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Spreading Code Assignment Technique for MIMO-CDMA Systems
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Spreading Code Assignment Techniques for MIMO-CDMA Systems

by

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Abstract

A MIMO-CDMA system with N_t transmit antennas can transmit N_t symbols on a given signaling interval, and those N_t symbols are referred to as a message vector. In conventional MIMO-CDMA systems, a message group is spread by using orthogonal direct sequence spreading codes. In this thesis, less known and recently introduced the parity-bit-selected spreading and the permutation spreading techniques are used for MIMO-CDMA system. This thesis develops the closed form theoretical expressions for parity-bit-selected spreading and permutation spreading techniques. We also introduce new design strategies for permutation spreading technique. In the MIMO-CDMA system employing parity bit selected spreading, rather than assigning each transmit antenna with different spreading sequences, the message vector is input to a systematic block encoder whose output parity bits select the spreading sequence to be used. In other words, with a given message vector, all the transmit antennas would use the same spreading sequence. In the MIMO-CDMA system using permutation spreading, rather than using the parity bits to select one spreading sequence, the parity bits are used to select N_t different spreading sequences from a set of spreading sequences. A unique permutation of spreading sequences is assigned for different parity bits. Compared to MIMO-CDMA systems employing conventional spreading method, the simulation results show that, in frequency-nonselective Rayleigh fading channel, parity bit selected spreading improves the system performance, while permutation spreading can further improve the system performance in both single-user and multi-user environments.

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Contents

List of Figures

List of Tables

List of Acronyms

2-FSK	2-ary Frequency Shift Keying
2G	Second Generation
3G	Third Generation
4G	Fourth Generation
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
CDMA	Code-Division Multiple-Access
CSI	Channel State Information
dB	Decibel
DS	Direct Sequence
DS-SS	Direct-Sequence Spread Spectrum
DS-CDMA	Direct-Sequence Code-Division Multiple Access
FDMA	Frequency-Division Multiple Access
FEC	Forward Error Correction
FH-SS	Frequency Hopped Spread Spectrum
ISI	Inter-Symbol Interference
MAI	Multiple Access Interference
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
ML	Maximum Likelihood
***M*-PSK**	*M*-ary Phase Shift Keying
MRC	Maximal Ratio Combing

OFDMA	Orthogonal Frequency-Division Multiple Access
PG	Processing Gain
PN	Pseudo-Noise
QPSK	Quadrature Phase Shift Keying
SINR	Signal-to-Interference-Noise Ratio
SISO	Single Input Single Output
SNR	Signal-to-Noise Ratio
SS	Spread Spectrum
STBC	Space Time Block Code
TDMA	Time-Division Multiple Access
TH-SS	Time Hopped Spread Spectrum

List of Symbols

(n,k)	Systematic block code with message length k and codeword length n
b_j	The j^{th} transmit message bit
$\tilde{b}_j$	Estimated message bit for b_j
$c_j(t)$	The j^{th} spreading sequence
d_{min}	Minimum distance between 2 message data group
$\mathrm{erfc}(x)$	The complementary error function of x
E_b	Bit energy level
G	Number of message vectors per coset
L	Total number of channel paths
M_j	The j^{th} message co-set
n_j	Additive white Gaussian noise received at the j^{th} receive antenna
N_o	Noise power spectral density
N_t	The number of transmit antennas
N_{tj}	The j^{th} transmit antenna
N_r	The number of receive antennas
PG	Processing gain
Q_j	The j^{th} QPSK mapped symbol
R_b	Direct sequence transmission rate (chip rate)
R_c	Message signal transmission rate
r_{jk}	Output from at the k^{th} matched filter in the j^{th} receive antenna
Rx	Total received signal
s_j	The j^{th} transmit message symbol
$\tilde{s}_j$	Estimated message bit for s_j

$sc_m(t))$	Scrambling code assigned for user *m*
U	Decision variable
U'	Total number of users in the multi-user system
$w_j(t))$	The j^{th} permutated spreading sequence
w_n	Sampled noise output from j^{th} received antenna
x^*	Complex conjugate of *x*
α_{kj}	Complex channel gain for k^{th} transmit antenna-j^{th} receive antenna link
$\bar{\gamma}_b$	Average signal-to-noise ratio (SNR)
$\bar{\gamma}_c$	Average SNR value per channel
$\bar{\gamma}_s$	Total SNR value
γ'_b	Average signal-to-interference-noise ratio (SINR)

Chapter 1

Introduction

1.1 Motivation and Literature Reviews

In a spread spectrum system, the narrowband message signal is spread over a much larger frequency band [1], [2], [3]. One of the more common spread spectrum techniques is direct sequence spread spectrum (DS-SS). In the direct sequence spread spectrum (DS-SS) system, the information symbols are directly multiplied by a wideband spreading sequence [1], [4], [5].

