Performance Comparative Study of Single and Multi-carrier CDMA-based Wireless Communication Systems

By

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Performance Comparative Study of Single and Multi-carrier CDMA-based Wireless Communication Systems

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Abstract

This project presents the system performance analysis on three self-developed system models: Single-carrier Wide-band CDMA, Multi-carrier DS SS CDMA and Hybrid CDMA / OFDM. These three models are developed from a basic Matlab-based wireless communication system model and have been put into hundreds of experimental simulations to rectify the functions of every single block. In the goal to evaluate the performance of a modern multiple access system, series of simulations that are carefully planned and adjusted are carried out. Characteristics such as spectrum, orthogonality, number of chips, multi-user interference and guard band are covered throughout the simulations. Simulation results are translated into mathematical plots and analyzed. Finally, the project is summarized and some conclusions are drawn as well.

Keywords: Digital Communications, CDMA, WCDMA, OFDM, Multi-Curier, DS SS, MATLAB.

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Chapter 1

Introduction

An ever growing cellular radio and personal communication services (PCS) market is driving the consumption of limited frequency spectrum stunningly fast. As a result, to achieve high system capacity with limited radio spectrum while at the same time covering as large area as possible has become an imperative goal in modern radio communication system design. The main concept in achieving this goal is frequency reusing scheme, which adopts various channel assignment strategies in a certain frequency band. And within each strategy, a corresponding backbone access technology would realize the goal of increasing the capacity and minimizing the interference. Two improved CDMA systems (single-carrier wide-band CDMA and CDMA / OFDM) that embody such strategies will be studied in this report. But before we reach the guided research and performance evaluation, it is necessary to have a basic understanding on the general technologies involved in building a basic CDMA system and alternative technologies of CDMA.

1.1 Wireless Communication Systems Supporting Multiple Access

In a simple wireless communication model shown in Figure 1-1, the original voice signal or other source signal will be first converted into digital signal in order to be processed in the system. The digital signal will then be encoded by one of the various encoding techniques, which interpret a unique symbol into a unique waveform to be transmitted. Carriers at different frequencies will modulate the base band encoded signals and transmit them as electromagnetic wave through the transmitter. The electromagnetic wave embedded with useful information will have to travel a long way before it reaches its destination (a receiver). The transmission path between the transmitter and the receiver is called channel, during which the power of the wave could be lost or the form of the wave could be distorted. And the noisy channel is the fundamental limitation on the performance of the wireless communication system.

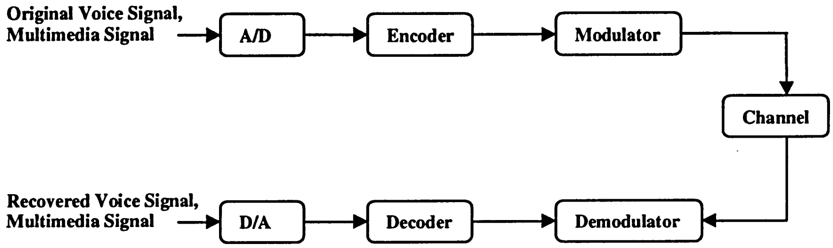


Figure 1-1: Basic Wireless Communication Model.

The loss of the electromagnetic wave is mainly attributed to reflection, diffraction and scattering within the channel. Various propagation models have been built to analyze the impact on system performance due to the change of a certain channel parameter. This is the reason why while conducting a simulation of a wireless system, a channel model must be involved to evaluate the performance of the system. As you will read in the following chapter, each simulation is based on a certain channel type so that the analysis of the system's behavior could be meaningful.

Another significant factor to consider while restructuring or improving wireless communications system is multiple access. Since most wireless communication systems are designed to accommodate as many users as they can, users of the systems will be simultaneously allocated the available bandwidth, or in another word, the available amount of channels. Time Division Multiple

Access (TDMA), Frequency Division Multiple Access (FDMA) and Code Division Multiple Access (CDMA) are three major implementations of wireless communications systems to enable multiple access.

1.1.2 Time Division Multiple Access (TDMA)

TDMA divides radio spectrum into multiple time slots and each user will be allocated one or more time slots cyclically to transmit his/her symbols as shown in Figure 1-2. Therefore, multiple users can transmit signals simultaneously via multiplexed channels (time slots). From a different perspective, the same carrier within certain bandwidth could be used to transmit signals from multiple users at the same time by assigning the slices of time to different users.

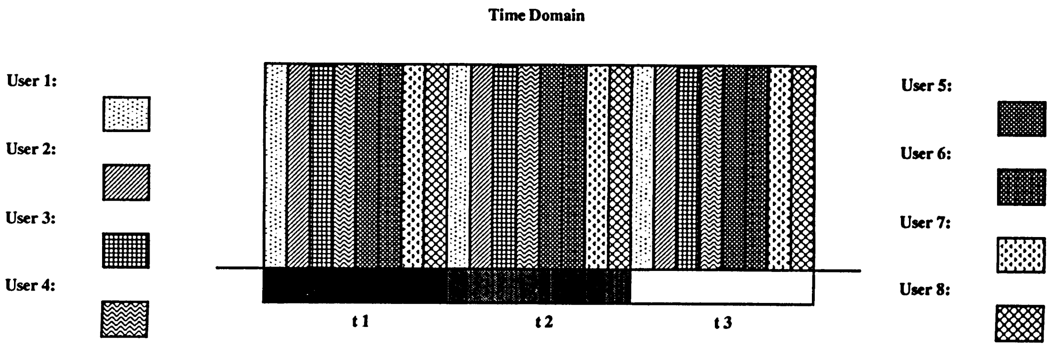


Figure 1-2: Eight users share the same carrier by occupying certain time slot in a TDMA system.

1.1.2 Frequency Division Multiple Access (FDMA)

FDMA systems transmit one user signal per channel as shown in Figure 1-3. and each channel is relatively narrow, usually 30 kHz or less and is defined as either transmit or receive channel in narrow band systems. Multiple access is realized by allocating one duplex channel to each user so that multiple users could transmit and receive his/her own signals simultaneously. Frequency Hopped Multiple Access (FHMA) is an alternative of FDMA techniques that allows multiple users to simultaneously occupy the same spectrum at the same time, where each user dwells at a specific narrowband channel at a particular instance of time, based on the particular code of the user.

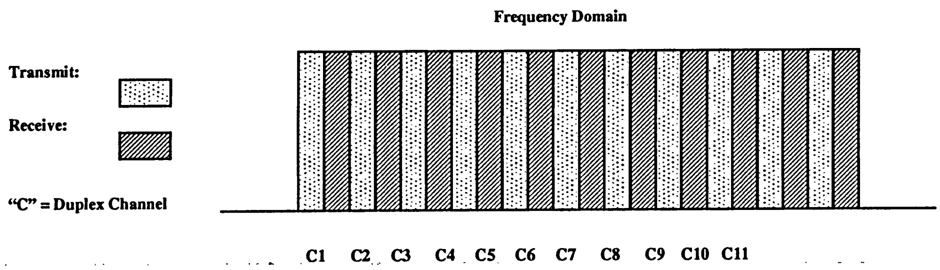


Figure 1-3: 11 users occupy 11 duplex channels in a FDMA system.

1.1.3 Code Division Multiple Access (CDMA)

In a CDMA system, message signal will be multiplied by a large bandwidth pseudo-noise code (PN) sequence that has a chip rate much greater than the data rate. Consequently, the original signal will be spread over a substantially wider spectrum than that of non-spread signal as shown in Figure 1-4. The unique PN sequence assigned to each user is almost orthogonal to the other ones so that the receiver could use it to detect the desired recipient of the transmitted signal. All users could be transmitted by one wideband carrier so that the allocated bandwidth is simultaneously used by a large group of users. System performance would gradually degrade for all users as the number of users is increased and improved for all users as the number of users is decreased. In CDMA systems, multi-path fading could be substantially reduced since the spread bandwidth is greater than the coherence bandwidth of the channel. Two other problems unique to CDMA systems are self-jamming, which caused by the fact that the pseudo-noise sequence are not exactly orthogonal, and near-far problem that is caused by a higher power interference signal from another user.

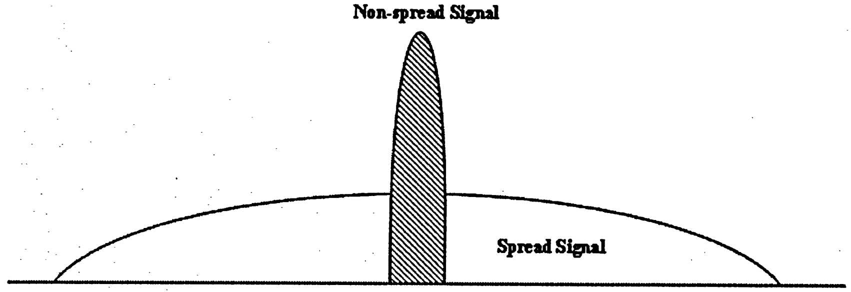


Figure 1-4: Illustration of the different spectrum of a spread and non-spread signal.

Wide-band CDMA was designed for high-speed data services and more particularly, internet-based packet-data offering up to 2 Mbps transmission speed in stationary or office environments, and up to 384 kbps in wide area or mobile environment. It is one of the key technologies in the research and development work of third-generation CDMA system.

1.14 Multi-carrier Technologies

Multi-carrier technology for wireless communications was first introduced in 1960s. Since then, analog multi-carrier implementations are broadly studied in the literature. However, due to the complexity it requires to implement, not much real world applications were drawn by it until a much simpler and faster in Orthogonal Frequency Division Multiplexing (OFDM) technology emerges. In OFDM, carrier modulation and demodulation could be completely realized by digital FFT and IFFT. The implementation complexity and costs are largely reduced in OFDM and consequently it has become the new edge of beyond third-generation high-speed wireless communications systems. Based on FDM system, OFDM system is developed to bring much better performance than FDM due to its orthogonal multi-carrier structure making the whole allocated broad spectrum more condense.

1.2 Motivation

The design of modern wireless communications systems requires a systematic perspective over the communicating channel, transmitter and receiver, also an in-depth understanding of the scheme that is adopted by the implementation. Building mathematical models to simulate the real types of CDMA systems is the best way to understand and analyze how an integrated wireless communications system works.

