% of the system one BERs are less than $10^{-8}$.
Comparing the plots of this histogram with those of Figure 3.10, fewer users have $P_b$ less than $2 \times 10^{-3}$ when $P_G = 512$, as expected.

**Figure 3.30**: Error probability $\log_{10}(P_b)$ histogram for $P_G=1024$.

Figures 3.31 to 3.33 show PDF and CDF fits for SNIR and BER. The Gaussian fits for the SNIRs have means and standard deviations given by $m_1=12.9$, $m_2=15.3$, $s_1=9.9$ and $s_2=10.13$, and when compared to results in Figure 3.11, larger $P_G$ yields higher mean SNIR values and slightly smaller standard deviations.
Figure 3.31: SNIR PDF plots when PG₁=1024.

Figure 3.32: SNIR CDF plots when PG₁=1024, over 100 node location trials
Figure 3.33: Error probability CDF when PG₁ = 1024.

Figure 3.34 depicts the histogram of SNIRs when we lower the processing gain value of system two to PG₂ = 128. As can be seen from the results of this figure compared to Figure 3.9, a similar percentage of users has SNIR more than 50 dB.
Figure 3.34: SNIR histogram when PG\textsubscript{2}=128.

Figure 3.35 illustrates $P_b$ histograms. It shows that 38.1\% of the system two BERs and 31\% of the system one BERs are less than $10^{-8}$. Comparing the plots of this histogram with those of Figure 3.10, more users have $P_b$ less than $2\times10^{-3}$ and fewer users have $P_b$ less than $10^{-8}$ when PG\textsubscript{2}=128.
Figures 3.35 to 3.38 show PDF and CDF fits for SNIR and BER. The Gaussian fits for the SNIRs have means and standard deviations given by $m_1=9.8$, $m_2=11.95$, $s_1=10.4$ and $s_2=11.5$. Comparing these values to those with the larger processing gain (Figure 3.11), the larger processing gain has larger mean values, and also larger standard. In addition, as we lower the value of PG$_2$ to 128 compared to Figure 3.12, the cumulative probability value when SNIR equal to 30 dB increases, from 90% to almost 98%.
Figure 3.36: SNIR PDF plots when PG₂=128.

Figure 3.37: SNIR CDF plots when PG₂=128.
Figure 3.38: Error probability CDF when PG₂=128.

Figure 3.39 shows the SNIR histogram results for two different sets of users when PG₂=64. As can be seen from the plot, 5% of the SNIR₂’s and 6.3% of the SNIR₁’s users are less than -10 dB. By comparing this figure with the corresponding figure for PG₂=256, it is clear that with smaller PG, a larger percentage of users has SNIR less than -10 dB.
Figure 3.39: SNIR histogram when PG₂=64.

Figure 3.40 shows the corresponding $P_b$ histograms for PG₂=64. It can be seen that 28.5% of the system two BERs and 17.6% of the system one BERs are less than $10^{-8}$, which shows fewer users with very good performance than when PG is larger, and similarly, a larger number of has BER less than $2 \times 10^{-3}$ than when PG is larger.
Figure 3.40: Log_{10}(P_b) histogram for PG_2=64.

Figure 3.41 presents the PDF fits for SNIR for PG_2=64. Comparing the Gaussian fits with means m_1=7 and m_2=10.3, and standard deviations s_1=9.6 and s_2=10.1, reducing PG substantially decreases the mean SNIR, but negligibly changes the standard deviation.
Figure 3.41: SNIR PDF plots when PG₂=64.

In Figure 3.42, which shows the CDF of SNIR for PG₂ =64, where 50% of users set two and 60% of users set one have SNIR >10 dB. Comparing this figure to Figure 3.12, more users in this figure have SNIR >10 dB than Figure 3.12 with higher PG₂. Figure 3.43 shows the BER CDFs, which illustrate that reduced PG generally means increased BER, as expected.
Figure 3.42: SNIR CDF plots when PG₂=64.

Figure 3.43: Error probability CDF when PG₂=64.
Figure 3.44 shows the histogram of SNIRs for both sets of users when PG\textsubscript{2} is further reduced to 32. In this case, 8.3\% of the SNIR\textsubscript{2}’s and 10.3\% of the SNIR\textsubscript{1}’s are less than -10dB, which is a substantially larger percentage than with larger PG.

![SNIR histogram when PG\textsubscript{2}=32.](image)

**Figure 3.44**: SNIR histogram when PG\textsubscript{2}=32.

Figure 3.45 shows BER histogram results for the two sets of users for PG\textsubscript{2}=32. It can be seen that 22.2\% of the system two BERs and 18.1\% of the system one BERs are less than $10^{-8}$, which are smaller percentages than when PG is larger. In addition, with smaller PG, a much larger fraction of users have BERs above $2\times10^{-3}$.
Figure 3.45: $\log_{10}(P_b)$ histogram for PG$_2$=32.

