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# ICI Reduction Methods for MC-CDMA Systems

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# ICI Reduction Methods for MC-CDMA Systems

A thesis submitted in partial fulfilment  
of the requirements for the degree of  
Master of Science in Engineering

By

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June 06, 2008

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY Meng Wu ENTITLED ICI Reduction Methods for MC-CDMA Systems BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF Master of Science in Engineering.

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## ABSTRACT

Wu, Meng. M.S.Egr. Department of Electrical Engineering, Wright State University, 2008. ICI reduction methods for MC-CDMA systems.

Multi-carrier code-division multiple-access (MC-CDMA) is an important multiple access candidate for 4G wireless communication system. While MC-CDMA provides high performance and high capacity in frequency selective fading channels, it is very sensitive to the signal distortion, especially the Inter Carrier Interference (ICI). We apply self-cancelation and a frequency transmission paradigm to MC-CDMA system to improve the sytem performance in an ICI rich environment. Furthermore, we combine the frequency transmission paradigm FD-MC-CDMA with ICI cancelation. Also, we apply all these three schemes into non-contiguous OFDM and non-contiguous MC-CDMA systems in simple Cognitive Radio communication environments and present the simulation results. Theoretical analysis and numerical results confirm the effectiveness of our proposed new schemes.

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# Introduction and Motivation

Multi-carrier code-division multiple-access (MC-CDMA) system was first proposed in [1], [2] and [3] and was further explored in [4]. MC-CDMA is a combination of CDMA and OFDM techniques. The principle of MC-CDMA is to transmit a single data symbol at multiple carriers. These carriers (also called subcarriers) have different frequencies and they are orthogonal to each other.

## 1.1 Code Division Multiple Access (CDMA)

Considerable research has been done in the field of CDMA. The first CDMA based standard IS-95 (Interim Standard) for North American cellular communications has been very successful. CDMA is a multiple access technique using spreading sequences to modulate signals and separate different users, thereby allowing multiple users to access shared radio channel resource simultaneously and even asynchronously [4]. In CDMA, each user is assigned a unique spreading sequence, which has a sufficiently low cross correlation with other users, to modulate the transmitted bits. The base station uses the knowledge of these codes to detect and estimate each user's bits [5]. Due to the special property of the spreading sequence, theoretically the information bearing signals of the desired user can be fully recovered. The chip duration of the spreading sequences is much lower than that of the original information-bearing signals. These faster variations in time increase the bandwidth of the signal in frequency. Consequently, if the spreading factor is sufficiently large, the signal experiences frequency selective fading, and it is unlikely that the entire signal will be lost to fades in frequency [1]. Unlike TDMA (Time-Division Multiple Access) and FDMA (Frequency-Division Multiple Access), where each user is assigned a unique time slot or channel, in CDMA, different users share the same frequency spectrum to transmit signal. Thus, users in CDMA experience direct interference from the other users, which is called MAI (Multiple Access Interference). Since the resolution in time at the receiver is increased, the signal is more susceptible to inter-chip interference.

## 1.2 Orthogonal Frequency Division Multiplexing (OFDM)

In both wired and wireless communications, orthogonal frequency division multiplexing techniques can be employed, such as the asymmetric digital subscriber line (ADSL) and the IEEE 802.11 standard. Orthogonal frequency division multiplexing (OFDM) is one of the multi-carrier modulation (MCM) techniques that transmits signals over multiple carriers (also called subcarriers) in divided frequency bands[6]. These subcarriers have different frequencies which are orthogonal to each other. Each subchannel requires a longer symbol period. Therefore OFDM systems can overcome the intersymbol interference (ISI). As a consequence, the OFDM systems can result in lower bit error rates and higher data rates than conventional communication systems.

The complexity of OFDM system can be reduced by applying the discrete Fourier Transform (DFT) to generate the orthogonal subcarriers waveforms [7]. In this model, baseband signals are modulated by the inverse DFT (IDFT) in the transmitter and then demodulated by DFT in the receiver. Therefore, all the subcarriers are overlapped with others in the frequency domain, while the DFT modulation still assures their orthogonality. Moreover, the windowing technique is used to attack the inter-symbol interference (ISI) and inter-carrier interference (ICI) problems.

## 1.3 Multicarrier Code Division Multiple Access (MC-CDMA)

MC-CDMA combines the benefits of CDMA with the natural robustness to frequency selectivity offered by OFDM. In MC-CDMA, the processing and spreading occurs in the frequency domain, rather than in temporal domain. With MC-CDMA, a data symbol is transmitted over  $N$  narrowband subcarriers with each subcarrier being encoded with a 0 or  $\pi$  phase based on the spreading code[1]. Different users transmit over the same set of subcarriers but with a spreading code which maintains the orthogonality. The resulting signal has an orthogonal code structure in the frequency domain. If the number of and the spacing between subcarriers is appropriately chosen, it is unlikely that all of the subcarriers will be located in a deep fade and consequently frequency diversity is achieved [8]. Ever since it is first proposed, the MC-CDMA technique has received much recognition as a candidate to support multimedia services in wireless communication because of its convenience for high-bit-rate applications (up to several hundred megabits per second). It requires a lower speed parallel-type digital signal processing while a DS-CDMA system requires much faster serial-type signal processing. DS-CDMA is not feasible for very high data rate applications also because of the severe inter-chip interference (ICI) and inter-symbol interference (ISI) at very high data rate. MC-CDMA is developed to alleviate the problem. As a MC-CDMA signal is composed of  $N$  narrowband subcarrier signals each of which has a symbol duration much larger than the delay spread. The long symbol duration mitigates the Inter Symbol Interference (ISI). The adaptive modulation and frequency diversity protect it against destruc-

tive fading [1].

The transmitted signal can be operated over multiple non-contiguous frequency bands. The excellent spectral efficiency is achieved without sacrificing equalization complexity. This aspect also makes it important in cognitive radio and dynamic spectrum access network, since the secondary user needs to transmit its data through multiple “spectrum holes” which are non-contiguous in frequency.

## 1.4 Cognitive Radio

Cognitive Radio is a paradigm for wireless communication, which can communicate efficiently by avoiding interference from licensed or unlicensed users by changing its transmission or reception parameters. Cognitive Radio can autonomously detect and exploit empty spectrum, automatically detect and interoperate with varying network standards, to increase the transfer rate of the files. This same radio could also remember the locations where the calls tend to drop and arrange for the call to be serviced by a different carrier for those locations.

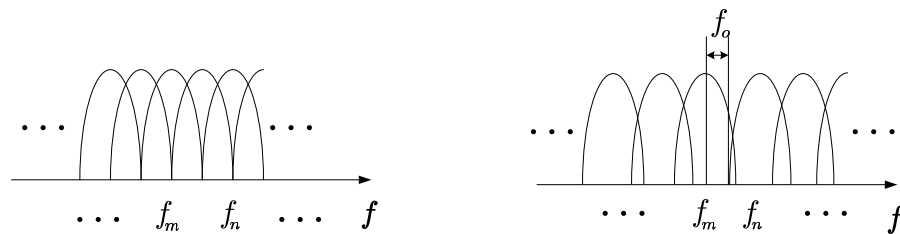
The idea of cognitive Radio was first presented officially in an article by Joseph Mitola III and Gerald Q Maguire Jr. in 1999 [9]. Mitola described it as: The point in which wireless devices and the related networks are sufficiently computationally intelligent about radio resources and related computer- to- computer communications to detect user communication needs as a function of use context, and to provide radio resources and wireless services most appropriate to those needs.

Cognitive Radio technology should enable nearly any wireless system to locate and link to any locally available unused radio spectrum to best serve the consumer. Employing adaptive software, these smart devices could reconfigure their communication functions to meet the demands of the transmission network or the user.

The aspect of MC-CDMA which can transmit signal over multiple non-contiguous frequency bands makes it a possible approach for Cognitive Radio to fill free radio frequency bands adaptively. Free bands sensed by nodes can be immediately filled by MC-CDMA subcarriers.

## 1.5 Carrier Frequency Offset Problem

MC-CDMA is one of the multi-carrier modulation (MCM) techniques which transmit signals through multiple carriers (subcarriers). These subcarriers have different frequencies and they are orthogonal to each other. However, in a high speed mobile communication channel, the orthogonality among subcarriers can be destroyed by frequency offset, as shown in Fig. 1.1. The source of the frequency offset can be Doppler shift due to high speed motion of vehicle, or by multi-path fading and phase variations in the received signal due to multiple scattering, or frequency mismatch between the transmitter and receiver oscillators [10]. The loss of orthogonality can cause the interferences from other subcarriers and this is known as Inter-Carrier Interference (ICI). The effect of ICI along with MAI on BER performance of synchronous MC-CDMA system has been extensively studied in [11] and [10], where [11] analyzed the effect of frequency offset using Hadamard-Walsh codes, while [10] employed random spreading sequences.



(a) orthogonal MC-CDMA subcarrier signals    (b) unorthogonal MC-CDMA subcarrier signals

Figure 1.1: Frequency spectrum of MC-CDMA subcarrier signals

## 1.6 Traditional MC-CDMA System and the Problem of ICI

### 1.6.1 Wireless Channel

In this section, channel models which are set as simulation environment are discussed. The traditional MC-CDMA system is also discussed as well as the problems the Multi-carrier Modulation is facing.

#### 1.6.1.1 AWGN Channel

The additive white Gaussian noise (AWGN) channel is the simplest channel model used in most communication systems. In this model, the only impairment is the linear additive white noise with constant spectral density and a Gaussian distribution of amplitude. This model does not account for the impairment of fading, frequency selectivity, interference, nonlinearity or dispersion. It produces a simple, tractable mathematical model which is useful for gaining insight into the underlying behavior of a system before the other phenom-

Wideband Gaussian noise comes from various natural sources. The thermal noise in the receivers can be characterized as an additive white Gaussian process. There are other factors introducing wideband Gaussian noise, such as shot noise, blackbody radiation from the earth and other warm objects, and from celestial sources such as the Sun.

### 1.6.1.2 Frequency Selective Fading Channel

Channel fading is generally categorized into large-scale and small-scale fading, which often occur simultaneously [12]. Large-scale fading results from shadowing terrain contours such as buildings, mountains, and foliage, relative to the distance between transmitter and receiver. Small-scale fading is not determined by the distance in communication. It is used to describe the rapid fluctuations of the amplitudes, phases, or multipath delays of a radio signal over a short period of time or travel distance. The multipath delays depend on the relation between the nature of the transmitted signal with respect to the characteristics of the channel. The small-scale fading is manifest in two ways: the signal spreading and the time variation. While multipath delay spread leads to time dispersion and frequency selective fading, Doppler spread leads to frequency dispersion and time selective fading. These two propagation mechanisms are independent of each other.

We focus on the frequency selective fading channel model in this thesis. If the channel possesses a constant-gain and linear phase response over a bandwidth that is smaller than the bandwidth of transmitted signal, then the channel creates frequency selective fading on the received signal [13][14]. In MC-CDMA system, each modulated subcarrier does not experience significant dispersion and overlapping between adjacent data symbols (ISI). Coherent bandwidth is the bandwidth over which the channel transfer function remains virtually constant. Since the bandwidth of each subcarrier in MC-CDMA system is much less than the coherent bandwidth, the transmitted signal undergoes flat fading on each subcarrier.

In this thesis, we assume a  $P$ -fold multipath fading channel, where the ratio between the bandwidth of each subcarrier and the coherent bandwidth is 1 : 8. For a contiguous  $N = 32$  system, the coherence bandwidth is:

$$BW_c = BW/P = BW/4 \quad (1.1)$$

where,  $BW$  is the total bandwidth of the channel and  $BW_c$  is the coherence bandwidth. Here we take  $P = 4, N = 32$ , which means the coherence bandwidth is 8 times greater than the bandwidth of each subcarrier. From this standpoint, the transmitted signal goes through a frequency selective fading channel over the entire bandwidth, but on each subcarrier it undergoes flat fading. The correlation between the  $i^{th}$

subcarrier fade and the  $j^{th}$  subcarrier fade is specified as:

$$\rho_{i,j} = \frac{1}{1 + ((f_i - f_j)/BW_c)^2} \quad (1.2)$$

where  $(f_i - f_j)$  stands for the frequency separation between the  $i^{th}$  subcarrier and the  $j^{th}$  subcarrier.

For a non-contiguous communication system, where the total bandwidth is of  $N = 1024$  subcarriers, the signals are transmitted on 4“frequency holes” which are separated by primary users. Each“frequency hole” has the bandwidth wide enough for 32 subcarriers. In this way, this MC-CDMA occupies 128 subcarriers for transmission. The empty frequencies are used and the system has higher frequency diversity than contiguously transmitting system.

We still assume the rate between the bandwidth of each subcarrier and the coherent bandwidth is 1 : 8, which means the coherence bandwidth is 8 times greater than the bandwidth of each subcarrier. Thus, this is a  $P = 128$ -fold multipath fading channel, where the coherent bandwidth remains the same.

## 1.6.2 System Model

### 1.6.2.1 Transmitter

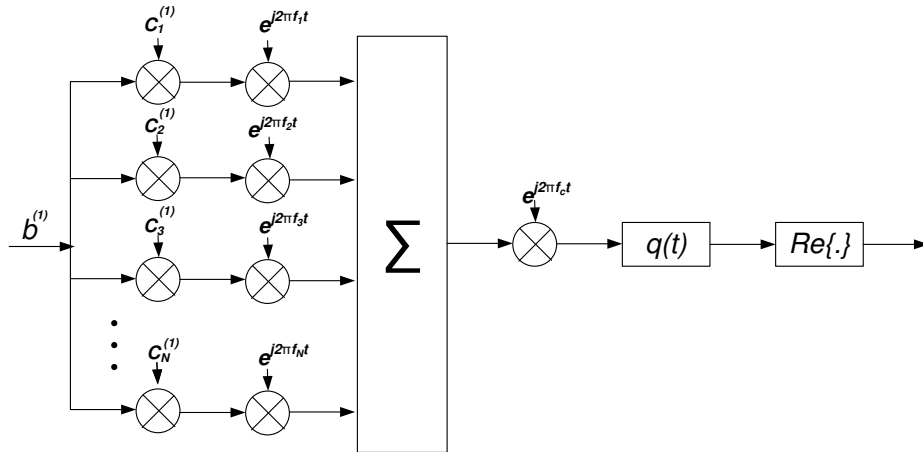


Figure 1.2: MC-CDMA transmitter

Fig. 1.2 illustrates the structure of the MC-CDMA transmitter system. A single data bit  $b^m$  from the input information sequence of user  $m$  is first replicated  $L$  times, and each of these  $L$  parallel copies is spread by the corresponding chip of the spreading code  $c_i^m$ . The data bits are BPSK modulated at a rate of  $1/T_b$ , with

the amplitude of  $(\sqrt{E_b/L})$  which means the composite sequence average energy is normalized to unity. The spreading sequence takes the value  $c_i^m \in \{-1, +1\}$ . The composite spread sequence  $v_i$  is the summation of  $M$  active users'  $i^{th}$  chip

$$v_i = \sum_{m=1}^M b^m c_i^m \quad i = 1, \dots, L \quad (1.3)$$

The rate of the symbols  $v_i$  is  $1/T$ , where  $T = L \cdot T_b$ . The composite sequence  $v_i$  is transmitted using the OFDM technique: each chip of  $v_i$  modulates a corresponding subcarrier branch,  $e^{(j2\pi f_i t)}$ . These branches are separated with their neighboring subcarriers by  $\Delta f$ , of which the minimum number leading to the closest possible spacing between subcarriers is  $\Delta f = \frac{1}{NT_b}$ , where  $N$  is the number of subcarriers. For simplicity, we assume  $L = N$ . However, it is important to note that  $L$  might take other values, so that the MC-CDMA system might operate over multiple non-contiguous frequency bands, as long as all the subcarriers are orthogonal to one another. The power spectrum of the transmitted signal is shown in Fig. 1.3. These subcarrier signals overlap each other on the spectrum. But since they are orthogonal over the symbol duration  $T$ , as long as the channel maintains the orthogonality, the signals can be recovered. In practice, the signal is generated by applying the inverse discrete Fourier Transform (IDFT), and a cyclic prefix is added at the output of the IDFT to protect the MC-CDMA signal from inter-symbol interference (ISI). At the receiver side, the cyclic prefix is removed before demodulating through DFT.

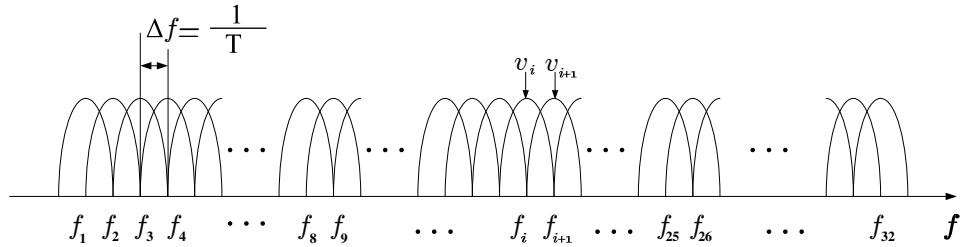


Figure 1.3: Signal structure of traditional MC-CDMA system

Assuming downlink transmission, the total transmitted signal of  $M$  users corresponds to:

$$w(t) = \sum_{i=1}^N v_i e^{(j2\pi(f_c+f_i)t)} q(t) = \sum_{i=1}^N \sum_{m=1}^M b^m c_i^m e^{(j2\pi(f_c+f_i)t)} q(t) \quad (1.4)$$

Where,  $f_i$  is the frequency of the  $i^{th}$  subcarrier. In a typical MC-CDMA system which operates over one contiguous frequency band,  $f_i = i\Delta f$ . However, it is important to note that  $f_i$  might take other values so that the MC-CDMA system might operate over multiple non-contiguous frequency bands, as long as all the subcarriers are orthogonal to each other.  $q(t)$  is the pulse shape which is an unit rectangular pulse in the interval of  $[0, T]$ .



### 1.6.2.2 Receiver

The receiver implementation for user 1 is shown in Fig. 1.4.

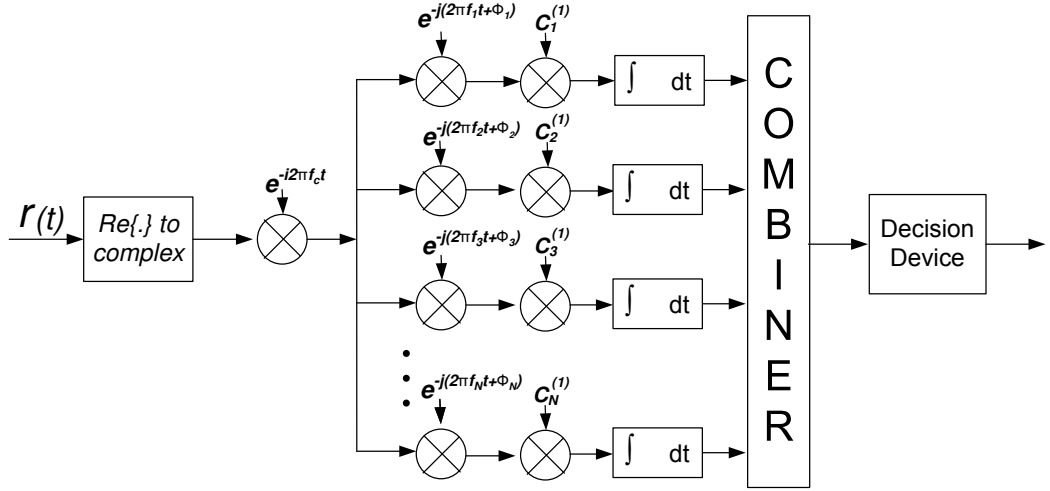


Figure 1.4: MC-CDMA receiver

The input of the receiver, impaired by the frequency offset is

$$r(t) = \sum_{i=1}^N \sum_{m=1}^M \alpha_i b^m c_i^m e^{j(2\pi(f_c + f_i + f_o)t + \theta_i)} q(t) + n(t) \quad (1.5)$$

where  $n(t)$  is the AWGN of zero mean and variance of  $\frac{N_0}{2}$ .  $\alpha_i$  and  $\theta_i$  are the path gain and phase shift variables, which are considered to be constant over  $[0, T]$  due to slow fading.  $f_o$  stands for the frequency offset brought in by the destroyed orthogonality between subcarriers.