In order to compare the system performance between single-carrier and multi-carrier systems, a Single-carrier Wide-band CDMA system is developed from a basic Matlab-based wireless communications system [1] model, a Multi-carrier Direct Sequence Spectrum Spreading (Multi-carrier DS SS) CDMA system model is later developed from the previous model, and a hybrid system combining both CDMA and OFDM is also developed from the basic model and a series of simulations were carried out upon different parameter settings on those three models.

System behaviors shown in frequency domain could disclose many significant facts about the system, especially in CDMA system. For this reason, spectrum of the wireless signal in different stages are plotted in order to observe the bandwidth changes, magnitude changes and shape changes during the processing, transmission and of the signal.

System parameters are the factors that influence the system performance. Therefore, it has significant meaning to analyze the relationship between these parameters and system performance. In this project, system parameters such as channel types, orthogonality of PN codes, length of PN codes, multi-user interference are varied in the simulations and the simulation results are analyzed.

1.3 Contributions

Three Matlab-based models, Single-carrier Wide-band CDMA, Multi-carrier DS SS CDMA, Hybrid CDMA/OFDM, are developed based on a basic wireless communication model. Additional sub functions are coded for each model and the primitive Matlab-based code is modified according to the needs for Monte-Carlo simulations. Analysis of system parameters, such as channel types, orthogonality of PN code, length of PN code and multi-user interference were conducted based on the simulation results.

1.4 Organization

This thesis report is organized in five chapters. Chapter 1 gives an introduction on the background knowledge needed for a better understanding of the guided research. Chapter 2 reviews and categorizes previous work on the development of first, second and third generation of CDMA system. Chapter 3 explains and illustrates the building of the three models and the Monte-Carlo simulation method that is to be used in Chapter 4. Chapter 4 describes the planning and conducting of series of simulations on those developed models, followed by the analysis of the simulation results. Chapter 5 summarizes and concludes on the guided research.

Chapter 2

Literature Review

2.1 Single-carrier Wide-band CDMA & Narrow-band CDMA

When we discuss the Wide-band and Narrow-band CDMA concepts, we are placing the major CDMA technologies from second and third generation together to make a comparison in terms of bandwidth. With the wider bandwidth, high-rate data service, such as wireless access to the Internet, can be supported; Cell coverage and system capacity can be largely improved.

The first W-CDMA concept, Alpha concept that answered to the third generation requirement was first decided by ETSI as the main technology for UTRA (UMTS Terrestrial Radio Access). Developed by Europe standardization body, UMTS has become one of the major air interface standards that symbolizes the start of third generation CDMA. During the similar time span, two other parties in China and North America were also working on the enhancements and refinements of UTRA in parallel. And later on, in 1998, both submitted their work to ITU [2]. That is why we are having three different wireless radio interface standards today. However, there is a very good potential for a truly global WCDMA-based radio interface for International Mobile Telecommunications-2000 IMT-2000.

Single-carrier narrow-band CDMA is used in 2G and 2.5G CDMA. In 2G CDMA standard, each radio channel is allocated with 1.25MHz bandwidth, within which only one carrier can carry and deliver signals. If we do a simple calculation, given a certain range of bandwidth, the number of channels it contains is very limited, and thus the number of users it can accommodate is rather restrained. On the other hand, Single-carrier Wide-band CDMA is inclined to give wider bandwidth to transfer each signal and thus providing better capacity and performance.

2.2 Standards for Single-carrier Wide-band CDMA and Multi-carrier CDMA

Following our discussion above, wide-band solutions far outweighs the narrow-band solutions. We can further elaborate this by analyzing the three most widely used approaches for 3G CDMA. There are three major wide-band CDMA standards that been proposed to ITU's IMT-2000 body in 1998 for consideration as a world standard. The 3G W-CDMA (UMTS) is mostly developed in Europe and Japan. Its requirement for minimum spectrum allocation is 5MHz, a distinctly wider spectrum compared with other third generation CDMA standards. W-CDMA air interface was designed for "always-on" packet based wireless service, i.e. personal computers, portable devices and telephones - all share the same wireless network as their tunnels through Internet. Data rates from as low as 8kbps to as high as 2Mbps can be carried at the same time within a 5MHz radio channel. And a single channel could roughly support 100 to 350 users simultaneously. However, because of the wider spectrum requirement, a complete change out of base station RF equipment is required to achieve the most optimized performance [3]. In this project, a Wide-band CDMA model will be developed and various performance factors will be tested through simulation.

Another third generation solution is developed mainly in North America, and is a major improvement from IS-95 CDMA standard, called 3G cdma2000. It was submitted by Telecommunications Industry Association (TIA) of the US to ITU in 1998. The ultimate cdma2000 3xRTT uses three adjacent 1.25MHz radio channels together as a super channel to provide wider bandwidth in multi-carrier mode. The three radio channels could be separated instead of adjacent but simultaneously operates, so that there are no large upgrades for base station RF equipment needed. This solution is much more seamless and less costly than W-CDMA, and at the same time provide equally high data rate up to 2 Mbps as W-CDMA did [3].

3G TD-SCDMA is another widely adopted 3G CDMA standard and was mainly applied in China. It was proposed together by China Academy of Telecommunications Technology (CATT) and Siemens Corporation to ITU. Developed mainly based on traditional GSM system, TD-CDMA adopted Time Division Synchronous CDMA technique and used 1.6MHz radio channel to transfer both low and high data rate packets. The core technique in TD-CDMA that supports broad bandwidth capacity is allocating time slots on a certain carrier frequency according to the different needs of low or high rate users. This solution could be implemented on existing GSM smoothly with less hassle [3].

2.3 Performance Evaluation and Comparison for CDMA Systems

For W-CDMA, the following frequency band has been allocated by IMT-2000. For Frequency Division Duplex (FDD) link, at least 5 MHz should be allocated to each of uplink and downlink pair in order to support high data rate packet transfer.

- **1920-1980** and **2110-2170** MHz: Frequency Division Duplex (FDD, W-CDMA) Paired uplink and downlink, channel spacing is 5 MHz and raster is 200 kHz. An Operator needs 3 - 4 channels (2x15 MHz or 2x20 MHz) to be able to build a high-speed, high-capacity network.
- **1900-1920** and **2010-2025** MHz: Time Division Duplex (TDD, TD/CDMA)

- Unpaired, channel spacing is 5 MHz and raster is 200 kHz. Transmitter and Receiver are not separated in frequency.
- **1980-2010** and **2170-2200** MHz: Satellite uplink and downlink.

In order to estimate a single transceiver and site capacity, in-cell noise, Eb/No requirements, planned data rates, coverage probability, air resources usage activity factor, target interference margin and processing gains are needed to approximate the transceiver and site capacity. Once the cell capacity and subscriber traffic profiles are known, network area base station requirements can be calculated. And then the number of mobile users each cell can serve can be roughly estimated.

However, the capacity estimation is quite sensitive to variations of download amount, retransmit rate and estimated cell capacity values and many other factors. Hence to analyze the impacts between mixed network factors is of significant use in evaluation the performance of 3G Wide-band CDMA. Researchers have done numerous works in this area in the latest decade [1]-[4] [7] [19].

In [1], a WCDMA test bed (WBTB) built by Ericsson is utilized as the testing model for performance evaluation for WCDMA. The performance test is conducted by three interactive functional entities: Base Station, Mobile Station and Radio Network Controller (RNC). See Fig. 2-1.

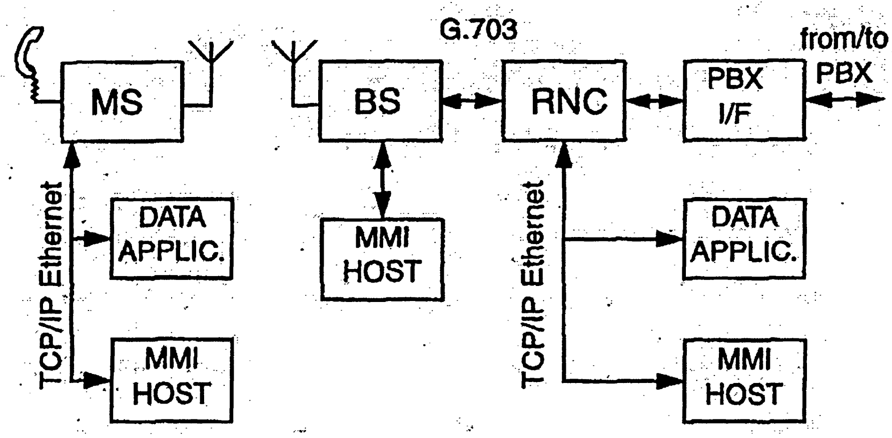


Figure 2-1 Three functional entities compose Ericsson Test System [1]

Both field measurements and laboratory measurements are undertaken in order to prove that Wide band CDMA could provide better services (speech service in particular in [1]) than Narrow band CDMA. There are two major performance characteristics being considered in [1]: multi-path diversity gain and interferer measurement. The former characteristic is concerned with the impact on bit error rate while higher chip rate is employed by Wide band CDMA. By picking up much better and much closer between two adjacent fading paths, W-CDMA can provide greater multi-path diversity gain than Narrow Band CDMA does. In this project, a self-built W-CDMA system to model multi-path diversity gain is used while changing the input data rate. And an AWGN channel, a Rayleigh fading channel and a 2-way Rayleigh fading channel are used to simulate the real world electromagnetic wave propagation.

The paper [4] provides a differently structured testing system that is more focused on user accommodation capacity for real geographic mapping in a certain channel. Instead of building upon physically separated functional entities, the test model in [4] is composed of three different mathematical modules that work together like a real CDMA system. And it is a Matlab based Monte-Carlo model that utilizes statistics method to compute system performance.

In this model, Inter user interferences that come from close users has become the center of attention. Eb/No relationship is the main performance standard while simulating various user mapping. In [4], it is emphasized that the conditions of microcellular systems and data traffic includes more variables to the problem that are difficult to solve pure logically. So it is a good approach to simulate right on the real geographical cover maps and somewhat disclose more real-life issues and phenomena while deploying carriers over certain cell cluster. In this project, all simulation components are built in similar Matlab environment. And they are integrated into one model that simulates an end-to-end CDMA System.

Performance evaluation regarding other technical layers is conducted as well, especially in high data rate Internet access services. In [3], Mobile internet access performance evaluation for W-CDMA is carried out on an NS-2 simulator.

