PERFORMANCE ANALYSIS OF A MC DS CDMA WIRELESS COMMUNICATION SYSTEM IN PRESENCE OF TIMING JITTER OVER RAYLEIGH FADING CHANNEL

By

Md. Ishtiaque Aziz Zahed

Student No: 0411062249P

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2015

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Date: 22 August, 2015
Dedication

To the martyrs of the Liberation War, 1971
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<td>3G</td>
<td>Third Generation of Wireless Communication Systems</td>
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<td>4G</td>
<td>Fourth Generation of Wireless Communication Systems</td>
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<tr>
<td>AWGN</td>
<td>Additive White Gaussian Noise</td>
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<td>BER</td>
<td>Bit Error Rate</td>
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<td>bps</td>
<td>Bits per second</td>
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<td>BPSK</td>
<td>Binary Phase Shift Keying</td>
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<td>BS</td>
<td>Base Station</td>
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<td>CDMA</td>
<td>Code Division Multiple Access</td>
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<tr>
<td>cdf</td>
<td>Cumulative Distribution Function</td>
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<tr>
<td>CFO</td>
<td>Carrier Frequency Offset</td>
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<td>CNR</td>
<td>Carrier to Noise ratio</td>
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<td>DAB</td>
<td>Digital Audio Broadcasting</td>
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<td>DFT</td>
<td>Discrete Fourier Transform</td>
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<td>DS CDMA</td>
<td>Direct Sequence Code Division Multiple Access</td>
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<td>DSL</td>
<td>Digital Subscriber Line</td>
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<td>DSSS</td>
<td>Direct Sequence Spread Spectrum</td>
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<td>DVB-T</td>
<td>Digital Video Broadcasting-Terrestrial</td>
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<td>EGC</td>
<td>Equal Gain Combining</td>
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<td>FDM</td>
<td>Frequency Division Multiplexing</td>
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<td>FDMA</td>
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<td>Fast Frequency Hopping Spread Spectrum</td>
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<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
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<td>FHSS</td>
<td>Frequency Hopping Spread Spectrum</td>
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<td>ICI</td>
<td>Inter Carrier Interference.</td>
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<tr>
<td>IDFT</td>
<td>Inverse Discrete Fourier Transform</td>
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<td>ISI</td>
<td>Inter Symbol Interference</td>
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<td>MAI</td>
<td>Multiple Access Interference</td>
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<td>Abbreviation</td>
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<td>MC DS CDMA</td>
<td>Multi Carrier Direct Sequence Code Division Multiple Access</td>
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<td>MRC</td>
<td>Maximal Ratio Combining</td>
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<td>MS</td>
<td>Mobile Subscriber</td>
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<td>MT DS CDMA</td>
<td>Multi Tone Direct Sequence Code Division Multiple Access</td>
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<td>OFDM</td>
<td>Orthogonal Frequency-Division Multiplexing</td>
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<td>PCS</td>
<td>Personal Communication Services</td>
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<td>pdf</td>
<td>Probability Density Function</td>
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<td>PN</td>
<td>Pseudo Noise</td>
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<td>QPSK</td>
<td>Quadrature Phase Shift Keying</td>
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<td>RF</td>
<td>Radio Frequency</td>
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<td>SFHSS</td>
<td>Slow Frequency Hopping Spread Spectrum</td>
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<td>SNIR</td>
<td>Signal-to-Noise plus Interference ratio</td>
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<td>SNR</td>
<td>Signal to Noise Ratio</td>
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<td>Spread Spectrum</td>
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<td>TDMA</td>
<td>Time Division Multiple Access</td>
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<td>WLANs</td>
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ABSTRACT

Multi carrier direct sequence code division multiple access (MC DS CDMA) technique, which is a combination of orthogonal frequency division multiplexing (OFDM) and code division multiple access (CDMA) has been considered as an important technique for the future generation wireless communication systems due to its bandwidth efficiency, frequency diversity and immunity to channel dispersion. OFDM has already been employed in many areas, such as digital audio and video broadcasting, wireless local/metropolitan area networks and asynchronous digital subscriber lines (ADSL). Leveraging the multiple access capability of CDMA, the MC DS CDMA technique is an important enhancement to OFDM.

Nevertheless, a major drawback of the MC DS CDMA system is the high sensitivity to timing errors between transmitter and receiver due to the use of a large number of carriers and the superposition of signals and multiple users. In this thesis, the expression of the signal power, multiple access interference (MAI) power in presence of timing jitter over a Rayleigh fading channel for MC DS CDMA wireless system is formulated which is used to determine the signal to interference noise ratio (SINR), average bit error rate (BER) and power penalty at the output with and without Rake Receiver. The average bit error rate (BER) is determined in terms of different system parameters and optimum system design parameters are evaluated for a given timing jitter variance. The analytical approach is further carried out for a MC OFDM DS CDMA system considering a Rake Receiver. The analysis is developed to find the probability density function (pdf) at the output of maximal ratio combining (MRC) receiver combiner considering combined influence of fading and timing jitter. The performance results are evaluated numerically in terms of BER and required power penalty considering system parameters like number of users, number of sub-carriers. The result shows significant deterioration in performance parameters due to fading. For a given power penalty at a fixed BER, how the allowable jitter variance is influenced by the number of users has also been represented. Moreover, numerical results show that the inclusion of Rake Receiver combats the limitations imposed by timing jitter by reducing the BER and power penalty.
Chapter -1

Introduction

1.1 Introduction to Wireless Communication:

Universal communications continues to be the goal of telecommunications companies worldwide. In order to provide ubiquitous coverage, service providers must eliminate the wire lines that keep users tethered to a stationary network. Wireless communication is the solution to eliminate fixed physical media for communications. Advances in semiconductor devices which began following World War II have motivated the development of wireless communications equipment. Of the varied forms of wireless communications, cellular radio and personal communication services (PCS) have been growing at high rates over the past few years. This rapid growth has increased demand for wireless services that will integrate seamlessly with existing backbone networks and allow future service expansion.

1.2 Multiple Access Techniques:

In communication systems, there are three types of multiple access techniques namely Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA) and Code Division Multiple Access (CDMA). TDMA and FDMA are techniques that use time and frequency slots to share system resources, while CDMA uses orthogonal code sequences to share resources in both frequency and time [1].

In the following sections these three techniques will be reviewed and the need for MC DS CDMA system will be discussed.
1.2.1 Frequency Division Multiple Access (FDMA):

Frequency division multiple access was the first multiple access technique, developed in the early 1900s [2]. With FDMA, the total frequency bandwidth is divided into frequency channels that are assigned to each user permanently, resulting in multiple user signals that are both spectrally separated and simultaneously transmitted and received. This has been graphically represented in Fig. 1.1.

![FDMA Diagram](image)

Fig: 1.1 Frequency Division Multiple Access (FDMA) [1]

The FDMA system requires a relatively simple algorithm and implementation compared to TDMA and CDMA [1], but there are several drawbacks. Firstly, due to the permanent assignment of FDMA channels, unused channels cannot be utilized by other users, resulting in wasted communication resources. Secondly, nonlinearities in the power amplifier can cause signal spreading in the frequency domain, causing inter-channel interference (ICI) in other FDMA channels. Finally the capacity of an FDMA system is limited by the number of channels available.
1.2.2 Time Division Multiple Access (TDMA):

Time division multiple access (TDMA) has been developed with a similar concept of FDMA, but with TDMA, multiple user signals are separated in the time domain rather than in the frequency domain. Fig. 1.2 shows a TDMA system with the transmission time divided into a number of cyclically repeating time slots that can be assigned to individual users, allowing all users access to all of the available bandwidth.

![Fig: 1.2 Time Division Multiple Access (TDMA) [1]](image)

Compared to FDMA systems, TDMA systems offer more flexibility in the assignment of time slots whereby different numbers of time slots can be allocated to different users depending on the service demanded. Furthermore, because TDMA users can transmit signals only in their own time slots, the transmission of TDMA signal is non continuous and occurs in bursts, resulting in less battery power consumption. However, the TDMA signal requires a large synchronization overhead due to its non-continuous transmission. Inter symbol interference (ISI), caused by multipath propagation, is a major problem for TDMA, especially during high data rate transmissions.
1.2.3 Code Division Multiple Access (CDMA):

Over the last decade, code division multiple access (CDMA) has been developed to overcome the limitations of other multiple techniques such as: FDMA and TDMA.

Fig. 1.3 demonstrates multiple CDMA users signals that are separated by spreading sequences. In particular, each user signal is spread using a pseudo random sequence which is orthogonal to the sequence of other users. As a result, only the intended user receiver can de-spread and receive the information correctly; other users on the system perceive the signal as noise, resulting in multiple user signals that can be transmitted within the same bandwidth simultaneously.