Figure 3.46 depicts fits for SNIRs for PG$_2$=32, which can be compared to the fits in Figure 3.39 for SNIR for PG$_2$=64. The PG=32 case has SNIR means m$_1$=7 and m$_2$=10.3, similar to those for PG$_2$=64, but smaller than those when PG$_2$=256.
Figure 3.46: SNIR PDF plots when $PG_2=32$.

Figure 3.47 shows the CDF plots and Gaussian fits for this case. As we lower the value of $PG_2$ to 32, a larger fraction of users has smaller SNIR values. Figure 3.48 shows the corresponding BER plots, which illustrate using this measure how performance degrades with the smaller $PG$. 
Figure 3.47: SNIR CDF plots when PG₂=32.

Figure 3.48: Error probability CDF when PG₂=32.
Next we vary data rates. In Figure 3.49, we show histograms of average SNIR results for the two sets of users when $R_b = 10^6$ bits/sec, and all other parameters are kept as in Table 4. It can be seen that 2.2% of the SNIR$_2$’s and 4% of the SNIR$_1$’s are less than -10 dB. Comparing this figure when data rates $R_b = 10^6$ bits/sec, with Figure 3.9 data rates $R_b = 10^4$ bits/sec, fewer users with SINR less than -10 dB in this figure, than in Figure 3.9. Here we observe that, as $R_b$ decreases, noise power decreases so MUI becomes even more significant, but since it already was dominant, results should not change much.

![Figure 3.49: SNIR histogram when $R_b=10^6$.](image)

Figure 3.50 shows histograms for SNIR for the two sets of users when $R_b = 10^6$ bits/sec. It can be observed that 42.6% of the $P_{b2}$’s and 41.5% of the $P_{b1}$’s users are less than $10^{-8}$, which is almost the same in comparison to the systems with $R_b = 10k$ bits/sec.
Figure 3.50: $\log_{10}(P_b)$ histogram for $R_b=10^6$.

Figure 3.51 depicts the PDF fits for SNIR for the data rate of $R_b=10^6$ bits/sec. The Gaussian fits with means $m_1=12.5$ and $m_2=13.6$ show that mean SNIR is increased compared with Figure 3.11. The standard deviations of $s_1=9.9$ and $s_2=10.6$ are comparable to that for the case of $R_b=10^4$ bits/sec.
In Figure 3.52, with $R_b = 10^6$ bits/sec compared to Figure 3.12, the percentile values in this figure when SNIR equal to 10 dB is more than 33% which is almost equal to Figure 3.12. Moreover, in Figure 3.53 we display the BER’s plots, which show equivalent in the number of BER compared to Figure 3.13 as we increase the data rates, both figures have 49% of BERs are below $10^{-5}$. 

**Figure 3.51**: SNIR PDF plots when $R_b=10^6$. 

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Figure 3.52: SNIR CDF plots when $R_b=10^6$.

Figure 3.53: Error probability CDF when $R_b=10^6$. 
Table 7 shows percentages of users with error probabilities \((P_{b2} \text{ and } P_{b1})\) less than \(10^{-8}\) for different parameter values. Clearly, based upon these error probabilities in comparison to those for the reference system, we can state the following:

- as transmit power decreases, lower BER’s result (we note that transmit power cannot be lowered without bound, and the minimum transmit power level for a given performance level would need to be determined for our 100m by 100m network)
- as the path loss exponent increases, BERs increase
- as the processing gain increases (and bandwidth increases) BERs decrease.

**Table 7: Percentage of Users with \(P_b\)'s less than \(10^{-8}\) from log10(P_b)histogram.**

<table>
<thead>
<tr>
<th>Reference System</th>
<th>(P_t=10) dBm</th>
<th>(P_t=0) dBm</th>
<th>(n=4)</th>
<th>(PG_1=1024)</th>
<th>(PG_2=128)</th>
<th>(PG_2=64)</th>
<th>(R_b=10^8) bits/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>(P_{b1}'s &lt; 10^{-8}) (600 Users)</td>
<td>38.3%</td>
<td>39%</td>
<td>37.6%</td>
<td>32.8%</td>
<td>37.3%</td>
<td>31%</td>
<td>17%</td>
</tr>
<tr>
<td>(P_{b2}'s &lt; 10^{-8}) (1200 Users)</td>
<td>42.8%</td>
<td>45%</td>
<td>45%</td>
<td>37.5%</td>
<td>47.6%</td>
<td>38.1%</td>
<td>28.5%</td>
</tr>
</tbody>
</table>