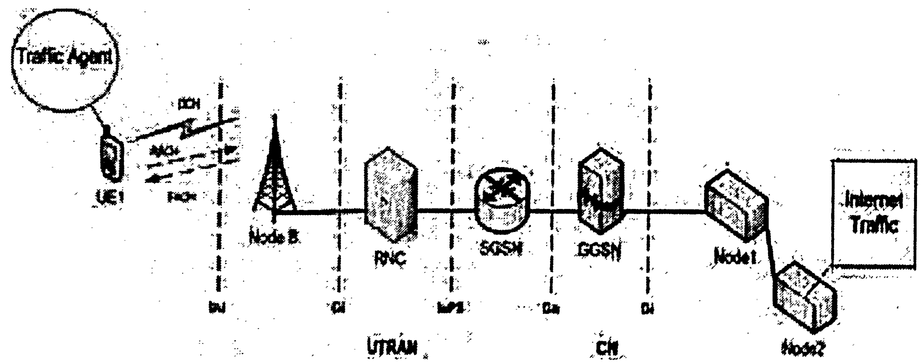


Figure 2-2: Simulation model for Mobile Internet Access. [3]

System parameters, such as end-to-end packet delay, delay in RAN and throughput in wireless link is considered in the simulation, and the experiment results are not quite optimistic on Internet access performance through wireless TCP tunnel. Lack of commercially regulated protocols over TCP and relatively low wireless connection speed, the 3G standard is still having a long way to go.

In today's Wide Band CDMA field, single-carrier solutions are not the only options in the competition of increasing capacity and reusing bandwidth, multi-carrier and multi-code are also major solutions for third generation Wide Band CDMA.

2.4 The Emerge of Multi-carrier CDMA and OFDM

Multi-carrier CDMA system has emerged to be an alternative wide-band CDMA that can utilize the existing traditional radio circuits to provide wide-band advantages through multiple carriers. A multi-carrier system has M carrier signals in the transmitter. In the receiver, M correlators are provided after dispreading, and then correlate outputs are combined with a maximal ratio combiner. Multi-carrier is mainly adopted by CDMA2000 since it does not require major hardware change in base station, but still can provide wide band channel capacity by concatenating multiple carriers. Like many others' research in multi-carrier WCDMA, Shiro and Laurence [8] [15] have proposed a simple multi-carrier model (Figure 2-3) to do the performance analysis.

In this model, spread signal is transmitted by a band of orthogonal sub-carriers. At the transmitter end, all modulated sub-carriers are summed up to be transmitted together. Since the carriers are orthogonal, ideally inter carrier interference could be avoided. Each sub-carrier could be low-frequency carriers that does not provide broad spectrum. However, the sum of their spectrum makes up a broad spectrum just as single-carrier W-CDMA does. Many people have done research in this field in the literature with valuable accomplishment [16] - [18].

In this project, a MC DS SS CDMA system model with four sub-carriers are developed and simulated.

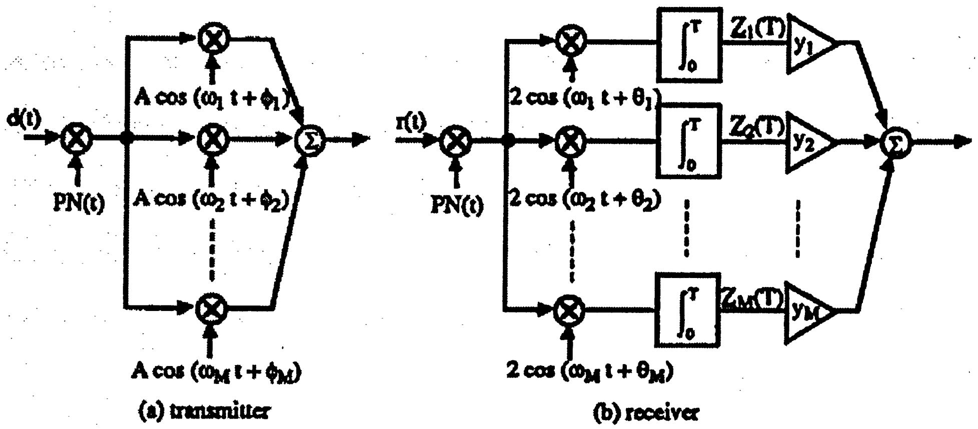


Figure 2-3. A Multi-carrier DS SS system [16]

Orthogonal Frequency Division Multiplexing (OFDM) is one of the methods that can effectively squeeze multiple modulated carriers tightly together. In addition, with more and more economically integrated circuits becoming available, the implementation of OFDM becomes more and more cost-effective for high speed bi-directional wireless communications. The typical interference faced by high-speed communications is inter symbol interference (ISI), and this can be largely reduced when using low-frequency carrier since the period of each sub-carrier is longer than multi-path spread delay, the longer the period, the less problems with ISI. However, wide spectrum can be preserved by binding more low-frequency carriers together in one system. Some researcher has done analysis between the performance of OFDM and Single-carrier technologies [20].

The simplest implementation of OFDM can be realized by using Inverse Fast Fourier Transform (IFFT) at the transmitter and Fast Fourier Transform (FFT) in the receiver [9]. Intensive computation occurs primarily in IFFT and FFT processing. However, with more and more economic high processing speed digital FFT circuits become available, so the implementation of OFDM excels other technologies in the same field.

Recently, OFDM has been combined with other techniques to provide even better performance. Among them, MIMO-OFDM absorbs most attentions. When OFDM is combined with antenna arrays at the transmitter and receiver to increase the diversity gain and / or to enhance the system capacity on time-variant and frequency-selective channels, resulting in a multiple-input multiple-output (MIMO) configuration, and this creation is called MIMO-OFDM [12]. Figure 2-4 is a typical MIMO-OFDM model with Q inputs and L outputs.

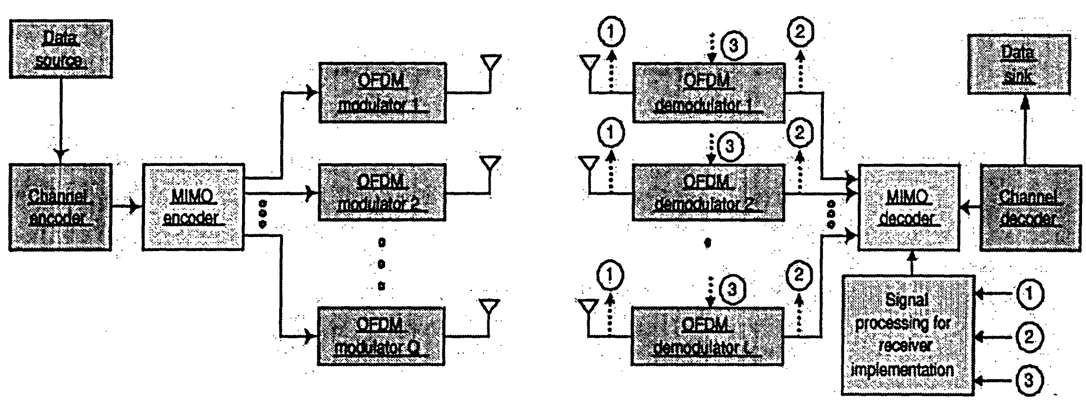


Figure 2-4: MIMO-OFDM model with Q inputs and L outputs. [12]

A MIMO system takes advantage of the spatial diversity that is obtained by spatially separated antennas in a dense multi-path scattering environment. MIMO systems may be implemented in a number of different ways to obtain either a diversity gain to combat signal fading or to obtain a capacity gain. There are quite a few research work undergoing for MIMO-OFDM, such as in [12] [13] [14]. Channel estimation, antenna and beam selection are the focus of their work.

In this project, a Hybrid CDMA / OFDM system model is developed from the basic CDMA model used to build the previously mentioned Single-carrier Wide-band CDMA and Multi-carrier DS SS CDMA model as well.

Chapter 3

System Model

3.1 Singler-carrier Narrow-band / Wide-band CDMA Models

Narrow-band Single-carrier and Wide-band Single-carrier CDMA models share the same system structure. The only difference resides in their chip duration and carrier frequency, and therefore bandwidth is the most significant distinction between them.

The shared model for both Narrow-band Single-carrier and Wide-band Single-carrier CDMA is based on the previous work of Vijaya Ramasami [5], in which a base-band radio signal transmission model is implemented in Matlab. It applies both QPSK and DQPSK encoders and transmits signals in three different channel combinations. Figure 3-1 shows the diagram of the basic transmission model that was reported in [5]. The project based on this model shows different performance of the model to various channels and diversified encoding techniques. The model has very clear module definitions and applies Monte Carlo simulation methodology in achieving the scientific results. It is a rather extensible model that can be rebuilt into multiple flavors of CDMA models.

In Figure 3-1, the incoming information bits b_k is first converted into two parallel bit streams that constitute the input symbol streams to $\pi/4$ – DQPSK Modulator. However, in the following simulations, only QPSK was used since it saved more computation time. Modulation symbols I_k and Q_k will then be transmitted by a transmitter, which is just a symbol repeater (represented by an FIR impulse response of all ones for the symbol interval). The transmitted signal S_k will then be sent through the channel module. In this diagram, a two-way Rayleigh fading channel is modeled with Rayleigh fading envelop α_1 and α_2 and delay period #1 and #2. Each propagation way is called a separate channel that has both Rayleigh fading and Line of Sight (LOS) AWGN.