The main advantage with CDMA is that the system capacity is limited only by the amount of interference; with a lower level of interference the system can support more users [1]. CDMA systems are also robust to narrow band jamming as the receiver signal can spread the jamming signals energy over the entire bandwidth making it insignificant in comparison to the signal itself [2]. If the spreading sequence is perfectly orthogonal, it is possible to transmit multiple CDMA signals without introducing multiple access interference (MAI) during synchronous transmission.
Various types of CDMA such as direct-sequence CDMA (DS CDMA) and wideband CDMA (WCDMA) have been developed and utilized in both 2G and 3G systems. These techniques are considered to be single carrier CDMA systems. Unfortunately when moving into the fourth generation of wireless communication systems (4G), in which data is transmitted at a rate as high as 1 Giga bits-per-second (bps) [3], single carrier CDMA systems are not suitable. This is because,

- With high data rates the symbol duration will become shortened, resulting in the channel delay spread exceeding the symbol duration causing ISI [4].

- When data rate goes beyond a hundred Mega bps, it becomes difficult to synchronize, as the data is sequenced at high speeds [5].

- Due to multipath propagation, signal energy is scattered in the time domain: in single carrier CDMA systems such as DS CDMA, Rake receivers are often used to combine the multipath signals. However, not all paths of signals can be successfully received. If the numbers of fingers in the Rake receiver is less than the number of resolvable paths, some of the received signal energy cannot be combined, thus a portion of the signal energy is lost [6]. But, if the number of fingers in the Rake receiver is more than the number of resolvable paths, noise will be enhanced.

Therefore a conventional single carrier CDMA such as DS CDMA is not practical for 4G systems where a high data rate is required.

1.3 Spread Spectrum Technique

The term spread spectrum (SS) has been used in a wide variety of military and commercial communication systems. It was first developed by military due to the use of wideband signals which are difficult to detect. In recent years, SS has become increasingly popular for commercial applications, especially in local area wireless networks.
Spread spectrum is a signal structuring technique that each signal to be transmitted requires significantly more RF bandwidth than a conventional modulated signal would require. In SS system, a sequential noise-like signal structure is used to spread normal narrowband information signal over a large bandwidth in frequency domain and receiver correlates received signals to retrieve the original information signal. That is to say, the information signal is spread as wide bandwidth as possible and as close to the background noise as possible in SS system. This makes SS communication very difficult to find the frequency spectrum and cannot be easily tracked and more difficult to jam [7]. Spread spectrum communication techniques are very promising for future generation wireless communication system [8, 9].

There are two different types of spread spectrum techniques that have been extensively used. These are direct sequence spread spectrum (DSSS) and frequency hopping spread spectrum (FHSS).

### 1.3.1 Direct Sequence Spread Spectrum (DSSS)

![Fig: 1.4 Direct Sequence Spread Spectrum (DSSS) block diagram [1]](image)

Direct sequence is one of the most popular types of spread spectrum techniques. In this method, spreading signal which is a high speed pseudo-noise (PN) code sequence created by a pseudo-random code generator is directly multiplied with narrow-band PSK modulated signal. Thus, desired transmission radio frequency (RF) bandwidth can be set directly by the spreading signal.
1.3.2 Frequency Hopping Spread Spectrum (FHSS)

Frequency hopping is another type of spread spectrum technique which has an implementation concept similar to that of DSSS technique. In this method, spreading occurs by hopping frequency synthesizer to one of many available frequencies over a wide band according to a hopping table defined by the PN sequence generator. If the hopping rate, which is chip rate, is higher than the bit rate, then it is called fast frequency hopping spread spectrum (FFHSS). If the hopping rate is lower than the data rate, there are several or many bits per frequency hop, and then it is called slow frequency hopping spread spectrum (SFHSS).

1.3.3 Multi Carrier Code Division Multiple Access Systems:

A number of CDMA systems based on the combination of CDMA and OFDM technique, which are referred as multi carrier CDMA systems, have received a lot of attention in the field of wireless communications due to their effectiveness in combating the effects of multipath fading channels and various kinds of interference in high speed data transmission by spreading signals over several carriers. Among these systems, the signal can be efficiently modulated and demodulated using Fast Fourier Transform (FFT) device without substantially increasing the transmitter and receiver’s complexity and these systems also exhibit the attractive features of high spectral efficiency and frequency diversity [10]. Multiple Access Schemes based on a combination of CDMA and OFDM technique can be classified as three types: multi carrier
CDMA (MC CDMA), multi carrier DS CDMA (MC DS CDMA) and multi tone DS CDMA (MT DS CDMA).

1.4 Review of Previous Works

In telecommunication systems, communication resources refer to the time and frequency bandwidth that is available in a given system. With multiple users on a system, resources (time/bandwidth) need to be shared among the users in order to establish communication links between mobile subscriber (MS) and the base station (BS). However the available resources are often limited for any given user, as the total bandwidth on a system is restricted. In order to improve the efficiency of resource allocations, multiple access techniques have been developed, with an ideal system illustrating the following qualities [2]: 1) available resources are fully utilized; 2) all resources are shared equally among users; 3) Interference is not introduced between users i.e. no multiple access interference (MAI), and 4) the capacity of the system is maximized.

But in spread spectrum techniques correlation properties of code sequence allows the bit error rate performance to be varied; as it determines the amount of interference from multiple accesses known as Multiple Access Interference (MAI) [11]. MAI caused by non zero cross-correlation between different spreading sequences is the major type of interference limiting the CDMA system capacity. Since the cross-correlation properties of most sets of spreading codes are either too complex to analyze or very difficult to compute when different transmissions are not synchronized, a random sequence model is usually assumed [12]. In the case of moderate to large processing gains, Gaussian distribution with variable variance is a good approximation for the MAI distribution [13]. Unfortunately, mobile radio links are subject to severe multipath fading due to the combination of randomly delayed reflected, scattered and diffracted signal components which leads to serious degradation in the link carrier-to-noise ratio (CNR), resulting in either a higher BER or a higher required transmit power for a given multilevel modulation technique due to interferences.
1.4.1 Orthogonal Frequency Division Multiplexing (OFDM):

Frequency division multiplexing (FDM) is a technology that transmits multiple signals simultaneously over a single transmission path. In frequency division multiple access (FDMA) each user is typically allocated a single channel that is used to transmit all the user information, each signal travels within its own unique frequency range (carrier), which is modulated by the data.

OFDM is a transmission technique based on the idea of FDM. In OFDM the transmitter transmits a single data stream over a number of lower rate orthogonal sub-carriers coupled with the use of advanced modulation techniques on each component, resulting in a signal with high resistance to interference. OFDM can be simply defined as multi carrier modulation where its carrier spacing is carefully selected so that each sub carrier is orthogonal to the other sub-carrier [14]. One main reason to use OFDM is to increase the robustness against frequency selective fading or narrowband interference. In a single carrier system, a single fade or interference can cause the entire link to fail, but in a multi carrier system only a small percentage of the sub-carriers will be affected.

Then error correction coding can be used to correct for the few erroneous sub-carriers. In a classical parallel data system, the total signal frequency band is divided into non overlapping frequency sub-channels. Each sub-channel is modulated with a separate symbol and then the sub-channels are frequency multiplexed. It seems good to avoid spectral overlap of channels and eliminate inter-channel interference (ICI). However, this leads to inefficient use of the available spectrum. To cope with the inefficiency, the ideas proposed from the mid 1960-s were to use parallel data and FDM with overlapping sub-channels to avoid the use of high speed equalization and to combat impulsive noise, and multi-path distortion as well as to fully use the available bandwidth [15].

Fig. 1.6 illustrates the difference between the conventional FDM multi-carrier modulation technique and the OFDM multi-carrier modulation technique. Over 50% of bandwidth can be saved by using OFDM multi carrier modulation technique.
However, crosstalk between sub-carriers needs to be reduced in OFDM technique, which means orthogonality between the different modulated carriers is necessary.
Fig. 1.7 (a) shows the spectrum of an OFDM sub-channel and Fig. 1.7 (b) presents the spectrum of the OFDM signal. From Fig. 1.7, it can be seen that at the central frequency of each sub-channel, there are no crosstalk from other channels. Therefore, if DFT is used at the receiver and correlation values are calculated with the center of frequency of each sub-carrier, then the transmitted data could be recovered with no crosstalk [13].

OFDM transmits a large number of narrowband sub-carriers, closely spaced in the frequency domain. In order to avoid a large number of modulators and filters at the transmitter and complementary filters and demodulators at the receiver, it is desirable to be able to use modern digital signal processing techniques.

On the other hand, Orthogonal Frequency-Division Multiplexing (OFDM) is effective to avoid inter symbol interference (ISI) due to multipath delay. Being very efficient in combating multipath fading as well as Inter Symbol Interference (ISI) and in the use of available bandwidth, OFDM has been widely adopted and implemented in wired and wireless communications, such as Digital Subscriber Line (DSL), European Digital Audio Broadcasting (DAB), Digital Video Broadcasting-Terrestrial (DVB-T) and its handheld version DVB-H, and IEEE 802.11a/g standards for Wireless Local Area Networks (WLANs) [17, 18] etc.