After down converter, the carrier frequency is removed,

$$\begin{aligned} y(t) &= e^{-j2\pi f_c t} \cdot r(t) \\ &= \sum_{i=1}^N \sum_{m=1}^M \alpha_i b^m c_i^m e^{j(2\pi(i+\epsilon)\Delta f t + \theta_i)} q(t) + n(t) \end{aligned} \quad (1.6)$$

As we mentioned above, we take the value of  $f_i$  for contiguous frequency band,  $f_i = i\Delta f, i = 1, \dots, N$ .  $\epsilon$  is the normalized frequency offset:  $\epsilon = f_o/\Delta f$ , where  $f_o$  is the frequency offset and  $\Delta f$  is the subcarrier distance.

The output for the desired  $d^{th}$  user on the  $g^{th}$  subcarrier after the despreader and integration over time  $T$  is derived as follow

$$\begin{aligned}
y_g(t) &= e^{-(j2\pi f_g t + \theta_g)} \cdot y(t) \\
&= \left\{ \sum_{m=1}^M \alpha_g b^m c_g^m e^{j2\pi\epsilon\Delta f t} \right. \\
&\quad \left. + \sum_{m=1}^M \sum_{i \neq g}^N \alpha_i b^m c_i^m e^{j\{2\pi(i+\epsilon-g)\Delta f t + \theta_i - \theta_g\}} \right\} q(t) \\
&\quad + \eta_g
\end{aligned} \tag{1.7}$$

$$\begin{aligned}
z_g(t) &= c_g^d \cdot y_g(t) \\
&= \left\{ \alpha_g b^d e^{j2\pi\epsilon\Delta f t} \right. \\
&\quad + \alpha_g \sum_{m \neq d}^M b^m c_g^d c_g^m e^{j2\pi\epsilon\Delta f t} \\
&\quad + b^d \sum_{i \neq g}^N \alpha_i c_g^d c_i^d e^{j2\pi(i+\epsilon-g)\Delta f t} e^{j(\theta_i - \theta_g)} \\
&\quad \left. + \sum_{m \neq d}^M \sum_{i \neq g}^N \alpha_i b^m c_i^m c_g^m e^{j2\pi(i+\epsilon-g)\Delta f t} e^{j(\theta_i - \theta_g)} \right\} q(t) \\
&\quad + \eta_g
\end{aligned} \tag{1.8}$$

$$\begin{aligned}
D_g^d &= \frac{1}{T} \int_T z_g(t) dt \\
&= \alpha_g b^d S_0 \\
&\quad + \alpha_g \sum_{m \neq d}^M b^m c_g^d c_g^m S_0 \\
&\quad + b^d \sum_{i \neq g}^N \alpha_i c_g^d c_i^d e^{j(\theta_i - \theta_g)} S_{i-g} \\
&\quad + \sum_{m \neq d}^M \sum_{i \neq g}^N \alpha_i b^m c_g^d c_i^m e^{j(\theta_i - \theta_g)} S_{i-g} \\
&\quad + \eta_g \\
&= D e_g + I_g + J^d + J^m + \eta_g
\end{aligned} \tag{1.9}$$

Where,  $S_0$  and  $S_{i-g}$  are  $N$  complex weighting coefficients defined to simplify the analysis of ICI effect.  $S_{i-g}$  controls the level of ICI, which comes from signals transmitting on other subcarriers to the signal on the desired subcarrier. We will explain this in details next.  $D e_g$  stands for the desired output; term  $I_g$  is the

multiple access interference (MAI), which is from other users on the same chip with the desired user;  $J^d$  and  $J^m$  represent the interference from other chips caused by the desired user's signal and other users' signal respectively, which can be generally designated as inter carrier interference (ICI).

Next, a MLC (maximum likelihood combining) [15] scheme is used to create the decision variable for user  $d$ :

$$\begin{aligned}
D^d &= \sum_{g=1}^N U_g^d \cdot W_g \\
&= \sum_{g=1}^N W_g \cdot \alpha_g b^d S_0 \\
&\quad + \sum_{g=1}^N W_g \cdot \alpha_g \sum_{m \neq d}^M b^m c_g^d c_i^m S_0 \\
&\quad + \sum_{g=1}^N W_g \cdot b^d \sum_{i \neq g}^N \alpha_i c_g^d c_i^d e^{j(\theta_i - \theta_g)} S_{i-g} \\
&\quad + \sum_{g=1}^N W_g \cdot \sum_{m \neq d}^M \sum_{i \neq g}^N \alpha_i b^m c_g^d c_i^m e^{j(\theta_i - \theta_g)} S_{i-g} \\
&\quad + \eta
\end{aligned} \tag{1.10}$$

Where,  $W_g = \frac{\alpha_g}{(M-1)\alpha_g^2 + N_0/2}$ ;  $\eta_g$  denotes the noise term which is a Gaussian random variable with zero mean and double-sided power spectral density of  $N_0/2$ , the term  $\eta = \sum_{g=1}^N W_g \cdot \eta_g$  is also a Gaussian random variable. Finally, a hard decision is made basing on  $D^d$  for user  $d$ .

### 1.6.3 Effects of MAI and ICI

Equation 1.8 implies that, if  $\epsilon$  reduce to 0,  $\alpha_i = 1$  and  $\theta_i = 0$  for all subcarriers, then Eq. 1.8 reduces to  $z_g = b^d + \eta_g$ .

In [11], the effect of MAI in MC-CDMA system has been studied. We extend it to MLC receiver. The MAI due to multi-users sharing the same channels is given by

$$I^d = \sum_{g=1}^N W_g \cdot \alpha_i \sum_{m \neq d}^M b^m c_g^d c_i^m S_0 \tag{1.11}$$

which depends on both of the effects of fading channel and frequency offset.

[10], [11] and [16] have extensively studied the impact of frequency offset in MC-CDMA system. Especially, [10] has introduced the term  $S_{i-g}$  to indicate the complex weighting coefficients which are defined to

simplify the analysis of ICI effect.

$$S_{i-g} = \frac{\sin(\pi(i+\epsilon-g))}{\pi(i+\epsilon-g)} e^{j\pi(i+\epsilon-g)} \quad (1.12)$$

$S_{i-g}$  gives contribution from each of the  $N$  subcarriers to the desired subcarrier on ICI. The output of the desired part is also impaired by the effect of frequency which leads to a change in amplitude and phase, given by

$$S_0 = \frac{\sin(\pi\epsilon)}{\pi\epsilon} e^{j\pi\epsilon} \quad (1.13)$$

Let  $\mu_g$  be the decoded signal transmitted on the desired subcarrier, then

$$\mu_g = \alpha_g \sum_{m=1}^M b^m c_g^d c_g^m \quad (1.14)$$

and  $\nu_i$  be the signals transmitted on the other subcarriers, where,  $i \neq g$

$$\nu_i = \sum_{m=1}^M \alpha_i b^m c_i^m c_g^d e^{j(\theta_i - \theta_g)} \quad (1.15)$$

then  $D_g^d$  can be rewritten as

$$D_g^d = \mu_g S_0 + \sum_{i \neq g}^N \nu_i S_{i-g} + \eta_g \quad (1.16)$$

And the final decision variable is

$$\begin{aligned} D^d &= \sum_{g=1}^N W_g \cdot D_g^d \\ &= \sum_{g=1}^N W_g \cdot \left\{ \mu_g S_0 + \sum_{i \neq g}^N \nu_i S_{i-g} + \eta_g \right\} \end{aligned} \quad (1.17)$$

This shows that, the MC-CDMA signal has the same structure as OFDM system on the spectrum. The received signal consists of two parts, desired part and interference part. The desired part from  $\mu_i$  (where,  $i = g$ ) subject to the effect of  $S_0$  and is impaired by the summed components dependent on each of the values  $\nu_g$ , with the contribution of the coefficients as  $S_{i-g}$ .

Fig. 1.5 shows an example of the ICI coefficient for a 32-subcarrier system. The normalized frequency offset values are  $\epsilon = 0.2$  and  $\epsilon = 0.4$ . It is evident from Fig. 1.5 that as the value of frequency offset increases, the desired signal weakens, while the undesired part grows. In addition, the coefficient changes smoothly on most subcarriers, the difference between two adjacent subcarriers is small. The contribution of ICI in terms

of  $S_{i-g}$  depends on  $i - g$  which is the distance between subcarriers, the closest signals give comparatively larger portion.

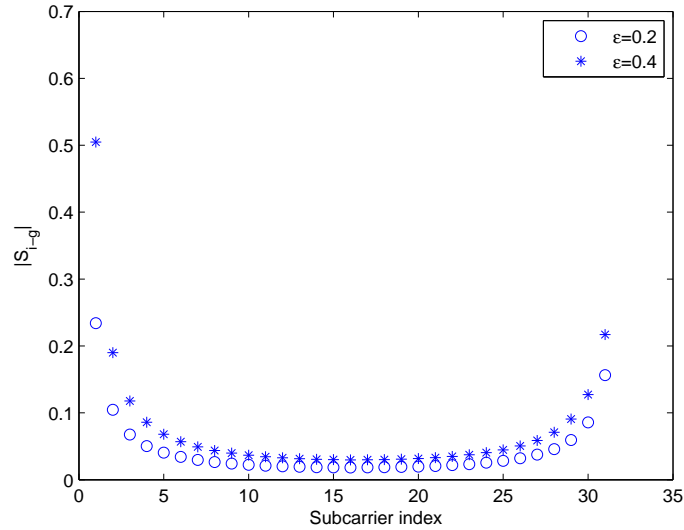


Figure 1.5: An example of  $|S_{i-g}|$  for  $N=32$ ,  $g=1$

#### 1.6.4 Simulation result

Fig. 1.6 and Fig. 1.7 show the BER performance of traditional MC-CDMA system in AWGN channel and frequency selective fading channel respectively. Fig. 1.8 and Fig. 1.9 show the BER performance of NC-MC-CDMA system with 128 active subcarriers on total  $N = 1024$  subcarriers in AWGN channel and frequency selective fading channel respectively. This is a simple Cognitive Radio communication environment.

From the simulation results we can see that, as the ratio of frequency offset grows, the system subjects to much severe interference. When the frequency offset grows to a high level, ( $\epsilon = 0.3$ ), the performance of the system degrades to an unbearable level. In addition, since the non-contiguous MC-CDMA systems has better frequency diversity, it has better performance than contiguous system in frequency selective fading channel. But the system performance does not have much difference in AWGN channel where the white gaussian noise and ICI are the only resources of performance degradation.

### 1.7 Previous ICI Cancelation Methods

[17] introduced a scheme combining on frequency division multiple access (FDMA) scheme and MC-CDMA, which can decrease the density of the transmitted signal without reducing the frequency diversity. It is shown

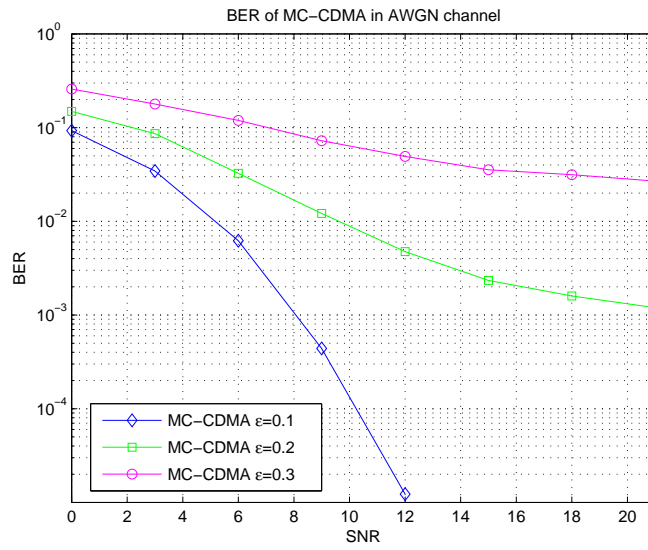


Figure 1.6: BER of MC-CDMA in AWGN channel

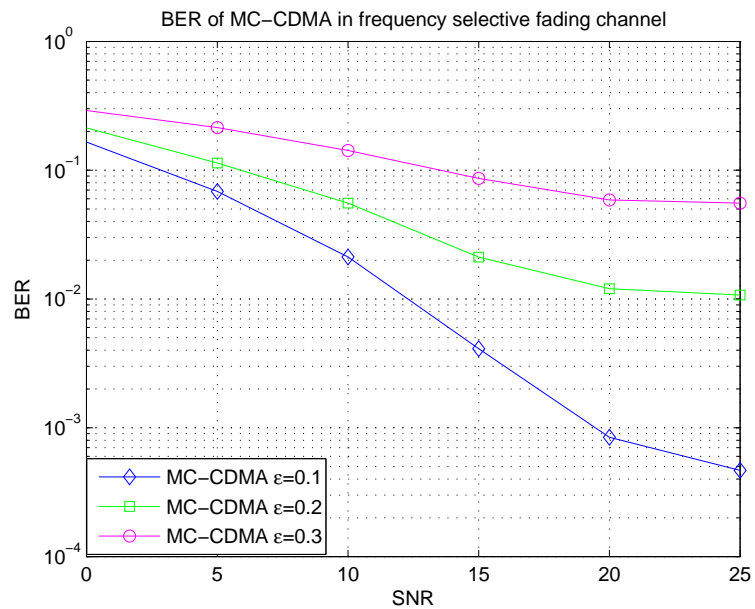


Figure 1.7: BER of MC-CDMA in frequency selective fading channel

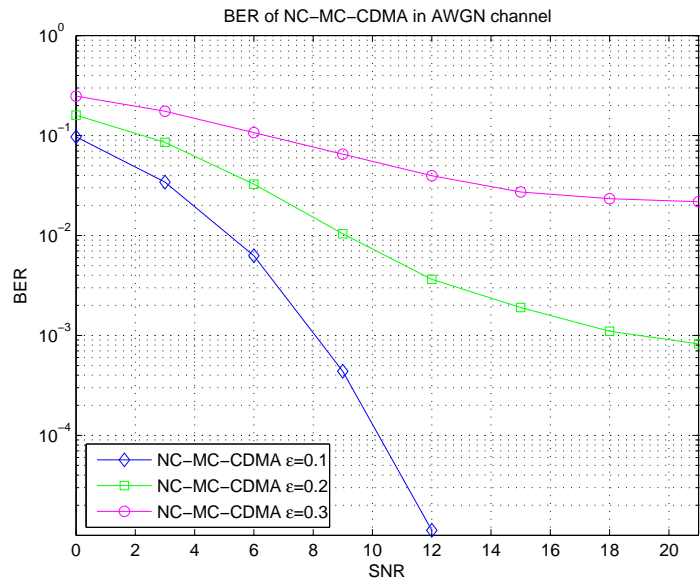


Figure 1.8: BER of non-contiguous MC-CDMA in AWGN channel

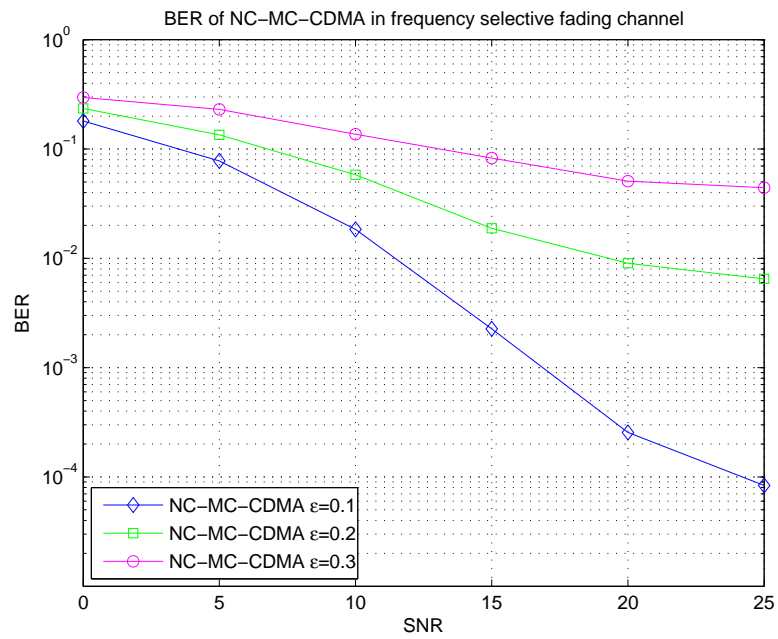


Figure 1.9: BER of non-contiguous MC-CDMA in frequency selective fading channel

that, the effect of MAI is lowered by this scheme, especially at lower system load. Furthermore, since the system computational complexity is low, a multi-user detector can be implemented to significantly improve the system performance.

On the other hand, ICI reduction schemes for OFDM have been investigated by many researchers [18]. Among them, ICI self-cancellation scheme developed in [19] offers significant ICI cancellation and BER performance improvement at little complexity increase. In the OFDM system, the scheme of ICI self-cancellation is to modulate the same data symbol onto a group of adjacent subcarriers with predefined weighting coefficients. In this way, the ICI on signals can be drastically diminished by each other within the subcarrier group [19]. As a direct result, the BER performance is significantly improved. Moreover, some frequency-domain coding methods can be used to achieve the ICI cancellation without reducing the data rate [20; 21].

## 1.8 Thesis Contribution

In this thesis, three schemes are discussed to attack the ICI problem. First, the ICI self-cancellation scheme is extended into MC-CDMA system, and bring the BER performance to a lower level. Then the FD-MC-CDMA scheme is extended into the ICI impaired MC-CDMA system to reduce the effect of ICI. Then these two schemes are further combined to improve the system BER performance. Simulation results over multipath fading channel are given and compared; the superiorities and deficiencies of each scheme are explained.

We further apply these schemes on non-contiguous OFDM and MC-CDMA systems, in simple Cognitive Radio communication environments and present the simulation results. These simulation results confirm the performance of these three schemes in reducing ICI in Cognitive Radio systems.

## 1.9 Thesis Outline

The thesis is organized as follow:

- In Chapter 2, 3 and 4, we develop three schemes to mitigate the effect of ICI problem: the self-cancellation scheme for MC-CDMA, the FD-MC-CDMA system, then these two schemes are combined to form the combinational scheme. Simulation results are presented in both AWGN channel and frequency selective fading channel.
- In Chapter 5, these three schemes are further applied to non-contiguous communication systems in Cognitive Radio environment. Simulation results are presented: these simulation results are presented in



both AWGN channel and frequency selective fading channel.

- In Chapter 6, the advantage and disadvantage of these three schemes are discussed.
- Chapter 7 presents the conclusion.

# Self ICI Cancellation Scheme

In this Chapter, the self ICI cancellation scheme is presented. The superiorities and deficiencies of this scheme are explained and compared.