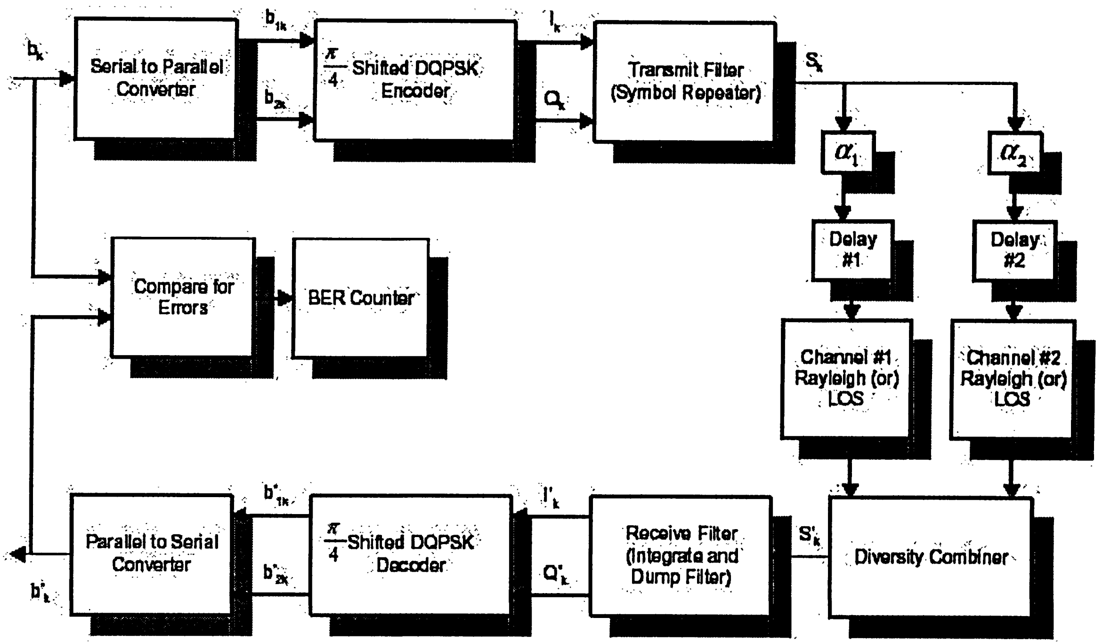


Figure 3-1: Vijaya's base-band radio signal transmission model [5].

At the receiver side, faded signals from different paths will be combined (S'_k) and go through an integrate and dump operation by using an all-ones finite FIR. After that, the converted parallel bit streams I'_k and Q'_k will be decoded and converted back to one serial stream that will be compared with the original bit stream in order to calculate the bit error rate (BER).

In this project, more modules, such as spectral spreading, modulation, demodulation and multi-path are added to the basic model and the input, output interface between these modules are tuned to meet the requirement of the Single-carrier CDMA system.

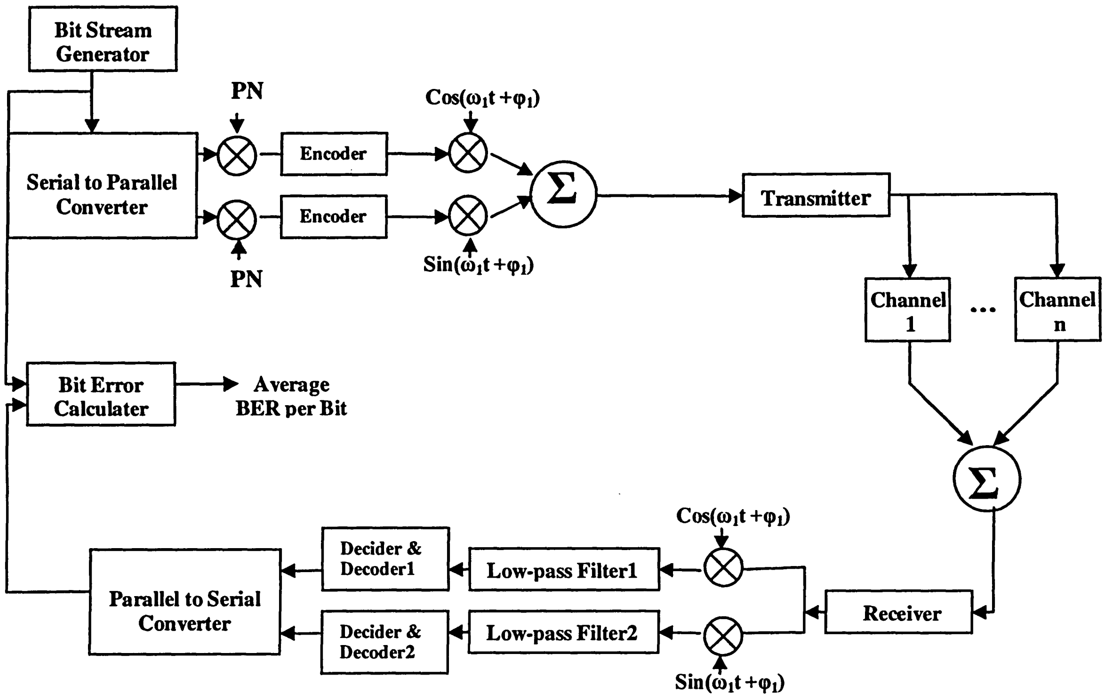


Figure 3-2: Block diagram for single-carrier CDMA.

Figure 3-2 illustrates the block diagram of this model. In this Single-carrier CDMA system, the input signal is a stream of randomly generated bits with value 0 and 1. To increase the transmission efficiency, the signal is first converted into two parallel bit streams in order to be transmitted parallel by orthogonal cosine and sine waveforms. One stream contains the even numbered bits and the other stream contains the odd numbered bits. These two bit streams are identified as In-phase and Quadrature components of the input signal.

Both In-phase and Quadrature bit streams will be spread in frequency domain simultaneously in a Spectral Spreading module. Both bit streams and the PN code signal are converted to bipolar signals first, i.e. +1 and -1 bits. An optional length can be chosen for the PN code according to the bandwidths requirement, and the PN code signal will be multiplied with each bit of the two streams. The spread streams will then be converted back to 0 and 1 bits and become the input for the Encoder module. Figure 3-3 elaborates the internal structure of Spectral Spreading Module.

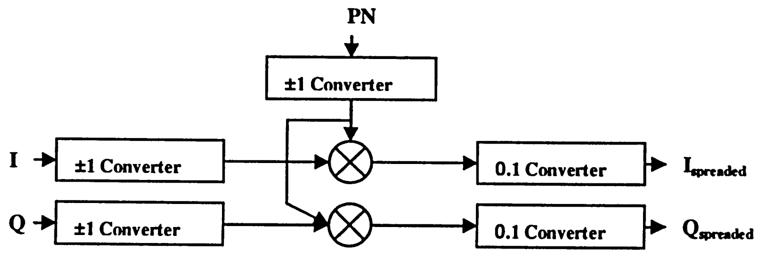


Figure 3-3: Block diagram of Spectral Spreading Module.

Encoder and Decoder module has two realizations – QPSK and $\pi/4$ Shifted DQPSK. The former has a maximum phase shift of π, while the latter has a maximum phase shift of ¾ π since it encodes the input information bits into modulation symbols using $\pi/4$-DQPSK signal mapping. We can think it as a special case of Differential M-ary Phase Shift Keying where M=4. Because of the smaller value of maximum phase shift in $\pi/4$-DQPSK, it preserves the constant envelop property better than QPSK. Table 3-1 illustrates the phase mapping of $\pi/4$-DQPSK encoding technique that adopted in this project.

b_{i1}	b_{i2}	$\Delta\theta_i = f(b_{i1}, b_{i2})$
0	0	$\pi/4$
0	1	$3\pi/4$
1	0	$-3\pi/4$
1	1	$-\pi/4$

Table 3-1: Phase mapping for π /4-DQPSK.

Encoded signal is in the form of ±1 bit stream and is to be modulated by a single carrier. In order to analyze the system performance with respect to bandwidth and frequency, both un-modulated and modulated time domain signals are transformed into frequency domain by Fourier transform. In frequency domain, the energy of the input signal is spread over a wider bandwidth, which can be decided by the chip duration of the PN code. The shorter the chip duration is, the wider the spread bandwidth is. On the receiver side, demodulation module first correlates the received signal with the corresponding waveforms and then filters it with low-pass filter. Before mapping to the binary mode, i.e. ±1 scale, it will be normalized based on the maximum value and compared to the mean value of the filtered signal.

The structure of the demodulation module for Single-carrier CDMA model is shown in Figure 3-4.

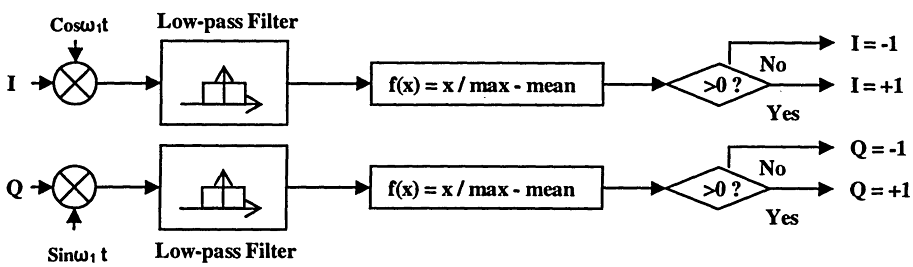


Figure 3-4: Structure of demodulation module.

Transmit filter samples and repeats the modulated symbols to transmit through the channel. An all ones FIR is adopted for this goal.

There are three types of channels to be applied for each simulation scenarios. Each scenario includes three cases of simulation and each case is based on one type of channel. To analyze the impact on system performance by applying parameters with optional values, one key parameter will be focused on each scenario, such as number of PN code chips, orthogonality of the PN code, and number of interfering users.

First simulation case is based on an AWGN channel with average power gain of 1dB. The log (Eb/No) was set from 0 (worst) to 8 (best), step-sized by 0.5dB.

Second was a Line of Sight (LOS) AWGN channel with an average power gain of 0.5dB plus a Rayleigh fading channel with an average power gain of 0.5dB.

Rayleigh fading envelop, $\alpha(n) = \sqrt{I_g(n)^2 + Q_g(n)^2}$, is generated based on the fact that the envelop of a complex Gaussian process (with independent real and imaginary parts) has a Rayleigh Distribution.

Third was a channel of Two-way Rayleigh fading model [3] with an average power gain of 0.5dB. An optional number of delay values (0, 0.125T and 0.25T ...) can be chosen for simulation. T is the symbol period.

For AWGN channel, for a given operating point, the value of N_o and E_b can be obtained as follows: If N_b is the number of bits used for simulation and I_k, Q_k represent the intra-phase and quadrature-phase components of the base-band signaling waveform, then the average energy per bit (Eb) is given by:

$$E_b = \frac{1}{N_b} \sum_{i=1}^{N_b/2} (I_k^2 + Q_k^2) \quad , \qquad (1)$$

where I_k and Q_k are represented by their sample values (sampled from the transmitter), and it was set as 8 samples per symbol. Then the value of noise PSD No can be found as:

$$N_0 = \frac{E_b}{(E_b / N_0)} \qquad (2)$$

For Rayleigh fading channel, the average SNR per bit needed to be redefined as

$$\gamma_b = E(\alpha_k^2)\frac{E_b}{N_0} \qquad (3)$$

The faded SNR per bit is a product of the average fade power $E(\alpha_k^2)$ and the unfaded Eb/No.