The key advantages of OFDM transmission system are –

- OFDM is an efficient way to deal with multipath. The overall signal spectrum is divided into narrow band flat fading sub-channels. As a result, channel equalization is accomplished through a simple bank of complex-valued multipliers, thereby avoiding the need for computationally demanding time domain equalizers.

- OFDM significantly enhances the capability of interference suppression through the use of cyclic prefix.

- OFDM is robust against frequency selective fading and narrowband interference, because such interference affects only a small percentage of the sub-carriers.
• OFDM has higher spectral efficiency. More than 50% of the Bandwidth can be saved compared with FDM due to overlapping sub-carriers in the frequency domain.

• OFDM makes digital implementation simple by using DFT/IDFT operations.

• OFDM provides an opportunity of selecting the most appropriate coding and modulation scheme on each individual sub-carrier according to the measured channel quality. In practice higher order constellations are normally used on less attenuated sub-carriers in order to increase the data throughput, while robust low order modulations are employed over sub-carriers characterized by low SNR values.

On the other hand, OFDM suffers from the following drawbacks compared with single carrier modulations –

• OFDM is more sensitive to frequency synchronization errors and phase noise.

• OFDM has a relatively large peak to average power ratio, which tends to reduce the power efficiency of the RF amplifier.

• OFDM has an inherent loss in spectral efficiency related to the use of the cyclic prefix.

1.4.2 MC CDMA

The MC CDMA transmitter spreads the original serial data stream in the frequency domain. In this scheme, it does not include serial to parallel data conversion and no spreading modulation is implemented on each sub-carrier. Therefore, the data rate on each of the sub-carriers is the same as the input data rate and the fading effects of multipath channels can be mitigated by spreading each data bit across all of the sub-carriers [19].

In the MC CDMA receiver the fading impaired signals of the sub-carrier from diverse users are first equalized and then separated according to their different spreading codes. The received
signal is also combined in the frequency domain. Therefore, the receiver can always make use of all the received signal energy scattered in the frequency domain. This is the main advantage of the MC CDMA scheme over other schemes [19]. However, in a frequency selective fading channel different sub-carriers may encounter different amplitude attenuations and phase shifts, which can consequently result in distortion of the orthogonality of the sub-carriers.

This MC CDMA scheme can be applied in multiple access system which allocates different spreading code for each user, and then the spreading codes can provide separation for different users. In addition, in MC CDMA scheme the number of sub-carrier does not have to be the same as the processing gain. If the original symbol rate is high, the signal suffers frequency selective fading. Then the signal needs to be serial-to-parallel converted, mapping the data to a number of reduced rate streams before spreading over the frequency domain [10].

1.4.3 MC DS CDMA

Among various spread spectrum techniques direct sequence code division multiple access (DS – CDMA) has shown very good performance over wireless faded channels [20]. In the Multi-Carrier CDMA system [21], the high rate data stream is divided into several low rate data sub-streams, each sub-stream modulates a different subcarrier and is spread over the whole bandwidth before transmitting the data stream.

MC DS CDMA has a very unique feature to combat difference interference effects by employing rake receiver by means of path diversity scheme. The rake receiver is a rake of correlation receivers which assigns different multipath components at different finger and applies code for desired user matched to exact delay of each multipath channel [22]. Each correlator is represented by three coefficients: time delay, phase shift and attenuation. It independently decodes a single multipath component. Then the contributions of all fingers are combined with the correct delays in order to make the most use of the different transmission characteristics of each transmission path. This provides higher Signal to Noise Ratio (SNR) in a multipath environment than in a clean environment which ultimately leads to a better system performance [23]. In addition, to consider the issue of multipath propagation in a wireless channel
environment, which causes severe degradation in the performance can be overcome with the help of different diversity schemes: maximal ratio combining (MRC), equal gain combining and selection diversity [24 -26].

In the previous investigations the probability distribution and the random timing error were not considered rather a fixed value of timing jitter was taken in evaluating the SNR and simulated BER [27]. It is also very important to investigate the BER performance of a MC DS CDMA system considering Rake Receiver to combat the limitations imposed by timing jitter, as previously performance of MC DS CDMA system were investigated without considering the effect of timing jitter [28, 29].

The MC DS CDMA scheme has the following advantages. First, the spreading processing gain is increased compared to the corresponding single-carrier DS CDMA scheme. Second, the effect of multipath interference is mitigated by implementing DS spreading. Finally, frequency/time diversity can be achieved [4].

In addition, each sub-carrier signal is subject to frequency selective fading in the MC DS CDMA scheme system. Consequently, a high complexity Rake receiver can be implemented and forward error control (FEC) techniques can be utilized in order to enhance its associated performance [10].

Introduction of Multicarrier OFDM technique with CDMA makes the system robust to frequency selectivity, helps the system utilizing the advantage of frequency diversity by spreading the signal across multiple subcarriers. As result, MC DS CDMA is a preferred technique used in third generation (3G) mobile wireless communication [30]. Still the performance is highly sensitive to orthogonality among the carriers which is sometimes affected by random timing error at the receiver. Timing errors would occur either when the clock signal is not correctly recovered, or when sampling is not performed at precise sampling instants. Because of the non-ideal nature of the sampling circuit the amplitude of the signal is affected by timing jitter and it introduces additional source of additive noise [31]. Several investigations have been reported on the effect of timing jitter on the signal to noise ratio (SNR) and the simulated bit error rate (BER)
Timing jitter degrades performance of the MC-DS-CDMA system because it destroys orthogonality among subcarriers and results in inter-carrier interference (ICI).

1.4.4 MT DS CDMA

The MT DS CDMA transmitter spreads the serial to parallel converted data streams using a given spreading code in the time domain so that the spectrum of each sub-carrier before spreading operation can satisfy the orthogonality condition with the minimum frequency separation [10]. Therefore, the resulting spectrum of each sub-carrier no longer satisfies the orthogonality condition and strong spectral overlap exists among the different sub-carrier signals after DS spreading [19]. In this scheme, the original binary data stream is firstly serial to parallel converted to parallel sub streams and then spectrum spreading occurs in multiplying parallel sub-streams with spreading code. Finally, the MT DS CDMA signal is generated by adding all of the different sub-carriers’ signals.

The receiver consists of Rake combiners and each of receivers has the same structure as the single carrier DS CDMA Rake receiver. Unfortunately, the MT DS CDMA scheme suffers from inter-sub-carrier interference and requires a high complexity Rake based receiver [10]. However, compared to the corresponding single carrier DS CDMA scheme, the capability to use longer spreading codes can reduce the self interference and multiple access interference (MAI) [16]. The MT DS CDMA scheme uses longer spreading codes than the normal single carrier DS CDMA scheme, where the relative code length extension is in proportion to the number of sub-carriers. Therefore, the MT DS CDMA system can accommodate more users [10].
1.5 **Objectives of the thesis:**

The objectives of the thesis with specific aims are:

- To carry out analysis of a MC-DS-CDMA wireless communication system to investigate the effect of timing jitter on the system BER considering the probability distribution of the timing jitter without and with a Rake Receiver, with maximal ratio combiner over Rayleigh fading environment.

- To find the expression of the conditional Bit error rate (BER) conditioned on a single value of timing jitter and the average BER using a Rake receiver with maximal ratio combining.

- To evaluate the BER performance results numerically for several system parameters and jitter variances.

- To determine the power penalty due to timing jitter at a given BER and to determine the optimum system design parameters like optimum number of OFDM carriers, number of Rake Fingers, optimum number of users; etc for a given system data rate and timing jitter variance.

1.6 **Organization of the thesis:**

The remainder of this chapter describes the layout of this thesis, which is organized into four chapters.

Chapter 2 presents the MC DS CDMA system model and the channel fading characteristics. The system model consisting of the transmitter, receiver and channel, is presented with mathematical models. As a channel model for multipath propagation Rayleigh fading has been considered and the receiver section represents both without Rake Receiver and with Rake Receiver systems.
Along with the model it introduces the analytical approach to measure BER performance due to timing jitter in AWGN channel and multipath Rayleigh fading channel. Then, the expressions for variances, Signal-to-Noise plus Interference ratio (SNIR) and probability error rate are derived. Finally, the average BER expressions for the system in presence of timing jitter are formulated.

Chapter 3 covers the results of the numerical analysis. The system performance is presented with respect to several parameters such as number of sub-carriers, timing jitter variances, different fading parameters, different number of users and Rake Receiver properties. All the results are measured in terms of the bit error rate (BER) and the power penalty. The performance improvement is also demonstrated with the implementation of Rake Receiver.