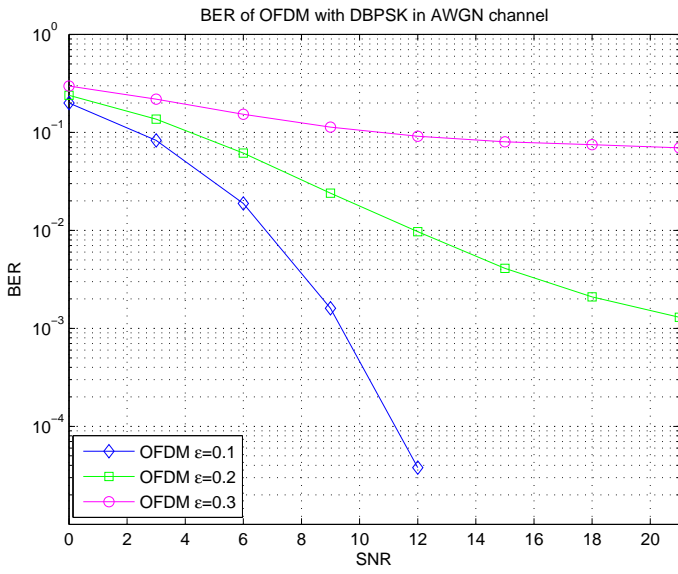
## 2.1 Background

Various methods have been developed in OFDM system to reduce its sensitivity of frequency offset, such as frequency-domain equalization, time-domain windowing and ICI self-cancellation scheme. Since the MC-CDMA systems have the same signal structure with OFDM system, these methods can be introduced into MC-CDMA systems to suppress ICI.

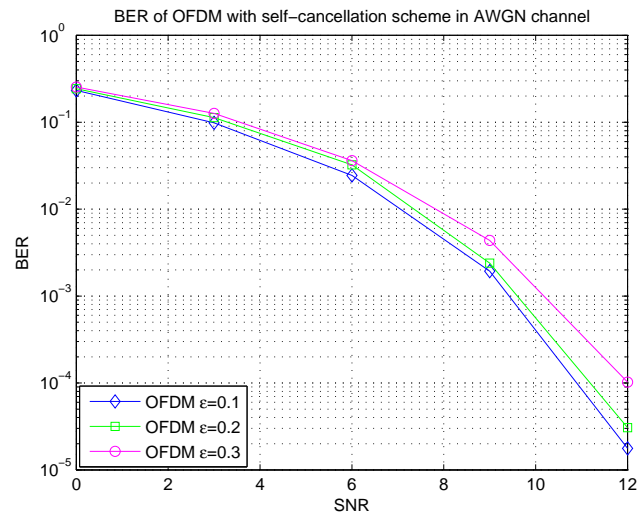
[19] developed an easy way to reduce the ICI. It maps the transmitted data onto adjacent subcarrier pairs rather than onto single subcarriers. In this way, system performance is improved by reducing the ICI coefficients.

Fig. 2.1 shows the system performance of OFDM system in AWGN channel with and without ICI self-cancellation scheme respectively. In this simulation, the signals are transmitted on non-contiguous subcarriers as we discussed above, which is a simple model of Cognitive Radio communication environment. Fig. 2.2 shows the performance of the same system in frequency selective fading channel. From the simulation result we can see that, this scheme can suppress the Inter-carrier Interference very well.

Here we notice, since the ICI self-cancellation scheme transmits the same signal twice on adjacent subcarriers, the transmission rate is cut to half of the original system. To maintain the transmission rate, the author of [19] needs to upgrade the modulation scheme to a higher order (from BPSK to QPSK). In addition, this scheme may introduce severe phase offset. The author also applies differential coding on frequency to overcome this problem.

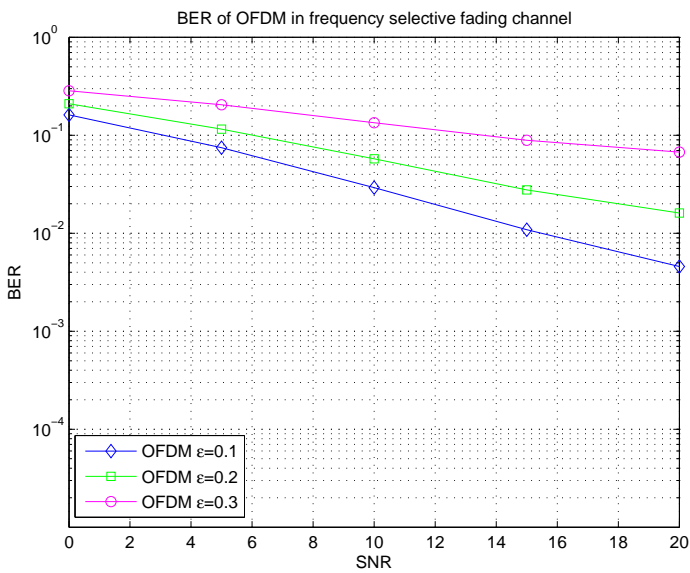


(a) OFDM system in AWGN channel

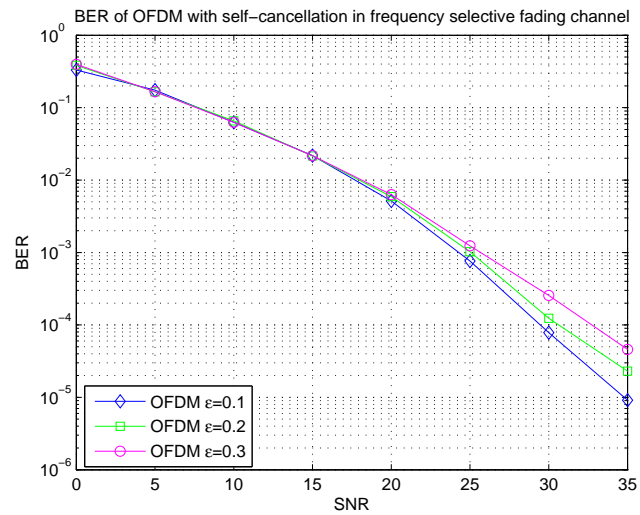


(b) OFDM with self-cancellation in AWGN channel

Figure 2.1: BER performance versus SNR of non-contiguous OFDM in AWGN channel



(a) OFDM system in frequency selective fading channel



(b) OFDM with self-cancellation in frequency selective fading channel

Figure 2.2: BER performance versus SNR of non-contiguous OFDM in frequency selective fading channel

## 2.2 Implementation

Here we extend this ICI self-cancellation scheme into MC-CDMA system to suppress the ICI. At transmitter side, the summation of all the users' signal is transmitted on adjacent pairs, which means: the signals transmitted on odd subcarriers are  $v_i$  and its counterpart  $-v_i$  are transmitted on even subcarriers. In this way,  $v_2 = -v_1, v_4 = -v_3, \dots, v_N = -v_{N-1}$ , as shown in Fig. 2.3

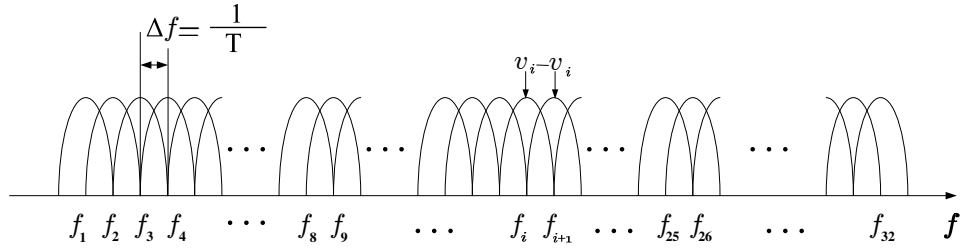


Figure 2.3: Signal structure of MC-CDMA system with ICI self-cancellation scheme

Then the decoded signal on the 1<sup>st</sup> subcarrier can be rewritten as

$$\begin{aligned}
 D_1^d &= \mu_1(S_0 - S_1) + \nu_3(S_2 - S_3) + \dots + \eta_1 \\
 &= \mu_1 S_0' + \sum_{i=3, \text{odd}}^{N-1} \nu_i S_{i-g}' + \eta_1
 \end{aligned} \tag{2.1}$$

Eq. 2.1 shows that, the ICI no longer depends on the coefficients  $S_{i-g}$ , but now depends on the difference between the coefficients on adjacent subcarriers  $S_{i-g}' = S_{i-g} - S_{i-g+1}$ . Since as we discussed in section 1.6.3, the difference between adjacent subcarriers is small, the ICI coefficients are now reduced.

In addition, the received values are subtracted pairwise, which is implemented by taking the opposite values of the signals on even-numbered subcarriers, and then sum them together with the signals on the

odd-numbered subcarriers. This makes the decoded signal for user  $d$  change to

$$\begin{aligned}
D^{td} &= \sum_{g=\text{odd}}^{N-1} W_g \cdot (D_g^{td} - D_{g+1}^{td}) \\
&= \sum_{g=\text{odd}}^{N-1} W_g \{(D_1^{td} - D_2^{td}) + (D_3^{td} - D_4^{td}) + \dots + \eta_g\} \\
&= \sum_{g=\text{odd}}^{N-1} W_g \{\mu_1(-S_{-1} + 2S_0 - S_1) + \nu_3(-S_{-1} + 2S_2 - S_3) \\
&\quad + \dots + \nu_1(-S_{-3} + 2S_{-2} - S_{-1}) + \mu_3(-S_{-1} + 2S_0 - S_1) \\
&\quad + \dots + \eta_g\} \\
&= \sum_{g=\text{odd}}^{N-1} W_g \{\mu_g S_0'' + \sum_{i=\text{odd}, i \neq g}^{N-1} \nu_i S_{i-g}''\} + \eta
\end{aligned} \tag{2.2}$$

Here  $\mu_i$  stands for the desired part, where  $i = g$ . The ICI now depends on the further reduced coefficients  $S''$ . For example, on the 1<sup>st</sup> subcarrier, the ICI from the closest subcarrier depends on  $(-S_{-1} + 2S_2 - S_{-3})$ .

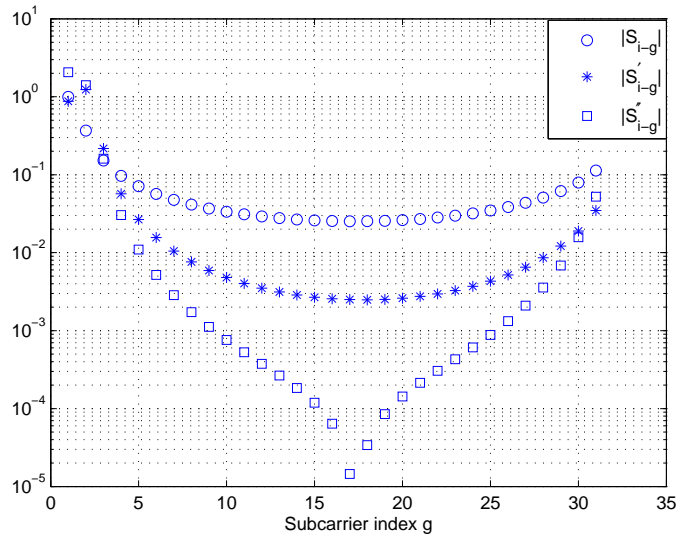


Figure 2.4: A comparison between  $|S(i-g)|$ ,  $|S'(i-g)|$  and  $|S''(i-g)|$ ,  $N = 32$

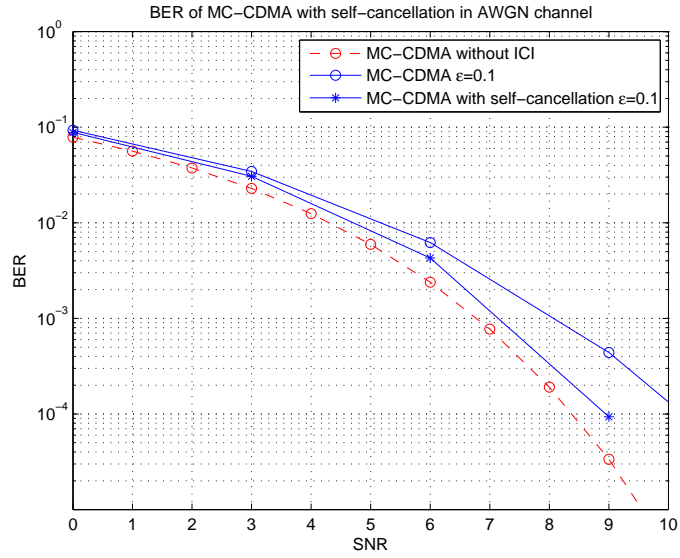
Fig. 2.4 shows the comparison of  $|S_{i-g}|$ ,  $|S'_{i-g}|$  and  $|S''_{i-g}|$  in logarithm scale. On the majority subcarriers, the value of  $|S'_{i-g}|$  is much smaller than the value of  $|S_{i-g}|$ , and the value of  $|S''_{i-g}|$  is much smaller than  $|S'_{i-g}|$ . The decreased value of ICI coefficients leads to better performance of the system.

Notice that, this scheme transmits the same signal twice on two adjacent subcarriers, the channel capacity reduces to half of traditional MC-CDMA system.

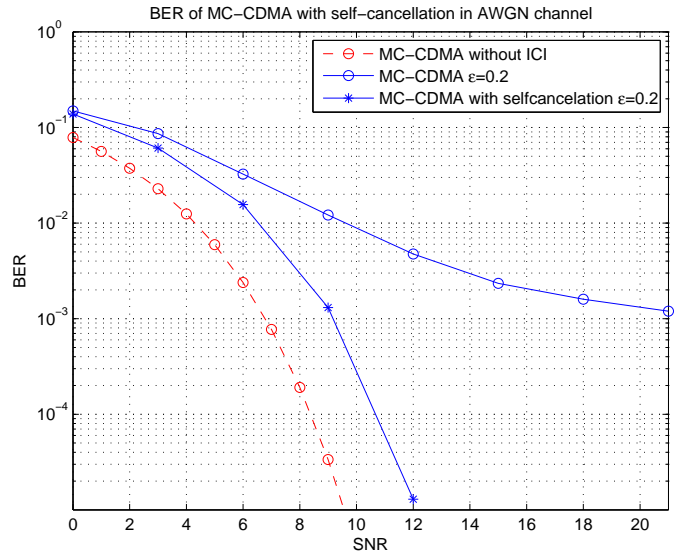
## 2.3 Simulation Result and Summary

Fig. 2.5 and Fig. 2.6 shows the BER performance comparison of traditional MC-CDMA system and the system employing the self ICI cancelation scheme. Fig. 2.5 shows the numerical result of the system in AWGN channel when  $\epsilon = 0.1, 0.2$  and  $0.3$ . Fig. 2.6 shows the result in frequency selective fading channel when  $\epsilon = 0.1, 0.2$  and  $0.3$ . Notice that, since the self-cancelation scheme in fact is doing repetition of the same signal, we lowered the bit energy to half of its original value, which yields a fair comparison between them. For fair comparison, both the traditional system and the system applying the new scheme are 'half-loaded'. Take a  $N = 32$  system for example, there are only 16 users in the system.

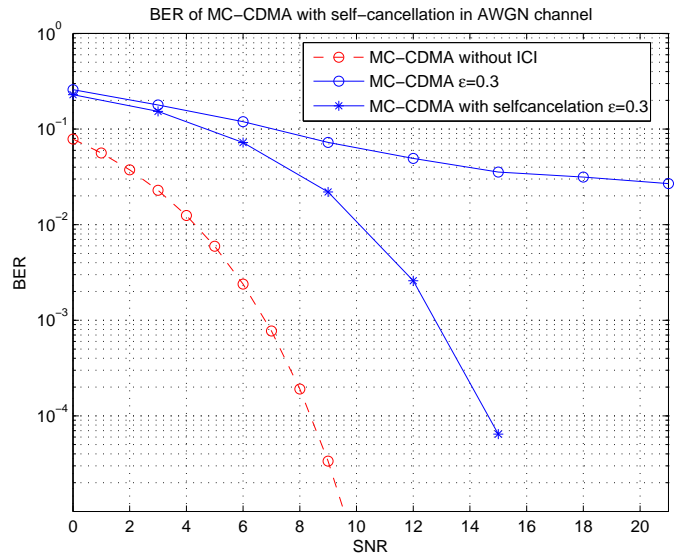
It is evident that as the Doppler spread grows, (from  $\epsilon = 0.1$  to  $\epsilon = 0.3$ ), the BER performance of the traditional MC-CDMA system degrades significantly, while the BER of the system employing self ICI cancelation scheme only degrades slightly. The self ICI cancelation scheme works well both in the AWGN channel with frequency offset and in the frequency selective fading channel with frequency offset. However, we can also notice that, since the ICI self-cancelation scheme is intended to minimize the system ICI, it has more performance gain in the system with high ratio of frequency offset.



(a) BER comparison  $\epsilon = 0.1$

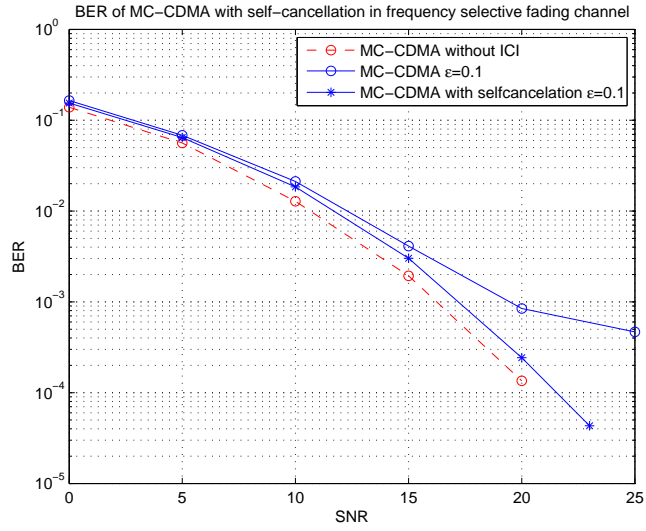


(b) BER comparison  $\epsilon = 0.2$

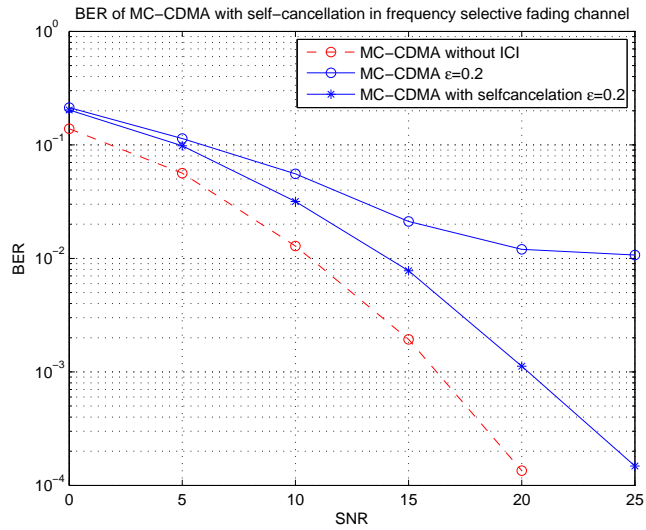


(c) BER comparison  $\epsilon = 0.3$

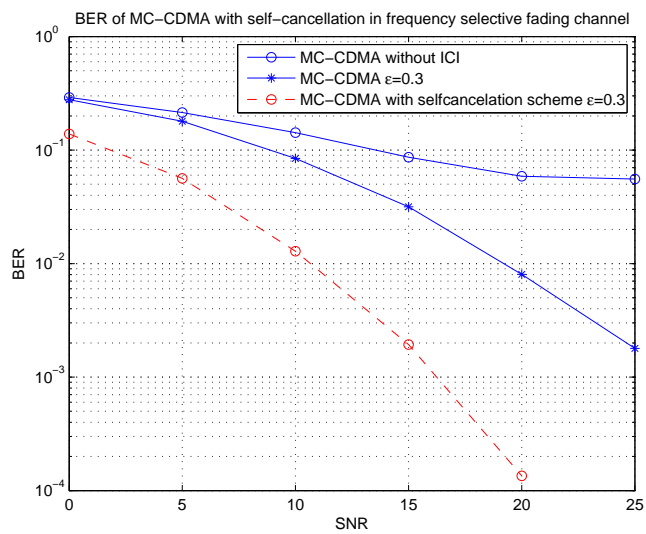
Figure 2.5: BER performance versus SNR in AWGN channel



(a) BER comparison  $\epsilon = 0.1$



(b) BER comparison  $\epsilon = 0.2$



(c) BER comparison  $\epsilon = 0.3$

Figure 2.6: BER performance versus SNR in frequency selective fading channel



# Frequency Division Scheme

In this Chapter, the frequency division scheme is presented. The superiorities and deficiencies of this scheme are explained and compared.