We can conclude from these results of our simplified 2D ad hoc network that we can improve performance of the ad hoc DS-SS overlay system when we modify different parameters. In general, to reduce the interference and to minimize the total error probability, we should reduce the transmit power to its lowest possible value for the desired performance level in our 100m by 100 m area. This minimum value is to be determined, and would be an important element of future work. The performance gain from reduced transmit power results because in our small area, the typical cell-phone power levels we used are larger than needed, especially when link distances are small.
Reducing transmit power reduces MUI. Increasing processing gain also helps, but comes at the cost of increased bandwidth. Similar to reduction of transmit power, a larger path loss exponent also reduces propagation of interference, and improves performance.
CHAPTER 4: SUMMARY, CONCLUSION AND FUTURE WORK

4.1 Summary

The goal of this thesis is to show the need of DS-SS CDMA Overlay system to advance ad hoc overlay networks design. We start by discussing the literature review of some works that have highlighted DS-SS overlay and ad hoc networks. For DS-SS Overlay systems analysis we extend an expression for numerical evaluations to approximate system performance. We investigate capacity and interference of a spectrally overlaid narrow band and wide band systems, making the hypothesis that all users have similar power levels for a given Eb/N0. Hence, the interference of all users is addictive. After that, for an ad hoc overlay networks, we describe the network in terrestrial area. Thus, for simplicity, in our simulations we performed node distribution randomly in two dimensions with a maximum distance of 100 meters. For linear analysis we assumed the curvature and the topographical features of the earth to be insignificant (the earth is flat) to generate an algorithm to provide node locations and compute the distances between nodes. In addition, we proposed free space propagation model as well as the range of data rate and transmit power. For analysis, we then depicted bit error rate for AWGN and Rayleigh fading channels. For AWGN channels, we assumed all the nodes are in the line of sight to all others. In order to validate our analysis we performed simulation to generate plots for a variety of system parameters. We attenuate the power transmitted, increase the propagation path loss exponent, maintain constant standard
deviation of the lognormal shadowing (Gaussian) random variable, modified the processing gain for system one and similarly for system two and increased the data rates. We compared our simulation SNIR and Pb to reference parameters values. For instance, we use in our simulation a transmit power value equal to one Watt (30 dBm) as the reference transmit power value and 10 Mbits/sec as our reference data rate.

4.2 Conclusion

In “DS-SS ad hoc networks overlay systems”, we show major improvement of the system per se, characteristics such as capacity, QoS, and energy, etc., by considering tradeoffs between different performance parameter values. Our simulation results illustrate that as the transmit power declines, less interference occurs within the systems that helps in maintaining realistic signal-to-noise ratio. Therefore, more users are transmitting with low power in near field. However, for far field reception higher power needed to be transmitted. As the path loss exponent value rises, the desired power decreases and the Pb increases. When the processing gain of system one rises, more users have less energy as well as less Pb. In contrast, as we lower the processing gain value, Pb value increases. Finally, for a higher value of data rates, the Pb is minimized with respect to the data rate. We therefore show the advantages of considering DS-SS in ad hoc networks overlay is spreading gain to reduce the interference at receiver, without any systems capacity and fidelity degradations, when subjected to interference from all transmitters within the same area.
4.3 Future Works

There are several future directions for related research area that seem promising. Even though there has been a lot of work regard DS-SS overlay, spectrally overlay system is still an interesting area that needed to be considered. Computer simulations along with our analysis and analytical expressions for related works can provided an interesting to foresee the system performance more precisely. Include synchronous and asynchronous AWGN as well as Rayleigh fading channels. Also, by applying different values of processing gain, transmit power, data rates, and number of users. Another direction for future work would be by trying refinement channel propagation models for an ad hoc networks, as well as different values of transmit power from different nodes. Near far problem to control the transmit and receive power needed to be consider more precisely.
REFERENCES


APPENDIX A: MONTE-CARLO SIMULATION FOR DS-SS OVERLAY SYSTEMS

% Program DS-SS CDMA Overlay
% simulates two sets of users of BPSK transmission over Rayleigh Fading Channel
% also, computes and plots bit error Probability Pb.