The Code-Division Multiple-Access (CDMA) proposed by Qualcomm for digital cellular phone applications is utilized in the second (2G) and third generation (3G) wireless communication systems [6]. It provides some attractive features such as interference rejection, protection from multipath interference, low transmit power density, etc. [7]. In its generic form, direct-sequence Code-Division Multiple Access (DS-CDMA) is a spread spectrum system [8], and is often referred to as DS-SS CDMA, or DS-CDMA. Employing forward error correction (FEC) in the DS-CDMA system can significantly improve the bit error rate (BER) performance as well as the spectral efficiency of the system.

Wireless communication system with multiple transmit and receive antennas are referred to as multiple input multiple output (MIMO) system. MIMO systems have been shown to provide an effective way to increase transmission rate over the fading channel

[9]. MIMO systems can also achieve large capacity gains [10]. The combination of CDMA and MIMO system can provide the advantages of both systems. The ideas of spatial multiplexing and transmit diversity have been applied to many systems including the third generation (3G) CDMA standards [10].

A MIMO-CDMA system using conventional method is given in [4]. It is a simple, easy to implement system, and does not use any space time coding technique. At the transmitter, each transmit antenna is assigned a unique spreading sequence, and all the information messages being transmitted by that antenna are spread by this spreading sequence.

The transmitter model for the conventional MIMO-CDMA system is given at Figure 1.1. The input message bits are grouped and mapped into symbols by signal mapping. Then the symbols are converted into parallel data streams through a serial-to-parallel converter. The information data (s_1~s_{Nt}) is directly multiplied with the spreading sequences ($c_1(t)$~$c_{Nt}(t)$) before transmission. A unique, orthogonal spreading sequence is assigned for each transmit antenna. If there are N_t antennas at transmitter; then, accordingly, N_t different spreading sequences are required.

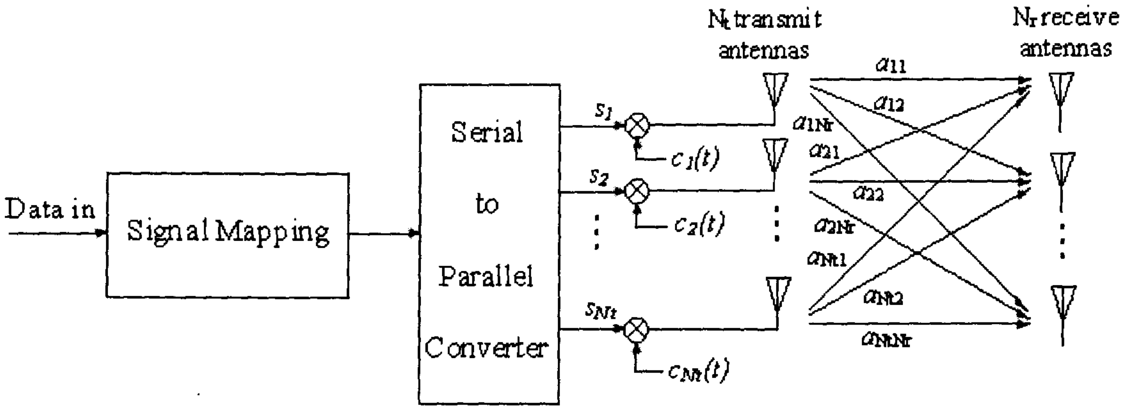

Figure 1.1: Transmitter Model of Conventional MIMO-CDMA System

Parity bit selected spreading sequence technique, based on FEC block code, was first proposed in [11]. In a CDMA system using *(n,k)* systematic block code, the calculated *n-k* parity bits are used to select a spreading sequence from a set of mutually orthogonal spreading sequences. Once the spreading sequence is selected, it is used to spread all *k* message bits in the block. At the receiver, the system first determines which spreading sequence in the set was most likely employed by the transmitter by observing the magnitudes of the matched filter outputs over the duration of the block. Then, assuming the first step is correct; it determines the most likely transmitted message block by comparing the matched filters outputs to the subset of messages that correspond to the selection of that spreading sequence.. Since the parity bits are not appended at the end of information message bits, this technique can improve the system performance in the additive white Gaussian noise (AWGN) channel with no transmission rate loss. The transmitter model for the CDMA system using parity bit selected spreading, given in [11], is shown in Figure 1.2.