## 3.1 Background

[17] introduced a novel MC-CDMA system combining with FDMA structure, called FD-MC-CDMA system. This structure can reduce the number of users in each subcarrier set, which leads to lower MAI. Due to the large frequency separation, the frequency diversity is also achieved. In addition, since the signal density is distributed, we can also expect it to bring down the ICI. Moreover, since the computational load is decreased, maximum likelihood multi-user detector (ML MUD) can be used to improve the BER performance significantly.

The FD-MC-CDMA system works in this way: rather than allocating all the users on each subcarrier, this scheme allocates each users' transmitting power on only  $P$  subcarriers for a  $P$ -fold coherent channel. This is enough for the system to exploit the frequency diversity. In this way, instead of letting all the users share the same subcarriers as what we did in the traditional MC-CDMA system, this scheme groups the users into several sets and assign each set with a different subcarrier group. In this way, both the number of users on each subcarrier and the number of subcarriers each user possesses are reduced.

## 3.2 Implementation

For implementation, the spreading code  $c_i^m$  is updated with one more key,

$$c_i^m = \begin{cases} \pm 1 & \text{if } i \in I_1^m, I_2^m, \dots, I_P^m \\ 0 & \text{else} \end{cases}$$

where  $i$  indicates the  $i^{\text{th}}$  chip of user  $m$ 's spreading sequence,  $I_1^m = \lfloor (m-1)/P \rfloor + 1$ ,  $I_2^m = \lfloor (m-1)/P \rfloor + (N/P) + 1, \dots, I_P^m = \lfloor (m-1)/P \rfloor + (P-1) \cdot (N/P) + 1$ . For example, for a  $P=4$ -fold diversity channel with  $N=32$

subcarriers, user 1, 9, 17 and 25 are assigned subcarrier set 1, which means,  $\{c_i^{(m)} \in \{-1, +1\} | i=1, 9, 17, 25\}$ , and  $\{c_i^{(m)} = 0 | i \neq 1, 9, 17, 25\}$ ; user 2, 10, 18 and 26 spread over subcarrier set 2, that is  $\{c_i^{(m)} \in \{-1, +1\} | i=2, 10, 18, 26\}$ , and  $\{c_i^{(m)} = 0 | i \neq 2, 10, 18, 26\}$ , and so on. This is like masking the original Hadamard-Walsh code with a sequence of ones and zeros, which blinds out the unused subcarriers, and leaves only one subcarrier in each fold. For each set of subcarrier, the orthogonality of Hadamard-Walsh code is not destroyed.

The signal structure of this scheme is shown in Fig. 3.1

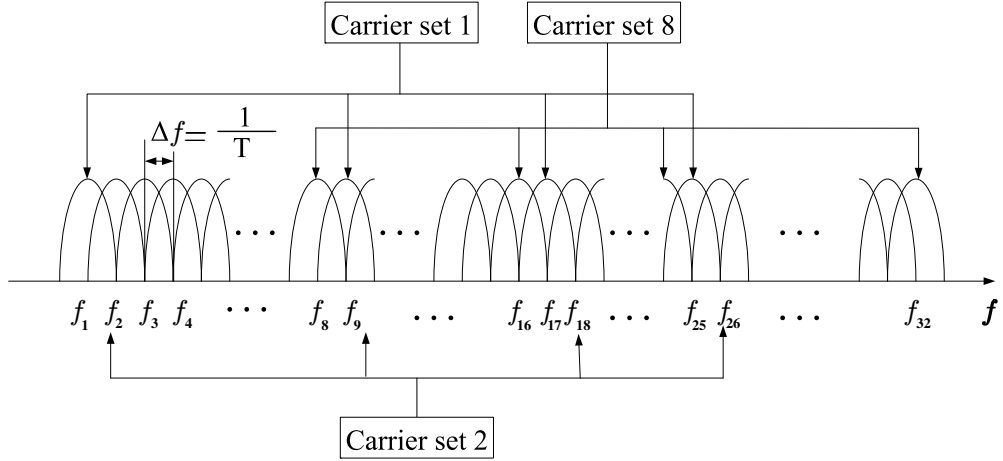


Figure 3.1: Signal structure of FD-MC-CDMA: N=32 carriers, M=4 fold diversity

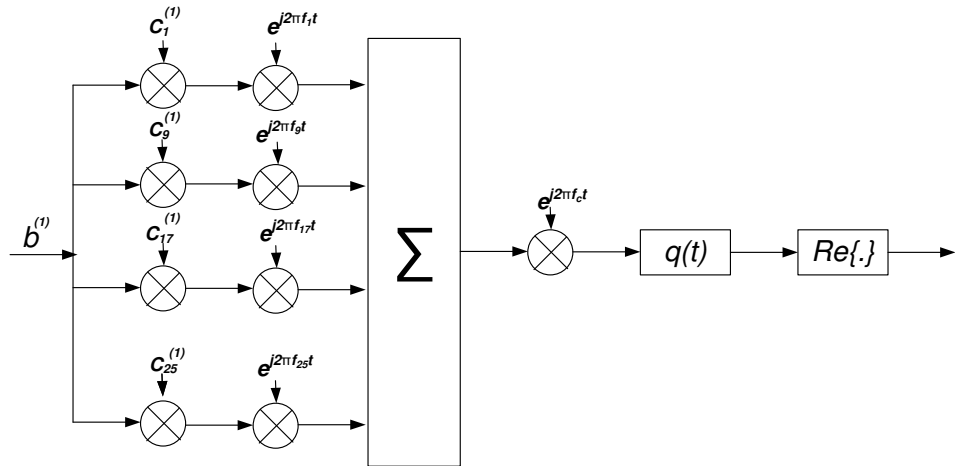


Figure 3.2: FD-MC-CDMA transmitter model for user 1

The transmitter of user 1 is shown in Fig. 3.2. Here we assume a 4-fold frequency channel of  $N=32$  subcarriers. Then the number of subcarriers in each set is  $P=4$ . Therefore, the number of users in each set is up to  $K = \lfloor \frac{M-1}{N/P} \rfloor + 1$  and  $K \ll M$  when the system is heavily loaded. Now a single data symbol is replicated 4 times and is multiplied by corresponding spreading sequence, then modulated to subcarrier branches. This

is same as in traditional MC-CDMA system. The new separation between two adjacent subcarriers in the same set is  $8\Delta f$ . Assuming downlink transmission, with  $M$  active users in total but  $K$  active users in each subcarrier set, the transmitted signal on baseband is:

$$w(t) = \sum_{i=1}^N v_i e^{(j2\pi f_i t)} = \sum_{i=1}^N \sum_{m=1}^K b^m c_i^m e^{(j2\pi f_i t)} q(t) \quad (3.1)$$

This transmitter can also be implemented by an IDFT system followed by a D/A (digital to analog) converter for implementing the multi-carrier mixer and combiner.

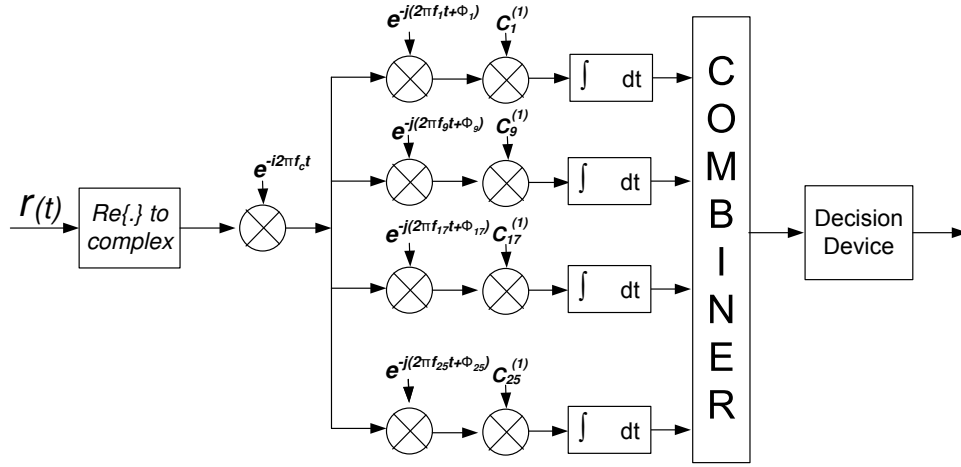


Figure 3.3: FD-MC-CDMA receiver model for user 1

Fig. 3.3 is the concept structure of FD-MC-CDMA receiver. For comparison, we still assume downlink transmission in a frequency selective fading channel with frequency offset  $f_o$ , same with what it is assumed in traditional MC-CDMA transmitting system. The received signal with up to  $K$  active users in each subcarrier set is

$$r(t) = \sum_{i=1}^N \sum_{m=1}^K \alpha_i b^m c_i^m e^{j(2\pi(f_c + f_i + f_o)t + \theta_i)} q(t) + n(t) \quad (3.2)$$

where,  $\alpha_i$  is the fading gain and  $\theta_i$  is the phase offset on the  $i^{th}$  subcarrier due to the channel fading,  $n(t)$  is additive white Gaussian noise (AWGN). Notice that for user  $m$ ,  $c_i^m$  is non-zero in only  $P$  subcarriers.

Fig. 3.3 shows the concept of user 1's receiver in an FD-MC-CDMA system. In practice, this receiver can also be implemented by simply applying DFT operation. As shown in the structure flow, the received signal is first decomposed into  $P$  information-bearing carriers and are multiplied by user 1's spreading code. The  $g$ th subcarrier generates

$$\begin{aligned}
D_g^1 &= \frac{1}{T} \int_T c_g^1 r(t) e^{-j2\pi(f_c+f_g)t+\theta_g} dt \\
&= \alpha_g b^1 S_0 \\
&+ \alpha_g \sum_{m \neq 1}^K b^m c_g^1 c_g^m S_0 \\
&+ b^1 \sum_{i \neq g}^N \alpha_i c_i^1 c_i^1 e^{j(\theta_i - \theta_g)} S_{i-g} \\
&+ \sum_{m \neq 1}^K \sum_{i \neq g}^N \alpha_i b^m c_g^d c_i^m e^{j(\theta_i - \theta_g)} S_{i-g} \\
&+ \eta_g
\end{aligned} \tag{3.3}$$

There are up to  $K$  users in the first carrier set, and  $\eta_g$  represent the Gaussian noise (perfect phase tracking and removal is assumed in Eq. 3.3).

The number of active users in each subcarrier is limited to up to  $K$ , in this example  $K=4$ . Comparing to up to 32 users in each subcarrier for traditional MC-CDMA system, the system complexity is substantially decreased, as well as the interfering users on other subcarriers. At the combiner, the ML multi-user detector is employed. It was treated as too complex to implement in traditional MC-CDMA system, since it requires the complexity increasing exponentially with the growth of the number of interfering users. For example, in traditional MC-CDMA, in case of a fully loaded system, the complexity for ML MUDs is on the order of  $2^{M-1}$  (e.g.,  $M=32$ ,  $2^{M-1}=2.1475 * 10^9$ ). However, in the FD-MC-CDMA system, since the number of interfering users is decreased, the computational complexity is reduced to a reasonably low level, which is on the order of  $2^{K-1}$  (e.g.,  $K=4$ ,  $2^{K-1}=8$ ).

Using the Maximum Likelihood criteria, assuming  $\vec{D}^1 = (D_{I_1^1}^1, D_{I_2^1}^{(1)}, \dots, D_{I_P^1}^1)$  is known via appropriate estimation algorithm. The optimal MUD for user 1 corresponds to

$$\log_e P(\vec{D}^1 | b^1 = 1) \geq \log_e P(\vec{D}^1 | b^1 = -1) \tag{3.4}$$

where

$$\begin{aligned}
& \log_e P(\vec{D}^1 | b^1) \\
&= \sum_{i \in I_1^1, I_2^1, \dots, I_P^1} \log_e P(D_i^1 | b^1) \\
&= \sum_{\vec{b}^{U_1}} \log_e \left[ P(\vec{b}^{U_1}) \cdot \sum_{i \in I_1^1, I_2^1, \dots, I_P^1} P(D_i^1 | \vec{b}^{U_1}, b^1) \right]
\end{aligned} \tag{3.5}$$

$U_1$  is a set of up to  $K$  users in the first carrier set,  $\vec{b}^{U_1}$  represents the possible bits of users in  $U_1$  excluding user 1, and  $\sum_{\vec{b}^{U_1}}$  represents the sum over all the bit vectors  $\vec{b}^{U_1}$ .

In Eq. 3.5, we treat MAI and ICI as deterministic quantity ( typical of MUD reception). Using Eq. 3.4 and Eq. 3.5,

$$\begin{aligned}
& \sum_{\vec{b}^{U_1} g \in I_1^1, I_2^1, \dots, I_P^1} \sum_{i \in I_1^1, I_2^1, \dots, I_P^1} \left( r_g^1 - \left( \alpha_g + \sum_{i \in I_1^1, I_2^1, \dots, I_P^1, m \in U_1, m \neq 1} \alpha_i \sum b^m c_i^m c_i^1 \right) \right)^2 \\
& \geq \\
& \sum_{\vec{b}^{U_1} g \in I_1^1, I_2^1, \dots, I_P^1} \sum_{i \in I_1^1, I_2^1, \dots, I_P^1} \left( r_g^1 - \left( -\alpha_g + \sum_{i \in I_1^1, I_2^1, \dots, I_P^1, m \in U_1, m \neq 1} \alpha_i \sum b^m c_i^m c_i^1 \right) \right)^2
\end{aligned} \tag{3.6}$$

This equation can be rewritten as

$$\sum_{\vec{b}^{U_1}} f_1(\vec{b}^{U_1}) \geq \sum_{\vec{b}^{U_1}} f_2(\vec{b}^{U_1}) \tag{3.7}$$

where  $f_1(\vec{b}^{U_1})$  refers to the inner sum on the left hand side of Eq. 3.6 and  $f_2(\vec{b}^{U_1})$  refers to the corresponding sum on the right hand side.

Equation 3.7 is solved by computing each term in each sum and then determine which one is smaller (finding the most closed one to the decision variable). Take  $P=4$  user-set for example: 3 interfering users are on the same subcarrier with the desired one. A total of 16 terms are computed (8 terms for the function  $f_1(\vec{b}^{U_1})$  and 8 for  $f_2(\vec{b}^{U_1})$ ). Furthermore, if the MUD receiver is intended to detect only user1's bit, since the spreading codes of other users are unknown, the number of terms evaluated in the calculation of  $f(\cdot)$  increases (because it requires averaging each term over possible spreading codes). The total number of terms computed in this case is  $2^{K_1} \cdot \binom{P-1}{K_1-1}$ , where  $K_1$  is the total number of active users in  $U_1$ . Notice that,

to implement the optimal multiuser detector, the following information is required: (1) the number of active users; (2) estimates of channel gains ( $\alpha_i^l$ s); (3) estimates of phase offsets ( $\phi_i^l$ s). This is consistent with the requirement of most traditional MC-CDMA receivers.

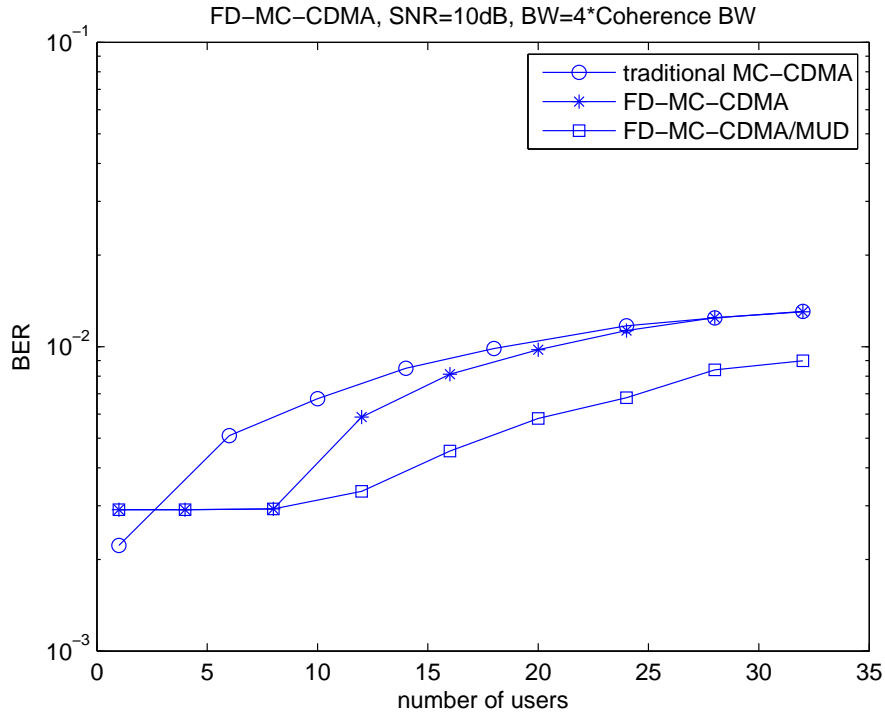


Figure 3.4: BER performance of FD-MC-CDMA for fixed SNR=10dB

### 3.3 Simulation results and Summary

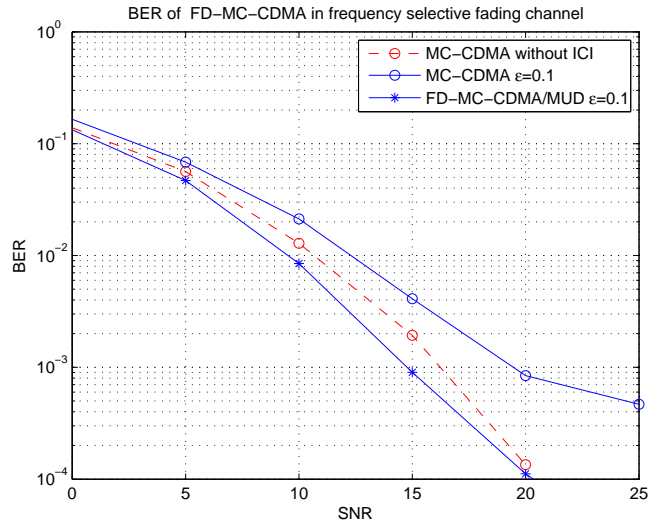
Fig. 3.4 shows the performance comparison of MC-CDMA, FD-MC-CDMA and FD-MC-CDMA with MUD, in terms of average bit error rate (BER) versus number of users, at a fixed SNR of 10dB.  $\epsilon = 0$  means no frequency offset and MAI is the only interference. By using the power allocating scheme described above, the MAI can be minimized. When the number of active users is less than 8, each user is allocated on a unique subcarrier set. Zero MAI is experienced in this system and the performance of FD-MC-CDMA and FD-MC-CDMA/MUD is identical. This results in the 'flat line' in Fig. 3.4 when  $M \leq 8$ . As the number of users grows beyond 8, both the FD-MC-CDMA and FD-MC-CDMA/MUD systems go through from that of no interfering users to that of some other interfering users in each subcarrier set. Here the systems begin to experience the MAI, the performance of both the FD-MC-CDMA and FD-MC-CDMA/MUD start to degrade, and the system with MUD begins to show its improvement over FD-MC-CDMA. Especially when  $M$  grows beyond 24, the FD-MC-CDMA system bears 2 – 3 interfering users on each subcarrier set, and the perfor-

mance approaches the traditional MC-CDMA system, and the performance gain of FD-MC-CDMA/MUD shows the advantage of MUD at this point.