clear all
close all
clc
%------------------------------------------------------------------%
K1=6; % Set maximum number of users set one
K2=4; % Set maximum number of users set two
K=K1+K2; % Set users one added to set users two
% Ne= 10; % # number of errors to count
% Nb1=ceil(Ne./Pba1); % Number of bit to use
% Nb2=ceil(Ne./Pba2); % Number of bit to use
% Nb=Nb1(1,1);
Nb=10000; % # of bits to use for test and debugging
PG1=128; %Set processing gain set one
PG2=64; %Set processing gain set two
fsTc2=2; % Oversampling rate (#samples/chip) set two
fsTc1=(PG2/PG1)*fsTc2; % Oversampling rate (#samples/chip) set one
EbN01=4; %Value of Eb/N0, in dB set one
EbN02=8; %Value of Eb/N0, in dB set two
N0=1;
Eb1=10.^(EbN01/10)*N0; % Energy for each bits set one
Eb2=10.^(EbN02/10)*N0; % Energy for each bits set two
LT=Nb*PG1*fsTc1; % length of Oversamples, spread and transmitted vectors
AVG=10; % Set average of run
Pb1=zeros(K1,AVG); % Initialize Pb1 vector
Pb2=zeros(K2,AVG); % Initialize Pb1 vector
count1=0; % Initialize count1
count2=0; % Initialize count2
%--------------------------------------------------------------------
%%%%%%%   AWGN+ Rayleigh Fading Pb Analytical for single user
%%%%%%%   Rayleigh Fading Pb Analytical for single user
% %
% Ebv1=EbN01*ones(1,K1); % Eb/N0 vector for K1 users, dB
gb1=10.^(Ebv1/10); % SNR vector, numeric
Pba1=erfc(sqrt(gb1))/2; % Analytical results for BPSK Pba1 on AWGN
Eb{\nu}2=EbN02{\ast}\text{ones}(1,K2); \ % \text{Eb/N0} \text{ vector for K2 users, dB}
\text{gb2}=10.\wedge(Eb{\nu}2/10); \ % \text{SNR} \text{ vector, numeric}
Pba2=\text{erfc}(\sqrt{\text{gb2}})/2; \ % \text{Analytical results for BPSK Pba2 on AWGN}

\text{Pbps=zeros(K,Nb); \ % Initialize Pbs Bit error Probability vector per simulation run}
\text{Pba=zeros(1,K1+K2); \ % Initialize Pba vector}

\text{----------- Analytical AWGN Channel MUI -----------}
\text{gb1=gb1(1,1);}
\text{gb2=gb2(1,1);}
\text{SNIR1}=(2*gb1)/(1+(K1*gb1/PG1)+(K2*gb2/PG2)) \ %
\text{PP1=qfunc(sqrt(SNIR1)); \ % Analytical results for MUI BPSK on AWGN}
\text{PP1=ones(1,K1).*PP1; \ % PP1 vector for K1 users}
\text{SNIR2}=(2*gb2)/(1+(K2*gb2/PG2)+(K1*gb1/PG1)); \ %
\text{PP2=qfunc(sqrt(SNIR2)); \ % Analytical results for MUI BPSK on AWGN}
\text{PP2=ones(1,K2).*PP2; \ %PP2 vector for K2 users}

\text{----------- fading -----------}
\text{PbFadingn}=(.5)*(1-sqrt(gb1/(1+gb1)));
\text{PbFadingw}=(.5)*(1-sqrt(gb2/(1+gb2)));
\text{PbFn=Eb1+PbFadingn;}
\text{PbFw=Eb2+PbFadingw;}
\text{PbFn=PbFadingn*ones(1,K1);}
\text{PbFw=PbFadingw*ones(1,K2);}