In each scenario, the behavior of the system with respect to different channel types will be investigated. And corresponding BER versus average SNR per bit relationship will be plotted to do the comparison.

3.2 Multi-carrier DS SS CDMA Model

As we mentioned before, Multi-carrier CDMA is robust against multi-path fading and performs better in achieving narrowband interference suppression. Based on the single-carrier CDMA model we described above, a Multi-carrier DS SS system is developed on top of it for analysis.

Four orthogonal carriers spaced by 10 MHz are implemented in the model. The number of carriers is optional, but in order to comply with the hardware performance limit, 4 sub-carriers are considered for the simulation. Each sub-carrier also multiplexes both in-phase and a quadrature components of the input signal. All four sub-carriers are orthogonal to each other. A block diagram of the multi-carrier CDMA model is illustrated in Figure 3-5.

Since in-phase and quadrature components are orthogonal to each other and all four sub-carriers are orthogonal as well. There will be in fact eight orthogonal waveforms in four different frequencies. To define orthogonal carriers, each pair of the four carrier waveforms should satisfy:

$$\int_0^T \cos(\omega_i t + \phi_i)\cos(\omega_j t + \phi_j)dt = 0 \qquad for \quad i \neq j, \qquad (4)$$

This can be accomplished by choosing

$$\omega_i = m\frac{\pi}{T} + (i-1)n\frac{2\pi}{T} = m\frac{\pi}{T} + (i-1)\frac{2\pi}{Tc}, \quad (5)$$

where m is an integer, T is the bit duration, n is the number of chips per bit, and Tc is the chip duration [8].

In this project, m is set to 1, T is set to 100μs, and Tc is set to 0.1μs. Based on equation (5), 0.025 MHz, 10.025 MHz, 20.025 MHz and 30.025 MHz can be calculated as the frequencies for the four orthogonal carriers. Since they are 10 MHz apart, and the bandwidth for each carrier is less than 10 MHz, their spectrum is not overlapping. Therefore inter carrier interference can be avoided.

As illustrated in the block diagram, all four modulated signals that output from the four sub-carriers will be summed up and then be transmitted from the transmitter. Through the channel, the diversity combined signal will be received by the receiver. On receiver side, the same four sub-carrier waveforms are used as correlators to multiply with the diversity combined signal. The results are then filtered by low-pass filter to recover the desired frequency components for the signal.

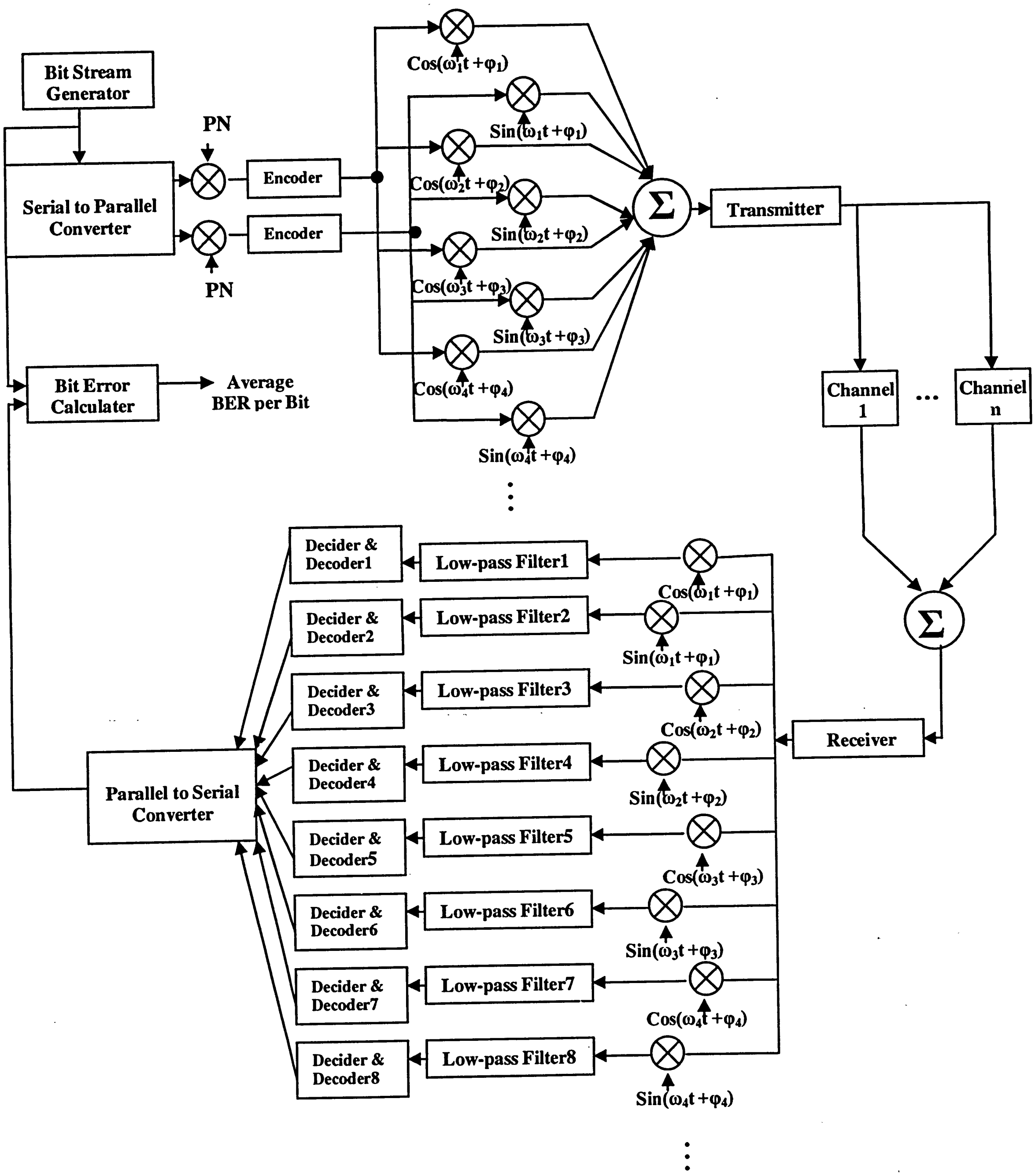
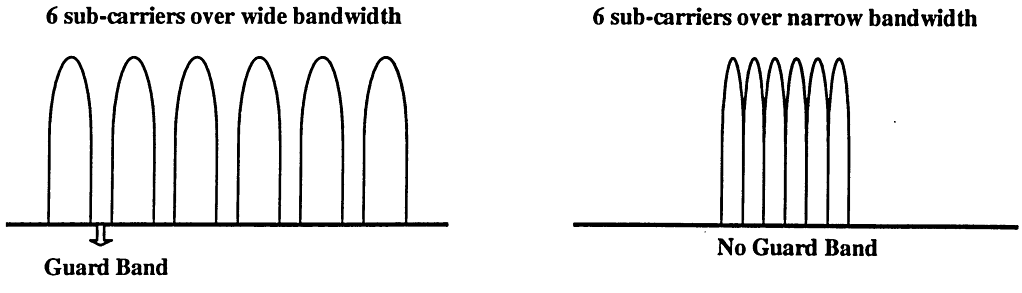


Figure 3-5: Multi-carrier Direct Sequence Spread Spectrum (DS SS) system.

3.3 Hybrid CDMA / OFDM Model

As introduced above, OFDM efficiently squeezes modulated sub-carriers tightly in a certain limited bandwidth by carefully inserting spacing between carriers in order to make the carriers orthogonal to each other. Therefore the sub-carriers can not interfere with one another. It is a technology based on frequency division multiplexing (FDM) that uses multiple frequencies to simultaneously transmit multiple signals in parallel. To avoid the overlapping between sub-carriers, a guard band is chosen to separate them. However, in OFDM, sub-carriers are much closely spaced than in general FDM because they are intentionally chosen to be orthogonal to each other. OFDM system can work properly even when the sub-carriers are overlapped.

Figure 3-6 illustrates the sub-carrier layout in frequency domain for both FDM (a) and OFDM (b). Notice that in OFDM, the bandwidth occupied by the same number of carriers is much condensed rather than in FDM. In case of no-spacing layout or overlapping, there is no guard band needed to prevent interference.



(a) FDM carrier mapping (b) OFDM carrier mapping

Figure3-6: FDM and OFDM carrier mapping.

The reason to use IFFT and FFT to modulate and demodulate the signal is as follows.

While doing a Discrete Fourier Transform to a complex data sequence $\{2d_n\}_{n=0}^{N-1}$, the result will be an N dimension vector S=(S_0, S_1, ... S_{n-1}) with

$$S_m = \sum_{n=0}^{N-1} 2d_n e^{-j(2\pi nm/N)} = 2\sum_{n=0}^{N-1} d_n e^{-j2\pi f_n t_m}, \qquad m = 0,1,\ldots,N-1, \qquad (6)$$

where $f_n = \frac{n}{n\Delta t}$, $t_m = m\Delta t$. Δt is an arbitrarily chosen interval. The real part of S has components:

$$Y_m = 2\sum_{n=0}^{N-1} (a_n \cos 2\pi f_n t_m + b_n \sin 2\pi f_n t_m), \qquad m = 0,1,\ldots,N-1, \qquad (7)$$

If a low-pass filter is applied to these components, then at time intervals Δt, a signal is obtained that approximates the FDM signal

$$y(t) = 2\sum_{n=0}^{N-1} (a_n \cos 2\pi f_n t + b_n \sin 2\pi f_n t), \qquad 0 \le t \le N\Delta t \qquad (8)$$

In this project, a four carrier Hybrid CDMA / OFDM system model is developed from the CDMA model. The diagram of the system is illustrated in Figure 3-7. The original signal is spread and encoded before it is modulated by four orthogonal carriers. The modulation is implemented by adopting an Inverse Forward Fourier Transform (IFFT) computation for the multiplexed (4 ways in this example) signal at the transmitter side. To combat multi-path fading, a guard band is added before IFFT. At the receiver side, after the guard band is removed, a FFT of the received signal is applied in order to demodulate the transmitted signal.