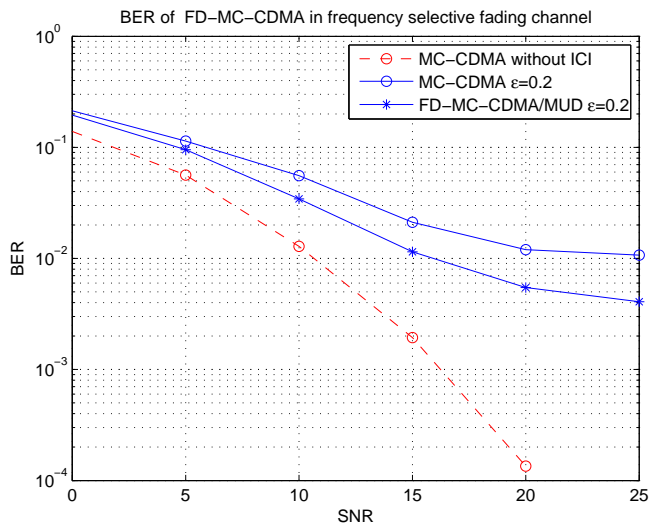
The performance of traditional MC-CDMA system and FD-MC-CDMA system with MUD are compared in Fig. 3.5, where  $\epsilon = 0.1$ ,  $\epsilon = 0.2$  and  $\epsilon = 0.3$  respectively. Here, signals are transmitted contiguously,  $N = 32$ . The FD-MC-CDMA/MUD system exploits the  $P = 4$ -fold frequency diversity by allocating each user on  $P = 4$  non-contiguous subcarriers, with  $N/P = 8$  subcarrier sets. For fair comparison, both the traditional system and the system applying the new scheme are 'half-loaded'. Take a  $N = 32$  system for example, there are only 16 users in the system.

It is evident from the result that as the Doppler spread grows, (from  $\epsilon = 0.1$  to  $\epsilon = 0.3$ ), the BER performance of both the traditional MC-CDMA system and FD-MC-CDMA/MUD degrade. But the FD-MC-CDMA/MUD outperforms the traditional system by more than  $5dB$  performance when  $\epsilon = 0.1$  at  $BER = 10^{-3}$  level. Also notice that, this scheme performs better at an environment when frequency offset is at a relatively low level.

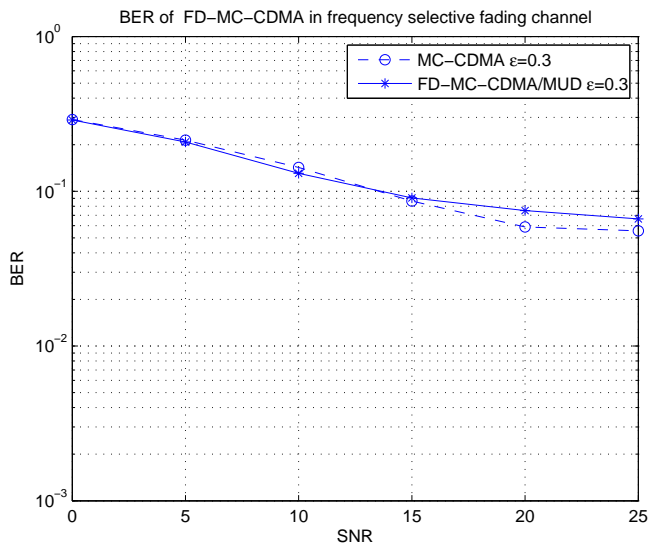
The above two schemes have their own superiorities and deficiencies respectively. To abate the effect of each scheme's deficiency and augment the superiorities, these two schemes are further combined together.



(a) BER comparison  $\epsilon = 0.1$



(b) BER comparison  $\epsilon = 0.2$



(c) BER comparison  $\epsilon = 0.3$

Figure 3.5: BER performance versus SNR in frequency selective fading channel



# Combinational Scheme with FD-MC-CDMA and ICI Self-cancelation Scheme

To compensate the disadvantage of the above mentioned two schemes and further improve the system performance, we develop a scheme which is the combination of the above two schemes.

## 4.1 Implementation

In this combinational scheme, the system has the similar structure with the FD-MC-CDMA system. The difference is that it transmits signals on the odd numbered carrier sets, and transmits their opposite values on the even numbered carrier sets. For example, on the first subcarrier set,  $v_i^1$  is transmitted:

$$v_i^1 = \sum_{m \in U'_1} b^m c_i^{2m-1} \quad i = 1, 9, 17, 25. \quad (4.1)$$

On the second subcarrier set,  $v_i^2$  is transmitted, which is:

$$v_i^2 = \sum_{m \in U'_1} -b^m c_i^{2m} = -v_i^1 \quad i = 2, 10, 18, 26. \quad (4.2)$$

Notice that, in this way, the channel capacity is cut to half of the traditional MC-CDMA system.  $U'_1$  is a set of up to  $K$  users on the first subcarrier set,  $K = \lfloor \frac{M-1}{N/2P} \rfloor + 1$ . Take  $N = 32, P = 4$  for example, if fully loaded,  $m \in U'_1, m = [1, 5, 9, 13]$ . The spreading code is contributed as follow:

$$c_i^m = \begin{cases} \pm 1 & \text{if } i \in I_1^m, I_2^m, \dots, I_P^m \\ 0 & \text{else} \end{cases}$$

To all the users in a specific subcarrier set, they are assigned a group of spreading code, which is a set of

length  $P$  Hadamard-Walsh code with zeros inserted in between these non-zero codes. Between every two subcarrier sets, although they are sharing the similar Hadamard-Walsh code set, they are allocated on different subcarriers separated by orthogonality on frequency. Thus, the orthogonality between different subcarrier sets is maintained.

The signal structure is similar with the MC-CDMA system with ICI self-cancellation scheme, with only up to  $K$  users on each subcarrier, instead of  $M$  users as what it is in traditional system. The signal structure is shown in Fig. 4.1

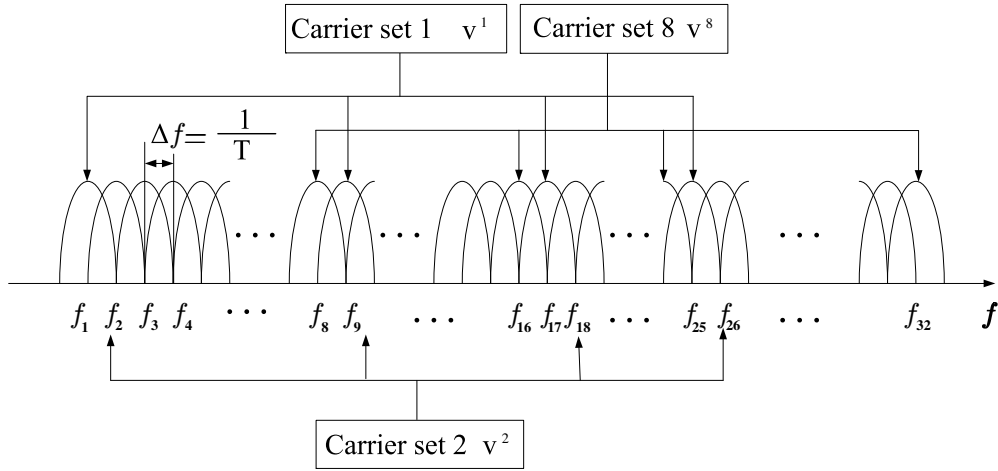


Figure 4.1: MC-CDMA transmitter

After going through the frequency selective fading channel, the received signal impaired by frequency offset is:

$$\begin{aligned}
 r(t) = & \left\{ \sum_{i \in \text{odd}}^N \sum_{m=1}^K \alpha_i b^m c_i^m e^{j(2\pi(f_c + f_i + f_o)t + \theta_i)} \right. \\
 & \left. + \sum_{i \in \text{even}}^N \sum_{m=1}^K -\alpha_i b^m c_i^m e^{j(2\pi(f_c + f_i + f_o)t + \theta_i)} \right\} q(t) + n(t)
 \end{aligned} \tag{4.3}$$

There for, the decoded signal on the 1<sup>st</sup> subcarrier for user  $d$  can be re-written as follow

$$\begin{aligned}
 D_1^d &= \frac{1}{T} \int_T c_g^d r(t) e^{-j2\pi(f_c + f_g)t + \theta_g} dt \\
 &= \mu_1(S_0 - S_1) + \nu_3(S_2 - S_3) + \dots + \eta_1 \\
 &= \mu_1 S'_0 + \sum_{i=3, \text{odd}}^{N-1} \nu_i S'_{i-g} + \eta_1
 \end{aligned} \tag{4.4}$$

where,  $\mu_1$  is the decoded signal transmitted on the 1<sup>st</sup> subcarrier,

$$\mu_1 = \alpha_1 \sum_{m=1}^K b^m c_1^d c_1^m \quad (4.5)$$

and  $\nu_i$  are the signals transmitted on the other subcarriers, where,  $i \neq 1$

$$\nu_i = \alpha_i \sum_{m=1}^K b^m c_i^m c_1^d e^{j(\theta_i - \theta_1)} \quad (4.6)$$

The coefficients become  $S'_{i-g} = S_{i-g} - S_{i-g+1}$ , which are less than the original coefficients as discussed in section 1.6.3. Furthermore, the number of interfering users on each subcarrier is reduced. All of these result in better performance.

To further improve the performance, at the receiver side, the received signals on even subcarrier sets are taken opposite value, and added to the odd subcarrier sets. Then the decision variable becomes

$$\begin{aligned} D^d &= \sum_{g=odd}^{N-1} W_g \cdot (D'_g{}^d - D'_{g+1}{}^d) \\ &= \sum_{g=odd}^{N-1} W_g \{(D'_1{}^d - D'_2{}^d) + (D'_3{}^d - D'_4{}^d) + \dots + \eta_g\} \\ &= \sum_{g=odd}^{N-1} W_g \{\mu_1(-S_{-1} + 2S_0 - S_1) + \nu_3(-S_1 + 2S_2 - S_3) \\ &\quad + \dots + \nu_1(-S_{-3} + 2S_{-2} - S_{-1}) + \mu_3(-S_{-1} + 2S_0 - S_1) \\ &\quad + \dots + \eta_g\} \\ &= \sum_{g=odd}^{N-1} W_g \{\mu_g S''_0 + \sum_{i=odd, i \neq g}^{N-1} \nu_i S''_{i-g}\} + \eta \end{aligned} \quad (4.7)$$

The ICI now depends on the further reduced coefficients  $S''_{i-g}$ . For example, on the 1<sup>st</sup> subcarrier, the ICI from the closest subcarrier depends on  $(-S_1 + 2S_2 - S_{-3})$ .

Especially when there are less than 4 active users in our example system ( $N = 32$ ,  $P = 4$ ), the number of users in each subcarrier set is  $K = 1$ , which means there is no MAI in the system. Moreover, the power of interfering source from other subcarriers is lower than traditional system. Accordingly, the performance is substantially improved.

Since the system maintains the computational simplicity, we can apply the ML MUD.

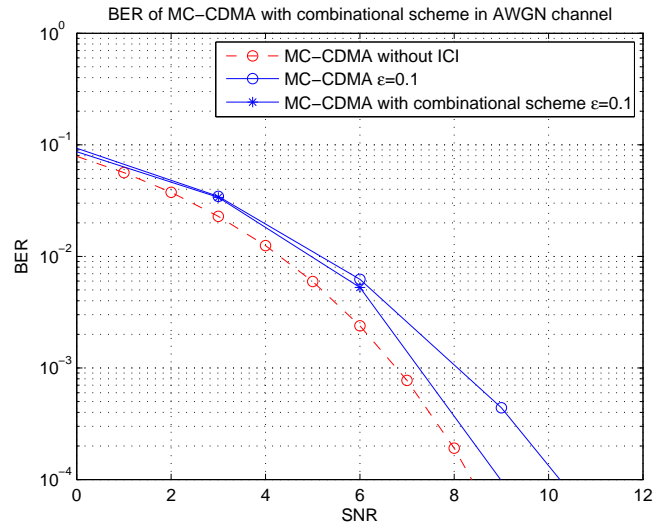
$$\begin{aligned}
& \sum_{\bar{b}^{U'_1 g} \in I_1^1, I_2^1, \dots, I_P^1} \sum \{r_g^1 - [(\alpha_g - \alpha_{g+1}) + \\
& \sum_{i \in I_1^1, I_2^1, \dots, I_P^1} ((\alpha_i - \alpha_{i+1}) \sum_{m \in U'_1, m \neq 1} b^m c_i^m c_i^1)]\}^2 \\
& \geq \\
& \sum_{\bar{b}^{U'_1 g} \in I_1^1, I_2^1, \dots, I_P^1} \sum \{r_g^1 - [(-\alpha_g + \alpha_{g+1}) + \\
& \sum_{i \in I_1^1, I_2^1, \dots, I_P^1} ((-\alpha_i + \alpha_{i+1}) \sum_{m \in U'_1, m \neq 1} b^m c_i^m c_i^1)]\}^2
\end{aligned} \tag{4.8}$$

where,  $U'_1$  is the user group allocated on the first subcarrier set which takes the number up to  $K$ . The first subcarrier set contains the subcarriers  $\{I_1^1, I_2^1, \dots, I_P^1\}$ .  $\bar{b}^{U'_1}$  represents the bits of the users in set  $U'_1$  excluding user1's. Notice that, in this novel system we need to consider also the neighbor subcarriers of the desired subcarrier set, which may give a large portion to ICI effect. Since these neighbor subcarriers are transmitting the opposite value of the desired subcarriers, the information is predictable. Thus, the computational complexity does not increase substantially, it is on the level of  $2 \cdot 2^{K-1}$ , which is still bearable.

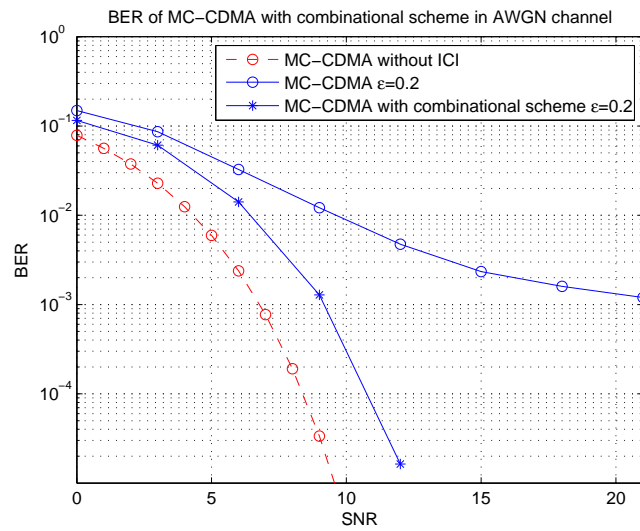
## 4.2 Simulation results and Summary

Fig. 4.2 and Fig. 4.3 show the BER performance comparison of traditional MC-CDMA system with the system applying the combinational scheme, where the normalized frequency offset are  $\epsilon = 0.1$ ,  $\epsilon = 0.2$  and  $\epsilon = 0.3$  respectively.

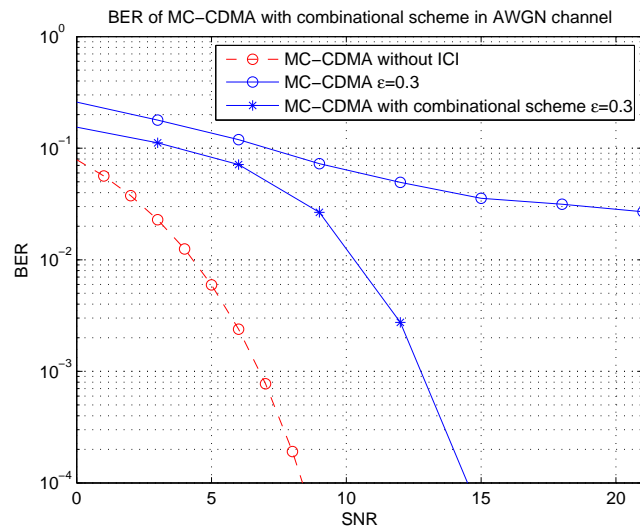
The simulation results show that, in the AWGN channel, as the frequency offset grows, (from  $\epsilon = 0.1$  to  $\epsilon = 0.3$ ), the BER performance of the traditional MC-CDMA system degrades significantly, while the BER of the system employing the combinational scheme only degrades slightly. In the frequency selective fading channel, the system with combinational scheme also outperforms the traditional MC-CDMA system. The combinational scheme works well both in the AWGN channel with the frequency offset and the multipath fading channel with the frequency offset.



(a) BER comparison  $\epsilon = 0.1$



(b) BER comparison  $\epsilon = 0.2$



(c) BER comparison  $\epsilon = 0.3$

Figure 4.2: BER performance versus SNR in AWGN channel

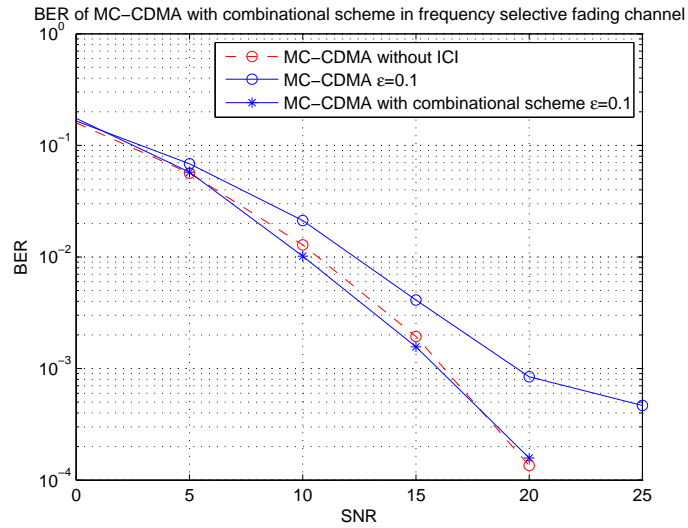
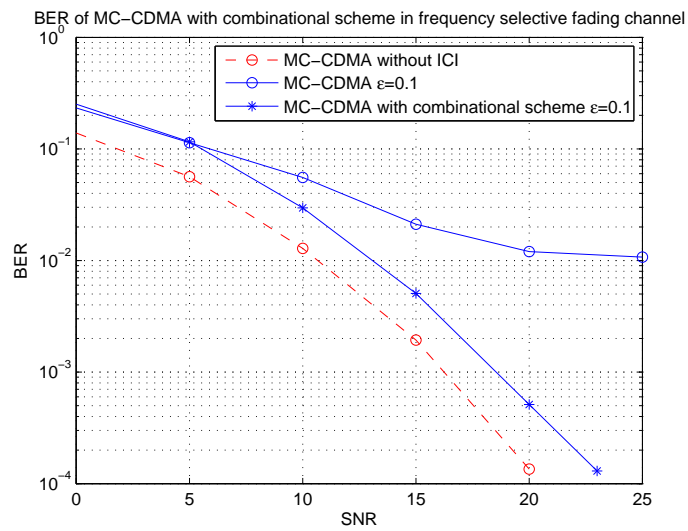
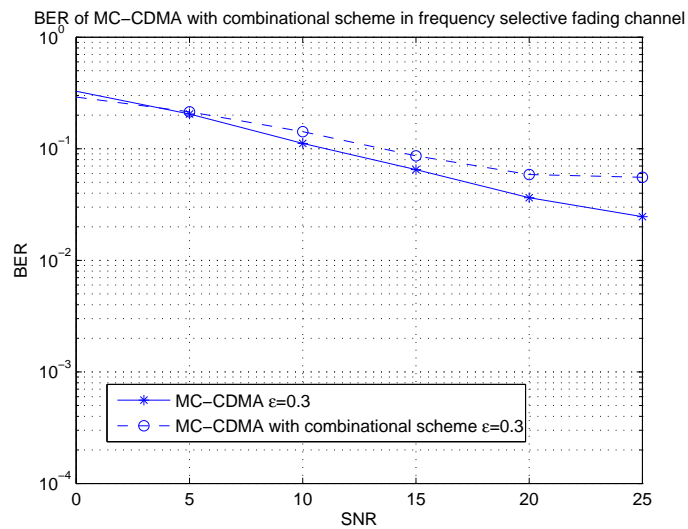
(a) BER comparison  $\epsilon = 0.1$ (b) BER comparison  $\epsilon = 0.2$ (c) BER comparison  $\epsilon = 0.3$ 

Figure 4.3: BER performance versus SNR in frequency selective fading channel

# Non-contiguous MC-CDMA with ICI Cancelation

In this chapter, we further extend these three schemes into the non-contiguous OFDM and MC-CDMA system in a simple Cognitive Radio communication environment.