\text{----------- Monti-carlo simulation -----------}
\text{for loop to calculate the averaged Pb}
\text{for avg=1:AVG}
\text{rancode1=0; Initialize}
\text{rancode2=0; Initialize}
\text{rancode1=2*(rand(K1,PG1)<0.5)-1; \%spreading code generation}
\text{rancode2=2*(rand(K2,PG2)<0.5)-1; \%spreading code generation}
\text{Echip1=Eb1/(PG1*fsTc1); \% energy per chip for Eb1}
\text{Echip2=Eb2/(PG2*fsTc2); \% energy per chip for Eb1}
\text{----------- Oversampling the spreading codes -----------}
\text{code1=0;}
\text{code2=0;}
\text{for is=1:K1}
\text{code1(is,1:fsTc1*PG1)=OverN(rancode1(is,1:PG1),fsTc1);}
\text{end}
\text{for is=1:K2}
\text{code2(is,1:fsTc2*PG2)=OverN(rancode2(is,1:PG2),fsTc2);}
end
b1=2*(rand(K1,Nb)<0.5)-1;% Generate random binary {-1,1}
b2=2*(rand(K2,Nb)<0.5)-1;% Generate random binary {-1,1}
dr1=floor(rand(1,K1)*fsTc1*PG1);% Random delay vector, uniform over (0,PG*fsTc)
dr2=floor(rand(1,K2)*fsTc2*PG2);% Random delay vector, uniform over (0,PG*fsTc)
%-------------------------------------------------------%
% transmission of user one
for ch=1:K1
    data1=OverN(b1(ch,:),PG1*fsTc1);% Oversample bit sequence for spreading
    cs1=repmat(code1(ch,:),1,Nb);% replicate code1 to size 1*Nb
    Tx1(ch,:)=sqrt(Echip1)*data1.*cs1;
    TxD1(ch,:)=cshift(Tx1(ch,:),dr1(ch)); % Delay shift to the right
end
%transmission of user two
for ch=1:K2
    data2=OverN(b2(ch,:),PG2*fsTc2);% Oversample bit sequence for spreading
    cs2=repmat(code2(ch,:),1,Nb);% replicate code2 to size 1*Nb
    Tx2(ch,:)=sqrt(Echip2)*data2.*cs2;
    TxD2(ch,:)=cshift(Tx2(ch,:),dr2(ch)); % Delay shift to the right
end
% Rayleigh Fading
a1=sqrt(randn(1,K1).^2+randn(1,K1).^2)/sqrt(2);
A1=diag(a1);
TxD1=A1*TxD1;
rx1=sum(TxD1,1);% Users transmitted vector
a2=sqrt(randn(1,K2).^2+randn(1,K2).^2)/sqrt(2);
A2=diag(a2);
TxD2=A2*TxD2;
rx2=sum(TxD2,1);% Users transmitted vector
EB=((K1*Eb1)+(K2*Eb2))/(K1+K2);% total energy per bit
noise=randn(1,LT)*sqrt(1/(EB));% generate noise Vector
rx=rx1+rx2+noise;% % received matrix
tx1=0;
tx2=0;
dr=[dr1 dr2];
code=[code1;code2];
b=[b1;b2];
%-------------------------------------------------------%
% received
for ch=1:K1
    rx1=cshiftLeft(rx,dr1(ch));% shift rx by dr1 to the left
    scode1=repmat(code1(ch,:),1,Nb);% to replicate code1, matrix 1*Nb
    despread=rx1.*scode1;% to despread the received bits
    dreshape=reshape(despread,PG1*fsTc1,Nb);% reshape the despread bits
dint1(ch,:) = sum(dreshape,1);
end
% to find the bit error for each users
bh1 = sign(dint1);  % Make sign decision on each bit
clear dint1
errb1 = sum(abs(b1-bh1)/2,2);  % Create bit error vector for the ch users
Pb1(:,avg) = Pb1(:,avg) + errb1;
clear errb1
count1 = count1 + 1;

%-------------------------------------------------------%
for ch = 1:K2
    rx2 = cshiftLeft(rx,dr2(ch));  % shift rx by dr2 to the left
    scode2 = repmat(code2(ch,:),1,Nb);  % to replicate code2, matrix 1*Nb
    dspread = rx2.*scode2;  % to despread the received bits
    dreshape = reshape(dspread,PG2*fsTc2,Nb);  % reshape the despread bits
    dint2(ch,:) = sum(dreshape,1);
end
% to find the bit error for each users
bh2 = sign(dint2);  % Make sign decision on each bit
clear dint2
errb2 = sum(abs(b2-bh2)/2,2);  % Create bit error vector for the ch users
Pb2(:,avg) = Pb2(:,avg) + errb2;
clear errb2
count2 = count2 + 1;
end
% end
K = K1 + K2;
N = avg.*Nb;
Ber1 = sum(Pb1'./N)  % Average over count1, and # users runs
PP1
Ber2 = sum(Pb2'./N)  % Average over count2, and # users runs
PP2
jk = 1:K;
jk1 = 1:K1;
jk2 = (K1+1):K2+K1;
% Plot
semilogy(jk1,Ber1,'g--',jk2,Ber2,'b*-',jk1,Pba1,'k--',jk2,Pba2,'k-o',jk1,PP1,'r--',jk2,PP2,'r-*',jk1,PbFn,'c--',jk2,PbFw,'k--','Linewidth',2);grid

xlabel('User Index');
ylabel('P_b');
title('P_b vs User index for DS-SS on Rayleigh Fading Channel')
legend('Pb1 simulated Avg','Pb2 Simulated Avg.','Single User SetOne PG1','Single User SetTwo PG2','Analy. AWGN Chan. G-MUI','Analy. AWGN Chan. G-MUI','SetOne P_b--theoretical fading','SetTwo P_b--theoretical fading');