In this project, the guard band is set to be zero since simulations did not show much performance enhancement while adding guard band to multi-path fading scenario. And the frequencies for the four orthogonal carriers are chosen as 8 MHz, 16 MHz, 24 MHz and 32 MHz with 8 MHz apart.

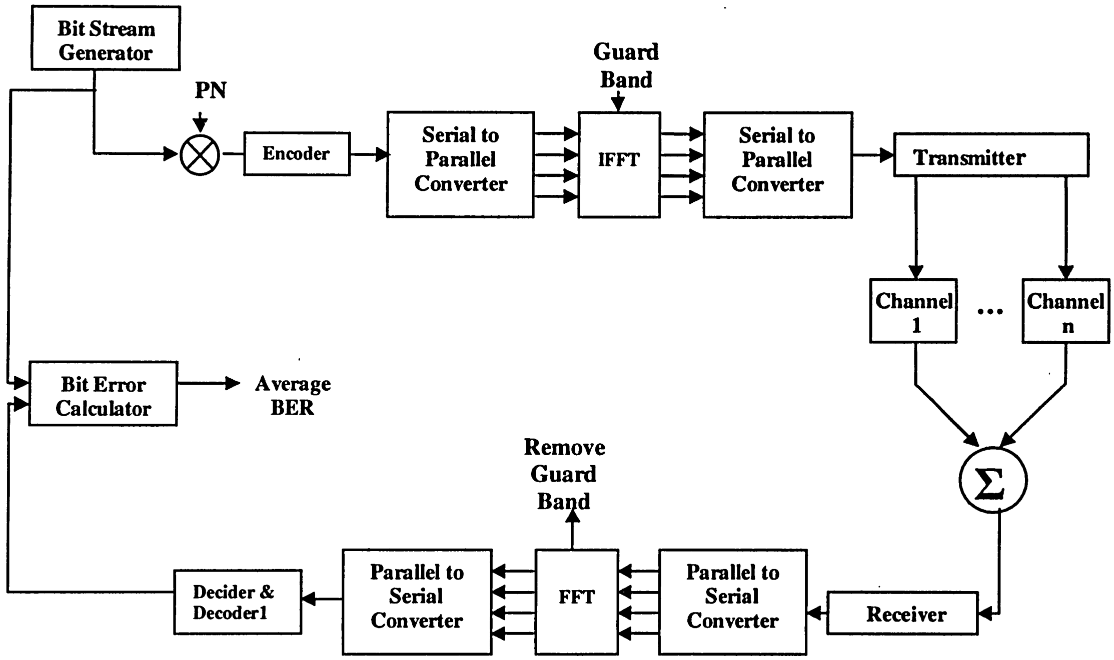


Figure 3-7: Hybrid CDMA / FDMA system model.

3.4 Monte-Carlo Simulation Scheme

Monte-Carlo simulation technique is one of the most popular simulation techniques that is widely used in wireless communication. Figure 3-8 illustrates the Monte-Carlo simulation flow chart that was used in this project.

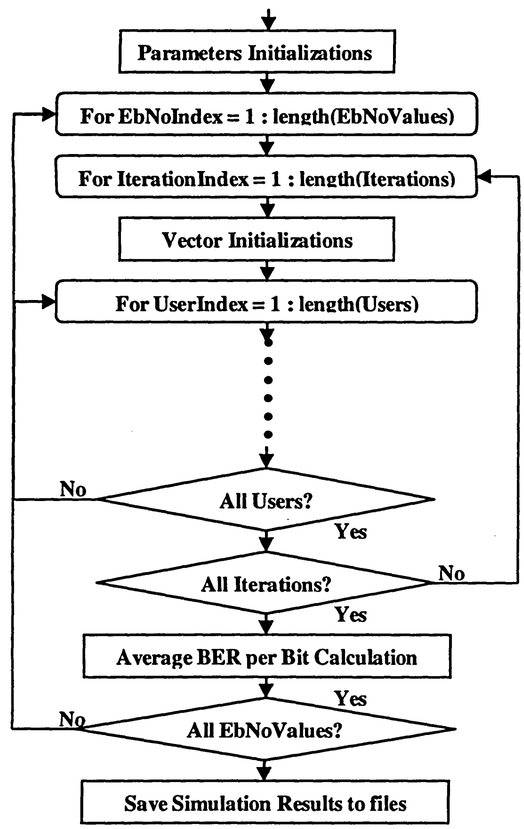


Figure 3-8: Monte-carlo simulation model.

All simulations are run in Matlab 6.5, on Intel PC with 2.40GHz CPU speed, 512 M RAM with maximum virtual memory set to 2000 M.

Chapter 4

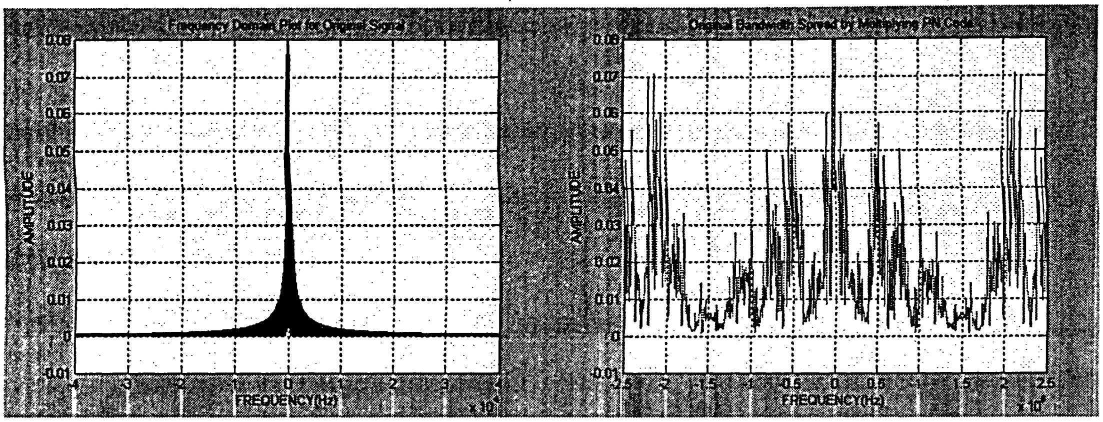
Performance Comparison and Analysis

4.1 System Performance Analysis for Wide-band CDMA in Frequency Domain

To analyze Wide-band CDMA system performance in frequency domain is of significant use in understanding the system's behavior with certain important parameters. To illustrate how Single Carrier Wide-band CDMA system behaves in frequency domain, a series of Fourier Transformed signal plots will be analyzed and compared.

In Figure 4-1 (a), the original 40-bit stream has been transformed into Fourier domain. This original base band signal is spread by a 100-chip PN code, and thus increases the bandwidth of the original signal and spread the power of the original signal over a wider frequency band. As the signal is duplexed into Intra-phase and Quadrature bit streams before the spreading, only one of the streams is needed to be observed during the simulation. The data rate is set to be 100 kbps, and the chip rate is set to be 10 Mbps.

After being multiplied with the PN sequence, the narrow band input signal is spread over a much wider spectrum as shown in Figure 4-1 (b).



(a) Base band signal (b) Base band signal being spread by PN code

Figure 4-1: Signal Spread by High Chip-rate PN code in Single Wide-band CDMA Systems.

Single Carrier modulation brings the base band spread signal to the carrier frequency band. Figure 4-2 shows the carrier with a center frequency of 2.5 MHz and Figure 4-3 (a) illustrates the transmitted signal modulated by this carrier.

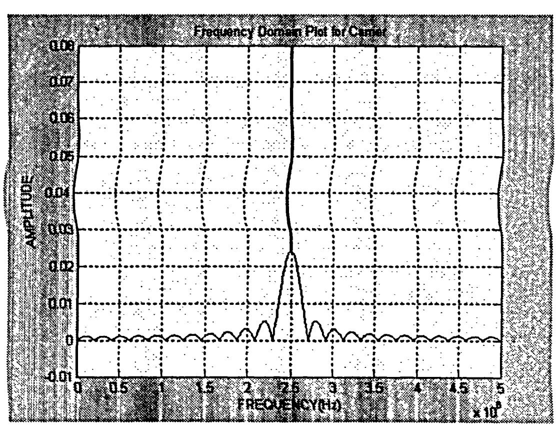
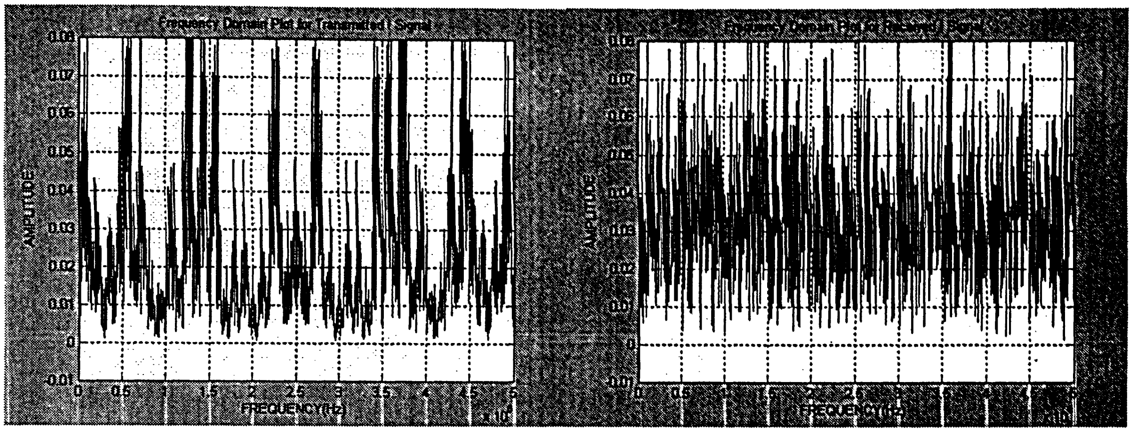


Figure 4-2: Carrier at frequency 2.5 MHz.