Chapter 4 concludes the thesis and summarizes the results of the work. Areas for future work are also detailed.
Chapter -2

Analysis of a MC DS CDMA System

2.1 System Model

For the analysis the system model is considered to have the following characteristics. The users are active all time and transmit signal power at the same level. Fading for all transmitted signals received by an antenna is assumed equal. As Rayleigh fading channel is considered, the amplitude distortion coefficients are Gaussian distributed while phase shift coefficient is uniformly distributed. The input signal, only having values of +1 and -1 is transmitted using OFDM multicarrier modulation technique over a dispersive Rayleigh fading channel. Maximal ratio combining (MRC) is used to combine all the outputs.

2.1.1 System Model without using Rake Receiver

Fig. 2.1 Block Diagram of MC DS CDMA System Transmitter Model [33]
Fig. 2.2 Block Diagram of MC DS CDMA System Receiver Model [33]

The system model considered for this analysis is shown in Fig. 2.1 and Fig. 2.2 where they represent the block diagrams of MC-DS-CDMA transmitter and receiver respectively.

Let, there are \( N_u \)-number of users and \( l \)-th user is taken as the reference for any period of time. Now, the input data of the \( l \)-th user are converted into \( N_c \) parallel data streams and each of the these parallel sequences is multiplied by the PN code sequence \( c^l \) and thereby spread in the time domain. Thus each data bit is split in time domain and then is modulated by the respective sub-carrier. To write the general expression of the sub-carriers, let us consider; \( \omega_c \) is the Frequency of the reference channel, \( \omega_k = \omega_c + (k - 1)\Delta\omega_c \) is the angular frequency of the \( k \)-th subcarrier, \( \Delta\omega_c \) is the Frequency spacing between two successive channels and \( \phi_k \) is Instantaneous phase angle of the \( k \)-th sub-carrier.
2.1.2 System Model with Rake Receiver

In Fig. 2.3, the receiver model is given.

Fig. 2.3 Receiver Model with Multiple Receiving Antenna [34]

In Fig. 2.3, the receiver model is given. For this system, we assume an array of several receiving antenna applying space diversity. Each of the antennas is so placed that the received signal undergoes independent fading. All the antennas are equipped with RAKE structure (Spread S
Receiver) so that a time-diversity reception becomes possible resulting a lucid improvement in BER performance. And last of all, the outputs of the antennas are combined using Maximal Ratio Combining (MRC).

### 2.2 Theoretical Analysis of MC DS CDMA System without using Rake Receiver

The transmitted MC-DS-CDMA signal of user \( j \); corresponding to the \( m \)-th chip of the spreading sequence can be written as

\[
s_{l,m}(t) = \sqrt{2p} \sum_{k=0}^{N_C-1} b_{k,l} c_{m,l} e^{j2\pi f_k(t-(m-1)\left(T_S+t_g\right))}
\]  

(2.1)

Here, for the duration \((m - 1)(T_S + t_g) - t_g \leq t \leq m(T_S + t_g) - t_g\), where \( f_k = k \times f_s \) is the frequency of the \( k \)-th subcarrier, \( f_s = \frac{1}{T_S} \) is the subcarrier spacing related to the chip duration \( T_S, T_g \) is the guard interval, \( N_c \) denotes number of subcarrier, \( N_u \) is the number of users and \( b_{k,l} \) is the data symbol transmitted by user \( l \) on the \( k \)-th subcarrier. \( c_{m,l} \) is the \( m \)-th chip of data sequence that spreads the symbols from user \( j \) and \( L \) is the length of spreading sequence.

The signal for \( l \)-th user will be,

\[
s_l(t) = \sqrt{2p} \sum_{m=1}^{L} \sum_{k=0}^{N_C-1} b_{k,l} c_{m,l} e^{j2\pi f_k(t-(m-1)(T_S+t_g))}
\]

(2.2)

The spreading sequence \( c_{m,l} \) does not depend on the subcarrier index \( k \), i.e., all data symbols from user \( l \) that are transmitted during the same symbol interval are spread with the same spreading sequence. Typically, orthogonal spreading sequences of length \( L \) are used to maintain orthogonality between signals of different users [35].

Then the MC-DS-CDMA signal is transmitted through a multipath Rayleigh fading wireless channel which introduces inter-symbol interference (ISI) due to the differences between time delays of multiple propagation paths [33]. The maximum delay difference is known as the delay spread of the channel and it is the channel parameter that determines the duration of ISI. Hence,
by using a guard interval $t_g$ that is no less than the delay spread, the ISI is completely confined within the guard interval [35]. By simply discarding the signal received over the guard interval, the receiver can get rid of the ISI.

The received signal for m-th chip can be considered as –

$$r(t) = \sqrt{2p/N_c} \sum_{l=1}^{N_u} \sum_{k=0}^{N_C-1} b_{k,l} c_{m,l} \alpha_{k,l} e^{j2\pi f_k(t-(m-1)(T_S+t_g))} + n_{ml}(t) \quad (2.3)$$

Where, $\alpha_{k,l}$ is the fading channel gain for the $k$-th subcarrier of user $l$ and it is a complex Gaussian random process with zero mean and variance $\sigma_{k,l}^2$. Thus, each subcarrier observes a frequency-flat fading channel although the actual channel is multipath frequency-selective [36].

The complex-valued additive white Gaussian noise (AWGN) process $n_{ml}(t)$ has zero mean and variance $\sigma_N^2$.

The signal received for a whole sequence

$$r(t) = \sqrt{2p/N_c} \sum_{m=1}^{L} \sum_{l=1}^{N_u} \sum_{k=0}^{N_C-1} b_{k,l} c_{m,l} \alpha_{k,l} e^{j2\pi f_k(t-(m-1)(T_S+t_g))} + n_{ml}(t) \quad (2.4)$$

As the focus is on the ICI effect, the normalized carrier frequency offset $\Delta f_k$ is considered which takes the value of an integer. We consider relative CFO to be a Gaussian process, statistically independent of the input signal and the signal will be

$$r(t) = \sqrt{2p/N_c} \sum_{m=1}^{L} \sum_{l=1}^{N_u} \sum_{k=0}^{N_C-1} b_{k,l} c_{m,l} \alpha_{k,l} e^{j2\pi (f_k+\Delta f_k)(t-(m-1)(T_S+t_g))} + n_{ml}(t) \quad (2.5)$$

Due to sampling, $t_{n,m}$ is supposed to be $nT + (m - 1)(T_s + t_g)$. But, random errors called timing jitters, occur at the receiver due to synchronization errors and limitations of sampling devices. This means the sampling instants are

$$t_{n,m} = nT + (m - 1)(T_s + t_g) + \epsilon_{n,m}$$

and $\epsilon_{n,m} \equiv T\epsilon(n,m)$, is the timing error due to $n^{th}$ sampling instant for MC DS CDMA. $\epsilon(n,m)$ is
the timing jitter normalized by the sampling interval T, which is a wide sense stationary Gaussian process with zero mean and variance $\sigma_J^2$. Therefore, the actual signal samples can be expressed as [35]

$$r_n = r(nT + (m - 1)(T_s + t_g) + \epsilon_{n,m})$$

$$= r_n = \sqrt{2p/N} \sum_{m=1}^{L} \sum_{l=1}^{N_u} \sum_{k=0}^{Nc-1} b_{k,l} c_{m,l} e^{j2\pi(f_k + \Delta f_k)(nT + (m-1)(T_s + t_g) + \epsilon_{n,m} -(m-1)(T_s + t_g))} + n_{l,n}$$ (2.6)

Where, $n_{l,n} = n_{ml}(nT + (m - 1)(T_s + t_g) + \epsilon_{n,m})$

Now,

$$r_n = \frac{\sqrt{2p}}{Nc} \sum_{m=1}^{L} \sum_{l=1}^{N_u} \sum_{k=0}^{Nc-1} b_{k,l} c_{m,l} \alpha_{k,l} e^{j2\pi f_k(nT + T\epsilon(n,m))} e^{j2\pi \Delta f_k(nT + T\epsilon(n,m))} + n_{l,n}$$ (2.7)

$$\Rightarrow r_n = \frac{\sqrt{2p}}{Nc} \sum_{m=1}^{L} \sum_{l=1}^{N_u} \sum_{k=0}^{Nc-1} b_{k,l} c_{m,l} \alpha_{k,l} e^{j2\pi \frac{k}{Nc}(n + \epsilon(n,m))} e^{j2\pi \Delta f_k T(n + \epsilon(n,m))} + n_{l,n}$$ (2.8)

$$\Rightarrow r_n = \frac{\sqrt{2p}}{Nc} \sum_{m=1}^{L} \sum_{l=1}^{N_u} \sum_{k=0}^{Nc-1} b_{k,l} c_{m,l} \alpha_{k,l} e^{j2\pi \frac{k}{Nc}(n + \epsilon(n,m))} e^{j2\pi \Delta f_k T(n + \epsilon(n,m))} + n_{l,n}$$ (2.9)

The interference caused by the timing jitter in the MC DS CDMA system without using a Rake Receiver, based on the AWGN and multipath Rayleigh fading channel is analyzed in this section.