Function to Oversample number of bits % provided by Dr. David Matolak
% Function OverN oversamples input vector x by N
function y=OverN(x,N)
[nr,nc]=size(x);
if min(nr,nc)<=1;
    % First loops for vector input
    Lx=length(x);
    y=zeros(1,N*Lx);
    for kk=1:Lx
        for jj=1:N
            y((kk-1)*N+jj)=x(kk);
        end
    end
else
    % Following loops for matrix input
    y=zeros(nr,nc);
    for ir=1:nr
        for iz=1:nc
            for jj=1:N
                y(ir,(iz-1)*N+jj)=x(ir,iz);
            end
        end
    end
end

Function to circularly shifts the input vector x to the right by M positions provided by Dr. David Matolak

cs = cshiftLeft(x,M)
Mm=M;
Lx=length(x);
if M > Lx
    Mm = mod(M,Lx);
end
% (shift of Lx yields original vector)
if M>=1
    cs=[x(M+1:Lx) x(1:M)];
elseif M<1
    cs=x;
end
APPENDIX B: CODE TO GENERATE DS-SS IN SPECTRAL OVERLAY AD HOC NETWORK

% generating random distance

clc
clear all
close all

%--------------------------------------------------

disp('-------------------------------------------------');
Z1=3;  % 'Number of nodes Set One
Z2=4;  % 'Number of nodes Set two
D=100; %'input Maximum Distance
n=3;   % 'Path Loss Exponents
XXX=7; % 'Zero mean Gaussian Random Var.
Rb=10^4; % 'bit rates 10^4, 10^6
nf=3;  % 'noise factor
disp('-------------------------------------------------');
d=1;  % 'distance in meter
Z=Z1+Z2;
PG1=512;% 'processing gain one 512, 1024
PG2=256;% 'processing gain two 256, 128, 64, 32
Pt=30;% 'transmit power in decibel 30dBm, 10 dBm, 0 dBm
c=3*10^8;       % 'is the speed of light given in meters/s
fc=900*10^6;    % 'carrier frequency
SNIR11=[];
SNIR22=[];
% for loop to generate random location and calculate SNIR, Pb
for AVG=1:100
    XY=zeros(1,Z);
    XY1=zeros(1,Z1);
    XY2=zeros(1,Z2);
    X=D*rand(1,Z); % 'random location in X-axis
    % X1=D*rand(1,Z1)
    % X2=D*rand(1,Z2)
    Y=D*rand(1,Z); % 'random location in Y-axis
    % Y1=D*rand(1,Z1)
    % Y2=D*rand(1,Z2)
    K=Z*(Z-1);
    K1=Z1*(Z1-1);% 'Pb values for set one
K2=Z2*(Z2-1);% Pb values for set two
k=(K/2)-Z;
k1=(K1/2)-Z1;
k2=(K2/2)-Z2;
% fixed nodes location for a single run
%X1=[54.7216,13.8624,14.9294];%
%X2=[25.7508,84.0717,25.4282,81.4285];
%Y1=[35.1660,83.0829,58.5264];
%Y2=[54.9724,91.7194,28.5839,75.7200];

% For loop to generate vector at X-axis and Y axis
for i=1:Z
    xy(:,i)=[X(1,i) Y(1,i)];
    xx(i)=xy(1,i);
    yy(i)=xy(2,i) ;
end
for i=1:Z1
    xy1(:,i)=[X1(1,i) Y1(1,i)];
    xx1(i)=xy1(1,i);
    yy1(i)=xy1(2,i) ;
end
for i=1:Z2
    xy2(:,i)=[X2(1,i) Y2(1,i)];
    xx2(i)=xy2(1,i);
    yy2(i)=xy2(2,i) ;
end
% for loops to arrange the locations of the nodes on x-axis and y-axis for
% user set two
KK1=K1/Z1;
XXxx1=zeros(K1,2);
for ii=1:Z1
    for jj=1:(Z1-1)
        JJ=jj+ii;
        if JJ<=Z1
            xx=xx1(jj+ii);
            yy=xx1(1,ii);
            XX=[yy,xx];
        else
            XX=[];
        end
    end
end
\[
\begin{align*}
x & = xx_1(jj+ii-Z_1) \\
y & = xx_1(1,ii) \\
XX & = [yy, xx]; \\
\end{align*}
\]
end
XXxx1=[XXxx1; XX]; end end