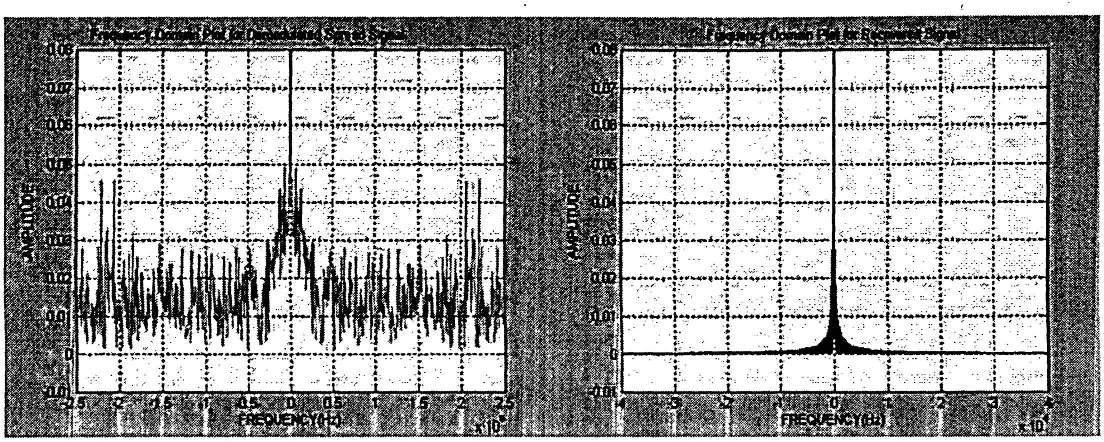
(a) Transmitted modulated signal (b) Received modulated signal

Figure 4-3: Modulated signals at both transmitter and receiver side.

Since the modulated signal is transmitted through an AWGN channel with log(Eb/No) set to 5 dB, the signal received at the receiver has been degraded due to the noise. In order to compare the spectrum from both transmitter and receiver side, the received spectrum magnitude in Figure 4-3 (b) has been reduced to half so that both could be put into the same range. The increased magnitude of received signal is due to the addition of noise power in the channel.

In order to demodulate the signal at receiver side, the pass-band transmitted signal will need to be shifted back to base-band by multiplying the same carrier in time domain and then filtered by a low-pass filter. Demodulated signal is then decoded and dispread to recover the original signal.

Figure 4-4 (a) shows the recovered signal before and after the dispreading and Figure 4-4(b) gives a zoom-in view of the recovered signal. In this run of simulation, no bit error is detected.



(a) Demodulated Signal (b) Recovered signal

Figure 4-4: The original signal is recovered.

4.2 BER Performance Comparison of Three Systems based on Three Channel Types

As mentioned in Chapter 3, three types of channels were considered with different channel conditions while comparing the system performance of the three CDMA systems that are in discussion. The three typical channel types are described as AWGN, LOS AWGN and Two-way Rayleigh Fading Model.

The simulation is carried out by using 6400-bit long bit stream for AWGN channel, and 4000-bit long for the latter two channel types, 10 iterations for each Eb/No index, and the Eb/No ranges from 0dB to 8dB with a 0.5dB step size. Only one user is considered. And the three channel types have been introduced in Chapter 3.

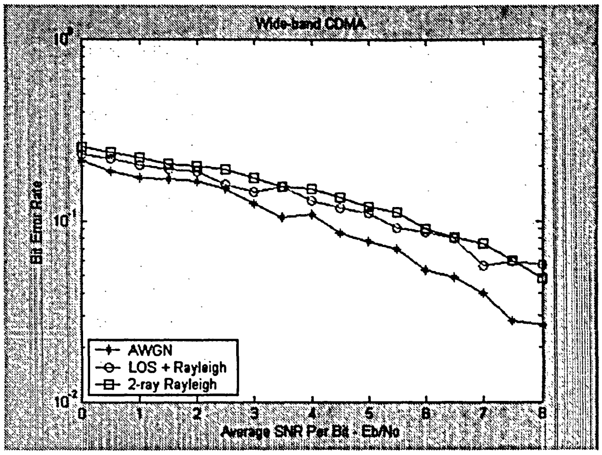


Figure 4-5: BER performance for Single-carrier Wide-band CDMA vs. three types of channels.

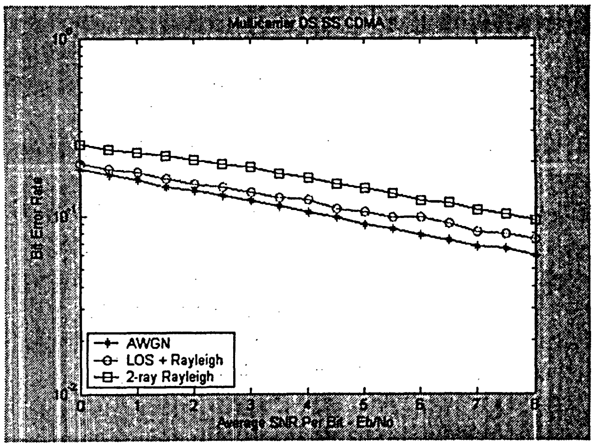


Figure 4-6 : BER performance for Multi-carrier DS SS CDMA vs. three types of channels.

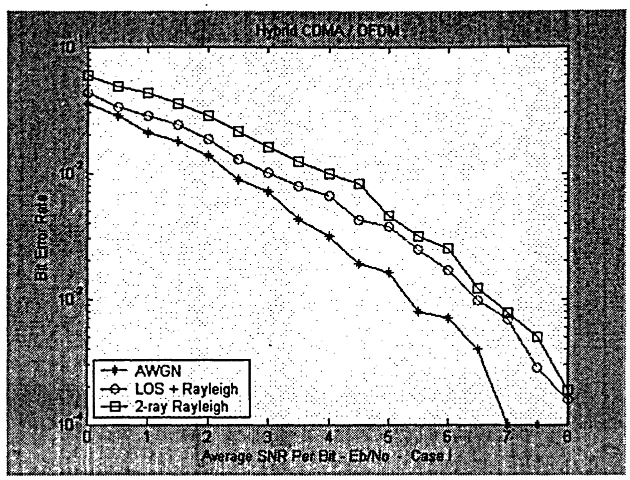


Figure 4-7: BER performance for Hybrid CDMA / OFDM vs. three types of channels.

As expected, the three channels impact the BER performance differently. Two-way Rayleigh fading channel causes multi-path fading plus Guassian white noise so that deteriorates the signal propagation most. And the simulations show that the BER output for all three models performs worst on this channel type. Line of Sight AWGN plus Rayleigh fading comes to the second, and AWGN only channel provides best BER performance of all three models.

Simulations on Multi-carrier DS SS CDMA shows a rather high BER and this implies that possible inter carrier interference existed even though the carriers were chosen to be orthogonal. The reason could be improperly matched bandwidth and carrier frequencies that actually caused bandwidth overlapping.

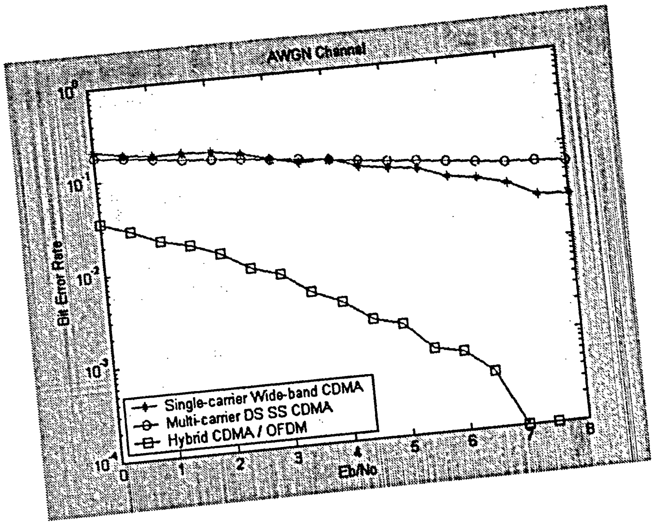


Figure 4-8: BER performance comparison for AWGN channel.

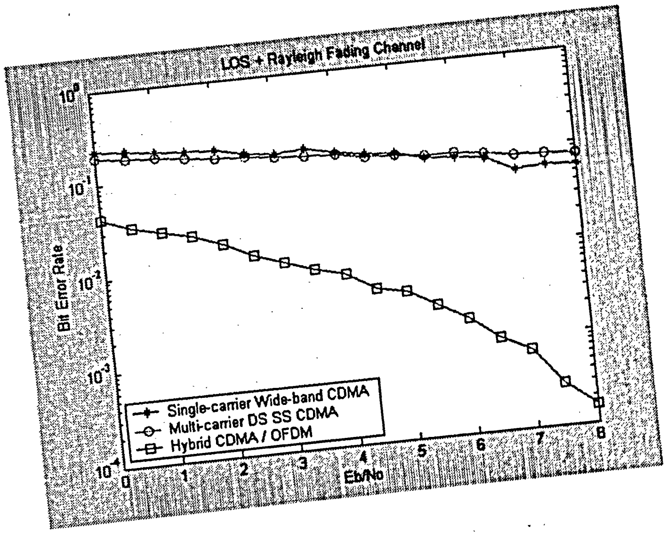


Figure 4-9: BER performance comparison for LOS + Rayleigh fading channel.

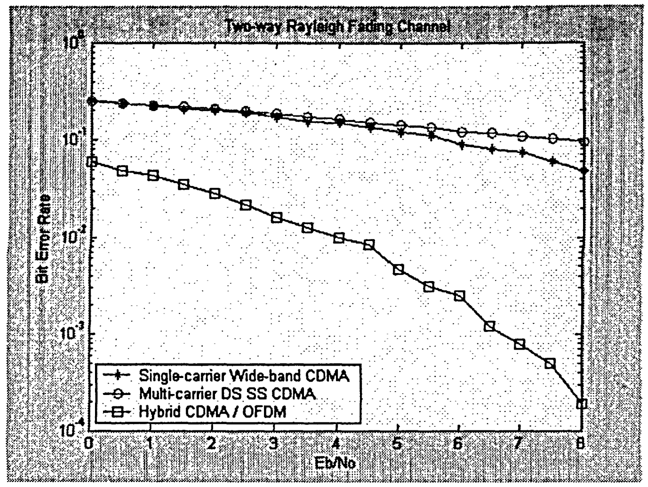


Figure 4-10: BER performance comparison for two-way Rayleigh fading channel.

Hybrid CDMA / OFDM shows the best performance among the three systems. It uses four orthogonal low-frequency carriers to transmit the 100-chip encoded signal and could keep BER well below 0.1. Multi-carrier DS SS CDMA could only have better performance than Single-carrier when all four sub-carriers are orthogonal low-frequency. However, due to a difficulty in finding four ideal orthogonal low-frequency carriers, there is in fact a mix of medium high-frequency and low-frequency carriers in the simulation. Therefore it performs no better then Single-carrier Wide-band. Single-carrier Wide-band CDMA is getting a BER below 0.2 in this simulation.