The test decision variable $Z_i$ for the data symbol carried by the $i$-th subcarrier of user $l$ can be obtained from the received signal samples after despread as [27]

$$Z_i = \frac{\alpha_{i,l}}{NcL} \sum_{n=0}^{Nc-1} (r_n c_{m,l}^*) e^{-j2\pi f_i nT}$$ (2.10)
$$ Z_i = \frac{\alpha_{i,l}^*}{N_c L} \sum_{n=0}^{N_c-1} \sqrt{2p} \sum_{m=1}^{L} \sum_{k=0}^{N_u} b_{k,l} C_{m,l} C_{m,l}^* e^{j2\pi N (n+\epsilon(n,m))} e^{j2\pi f_k T(n+\epsilon(n,m))} e^{-j2\pi n T} + n_i $$

$$ Z_i = \frac{\sqrt{2p\alpha_{i,l}^*}}{N_c L} \sum_{l=1}^{N_u} \sum_{k=0}^{N_c-1} b_{k,l} \alpha_{k,l} \sum_{m=1}^{L} C_{m,l} C_{m,l}^* \sum_{n=0}^{N_c-1} e^{j2\pi N (n+\epsilon(n,m))} e^{j2\pi f_k T(n+\epsilon(n,m))} e^{-j2\pi n T} + n_i $$

$$ Z_i = \frac{\sqrt{2p\alpha_{i,l}^*}}{N_c L} \sum_{l=1}^{N_u} \sum_{k=0}^{N_c-1} b_{k,l} \alpha_{k,l} \sum_{m=1}^{L} C_{m,l} C_{m,l}^* \sum_{n=0}^{N_c-1} e^{j2\pi N (n+\epsilon(n,m))} e^{j2\pi f_k T(n+\epsilon(n,m))} e^{-j2\pi n T} + n_i $$

Where the noise term,

$$ n_i = \frac{\alpha_{i,l}^*}{NL} \sum_{m=1}^{L} \sum_{n=0}^{N-1} (n_{i,n} C_{m,l}^*) e^{-j2\pi n T} $$

is due to the AWGN.

To recognize different types of interference we break the decision variable into different components.

If we take $l=l$ and $k=i$, then the desired signal for $l^{th}$ user and $i^{th}$ subcarrier will be;

$$ s_i = \frac{\sqrt{2p}}{N_c L} \alpha_{i,l}^2 \sum_{m=1}^{L} \sum_{n=0}^{N_c-1} e^{j2\pi \epsilon(n,m)/N} $$

$$ => s_i = \frac{\sqrt{2p}}{N_c L} \alpha_{i,l}^2 \sum_{m=1}^{L} \sum_{n=0}^{N_c-1} \cos\left\{\frac{2\pi}{N} i \epsilon(n,m)\right\} $$

(2.12)

So, desired signal power,

$$ P_S = \frac{p}{(N_c L)^2} (b_{i,l} \alpha_{i,l}^2)^2 \sum_{m=1}^{L} \sum_{n=0}^{N_c-1} \cos^2\left\{\frac{2\pi}{N} i \epsilon(n,m)\right\} $$

(2.13)

Again, for self interference, $l=l$ and $k \neq i$,

$$ I_s = \frac{\sqrt{2p\alpha_{i,l}^*}}{N_c L} \sum_{k=0}^{N_c-1} \sum_{k \neq i} b_{k,l} \alpha_{k,l} \sum_{m=1}^{L} \sum_{n=0}^{N_c-1} e^{j2\pi N ((k-l) n + k \epsilon(n,m))} e^{-j2\pi f_k T(n+\epsilon(n,m))} $$

24
\[
I_s = \sqrt{2p\alpha^*_{i,l}} \frac{N_c}{N_c L} \sum_{k=0}^{N_c-1} b_{k,l} \alpha_{k,l} \sum_{m=1}^{L} \sum_{n=0}^{N_c-1} e^{j2\pi \frac{1}{N} (k-i)n} e^{j2\pi \frac{1}{N} k\epsilon(n,m)} e^{-j2\pi \Delta f_k T} e^{-j2\pi \Delta f_k T e(n,m)}
\]

\[
= \sqrt{2p\alpha^*_{i,l}} \frac{N_c}{N_c L} \sum_{k=0}^{N_c-1} b_{k,l} \alpha_{k,l} \sum_{m=1}^{L} \sum_{n=0}^{N_c-1} e^{j2\pi \frac{1}{N} (k-i)\epsilon(n,m)} e^{j2\pi \frac{1}{N} k\epsilon(n,m)} \epsilon(n,m)
\]

\[
\Rightarrow I_s = \sqrt{2p\alpha^*_{i,l}} \frac{N_c}{N_c L} \sum_{k=0}^{N_c-1} b_{k,l} \alpha_{k,l} \sum_{m=1}^{L} \sum_{n=0}^{N_c-1} \cos \left\{ 2\pi \frac{1}{N} (k-i) \epsilon(n,m) \right\}
\]

So, Self Interference power,

\[
P_{I_s} = \frac{p|\alpha^*_{i,l}|^2}{(N_c L)^2} \sum_{k=0}^{N_c-1} |b_{k,l}|^2 |\alpha_{k,l}|^2 \sum_{m=1}^{L} \sum_{n=0}^{N_c-1} \cos \left\{ 2\pi \frac{1}{N} (k-i) \epsilon(n,m) \right\}
\]

\[
(2.14)
\]

Interference from other carriers of other users, we take \( l \neq l \) and \( k \neq i \),

\[
I_C = \sqrt{2p\alpha^*_{i,l}} \frac{N_u}{N_u L} \sum_{i=1}^{N_u} \sum_{l=0}^{N_u-1} b_{k,l} \alpha_{k,l} \sum_{m=1}^{L} \sum_{m=1}^{L} C_{m,l} C_{m,l}^* \sum_{n=0}^{N_c-1} e^{j2\pi \frac{1}{N} (k-i)\epsilon(n,m)} e^{-j2\pi \Delta f_k T} e(n,m)
\]

\[
\Rightarrow I_C = \sqrt{2p\alpha^*_{i,l}} \frac{N_u}{N_u L} \sum_{i=1}^{N_u} \sum_{l=0}^{N_u-1} b_{k,l} \alpha_{k,l} \sum_{m=1}^{L} \sum_{m=1}^{L} C_{m,l} C_{m,l}^* \sum_{n=0}^{N_c-1} e^{j2\pi \frac{1}{N} (k-i)\epsilon(n,m)} e^{-j2\pi \Delta f_k T} e(n,m)
\]

\[
= \sqrt{2p\alpha^*_{i,l}} \frac{N_u}{N_u L} \sum_{i=1}^{N_u} \sum_{l=0}^{N_u-1} b_{k,l} \alpha_{k,l} \sum_{m=1}^{L} \sum_{m=1}^{L} C_{m,l} C_{m,l}^* \sum_{n=0}^{N_c-1} \cos \left\{ 2\pi \frac{1}{N} (k-i) \epsilon(n,m) \right\}
\]

\[
+ 2\pi \left\{ \frac{1}{N} k - \Delta f_k T \right\} \epsilon(n,m)
\]

\[
(2.16)
\]

So, Interference power from other carriers of other users,

\[
P_{I_C} = \frac{p|\alpha^*_{i,l}|^2}{(N_c L)^2} \sum_{i=1}^{N_u} \sum_{l=0}^{N_u-1} |b_{k,l}|^2 |\alpha_{k,l}|^2 \sum_{m=1}^{L} \sum_{m=1}^{L} |C_{m,l}|^2 |C_{m,l}|^2 \sum_{n=0}^{N_c-1} \cos \left\{ 2\pi \frac{1}{N} (k-i) \epsilon(n,m) \right\}
\]

\[
(2.17)
\]

25
Interference from same carrier of other users, we take \( l \neq l \) and \( k = i \),

\[
I_U = \frac{\sqrt{2} p a_i^*}{N_c L} \sum_{l=1}^{N_u} b_{i,l} \alpha_{i,l} \sum_{m=1}^{L} C_{m,l} C_{m,l}^* \sum_{n=0}^{N_c-1} e^{j2\pi \frac{1}{N} ((k-i)n+k\epsilon(n,m))} e^{-j2\pi f_i T(n+\epsilon(n,m))} \\
= \frac{\sqrt{2} p a_i^*}{N_c L} \sum_{l=1}^{N_u} b_{i,l} \alpha_{i,l} \sum_{m=1}^{L} C_{m,l} C_{m,l}^* \sum_{n=0}^{N_c-1} e^{-j2\pi (\Delta f) n} e^{j2\pi \frac{1}{N} (\Delta f) \epsilon(n,m)}
\]

\( \Rightarrow I_U = \frac{\sqrt{2} p a_i^*}{N_c L} \sum_{l=1}^{N_u} b_{i,l} \alpha_{i,l} \sum_{m=1}^{L} C_{m,l} C_{m,l}^* \sum_{n=0}^{N_c-1} \cos \left\{ 2\pi \{ -\Delta f_i T \} n + 2\pi \left\{ \frac{1}{N} i - \Delta f_i T \right\} \epsilon(n,m) \right\} \tag{2.18} \)

So, Interference power from same carrier of other users,

\[
P_{l_U} = \frac{p |a_i|^2}{(N_c L)^2} \sum_{l=1}^{N_u} |b_{i,l}|^2 |\alpha_{i,l}|^2 \sum_{m=1}^{L} |C_{m,l}|^2 |C_{m,l}|^2 \sum_{n=0}^{N_c-1} \cos^2 \left\{ 2\pi \left\{ \frac{1}{N} i - \Delta f_i T \right\} \epsilon(n,m) \right\} \tag{2.19} \)

From the equations it is clear that, in spite of using orthogonal codes, timing jitter has introduced not only self interference but also multi user interference. As, \( b_{k,l} \) has zero mean, the interference components are random variables with zero mean [27].