## 5.1 Background

As cognitive radio sends and receives signals, they nimbly bound in and out of free bands, avoiding those frequency bands that are already in use. This fast channel jumping permits cognitive radio systems to transmit voice and data streams at reasonable speeds. By making efficient use of existing radio-frequency (RF) holes to work around spectrum-availability traffic jams, wireless communications become more dependable and convenient.

When transmitting non-contiguously, the Multi-carrier Modulation (MCM) systems face severe problem of Inter-carrier Interference. The three discussed ICI canceling schemes can also be employed in non-contiguous communication systems. By applying these three schemes introduced above, we can expect the effect of ICI being mitigated.

In this chapter, we assume a non-contiguous transmission environment, where the total bandwidth is of  $N = 1024$  subcarriers, the signals are transmitted on 4 "frequency holes" which are separated by the bands occupied by primary users. Each "frequency hole" has the bandwidth of 32 contiguous subcarriers. In this way, this MC-CDMA system allocates its signal on  $N_u = 128$  non-contiguous subcarriers for transmission. The free frequencies are used and the system has higher frequency diversity than contiguously transmitting system.

Fig. 5.1 shows the block diagram of this system. In this system, the "zero padding" block is used to disperse the signals and allocate them into the "frequency holes", while the "zero-removing" block is used to

remove the spacing and reallocate the signals. The "filter" block is applied to remove the signals transmitted by primary users.

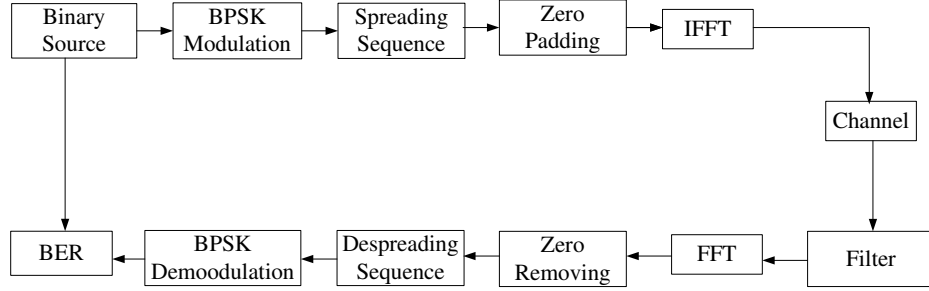


Figure 5.1: Block diagram of the non-contiguous MC-CDMA (NC-MC-CDMA) system

In this transmitting environment, we still assume the rate between the bandwidth of each subcarrier and the coherent bandwidth is 1 : 8, which means the coherent bandwidth is 8 times greater than the bandwidth of each subcarrier. Thus, this is a  $P = 128$ -fold multipath fading channel, where the coherent bandwidth remains the same. The transmitted signal goes through a frequency select fading channel over the entire bandwidth, but on each subcarrier it undergoes flat fading.

$$BW_c = BW/P \quad (5.1)$$

At receiver side, the received signal is

$$r(t) = \sum_{i=1}^{N_u} \sum_{m=1}^M \alpha_i b^m c_i^m e^{j(2\pi(f_c + f_i + f_o)t + \theta_i)} q(t) + n(t) \quad (5.2)$$

where,  $N_u$  is the number of free sub-bands which are used for transmission in this cognitive radio system.  $f_i$  is the frequency of the  $i^{th}$  subcarrier. In the above described non-contiguous environment,  $f_i = (256 \cdot \lfloor i/32 \rfloor + i) \cdot \Delta f, i = 1, \dots, N_u$ .  $\lfloor x \rfloor$  means the closest integer less than or equal to  $x$ .

Correspondingly, the output for the desired  $d^{th}$  user on the  $g^{th}$  subcarrier after the despreader and integration is



$$\begin{aligned}
D_g^d &= \alpha_g b^d S_0 \\
&+ \alpha_g \sum_{m \neq d}^M b^m c_g^d c_g^m S_0 \\
&+ b^d \sum_{i \neq g}^{N_u} \alpha_i c_g^d c_i^d e^{j(\theta_i - \theta_g)} S_{i-g} \\
&+ \sum_{m \neq d}^M \sum_{i \neq g}^{N_u} \alpha_i b^m c_g^d c_i^m e^{j(\theta_i - \theta_g)} S_{i-g} \\
&+ \eta_g
\end{aligned} \tag{5.3}$$

The decision variable for user  $d$  after applying MLC is:

$$\begin{aligned}
D^d &= \sum_{g=1}^{N_u} U_g^d \cdot W_g \\
&= \sum_{g=1}^{N_u} W_g \cdot \alpha_g b^d S_0 \\
&+ \sum_{g=1}^{N_u} W_g \cdot \alpha_g \sum_{m \neq d}^M b^m c_g^d c_i^m S_0 \\
&+ \sum_{g=1}^{N_u} W_g \cdot b^d \sum_{i \neq g}^{N_u} \alpha_i c_g^d c_i^d e^{j(\theta_i - \theta_g)} S_{i-g} \\
&+ \sum_{g=1}^{N_u} W_g \cdot \sum_{m \neq d}^M \sum_{i \neq g}^{N_u} \alpha_i b^m c_g^d c_i^m e^{j(\theta_i - \theta_g)} S_{i-g} \\
&+ \eta
\end{aligned} \tag{5.4}$$

Finally, a hard decision for user  $d$  is made basing on  $D^d$ .

## 5.2 Implementation of ICI cancelation schemes and Simulation

In this section, we will introduce the implementation of these three schemes in non-contiguous communication systems.

### 5.2.1 ICI Self-Cancelation Scheme

The ICI self-cancelation scheme can be applied in non-contiguous OFDM system. Fig. 5.2 shows the block diagram of this system.

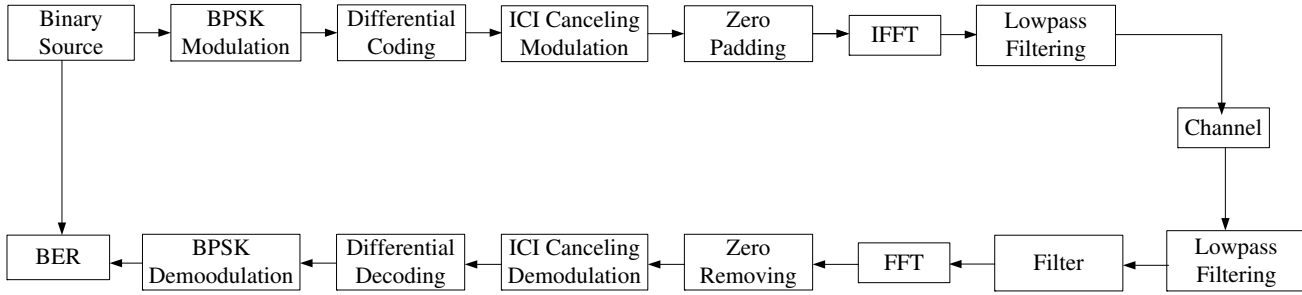
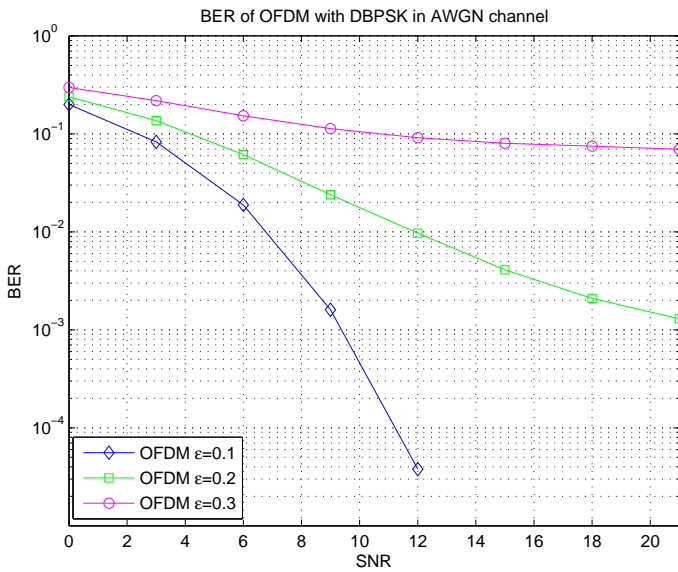
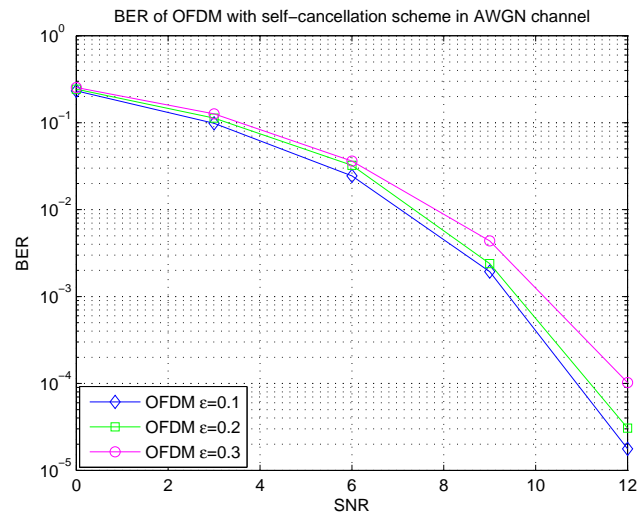


Figure 5.2: Block diagram of the non-contiguous OFDM system with ICI self-cancellation scheme



(a) OFDM system in AWGN channel



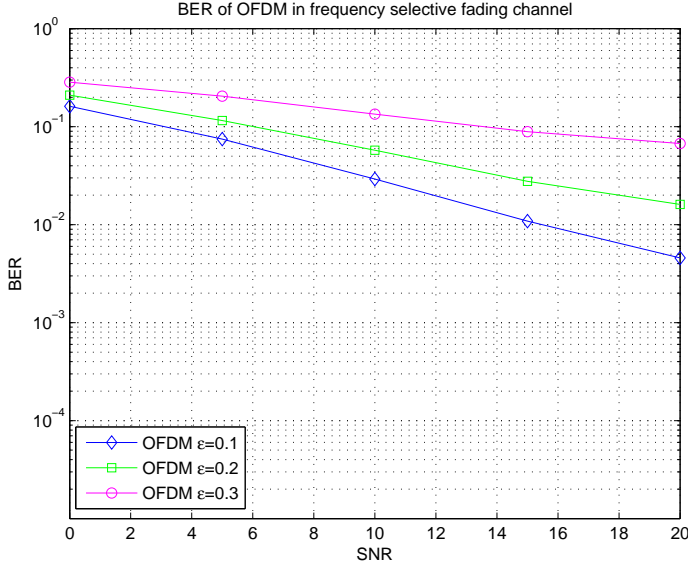
(b) OFDM with self-cancellation in AWGN channel

Figure 5.3: BER performance versus SNR in AWGN channel

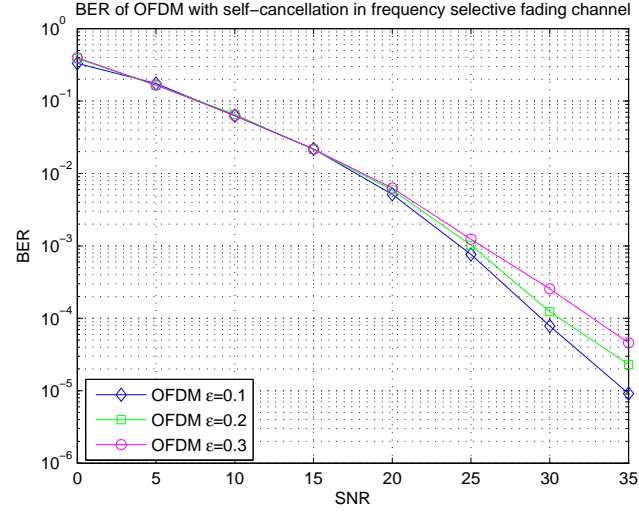
Fig. 5.3 shows the system performance of OFDM system in AWGN channel with and without ICI self-cancellation scheme respectively. In this simulation, the signals are transmitted on non-contiguous subcarriers as we discussed above, which is a simple Cognitive Radio communication environment. Fig. 5.4 shows the performance of the same system in frequency selective fading channel. From the simulation result we can see that, this scheme can suppress the Inter-carrier Interference very well.

Here we notice, since the ICI self-cancellation scheme transmits the same signal twice on adjacent subcarriers, the transmitting rate is cut to half of the original system. In addition, this scheme may introduce severe phase offset, so the author applies differential coding on frequency to overcome this problem.

Fig. 5.5 shows the block diagram of non-contiguous MC-CDMA (NC-MC-CDMA) system with self-cancellation scheme. In this system, the signal is also transmitted pairwise, but the signal on each subcarrier



(a) OFDM system in frequency selective fading channel



(b) OFDM with self-cancellation in frequency selective fading channel

Figure 5.4: BER performance versus SNR in frequency selective fading

$(v_i)$  is the summation of all the users' signal multiplied by spreading sequence. In this way,  $v_2 = -v_1, v_4 = -v_3, \dots, v_{N_u} = -v_{N_u-1}$ .

Then the decoded signal on the 1<sup>st</sup> subcarrier is

$$\begin{aligned}
 D_1^{d'} &= \mu_1(S_0 - S_1) + \nu_3(S_2 - S_3) + \dots + \eta_1 \\
 &= \mu_1 S'_0 + \sum_{i=3, \text{odd}}^{N_u-1} \nu_i S'_{i-g} + \eta_1
 \end{aligned} \tag{5.5}$$

Eq. 5.5 shows that, the ICI no longer depends on the coefficients  $S_{i-g}$ , but now depends on the difference between the coefficients on adjacent subcarriers  $S'_{i-g} = S_{i-g} - S_{i-g+1}$ . Since as we discussed in section 1.6.3, the difference between adjacent subcarriers is small, therefore, the ICI coefficients are now reduced.

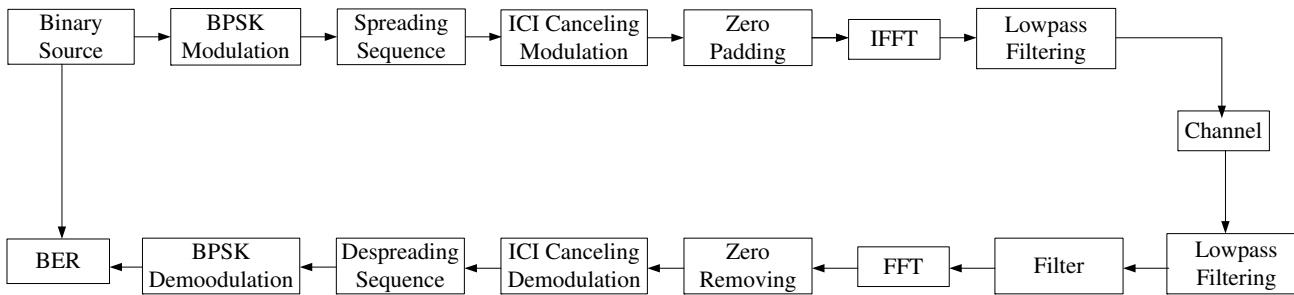


Figure 5.5: Block diagram of the NC-MC-CDMA with ICI self-cancellation scheme

Then the received values are subtracted pair-wise, which is implemented by taking the opposite values of the signals on even-numbered subcarriers and sum them together with the signals on the odd-numbered subcarriers. The decoded signal for user  $d$  is

$$\begin{aligned}
D'^d &= \sum_{g=odd}^{N_u-1} W_g \cdot (D'_g{}^d - D'_{g+1}{}^d) \\
&= \sum_{g=odd}^{N_u-1} W_g \{ (D'_1{}^d - D'_2{}^d) + (D'_3{}^d - D'_4{}^d) + \dots + \eta_g \} \\
&= \sum_{g=odd}^{N_u-1} W_g \{ \mu_1(-S_{-1} + 2S_0 - S_1) + \nu_3(-S_1 + 2S_2 - S_3) \\
&\quad + \dots + \nu_1(-S_{-3} + 2S_{-2} - S_{-1}) + \mu_3(-S_{-1} + 2S_0 - S_1) \\
&\quad + \dots + \eta_g \} \\
&= \sum_{g=odd}^{N_u-1} W_g \{ \mu_g S''_0 + \sum_{i=odd, i \neq g}^{N_u-1} \nu_i S''_{i-g} \} + \eta
\end{aligned} \tag{5.6}$$

In this way, the ICI depends on the further reduced coefficients  $S''$ . For example, on the 1<sup>st</sup> subcarrier, the ICI from the closest subcarrier depends on  $(-S_{-1} + 2S_2 - S_{-3})$ .

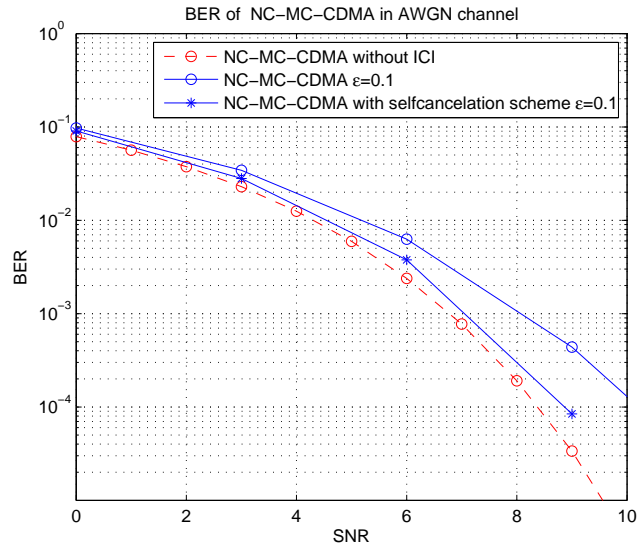
Fig. 5.6 and Fig. 5.7 show the BER performance comparison of non-contiguous MC-CDMA (NC-MC-CDMA) system with the NC-MC-CDMA system employing ICI self-cancelation scheme. The simulation results show that, in the non-contiguous environment, the ICI self-cancelation scheme has robustness and can perform better than traditional MC-CDMA system.