XXxx1=XXxx1((K1)+1:(K1)*2,:); XXXX1=XXxx1'; 
X11=reshape(XXXX1,1,(K1)*2);
YYyy1=zeros(K1,2);
for ii=1:Z1
for jj=1:(Z1-1)
JJ=jj+ii;
if JJ<=Z1
xx=yy1(jj+ii);
yy=yy1(1,ii);
YY=[yy, xx];
else
xx=yy1(jj+ii-Z1)
yy=yy1(1,ii);
YY=[yy, xx];
end
YYyy1=[YYyy1; YY];
end
end
YYyy1=YYyy1((K1)+1:(K1)*2,:); YYYY1=YYyy1'; 
Y11=reshape(YYYY1,1,(K1)*2);
\%
% for loops to arrange the locations of the nodes on x-axis and y-axis for 
% user set two

KK2=K2/Z2;
XXxx2=zeros(K2,2);
for ii=1:Z2
for jj=1:(Z2-1)
    JJ=jj+ii;
    if JJ<=Z2
        xx=xx2(jj+ii);
        yy=xx2(1,ii);
        XX=[yy,xx];
    else
        xx=xx2(jj+ii-Z2)
        yy=xx2(1,ii);
        XX=[yy,xx];
    end
    XXxx2=[XXxx2; XX];
end
end
XXxx2=XXxx2((K2)+1:(K2)*2,:);
XXXX2=XXxx2';
X22=reshape(XXXX2,1,(K2)*2);

YYyy2=zeros(K2,2);
for ii=1:Z2
    for jj=1:(Z2-1)
        JJ=jj+ii;
        if JJ<=Z2
            xx=yy2(jj+ii);
            yy=yy2(1,ii);
            YY=[yy,xx];
        else
            xx=yy2(jj+ii-Z2)
            yy=yy2(1,ii);
            YY=[yy,xx];
        end
        YYyy2=[YYyy2; YY];
    end
end
YYyy2=YYyy2((K2)+1:(K2)*2,:);
YYYY2=YYyy2';
Y22=reshape(YYYY2,1,(K2)*2);
%------------------------------------------------------%
%--------------------------------------------------------%

KK1=K1/2;
xz1=abs(XXxx1(:,1)-XXxx1(:,2))
yz1=abs(YYyy1(:,1)-YYyy1(:,2))

dd1=sqrt(yz1.^2+xz1.^2);
d1=dd1';
dij1=[d1(1,:)]

KK2=K2/2;% max number of distance betwen nodes

xz=abs(XXxx2(:,1)-XXxx2(:,2))
yz=abs(YYyy2(:,1)-YYyy2(:,2))

dd=sqrt(yz.^2+xz.^2);
d2=dd';
dij2=[d2(1,:)]

disp(blanks(5)');    % moves the cursor down n lines.
disp('The distances between nodes "set two"are: ');
disp(blanks(2)');    % moves the cursor down n lines.
disp(dij2);
disp('-------------------------------------------------');
%--------------------------------------------%
% Distance between set two and set one for node one
for jj=1:Z1
  for i=1:Z2
    s1(jj,i)=abs(xx1(jj)-xx2(i)); % for X
    d1(jj,i)=abs(yy1(jj)-yy2(i)); % for Y axis
    dij21(jj,i)=sqrt((s1(jj,i))^2+(d1(jj,i))^2);        % vactor length
  end
end
%----------------------------------------------%
for jj=1:Z2
  for i=1:Z1
    s1(jj,i)=abs(xx2(jj)-xx1(i)); % for X
    d1(jj,i)=abs(yy2(jj)-yy1(i)); % for Y axis
    dij21(jj,i)=sqrt((s1(jj,i))^2+(d1(jj,i))^2);        % vactor length
  end
end
%---------------------------------------------------%
%--------------------------------------------------------% 
WaveL=(c/fc); % wave length in meters 

% the path loss for free space model Unity antenna gain 
Lfs=20*\log((4*\pi*d/c)*f_{c})/\log(10); %average large-scale path loss between user one in system one and user two in system one 

% the losses between all nodes 
L1=Lfs+10*n*\log(dij1)/\log(10)+XXX; 
L2=Lfs+10*n*\log(dij2)/\log(10)+XXX; 
L21=Lfs+10*n*\log(dij21)/\log(10)+XXX; 
L12=Lfs+10*n*\log(dij12)/\log(10)+XXX; 

% received power 
% Pr=Pt-Ls-10*n*\log(dij)/\log(10)+XXX; 
Pr1=Pt-L1; % received power 
Pr2=Pt-L2; % received power 
Pr21=Pt-L21; 
Pr12=Pt-L12; 
N0=-174; % Noise dBm/Hz 
Pn=N0+nf+10*\log(Rb)/\log(10); % nosie power 
EbN01=Pt-L1-Pn+nf; % Eb/No for set one 
EbN02=Pt-L2-Pn+nf; % Eb/No for set two 
\textcolor{red}{gb1=10^{(EbN01/10)};} 
\textcolor{red}{gb2=10^{(EbN02/10)};} 