The variance due to channel noise,

\[
\sigma_n^2 = \frac{N_0}{4T_b} \sum_{l=0}^{N_c-1} |\alpha_{i,l}|^2 \tag{2.20} \)

So, the Signal to Interference Noise Ratio (SINR)

\[
SINR(\epsilon, \alpha) = \frac{P_S}{P_{l_s} + P_{l_c} + P_{l_U} + \sigma_n^2} \tag{2.21} \)

For the Rayleigh fading channel when \( \alpha \) is Rayleigh distributed; pdf of \( \alpha \) is :

\[
p(\alpha) = \frac{\alpha}{\sigma_{\alpha}^2} \exp \left( -\frac{\alpha^2}{2\sigma_{\alpha}^2} \right) \tag{2.22} \)
But, the pdf of zero mean Gaussian distributed jitter is [35],

\[
p(\epsilon) = \frac{1}{\sqrt{2\pi}\sigma^2_\epsilon} \exp \left( - \frac{\epsilon^2}{2\sigma^2_\epsilon} \right)
\]  

(2.23)

Where, \(\sigma^2_\epsilon\) is the variance of the timing jitter.

The conditional BER expression for BPSK is,

\[
P_b(\epsilon, \alpha) = Q\left[\sqrt{SINR(\epsilon, \alpha)}\right] = \frac{1}{2}erfc\left(\sqrt{\frac{SINR(\epsilon, \alpha)}{2}}\right)
\]  

(2.24)

Where, \(Q(x) = \frac{1}{\sqrt{2\pi}} \int_0^x e^{-\frac{y^2}{2}} dy\)

The unconditional or average BER can be calculated by averaging the conditional BER \(P_b(\epsilon, \alpha)\), over all possible values of \(\epsilon\) and \(\alpha\).

\[
BER = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} P_b(\epsilon, \alpha) \ p(\alpha) \ p(\epsilon) \ d\alpha \ d\epsilon
\]  

(2.25)

### 2.3 Theoretical Analysis of MC DS CDMA System with Rake Receiver

In this part the interference caused by the timing jitter in the MC DS CDMA system in presence of a Rake Receiver, based on the AWGN and multipath Rayleigh fading channel is analyzed.

Suppose, in the system with Rake Receiver there are total W antennas in the system each of them having RAKE receiver with \(L_f\) branch received by the \(q^{th}\) channel can be expressed as:

\[
r_q(t) = \sqrt{2p} \sum_{l=1}^{N_u} \sum_{k=0}^{N_C-1} b_{k,l} c_{m,l} \alpha_{k,l} e^{j2\pi f_{k}(t-qT_p-(m-1)(T_s+t_g))} + n_{wq}(t)
\]  

(2.26)

The composite signal received by \(w^{th}\) antenna is given by:
\[ r(t) = \sqrt{2p} N_C \sum_{q=0}^{L_f-1} \sum_{m=1}^L \sum_{l=1}^L \sum_{k=0}^{N_u} b_{k,l} c_{m,l} \alpha_{k,l} e^{j2\pi f_k (t - q T_D - (m-1)(T_S + t_g))} + n_w(t) \] (2.27)

The signal received for a whole sequence is:

\[ r(t) = \sqrt{2p} N_C \sum_{q=0}^{L_f-1} \sum_{m=1}^L \sum_{l=1}^L \sum_{k=0}^{N_u} b_{k,l} c_{m,l} \alpha_{k,l} e^{j2\pi f_k (t - q T_D - (m-1)(T_S + t_g))} + n_w(t) \] (2.28)

If relative CFO is considered to be a Gaussian process we get the signal will be

\[ r(t) = \sqrt{2p} N_C \sum_{q=0}^{L_f-1} \sum_{m=1}^L \sum_{l=1}^L \sum_{k=0}^{N_u} b_{k,l} c_{m,l} \alpha_{k,l} e^{j2\pi (f_k + \Delta f_k) (t - q T_D - (m-1)(T_S + t_g))} + n_w(t) \] (2.29)

Due to sampling and random errors, \( t_{n,m} \) is supposed to be \( n T + (m - 1)(T_S + t_g) + \epsilon_{n,m} \) and \( \epsilon_{n,m} \equiv T \epsilon(n, m) \).

Therefore, the actual signal samples can be expressed as

\[ r_n = r(n T + (m - 1)(T_S + t_g) + \epsilon_{n,m}) \]

\[ \Rightarrow r_n = \sqrt{2p} \frac{N_u}{N_C} \sum_{q=0}^{L_f-1} \sum_{m=1}^L \sum_{l=1}^L \sum_{k=0}^{N_u} b_{k,l} c_{m,l} \alpha_{k,l} e^{j2\pi (f_k + \Delta f_k) (n T - q T_D + (m-1)(T_S + t_g) + \epsilon_{n,m} - (m-1)(T_S + t_g))} + n_{wn} \] (2.30)

Where, \( n_{wn} = n_w(n T + (m - 1)(T_S + t_g) + \epsilon_{n,m}) \)

\[ \Rightarrow r_n = \sqrt{2p} \frac{N_u}{N_C} \sum_{q=0}^{L_f-1} \sum_{m=1}^L \sum_{l=1}^L \sum_{k=0}^{N_u} b_{k,l} c_{m,l} \alpha_{k,l} e^{j2\pi (f_k + \Delta f_k) (n T - q T_D + T \epsilon(n,m))} + n_{wn} \] (2.31)

\[ \Rightarrow r_n = \sqrt{2p} \frac{N_u}{N_C} \sum_{q=0}^{L_f-1} \sum_{m=1}^L \sum_{l=1}^L \sum_{k=0}^{N_u} b_{k,l} c_{m,l} \alpha_{k,l} e^{j2\pi \frac{k}{NT} (n T - q T_D + T \epsilon(n,m))} e^{j2\pi \Delta f_k (n T - q T_D + T \epsilon(n,m))} e^{j2\pi \Delta f_k (n T - q T_D + T \epsilon(n,m))} + n_{wn} \] (2.32)
\[ r_n = \frac{\sqrt{2p}}{N_C} \sum_{q=0}^{L_f-1} \sum_{n=0}^{L_u} \sum_{N_u} \sum_{l=1}^{N_C-1} b_{k,l} c_{m,l} e^{j2\pi \frac{k}{N}(n+\epsilon(n,m))} \]
\[ \times e^{j2\pi f_k T(n+\epsilon(n,m))} e^{-j2\pi \frac{k}{NT} q T_D} e^{-j2\pi f_k q T_D} + n_{wn} \]  
(2.33)

The test decision variable \( Z_i \) for the data symbol carried by the \( i \)-th subcarrier of user \( l \) can be obtained from the received signal samples after despreading as [27]

\[ Z_i = \alpha_{i,l}^* \sum_{n=0}^{N_C-1} \left( r_n C_{mlq}^* \right) e^{-j2\pi f_i nT} \]  
(2.34)

\[ \Rightarrow Z_i = \sqrt{2p} \alpha_{i,l}^* \sum_{n=0}^{N_C-1} \left( r_n C_{mlq}^* \right) e^{-j2\pi f_i nT} + n_i \]

Where the noise term,
\[ n_i = \alpha_{i,l}^* \sum_{n=0}^{N_C-1} \left( n_{wn} C_{mlq}^* \right) e^{-j2\pi f_i nT} \]

is due to the AWGN.