## 5.2.2 Frequency Division Scheme

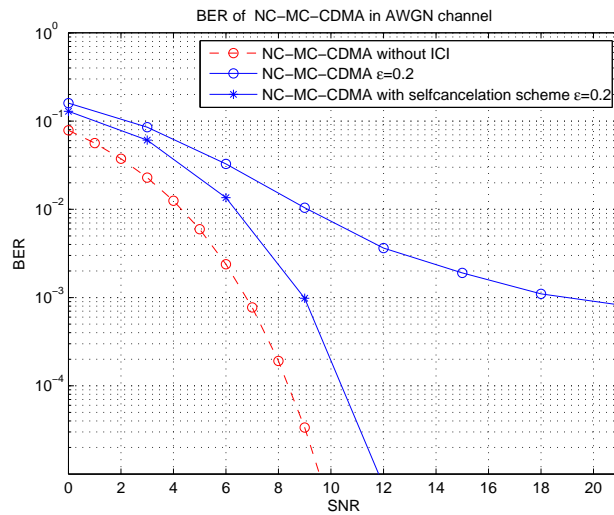
In the non-contiguous MC-CDMA (NC-MC-CDMA) system where  $N=1024$ ,  $N_u=128$  is the number of subcarriers on the  $H=4$  available frequency bands and the bandwidth of each "frequency hole" is  $32\Delta f$ . The FD-MC-CDMA/MUD system exploits the frequency diversity by allocating each user on non-contiguous subcarrier sets. On each "frequency hole", the coherent bandwidth is still  $8\Delta f$ , and the number of folds on each "frequency hole" is 4. Thus, each subcarrier-set consists of  $P_h = 16$  subcarriers and the number of subcarrier-set is  $N_u/P_h=8$ .

$$\text{The spreading code } c_i^m \text{ is } c_i^m = \begin{cases} \pm 1 & \text{if } i \in I_1^m, I_2^m, \dots, I_p^m, \dots, I_{P_h}^m \\ 0 & \text{else} \end{cases}$$

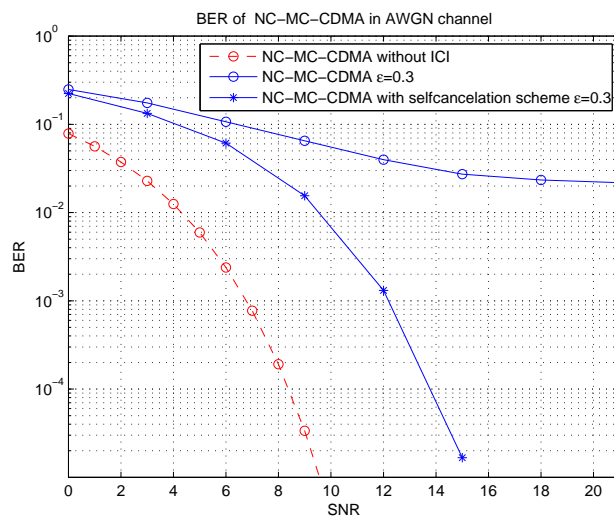
where  $i$  indicates the  $i^{\text{th}}$  chip of user  $m$ 's spreading sequence,  $I_p^m = \lfloor (m-1)/P_h \rfloor + (N/P) \cdot (p-1) + ((N -$



(a) BER comparison  $\epsilon = 0.1$

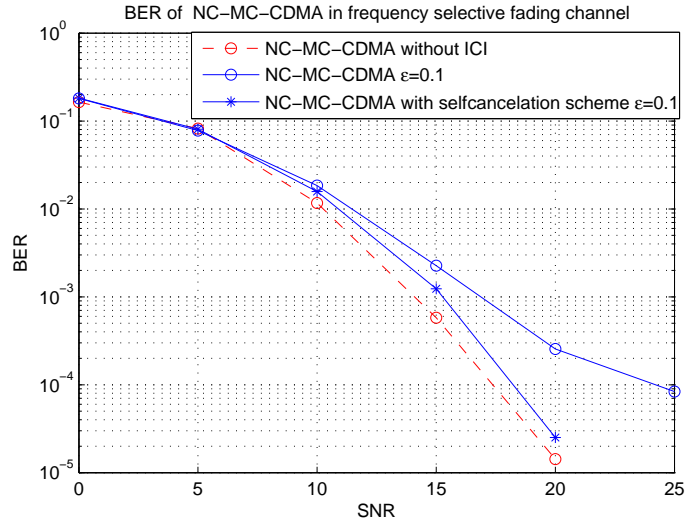


(b) BER comparison  $\epsilon = 0.2$

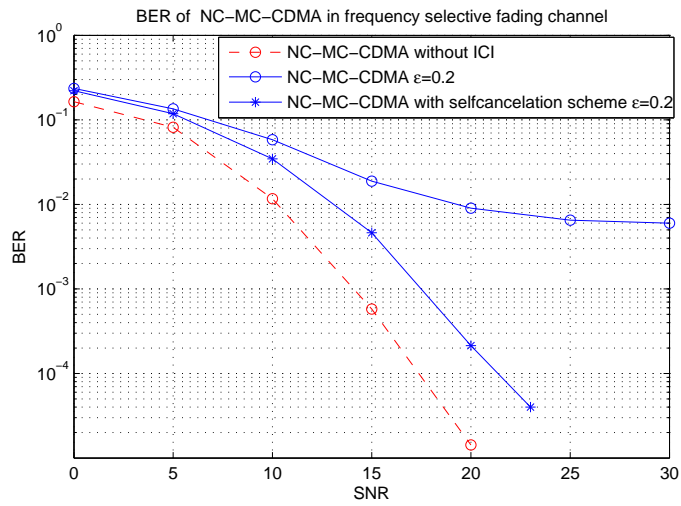


(c) BER comparison  $\epsilon = 0.3$

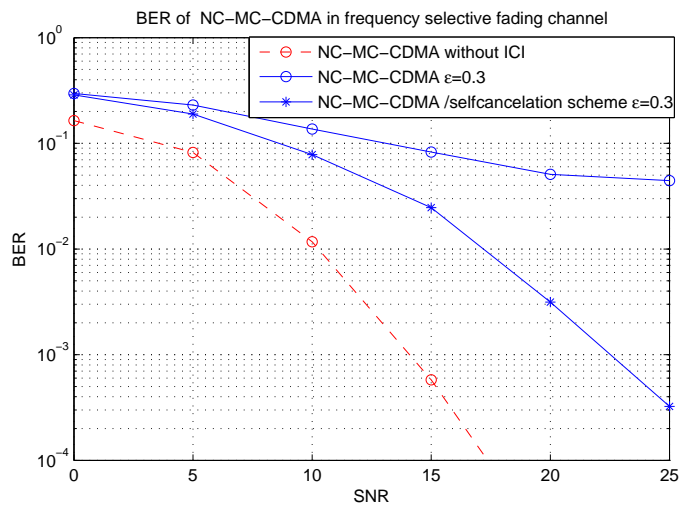
Figure 5.6: NC-MC-CDMA BER performance versus SNR in AWGN channel



(a) BER comparison  $\epsilon = 0.1$



(b) BER comparison  $\epsilon = 0.2$



(c) BER comparison  $\epsilon = 0.3$

Figure 5.7: NC-MC-CDMA BER performance versus SNR in frequency selective fading channel

$N_u)/H) \cdot \lfloor p/H \rfloor + 1$ . In this way, only one subcarrier is left for transmission in every fold on each "frequency hole".  $c_i^m$  is non-zero on only  $P_h$  subcarriers. The new separation between two adjacent subcarriers in the same set is  $8\Delta f$  or larger. And the number of users in each set is up to  $K = \lfloor \frac{M-1}{N/P} \rfloor + 1$  and  $K \ll M$  when the system is heavily loaded. Assuming downlink transmission, with  $M$  active users in total but only  $K$  active users in each subcarrier set, the received signal is:

$$r(t) = \sum_{i=1}^{N_u} \sum_{m=1}^K \alpha_i b^m c_i^m e^{j(2\pi(f_c + f_i + f_o)t + \theta_i)} q(t) + n(t) \quad (5.7)$$

The received signal is first decomposed into  $P_h$  information-bearing carriers and are multiplied by user 1's spreading code. The  $g$ th subcarrier generates

$$\begin{aligned} D_g^1 &= \frac{1}{T} \int_T c_g^1 r(t) e^{-j2\pi(f_c + f_g)t + \theta_g} dt \\ &= \alpha_g b^1 S_0 \\ &\quad + \alpha_g \sum_{m \neq 1}^K b^m c_g^1 c_g^m S_0 \\ &\quad + b^1 \sum_{i \neq g}^{N_u} \alpha_i c_g^1 c_i^1 e^{j(\theta_i - \theta_g)} S_{i-g} \\ &\quad + \sum_{m \neq 1}^K \sum_{i \neq g}^{N_u} \alpha_i b^m c_g^d c_i^m e^{j(\theta_i - \theta_g)} S_{i-g} \\ &\quad + \eta_g \end{aligned} \quad (5.8)$$

The number of active users in each subcarrier set is limited to up to  $K$ , in this example  $K=16$ . Comparing to up to  $N = 128$  users in each subcarrier set for traditional MC-CDMA system, the system complexity is substantially decreased, as well as the interfering users on other subcarriers. Since the number of interfering users is decreased, the computational complexity for ML MUD is reduced to a reasonably low level, which is on the order of  $2^{K-1}$  and the ML MUD can be implemented. The optimal MUD for user 1 corresponds to

$$\begin{aligned} &\sum_{\bar{b}^{U_1} g \in I_1^1, I_2^1, \dots, I_P^1} \sum \left( r_g^1 - \left( \alpha_g + \sum_{i \in I_1^1, I_2^1, \dots, I_P^1} \alpha_i \sum_{m \in U_1, m \neq 1} b^m c_i^m c_i^1 \right) \right)^2 \\ &\geq \\ &\sum_{\bar{b}^{U_1} g \in I_1^1, I_2^1, \dots, I_P^1} \sum \left( r_g^1 - \left( -\alpha_g + \sum_{i \in I_1^1, I_2^1, \dots, I_P^1} \alpha_i \sum_{m \in U_1, m \neq 1} b^m c_i^m c_i^1 \right) \right)^2 \end{aligned} \quad (5.9)$$

where  $U_1$  is a set of up to  $K$  users in the first carrier set,  $\bar{b}^{U_1}$  represents the possible bits of users in  $U_1$  excluding user1, and  $\sum_{\bar{b}^{U_1}}$  represents the sum over all the bit vectors  $\bar{b}^{U_1}$ .

Fig. 5.8 shows the performance comparison of non-contiguous MC-CDMA systems with or without frequency division scheme, where  $\epsilon = 0.1$ ,  $\epsilon = 0.2$  and  $\epsilon = 0.3$  respectively. We assume the rate between the bandwidth of each subcarrier and the coherent bandwidth is 1 : 8, which means the coherence bandwidth is 8 times greater than the bandwidth of each subcarrier. Thus, this  $N = 1024$  channel has  $P = 128$  folds, in which  $N_u = 128$  subcarriers are free to use, with  $P_h = 16$  folds. The FD-MC-CDMA/MUD system allocates each user on  $P_h = 16$  non-contiguous subcarriers to exploit the frequency diversity, with  $N_u/P_h = 8$  subcarrier sets.

In the non-contiguous communication environment, the FD-MC-CDMA/MUD outperforms the traditional MC-CDMA system. Especially, when  $\epsilon = 0.1$ , the FD-MC-CDMA/MUD system even outperforms the MC-CDMA system without ICI. This is from the application of MUD, which can bring performance gain to the system when there is no frequency offset or the frequency offset is relatively low.

### 5.2.3 Combinational scheme

To implement the combinational scheme, the signals are transmitted on the odd numbered carrier sets, and their opposite values are transmitted on the even numbered carrier sets. For example, on the first subcarrier set,  $v_i^1$  is transmitted:

$$v_i^1 = \sum_{m \in U'_1} b^m c_i^{2m-1} \quad i = 1, 9, 17, 25, 257, 265\dots \quad (5.10)$$

On the second subcarrier set,  $v_i^2$  is transmitted, which is:

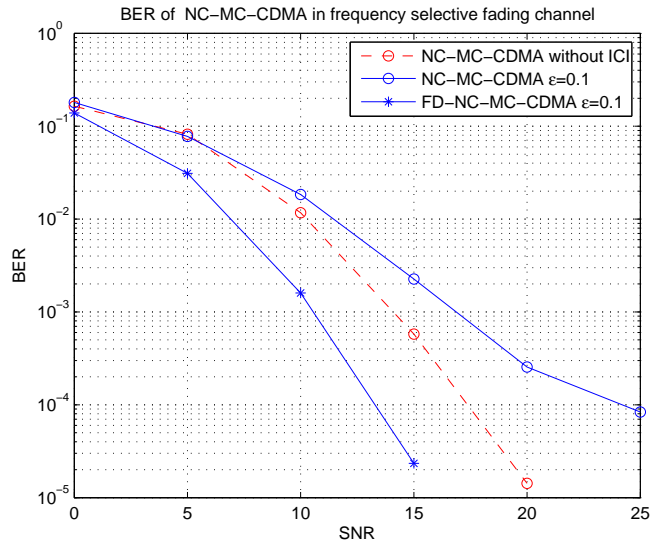
$$v_i^2 = \sum_{m \in U'_1} -b^m c_i^{2m} = -v_i^1 \quad i = 2, 10, 18, 26, 258, 266\dots \quad (5.11)$$

$U'_1$  is a set of up to  $K$  users on the first subcarrier set,  $K = \lfloor \frac{M-1}{N/2P} \rfloor + 1$ . Take  $N_u = 128$ ,  $P_h = 16$  for example, if fully loaded,  $m \in U'_1$ ,  $m = [1, 5, 9, 13, \dots, 61]$ . Notice that, in this way, the channel capacity is cut to half of the traditional MC-CDMA system. The spreading code is contributed as follow:

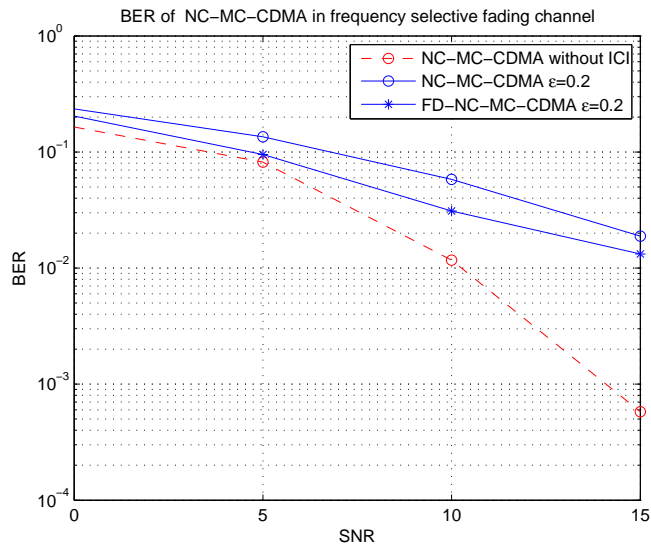
$$c_i^m = \begin{cases} \pm 1 & \text{if } i \in I_1^m, I_2^m, \dots, I_P^m \\ 0 & \text{else} \end{cases}$$

where  $i$  indicates the  $i^{th}$  chip of user  $m$ 's spreading sequence,  $I_p^m = \lfloor 2(m-1)/P_h \rfloor + (N/P) \cdot (p-1) + ((N -$

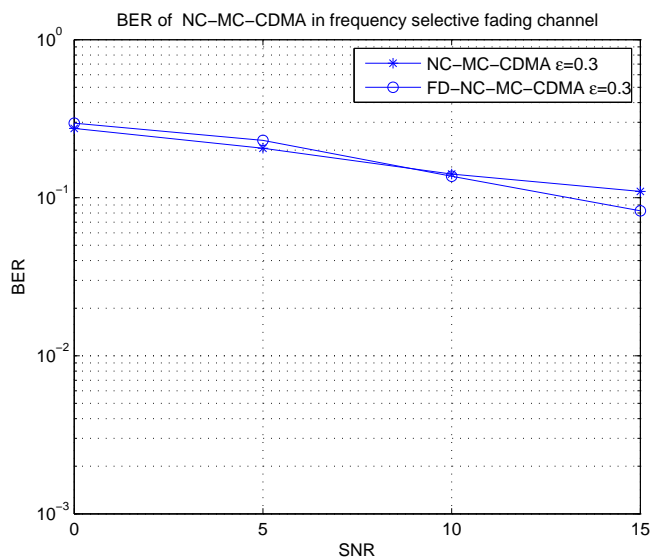




(a) BER comparison  $\epsilon = 0.1$



(b) BER comparison  $\epsilon = 0.2$



(c) BER comparison  $\epsilon = 0.3$

Figure 5.8: NC-MC-CDMA BER performance versus SNR in frequency selective fading channel

$N_u)/H) \cdot \lfloor p/H \rfloor + 1$ .  $c_i^m$  is non-zero on only  $P_h$  subcarriers. For example, for a  $P_h=16$ -fold diversity channel with  $N_u=128$  subcarriers, user 1, 5, 9, ..., 61 are assigned subcarrier set 1, which means,  $\{c_i^{(m)} \in \{-1, +1\} \mid i=1, 9, 17, 25, 257, 265 \dots, 785, 793\}$ , and  $\{c_i^{(m)} = 0 \mid i \neq 1, 9, 17, 25, 257, 265 \dots, 785, 793\}$ . The number of users in each set is up to  $K = \lfloor \frac{M-1}{N/P} \rfloor + 1$  and  $K \ll M$  when the system is heavily loaded. The received signal after going through frequency selective fading channel and impaired by frequency offset is:

$$r(t) = \left\{ \sum_{i \in \text{odd}}^{N_u} \sum_{m=1}^K \alpha_i b^m c_i^m e^{j(2\pi(f_c + f_i + f_o)t + \theta_i)} + \sum_{i \in \text{even}}^{N_u} \sum_{m=1}^K -\alpha_i b^m c_i^m e^{j(2\pi(f_c + f_i + f_o)t + \theta_i)} \right\} q(t) + n(t) \quad (5.12)$$

The decoded signal on the 1<sup>st</sup> subcarrier for user  $d$  can be written as follow:

$$\begin{aligned} D_1^d &= \frac{1}{T} \int_T c_g^d r(t) e^{-j(2\pi(f_c + f_g)t + \theta_g)} dt \\ &= \mu_1 (S_0 - S_1) + \nu_3 (S_2 - S_3) + \dots + \eta_1 \\ &= \mu_1 S_0' + \sum_{i=3, \text{odd}}^{N_u-1} \nu_i S_{i-g}' + \eta_1 \end{aligned} \quad (5.13)$$

where,  $\mu_1$  is the decoded signal transmitted on the 1<sup>st</sup> subcarrier,

$$\mu_1 = \alpha_1 \sum_{m=1}^K b^m c_1^d c_1^m \quad (5.14)$$

and  $\nu_i$  are the signals transmitted on the other subcarriers, where,  $i \neq 1$

$$\nu_i = \alpha_i \sum_{m=1}^K b^m c_i^m c_1^d e^{j(\theta_i - \theta_1)} \quad (5.15)$$

To further improve the performance, at the receiver side, the received signals on even subcarriers are taken opposite value, and added to the odd subcarriers. Then the decision variable becomes

$$\begin{aligned}
D^d &= \sum_{g=odd}^{N_u-1} W_g \cdot (D'_g{}^d - D'_{g+1}{}^d) \\
&= \sum_{g=odd}^{N_u-1} W_g \{ (D'_1{}^d - D'_2{}^d) + (D'_3{}^d - D'_4{}^d) + \dots + \eta_g \} \\
&= \sum_{g=odd}^{N_u-1} W_g \{ \mu_1(-S_{-1} + 2S_0 - S_1) + \nu_3(-S_1 + 2S_2 - S_3) \\
&\quad + \dots + \nu_1(-S_{-3} + 2S_{-2} - S_{-1}) + \mu_3(-S_{-1} + 2S_0 - S_1) \\
&\quad + \dots + \eta_g \} \\
&= \sum_{g=odd}^{N_u-1} W_g \{ \mu_g S''_0 + \sum_{i=odd, i \neq g}^{N_u-1} \nu_i S''_{i-g} \} + \eta
\end{aligned} \tag{5.16}$$

After the first step, the coefficients become  $S'_{i-g} = S_{i-g} - S_{i-g+1}$ . After the second step, the ICI coefficients further reduce to  $S''_{i-g}$ . For example, on the 1<sup>st</sup> subcarrier, the ICI from the closest subcarriers depends on  $(-S_1 + 2S_2 - S_3)$ . Furthermore, the number of interfering users on each subcarrier is reduced. All of these result in better performance.