%-------------------------------------------------------% 
% SNIR for system one and two 
EbN021=Pt-L21-Pn+nf; 
\textcolor{red}{gb21=10^{(EbN021/10)};} 
for nu=1:KK1 
for nn=1:2 
\textcolor{red}{if nu==1} 
\textcolor{red}{gbb1(1,1)=gb1(1,2);} 
\textcolor{red}{gbb1(1,2)=gb1(1,3);} 
\textcolor{red}{elseif nu==2} 
\textcolor{red}{gbb1(1,1)=gb1(1,1);} 
\textcolor{red}{gbb1(1,2)=gb1(1,3);
elseif nu==3
gbb1(1,1)=gb1(1,1);
gbb1(1,2)=gb1(1,2);
end
SNIR1(nu,nn)=gb1(1,nu)/(1+((gbb1(1,nn)/PG1)+(sum(gb21(nu,:))/PG2)))
end
end
SNIR1
SNIR11=[SNIR11,SNIR1];

EbN012=Pt-L12-Pn+nf;
gb12=10.^((EbN012/10);
for nu=1:Z2
    for nn=1:3
        if nu==1
            gbb2=gb2(1,1:3)
        elseif nu==2
            gbb2=gb2(1,4:6)
        elseif nu==3
            gbb2=gb2(1,7:9)
        elseif nu==4
            gbb2=gb2(1,10:12)
        end
        SNIR2(nu,nn)=gbb2(1,nn)/(1+(((sum(gbb2))-gbb2(1,nn))/PG2)+(sum(gb12(nu,:))/PG1))
    end
end

PP2=qfunc(sqrt(SNIR2));
P2(AVG,:)=reshape(PP2',1,12);
SNIR22(AVG,:)=reshape(SNIR2',1,12);
SNIR22=[SNIR22,SNIR2];
SNIR222=reshape(SNIR22,1,AVG*12);
SINR22=10*log(SNIR222)/log(10);
SNIR2dB=SNIR22
SNIR111=reshape(SNIR11,1,AVG*6);
SINR11=10*log(SNIR111)/log(10);
SINR1dB=SNIR11
for iy=1:length(SNIR222)
    if SNIR222(iy)>=50
        SNIR2222(iy)=50;
    elseif SNIR222(iy)<=-10
        SNIR2222(iy)=-10;
    else
        SNIR2222(iy)=SNIR222(iy);
    end
end
for iy=1:length(SNIR111)
    if SNIR111(iy)>=50
        SNIR1111(iy)=50;
    elseif SNIR111(iy)<=-10
        SNIR1111(iy)=-10;
    else
        SNIR1111(iy)=SNIR111(iy);
    end
end
SNIR1num=10.^((SNIR1111/10));
SNIR2num=10.^((SNIR2222/10));
P22=qfunc(sqrt(SNIR2num));
P11=qfunc(sqrt(SNIR1num));
% m1=mean(SNIR111)
% m2=mean(SNIR222)
% Plot of the simulation results
figure
hist(SNIR2222,50);hold on
h = findobj(gca,'Type','patch');
set(h,'FaceColor','g','EdgeColor','w')
hist(SNIR1111,50)
xlabel('SNIR(dB)');
title(' Histogram plot(K1=6,K2=12,PG1=512,PG2=256,Pt=30,Rb=10^4,n=3,X=7)');grid
legend('SNIR2','SNIR1');
for iy=1:length(P22)
    if P22(iy)>=10^(-1)
        PP22(iy)=10^(-1);
    elseif P22(iy)<=10^(-8)
        PP22(iy)=10^(-8);
    else
        PP22(iy)=P22(iy);
    end
end
for iy=1:length(P11)
if $P_{11}(iy) \geq 10^{-1}$
    $PP_{11}(iy) = 10^{-1}$;
elseif $P_{11}(iy) \leq 10^{-8}$;
    $PP_{11}(iy) = 10^{-8}$;
else
    $PP_{11}(iy) = P_{11}(iy)$;
end
end
figure
hist(PP22,50); hold on
h = findobj(gca,'Type','patch');
set(h,'FaceColor','g','EdgeColor','w')
hist(PP11,50);
xlabel('Pb');
title('Histogram plot(K1=6,K2=12,PG1=512,PG2=256,Pt=30,Rb=10^4,n=3,X=7)'); grid
legend('P22','P11');