To recognize different types of interference we break the decision variable into different components.
If we take \( l = l \) and \( k = i \), then the desired signal for \( l \)th user and \( i \)th subcarrier will be;

\[
s_i = \sqrt{2p} \frac{\alpha_i}{N_C L} \sum_{q=0}^{L_f-1} b_{l,q} \alpha_{l,l}^2 \sum_{m=1}^{L} \sum_{n=0}^{N_C-1} e^{j2\pi \frac{i}{N} \epsilon(n,m)}
\]

\[
=> s_i = \sqrt{2p} \frac{\alpha_i}{N_C L} \sum_{q=0}^{L_f-1} b_{l,q} \alpha_{l,l}^2 \sum_{m=1}^{L} \sum_{n=0}^{N_C-1} \cos\left\{2\pi \frac{i}{N} \epsilon(n,m)\right\}
\]  

(2.36)

So, desired signal power,

\[
P_S = \frac{p}{(N_C L)^2} \left( \sum_{q=0}^{L_f-1} \sum_{m=1}^{L} \sum_{n=0}^{N_C-1} \cos^2\left\{2\pi \frac{i}{N} \epsilon(n,m)\right\} \right)
\]  

(2.37)

Again, for self interference, \( l = l \) and \( k \neq i \),

\[
I_s = \sqrt{2p} \frac{\alpha_i^*}{N_C L} \sum_{q=0}^{L_f-1} \sum_{k=0}^{L_f-1} \sum_{m=1}^{L} \sum_{n=0}^{N_C-1} e^{j2\pi \frac{i}{N} [(k-i)n + k \epsilon(n,m)]} \epsilon(n,m)
\]

\[
\times e^{-j2\pi k \frac{\Delta f}{N} T(n+\epsilon(n,m))} e^{-j2\pi q T_D(\frac{k}{NT} + \Delta f_k)}
\]

\[
=> I_s = \sqrt{2p} \frac{\alpha_i^*}{N_C L} \sum_{q=0}^{L_f-1} \sum_{k=0}^{L_f-1} \sum_{m=1}^{L} \sum_{n=0}^{N_C-1} e^{j2\pi \frac{i}{N} [(k-i) - \Delta f_k] T} e^{-j2\pi q T_D(\frac{k}{NT} + \Delta f_k)}
\]

\[
\times \cos\left\{2\pi \frac{1}{N} (k - i) - \Delta f_k T\right\} e^{-j2\pi q T_D(\frac{k}{NT})}
\]

(2.38)

So, Self Interference power,

\[
P_{I_s} = \frac{p |\alpha_i^*|^2}{(N_C L)^2} \sum_{q=0}^{L_f-1} \sum_{k=0}^{L_f-1} |b_{k,l}|^2 |\alpha_{k,l}|^2 \sum_{m=1}^{L} \sum_{n=0}^{N_C-1} \cos^2\left\{2\pi \frac{1}{N} (k - \Delta f_k T) \epsilon(n,m) - 2\pi q T_D(\frac{k}{NT}) + \Delta f_k\right\}
\]  

(2.39)
Interference from other carriers of other users, we take \( l \neq l \) and \( k \neq i \),

\[
I_c = \frac{\sqrt{2}p}{N_c L} \sum_{q=0}^{L_f-1} \sum_{k=0}^{N_c-1} \sum_{l \neq l} b_{k,l} \alpha_{k,l} \sum_{m=1}^{L} C_{m,l}^* \sum_{n=0}^{N_c-1} e^{j\frac{2\pi}{N}((k-i)n+k\epsilon(n,m))} \\
\times e^{-j2\pi\Delta f_k T(n+\epsilon(n,m))} e^{-j2\pi q T_D(k N_T + \Delta f_k)}
\]

\[
= \frac{\sqrt{2}p}{N_c L} \sum_{q=0}^{L_f-1} \sum_{k=0}^{N_c-1} \sum_{l \neq l} b_{k,l} \alpha_{k,l} \sum_{m=1}^{L} C_{m,l}^* \sum_{n=0}^{N_c-1} e^{2\pi \left\{ \frac{1}{N} (k - i) - \Delta f_k T \right\} n} \\
+ 2\pi \left\{ \frac{1}{N} k - \Delta f_k T \right\} \epsilon(n, m) - 2\pi q T_D \left( \frac{k}{N_T} + \Delta f_k \right) \right\} \tag{2.40}
\]

So, interference power from other carriers of other users,

\[
P_{I_c} = p |\alpha_{i,l}^*|^2 \sum_{q=0}^{L_f-1} \sum_{l \neq l} \sum_{k=0}^{N_c-1} |b_{k,l}|^2 |\alpha_{k,l}|^2 \sum_{m=1}^{L} |C_{m,l}|^2 |C_{m,l}^*|^2 \\
\times \sum_{n=0}^{N_c-1} \cos \left\{ 2\pi \left\{ \frac{1}{N} k - \Delta f_k T \right\} \epsilon(n, m) - 2\pi q T_D \left( \frac{k}{N_T} + \Delta f_k \right) \right\} \tag{2.41}
\]

Interference from same carrier of other users, we take \( l \neq l \) and \( k = i \),

\[
I_u = \frac{\sqrt{2}p}{N_c L} \sum_{q=0}^{L_f-1} \sum_{l \neq l} \sum_{k=0}^{N_c-1} b_{k,l} \alpha_{l,l} \sum_{m=1}^{L} C_{m,l}^* \sum_{n=0}^{N_c-1} e^{j\frac{2\pi}{N}((k-i)n+k\epsilon(n,m))} \\
\times e^{-j2\pi\Delta f_i T(n+\epsilon(n,m))} e^{-j2\pi q T_D(k N_T + \Delta f_k)}
\]

\[
= \frac{\sqrt{2}p}{N_c L} \sum_{q=0}^{L_f-1} \sum_{l \neq l} \sum_{k=0}^{N_c-1} b_{k,l} \alpha_{l,l} \sum_{m=1}^{L} C_{m,l}^* \\
\times \sum_{n=0}^{N_c-1} \cos \left\{ 2\pi (-\Delta f_i T) n + 2\pi \left\{ \frac{1}{N} i - \Delta f_i T \right\} \epsilon(n, m) - 2\pi q T_D \left( \frac{k}{N_T} + \Delta f_k \right) \right\} \tag{2.42}
\]
So, Interference power from same carrier of other users,

\[
P_{l_u} = p|\alpha_{i,l}|^2 \sum_{l=1}^{L} \sum_{i=1}^{L-1} |b_{i,l}|^2 |\alpha_{i,l}|^2 \sum_{m=1}^{L} |C_{m,l}|^2 |C_{m+l}^*| \times \sum_{n=0}^{N_C-1} \cos^2 \left\{2\pi \left\{\frac{1}{N} i - \Delta f_i T \right\} e(n,m) - 2\pi q T_D \left(k N_T + \Delta f_k \right)\right\}
\] (2.43)

From the equations it is clear that, in spite of using orthogonal codes, timing jitter has introduced not only self interference but also multi user interference. As, \(b_{k,l}\) has zero mean, the interference components are random variables with zero mean.

The variance due to channel noise,

\[
\sigma_n^2 = \frac{N_0}{4T_b} \sum_{i=0}^{N_C-1} |\alpha_{i,l}|^2
\] (2.44)

So, the Signal to Interference Noise Ratio (SINR),

\[
SINR(\gamma) = \frac{P_S}{P_{l_s} + P_{l_c} + P_{l_u} + \sigma_n^2}
\] (2.45)

Let us consider there are rake receivers in each sub-carrier channel which have Q branches and they are considered for Maximal Ratio Combining. With \(\gamma\) as the instantaneous SINR, the probability of bit error rate at the output is given as follows:

\[
P_b(\gamma) = Q\left[\sqrt{\gamma}\right] = \frac{1}{2} erfc \left(\sqrt{\gamma}/2\right)
\] (2.46)

Where,

\[
Q(x) = \frac{1}{\sqrt{2\pi}} \int_0^x e^{-\frac{y^2}{2}} dy
\]

In a Rayleigh fading environment, \(\alpha_{k,l}\) values are identically distributed independent Rayleigh random variables with parameter \(\sigma_a^2\) [34]. The probability density function (pdf) for M no. of antenna can be obtained by differentiating the cumulative distribution function (cdf) of \(F(\gamma)\)
\[ F(\gamma) = \left[ \sum_{k=0}^{L_f-1} \psi_k \left(1 - e^{-\frac{\gamma}{\Lambda_k}}\right) \right]^M \] (2.47)

Where, \( \psi_k = \sum_{\substack{i=0 \atop i \neq k}}^{L_f-1} \frac{\Lambda_k}{\Lambda_k - \Lambda_i} \) and \( \Lambda_k = 2\sigma^2 \left( \frac{E_b}{N_o} \right) \beta e^{-k\beta}, \beta = \frac{T_c}{T_m} \epsilon(n, m) \)

and \( T_m = \) multipath delay spread

Thus, pdf of \( \gamma \) is given as [34]:

\[ f(\gamma) = M \left[ \sum_{k=0}^{L_f-1} \psi_k \left(1 - e^{-\frac{\gamma}{\Lambda_k}}\right) \right] \sum_{k=0}^{M-1} \frac{\psi_k}{\Lambda_k} e^{-\frac{\gamma}{\Lambda_k}} \] (2.48)

The unconditional or average BER can be calculated by averaging the conditional BER \( P_b(\gamma) \), over all possible values of \( \gamma \).

\[ BER = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} P_b(\gamma) f(\gamma) p(\epsilon) \, d\gamma \, d\epsilon \] (2.49)
Chapter -3

Results and Discussions

3.1 Results for MC DS CDMA System without using Rake Receiver

In this section following the analytical approach presented in chapter 2, we evaluate the BER performance of a MC DS CDMA system over Rayleigh fading channel without a Rake Receiver in presence of timing jitter [37]. For the computations, number of subcarrier is represented by $N_c$, Number of Users by $N_u$, Jitter Variances by $\sigma^2_\epsilon$. The parameters have been varied to determine the optimum system parameters for the system design.