4.3 BER Performance vs. Orthogonality of PN Code

As we know, orthogonality between two signals can be judged by their inner product. If the inner product equals to zero, then they can be defined as having 100% orthogonal. In the implementation of a CDMA system, it is significant to know whether the randomly generated PN codes of two users are orthogonal or not since orthogonality is critical in evaluating the multi-user interference [2]. In the example below (Table 4-1), an easy way to calculate the orthogonality of two binary bit streams is illustrated.

Two identical 20-bit long PN codes (Table 4-1. (a)) has 20 matching bits and zero non-matching bits. The difference in number of matching and non-matching bits is significant. Under such circumstances, we say the two PN codes are non-orthogonal, which could be easily proved by this special example. Any signal or bit stream correlated to itself, in another word, is non-orthogonal to itself.

PN1	1	0	1	1	0	0	0	1	1	0	1	0	1	0	1	1	0	1	0	1
PN2	1	0	1	1	0	0	0	1	1	0	1	0	1	0	1	1	0	1	0	1
	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+

Matching bits: 20 Non-matching bits: 0 20 >> 0

(a) Two identical PN codes are not orthogonal at all.

PN1	0	1	0	1	0	1	0	1	0	1	1	1	1	0	0	1	1	1	1	1
PN2	1	0	1	1	0	0	0	1	1	0	1	0	1	0	1	1	0	1	0	1
	-	-	-	+	+	-	+	+	-	-	+	-	+	+	-	+	-	+	-	+

Matching bits: 10 Non-matching bits: 10 10 = 10

(b) Two PN codes having same amount of matching bits and non-matching bits are orthogonal.

Table 4-1: The calculation of orthogonality of two bit streams.

In Table 4-1 (b), two randomly generated 20-bit long PN codes (in form of bit streams) are given for a calculation of orthogonality between them. The number of matching bits is equal to the number of non-matching bits (10 for each), therefore they are orthogonal.

In most cases, two randomly generated PN codes could have unequal number of matching and non-matching bits and none of them is zero. We can only say they are not 100% orthogonal or non-orthogonal. But by comparing how close the numbers of matching and non-matching bits are, we could loosely tell how orthogonal the two signals are. The closer the numbers of matching and non-matching bits are, the more orthogonal the two signals are.

Suppose we only have two users in a CDMA system, each of whom has one unique PN code. In order to show the impact that directly caused by orthogonality of PN codes on the performance of CDMA system, two scenarios are chosen in the experiment. In scenario one, the two PN codes are randomly selected, thus orthogonality is not guarantied. While in scenario two, the two PN codes are 100% orthogonal.

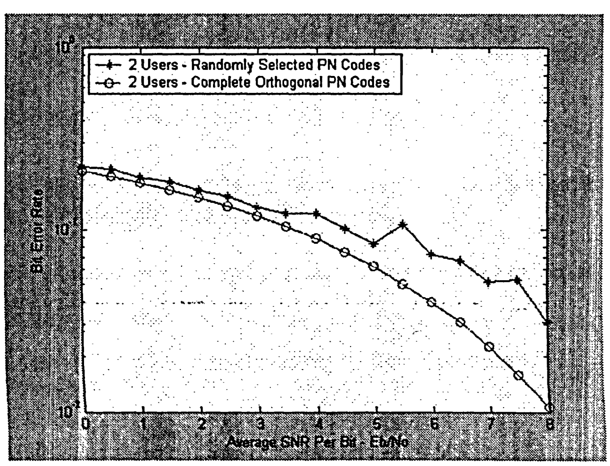


Figure 4-11: Comparison of the BER performance based on PN orthogonality.

Observed from Figure 4-8, 100% orthogonal PN codes definitely bring the best performance of the system since it significantly reduces the multi-acess interference.

4.4 BER Performance vs. Length of PN Code

As aforementioned, length of PN codes is one of the determined factors in differentiating Wide-band CDMA from Narrow-band CDMA. However, considering that the chip rate is fixed, could the length of PN codes influence the system performance? Would the system behave better with longer PN codes or vice versa? To answer this question, a simulation in both Narrow-band CDMA and Wide-band CDMA system is carried out by selecting three almost evenly spaced code length, 6, 64 and 128. 4000 bits used for each of the 10 iteration. And only one user is considered.

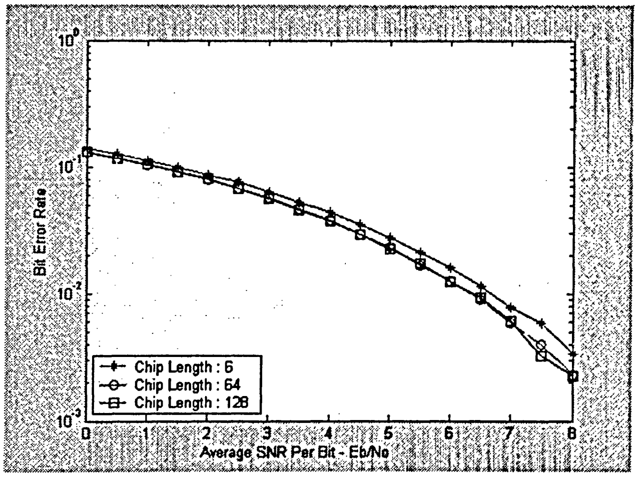


Figure 4-9: PN code length influence system performance nonlinearly.

As shown in Figure 4-9, while the code length is rather small, the system under performs than when the code length is largely increased without considering multi-user interference. However, while the code length increases to certain level, such as 64 in this experiment, the BER would not obviously decreases.

4.5 BER Performance vs. Multi-user Interference

Multi-user interference is also a very important aspect while considering system design or improvement. Generally speaking, as the number of users in the system increases, the interference caused by other users increases. And this would lead to a decrease in average SNR per bit, and in turn lead to coverage shrinkage.

In this project, a multi-user environment in CDMA system is simulated. Different numbers of interfering users (1 to 4) with even interfering power are used as simulation parameters. And the relationship between numbers of interfering users and the system performance in terms of Eb/No is analyzed.

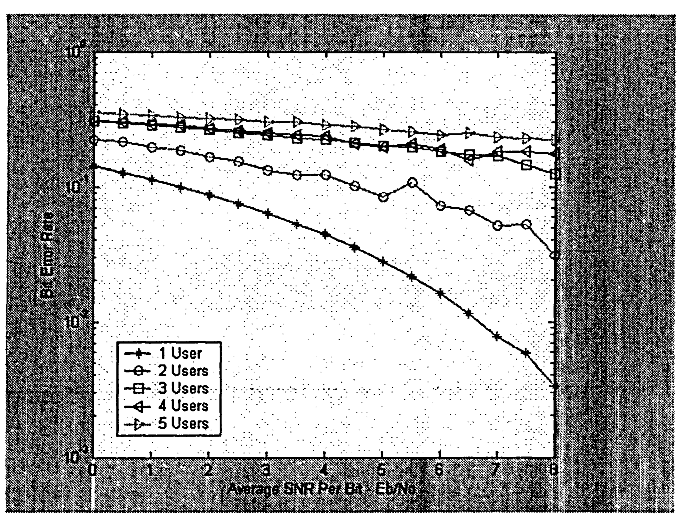


Figure 4-10: BER performance with number of interfering users.

This is a base-band simulation based on Wide-band CDMA. Each interfering user has the same power as the main user. It resembles the near-far phenomena that the interfering power is the same as or even stronger than the sender's signal power. Once this situation is formed, the system performance would decrease very fast. When we observe the fifth user's BER in Figure 4-10, its BER already goes above 0.3.

Chapter 5

Summary & Conclusions

5.1 Summary

In the earlier part of this project, both single-carrier (Narrow-band and Wide-band CDMA) and multi-carrier CDMA models (Multi-carrier DS SS CDMA and Hybrid CDMA / OFDM) are developed from a Matlab-based basic wireless communication model. The structures of these models are designed to embody the characteristics of the type. Numerous runs of testing simulations are taken during the development in order to rectify the behavior of the systems.

Simulations focused on spectrum behavior, channel types, orthogonality of PN codes, length of PN codes, multi-user interference and number of sub-carriers are analyzed. Simulations results are plotted to visually display the properties of the result data and to be compared and analyzed upon. System performance is studied and compared through the simulations via the analysis of the system behavior under different parameter settings.

5.2 Conclusions

Spectrum of the original narrow-band signal could be spread by multiplying with a higher frequency-band pseudo-noise code. This leads to the fact that the power of the original signal is then spread over a much wider bandwidth. The interference between multiple users in frequency domain is then broken into small-scale pieces. As long as the PN codes are chosen properly, the multiple access interference (MAI) could be largely reduced and therefore benefit the goal of multiple access in wireless communication. Finally, it enables more users to occupy the same wide band spectrum and at the same time keeps the user interference minimum.

Three channels, AWGN, LOS AWGN and Two-way Raleigh Fading, are used to test the system performance (in terms of Bit Error Rate) by tuning the power gain. Two-way Raleigh Fading channel brings the propagation multi-fading effect into account and deteriorates the transmitted signal most. According to the simulation results, Multi-carrier DS SS CDMA system has similar system performance as Single-carrier Wide-band system while its carrier frequencies are a mix of low-frequencies and high-frequencies. While Hybrid CDMA / OFDM combats interference much better than the other two do. It outweighs Single-carrier Wide-band CDMA by using low frequency carriers to avoid inter symbol interference that normally becomes worse in high-speed communication, and at the same time preserves wide-band. It outweighs Multi-carrier DS SS CDMA by significantly reducing system complexity and thus makes it more scalable than the former.

In CDMA systems, orthogonality of PN code is always one of the critical factors that decides the severity level of interference that caused by other users. The simulation results quantitatively show that the more orthogonal the PN codes are, the less the multi access interference, the better the system performs.

Code length with the fixed chip rate influences the system performance nonlinearly. The simulation shows when the chip rate and other parameters are defined, increasing PN code length will non-linearly improve the system performance.

Multi-user interference is simulated on Wide-band CDMA model, and the inclination for the system capacity to decrease when the interfering users are increasing is prominent. Especially when the interfering user is at least evenly strong in power, the capacity of the CDMA system reaches its limit fast.

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