Especially when there are less than  $N_u/(2P_h)=4$  active users in our example system ( $N_u=128$ ,  $P_h=16$ ), the number of users in each subcarrier set is  $K=1$ , which means there is no MAI in the system. Moreover, the power of interfering source from other subcarriers is lower than traditional system. Accordingly, the performance is substantially improved.

Since the system maintains the computational simplicity, we can apply the ML MUD.

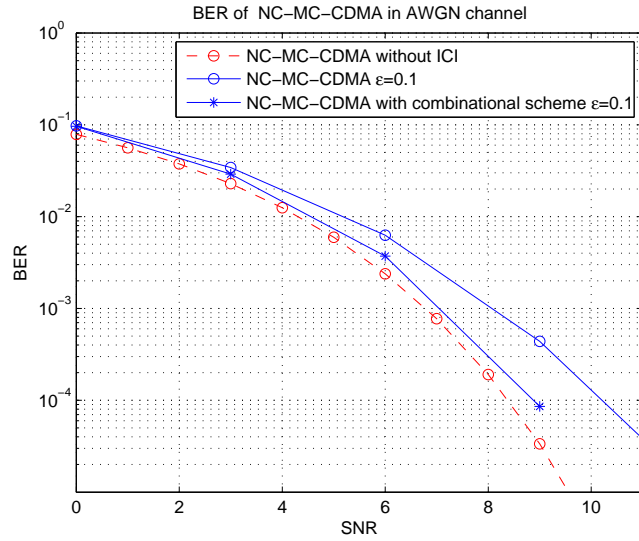
$$\begin{aligned}
&\sum_{\bar{b}^{U'_1} g \in I_1^1, I_2^1, \dots, I_{P_h}^1} \{ r_g^1 - [(\alpha_g - \alpha_{g+1}) + \\
&\quad \sum_{i \in I_1^1, I_2^1, \dots, I_{P_h}^1} ((\alpha_i - \alpha_{i+1}) \sum_{m \in U'_1, m \neq 1} b^m c_i^m c_i^1)] \}^2 \\
&\geq \\
&\sum_{\bar{b}^{U'_1} g \in I_1^1, I_2^1, \dots, I_{P_h}^1} \{ r_g^1 - [(-\alpha_g + \alpha_{g+1}) + \\
&\quad \sum_{i \in I_1^1, I_2^1, \dots, I_{P_h}^1} ((-\alpha_i + \alpha_{i+1}) \sum_{m \in U'_1, m \neq 1} b^m c_i^m c_i^1)] \}^2
\end{aligned} \tag{5.17}$$

where,  $U'_1$  is the user group allocated on the first subcarrier set which takes the number up to  $K$ . The first subcarrier set contains the subcarriers  $\{I_1^1, I_2^1, \dots, I_{P_h}^1\}$ .  $\bar{b}^{U'_1}$  represents the bits of the users in set  $U'_1$  exclud-

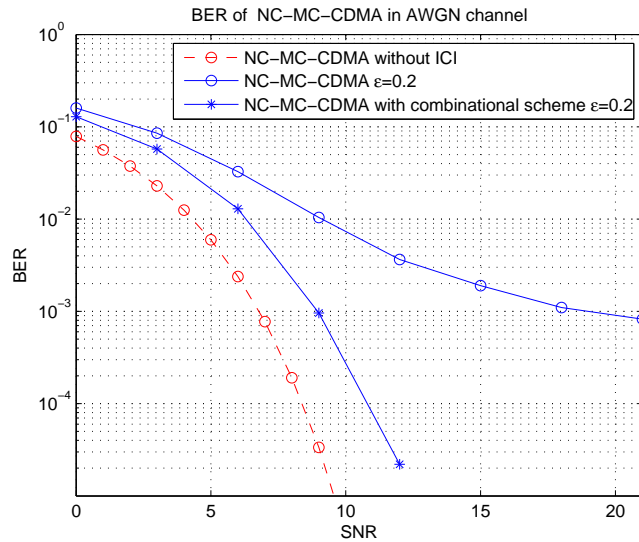
ing user's. Notice that, in this novel system we need to consider also the neighbor subcarriers of the desired subcarrier set, which may give a large portion to ICI effect. Since these neighbor subcarriers are transmitting the opposite value of the desired subcarriers, the information is predictable. Thus, the computational complexity does not increase substantially, it is on the level of  $2 \cdot 2^{K-1}$ , which is still bearable.

The comparison of the MC-CDMA system with or without combinational scheme transmitting in non-contiguous channel are shown in Fig. 5.9 and Fig. 5.10. For fair comparison, both the traditional system and the system applying the new scheme are 'half-loaded'. Take a  $N_u = 128$  system for example, there are only 64 users in the system.

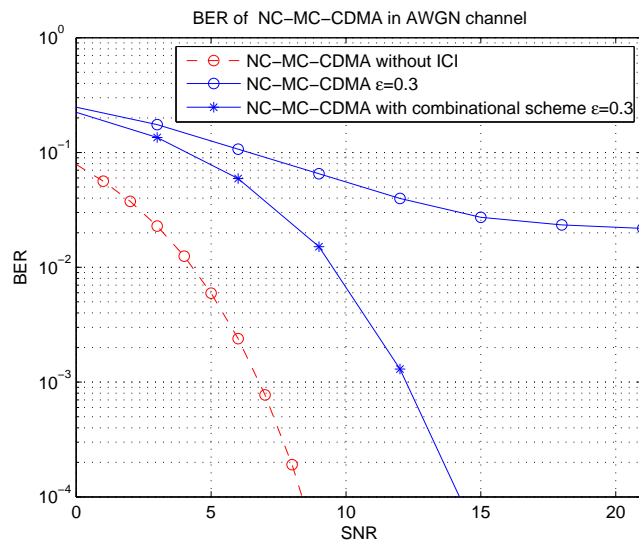
The simulation results show that, in the AWGN channel, as the frequency offset grows, (from  $\epsilon = 0.1$  to  $\epsilon = 0.3$ ), the BER performance of the traditional MC-CDMA system degrades significantly, while the BER of the system employing the combinational scheme only degrades slightly. In the frequency selective fading channel, the system with combinational scheme can also outperform the traditional MC-CDMA system. Especially when  $\epsilon = 0.1$ , after applying the combinational scheme, the system can even outperform the system with no Inter-carrier Interference. The performance gain comes from the system robustness of Multi-access Interference as we discussed. The combinational scheme works well both in the AWGN channel with the frequency offset. and the multi-path fading channel with the frequency offset.



(a) BER comparison  $\epsilon = 0.1$

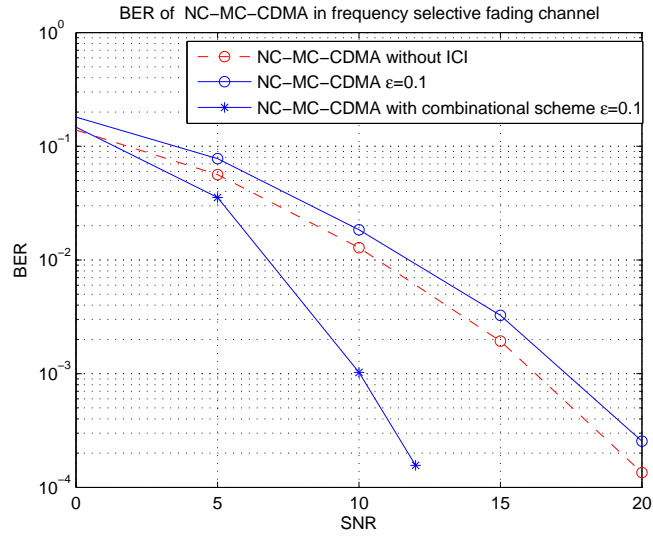


(b) BER comparison  $\epsilon = 0.2$

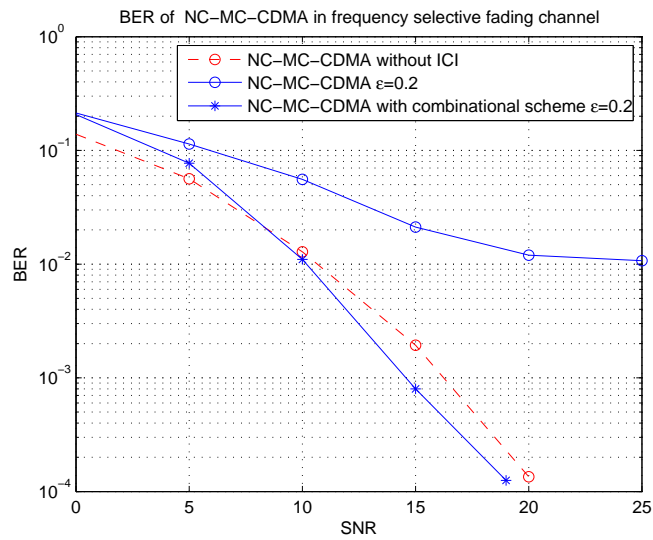


(c) BER comparison  $\epsilon = 0.3$

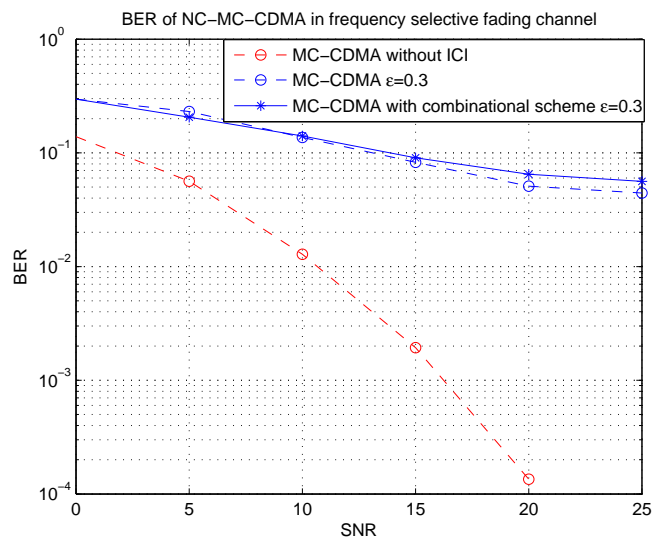
Figure 5.9: NC-MC-CDMA BER performance versus SNR in AWGN channel



(a) BER comparison  $\epsilon = 0.1$



(b) BER comparison  $\epsilon = 0.2$



(c) BER comparison  $\epsilon = 0.3$

Figure 5.10: NC-MC-CDMA BER performance versus SNR in frequency selective fading channel

# Summary and Future Work

In this chapter, we compare the three schemes we introduced above, and compare the performance as well as the advantages and disadvantages of each scheme.

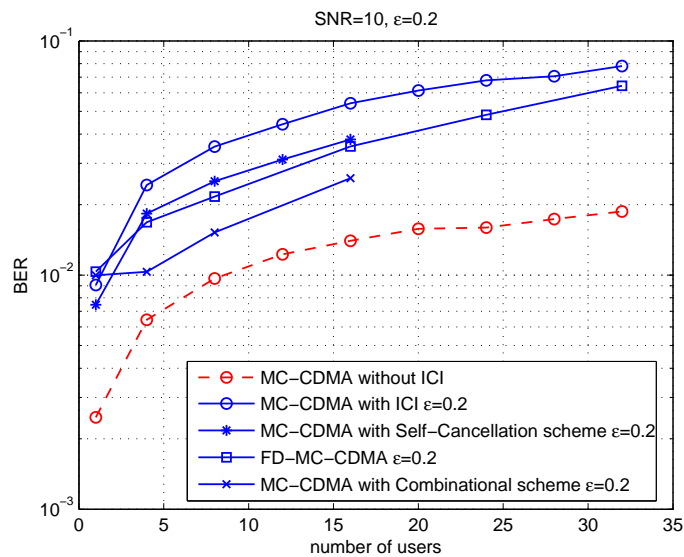


Figure 6.1: BER performance comparison versus number of users

Fig. 6.1 shows the BER comparison versus number of users of traditional MC-CDMA system and the systems applying the three schemes discussed above. Here, the normalized frequency offset is  $\epsilon = 0.2$ , while the signal to noise ratio is fixed at  $SNR = 10$ . The BER performance of traditional system with no Inter-carrier Interference is also shown as a reference, where  $\epsilon = 0$ . Here we assume the 4-fold channel with 32 contiguous subcarriers.

Since the ICI self-cancellation scheme and the combinational scheme both transmit the same signal twice on adjacent subcarriers, the length of spreading code is cut to half. As a result, the maximum number of users these two schemes can carry is cut to one half of the number which the traditional MC-CDMA system can carry. The FD-MC-CDMA/MUD can carry the same number of users as the traditional MC-CDMA system. Take  $N = 32$ -subcarrier system as example, the number of users a traditional MC-CDMA system and the

FD-MC-CDMA/MUD system can carry is up to  $M = 32$ , while for the other two schemes, the number is up to  $M = 16$ .

For the combinational scheme, when the number of active users is less than 4, each user is allocated on a unique subcarrier set. The power of active users is separated on different subcarrier sets, thus, zero MAI is experienced in this system. Moreover, since the ICI self-cancelation scheme is also applied, the effect of ICI is minimized to a relatively low level. This results in the almost flat line in Fig. 6.1 when  $M \leq 4$ . As the number of users grows beyond 4, the performance of the combinational scheme start to degrade, but the rate of degradation is relatively low. When the system with combinational scheme is fully loaded, though the capacity is half of the traditional MC-CDMA system, the BER performance is kept at a low level while the traditional MC-CDMA system is bearing unacceptably high level of interference.

In the future, there are following possible topics to continue this research work:

So far, all these schemes are applied under BPSK modulation environment. When extending into QPSK modulation, these systems will be more sensitive to the phase offset. Fig. 6.2 shows the BER comparison in QPSK modulated systems. From the simulation results we can see that, in QPSK modulated system, the robustness of the schemes decreased.

In [19], this problem is solved by applying frequency-domain differential coding. While in MC-CDMA system, applying differential coding on frequency domain is hard to implement. Therefore it is necessary to look for a good way to solve this problem.

The capacity of ICI self-cancelation scheme and combinational scheme is limited at a lower level comparing to the traditional MC-CDMA system and FD-MC-CDMA system. In BPSK modulated system, this problem may be solved by adding one more dimension to the spreading sequence. The traditional Hadamard-Walsh code consist two keys  $\{+1, -1\}$ , it can be upgraded by adding one more set of Hardamard-Walsh code on the imaginary dimension, which is a sequence consisting of  $\{+j, -j\}$ . At receiver side, the despreading code is the complex conjugate of the original spreading code, which consists of  $\{+1, -1\}$  set and  $\{-j, +j\}$  set. In this way, the system capacity can be maintained. The draw back is, this can only be applied in the system with BPSK modulation, when a higher-order modulation is applied, this scheme can not be employed. It may be interesting to investigate a simple scheme to solve this problem.



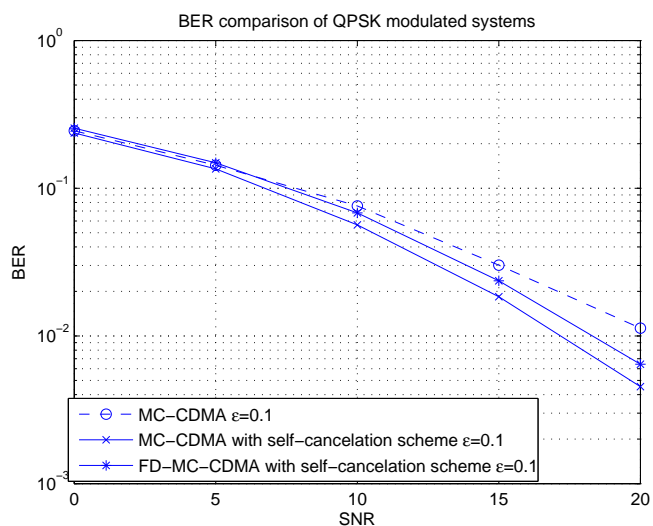
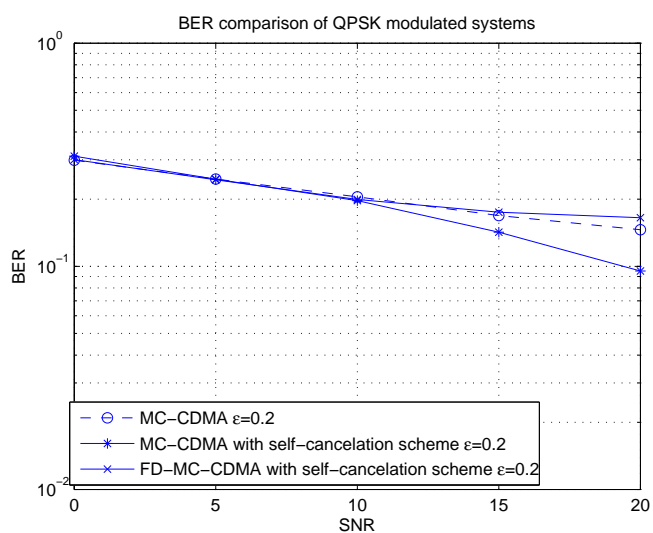
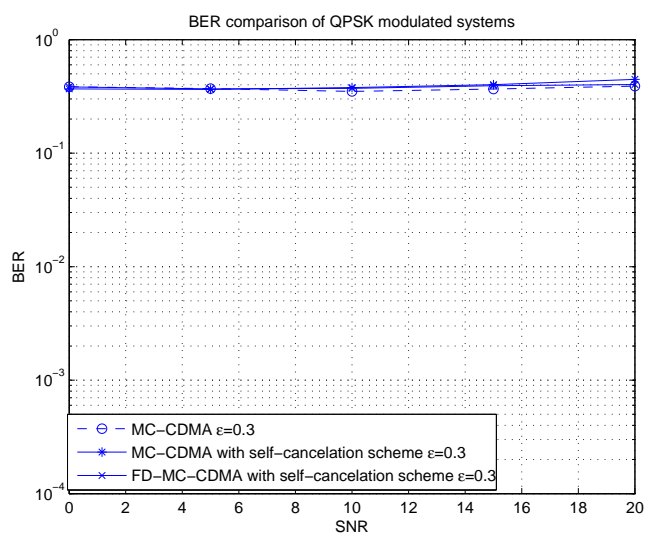
(a) BER comparison  $\epsilon = 0.1$ (b) BER comparison  $\epsilon = 0.2$ (c) BER comparison  $\epsilon = 0.3$ 

Figure 6.2: MC-CDMA BER performance versus SNR in frequency selective fading channel

# Conclusions

In this thesis, the effect of MAI and ICI are analyzed in terms of the complex weighting coefficients in MC-CDMA scheme for the downlink mobile communication system operating in frequency selective fading channel. Previously described self-intercarrier interference cancelation scheme in OFDM system is extended into MC-CDMA system and analyzed. The self ICI cancelation scheme shows robustness both in the AWGN and in the frequency selective fading channel with frequency offset. The FD-MC-CDMA scheme is also extended into the transmitting environment with frequency offset to reduce the effect of ICI. It is shown that, combining with Multiuser Detection, the FD-MC-CDMA system can reduce the effect of ICI. This scheme also shows robustness when the frequency offset is at a relatively low level. A novel scheme in MC-CDMA system to suppress the effect of both MAI and ICI is proposed, which is the combination of the two schemes described above. Because of the simplicity of this novel system, the Multiuser Detection scheme is employed to further improve the BER performance. These three schemes are further applied in non-contiguous communication systems in simple Cognitive Radio environment.

Numerical results of all these schemes are obtained, which indicate that with these schemes, the performance of the MC-CDMA system is improved. The computer simulation is also taken in non-contiguous communication systems, which are in simple Cognitive Radio communication environment. The numerical results also show the robustness of these schemes in Cognitive Radio environment.

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