Fig: 3.1 (a) BER comparisons for different jitter variances
Fig. 3.1 reflects how different system parameters influence the BER. In fig 3.1 (a) the increase in Jitter variance increases the interference and as a consequence the BER increases significantly.
Again from fig 3.1 (b) it is evident that by introducing more subcarriers the interference effect can be compensated and BER can be reduced. But, from fig 3.1 (c) if all the parameters remain then the introduction of more users will cause more interference and BER eventually increases significantly.

Fig: 3.2 (a) BER comparisons for different number of users for varying number of subcarriers
Fig 3.2 (b) BER comparisons for different number of users for different jitter variances

Fig 3.2 reflects how the BER gets varied along with changing number of users for different system parameter conditions. In fig 3.2 (a), it is shown, to accommodate more users at an acceptable BER inclusion of new sub-carriers are required. Again, fig 3.2 (b) expresses for a fixed amount of BER, increase in jitter variance reduces the acceptable number of users.

The jitter variance in MC DS CDMA system influences the BER significantly, which leads to the huge requirement of power penalty. In fig 3.3 this effect has been shown for different conditions.
Fig: 3.3 (a) For 8 subcarriers

Fig: 3.3 (b) For 16 subcarriers

Fig: 3.3 (c) For 32 subcarriers

Fig: 3.3 (d) For 64 subcarriers

Fig 3.3 shows that more jitter variance causes more power penalty for an acceptable BER, while introduction of more users deteriorate the situation and causes more power penalty. But, it can be compensated by increasing the number of subcarriers.
Fig 3.4 shows by introducing more sub-carriers the power penalty can be reduced to some extent at a fixed jitter variance. But, more users will cause higher power penalty even at that condition.
From fig 3.5 it is clear that for an acceptable power penalty (5dB) to accommodate more users the jitter variance should be reduced. By employing more subcarriers the system can be improved also. While, for 32 users in presence of 32 subcarriers the acceptable jitter variance is around 0.2 but to accommodate 64 users it should get reduced to 0.15. On the other hand, if the number of subcarrier is reduced then acceptable jitter variance gets down to 0.17 also.
3.2 Results for MC DS CDMA System with Rake Receiver

In this section the BER performance of MC DS CDMA system with Rake Receiver in presence of timing jitter are outlined. So far for all the cases numbers of Rake fingers are chosen to be 8.

![Figure 3.6 (a) BER comparisons for different jitter variances in presence of Rake Receiver](image)

![Figure 3.6 (b) BER comparisons for different number of subcarriers in presence of Rake Receiver](image)
Fig 3.6 (c) BER comparisons for different number of users in presence of Rake Receiver

Fig. 3.6 reflects how different system parameters influence the BER just as an in fig 3.1. But the difference is in presence of Rake Receiver the BER gets reduced significantly and it is around 10 to 100 times for different cases.

Fig 3.7 (a) BER comparisons for different number of users for varying number of subcarriers in presence of Rake Receiver
Fig 3.7 (b) BER comparisons for different number of users for varying jitter variances in presence of Rake Receiver

Fig 3.7 reflects how the BER gets varied along with changing number of users for different system parameter conditions when the system incorporates a Rake Receiver. Though the BER gets reduced significantly due to the inclusion of Rake Receiver, still to accommodate more users at an acceptable BER inclusion of new sub-carriers are required. On the other hand for fixed BER, increase in jitter variance will reduce the acceptable number of users.

The jitter variance in MC DS CDMA system influences the BER significantly even a system having Rake Receiver, which leads to the huge requirement of power penalty. In fig 3.8 this effect has been shown for different conditions.
Fig 3.8 (a) For 8 subcarriers

Fig 3.8 (b) For 16 subcarriers

Fig 3.8 (c) For 32 subcarriers

Fig 3.8 (d) For 64 subcarriers

Fig 3.8 Power Penalty as a function of Jitter Variances for different number of users for a system with Rake Receiver

Fig 3.8 shows that more jitter variance causes more power penalty for an acceptable BER even in a system having Rake Receiver. But, in this case the power penalty gets reduced significantly and it becomes possible to accommodate more users in the system.
Fig: 3.9 (a) For 16 users

Fig: 3.9 (b) For 32 users

Fig: 3.9 (c) For 64 users

Fig: 3.9 (d) For 128 users

Fig: 3.9 Power Penalty as a function of Jitter Variances for different number of subcarriers for a system with Rake Receiver
Fig 3.9 shows by introducing more sub-carriers the power penalty can be reduced to some extent at a fixed jitter variance. In a system having Rake Receiver the power penalty is quite small comparing to that in a system without Rake Receiver.

![Graph showing Power penalty vs Number of users](image)

**Fig: 3.10 Jitter Variance as a function of number of users for fixed power penalty for a system with Rake Receiver**

Fig 3.10 reflects for an acceptable power penalty (5dB) to accommodate more users the jitter variance should be reduced. By employing more subcarriers the system can be improved also. But in presence of Rake Receiver the system can handle a higher amount of jitter variances while the other parameters are same. Here, for 32 users in presence of 32 subcarriers the acceptable jitter variance is around 0.33, without Rake Receiver it was around 0.2 only.
3.3 Performance Improvement through the introduction of Rake Receiver

Fig: 3.11 (a) For 8 subcarriers

Fig: 3.11 (b) For 16 subcarriers

Fig: 3.11 (c) For 32 subcarriers

Fig: 3.11 (d) For 64 subcarriers

Fig: 3.11 Comparison of allowable Jitter Variance as a function of number of users for fixed power penalty for the systems with Rake Receiver and without Rake Receiver
Fig 3.11 shows inclusion of Rake Receiver increases the allowable jitter variance when the number of user is fixed or at a fixed jitter variance more users can be accommodated at a fixed power penalty condition. Introducing more subcarriers can also increase the performance by allowing more users or increasing the allowable jitter variance value.

Fig: 3.12 Comparison of BER for different number of Rake fingers in the Rake Receiver

Fig. 3.12 shows along with the increase in the number of Rake Fingers BER decreases when all other system parameters remain unchanged. Ultimately the presence of the Rake Receiver increases the allowable number of users, acceptable jitter variance and reduces the requirement of subcarriers when the allowable BER remains fixed.
Chapter -4

Conclusion and Future Work

4.1 Conclusion

In this thesis, the performance analysis of a Multi Carrier Direct Sequence CDMA (MC DS CDMA) is carried out in a Rayleigh faded channel in presence of timing jitter. The analytical expression is formulated for the MC-DS-CDMA system to determine the impact of timing jitter variance over a Rayleigh fading channel by determining the expression of multiple access interference (MAI) and the expression of the SINR and BER. The jitter variance is found to influence the BER which eventually affect the system parameters like number of subcarriers, number of users. Ultimately it leads to huge power penalty at a given BER. To compensate the effect we need either to reduce number of users or to introduce more sub-carriers. The number of subcarriers used is a very dominating factor for improving BER performance in the multicarrier system. For a better BER performance, the number of subcarrier should be increased and also reversely, increasing the subcarrier number requires less $Eb/N_0$ to achieve the desired BER. For example, in a system having 32 users and jitter variances $0.4$ to achieve a BER of $10^{-6}$ the number of subcarrier is reduced from 128 to 32 when the value of Eb/No becomes 10dB from 5dB.

Here, the model in presence of Rake Receiver and applied maximal ratio combining (MRC) scheme. It has reduced the BER as well as power penalty for fixed system parameters significantly. By changing the number of Rake fingers how the system can be configured is also analyzed. Now, for the system with Rake receiver having 32 users and jitter variances $0.4$ to
achieve a BER of $10^{-6}$ the number of subcarrier can be reduced from 128 to 32 while the required value of Eb/No changes from 2dB to 5dB.

4.2 Scope of Future Work

This thesis developed the framework for MC DS CDMA system. Although several issues were investigated, some of issues were not considered due to the work required and complexity of analytical solutions. Among the modulation techniques Binary Phase Shift Keying (BPSK) has been considered while in future the analysis can be carried out for Quadrature Phase Shift Keying (QPSK) and 8PSK. Maximal Ratio Combining (MRC) is chosen for the thesis, but Equal Gain Combining (EGC) is also a very good diversity scheme. Variable processing gain technique can be used and compared with multi-code technique to provide multi-rate systems. In addition, some forward error correction coding techniques like convolution coding and Turbo coding can be considered in this thesis to further improve system performance.
REFERENCES