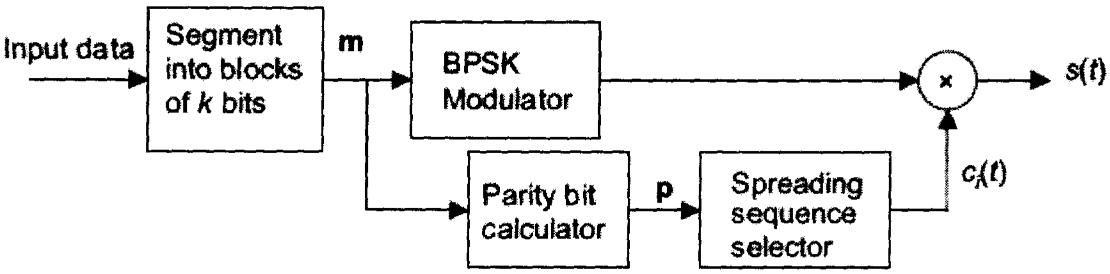

Figure 1.2: Transmitter Model of Parity Bit Selected Spreading CDMA System

As an example, consider a (6,3) systematic code with the following generator matrix

$$G = \begin{bmatrix} 1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 & 1 \end{bmatrix} \tag{1.1}$$

The generator matrix in (1.1) can be written as **G**=[**I**|**P**], [25]; where **I** is the $k \times k$ identity matrix, and **P** is the parity matrix. Then **P** is written as

$$P = \begin{bmatrix} 1 & 1 & 0 \\ 0 & 1 & 1 \\ 1 & 0 & 1 \end{bmatrix} \tag{1.2}$$

The message vectors and corresponding codewords are given in Table 1.1.

Table 1.1: (6,3) Systematic Block Code

Message vector	Parity bits	Codeword
000	000	000 000
001	101	001 101
010	011	010 011
011	110	011 110
100	110	100 110
101	011	101 011
110	101	110 101
111	000	111 000

Table 1.1 shows there are two message vectors associated with each set of parity bits. Thus both of the two message vectors will be spread by the same spreading sequence. The spreading sequence in this case would be any appropriate length Walsh-Hadamard code. For the (6,3) block code, the total numbers of orthogonal spreading sequences would be $2^{6-3}=8$. Then the relationship between the message vector and its corresponding selected spreading sequence ($c_i(t)$) is given in Table 1.2. We notice that the maximum numbers of spreading sequences needed for (n,k) parity bit selected spreading is 2^{n-k}, but if there are 2 or more message vectors having the same parity bits, the actual number of spreading sequences would be less than 2^{n-k}. Table 1.2 shows, for the given (6,3) parity bit selected spreading CDMA system, the actual number of spreading sequences is 4, while the maximum numbers of spreading sequences is 8.

Table 1.2: (6,3) Parity Bit Selected Spreading table

Message vector	Parity bits	Spreading sequence
000 111	000	$c_1(t)$
001 110	101	$c_2(t)$
010 101	011	$c_3(t)$
011 100	110	$c_4(t)$

The receiver model of the CDMA system using parity bit selected spreading is given in Figure 1.3. The receiver model is the same as the one given in [11]. A set of matched filters are used at the receiver; each matched filter corresponds to one of the spreading sequences. Once the parity bits select the spreading sequence, all the k bits uses the same spreading sequences, the output from the i^{th} matched filter for the j^{th} message bit would be $r_i^{(j)}$.

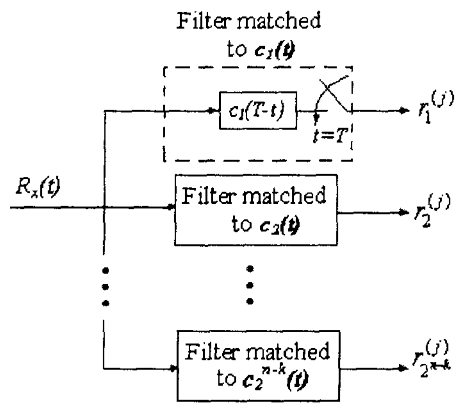

Figure 1.3: Receiver Model of Parity Bit Selected Spreading CDMA System

The determination of the most likely transmitted message vectors has two steps: first, determine the most likely selected spreading sequence; then, determine the most likely transmitted message vector for using that spreading sequence.

The decision variable for the most likely selected spreading sequence $c_i(t)$ is given in [11], which is expressed as

$$\sum_{j=1}^{k}\left|r_i^{(j)}\right|^2 > \sum_{j=1}^{k}\left|r_m^{(j)}\right|^2 \quad \text{for all } m \neq i \tag{1.3}$$

Once the selected spreading sequence is determined, we use only the decision variables at the output of the filter matched to the spreading waveform detected by equation (1.3) to determine which message vector was transmitted. We compare these decision variables only to the message vectors associated with that spreading sequence.

For example, if we use the parity bit selected technique of Table 1.2 and the receiver determines that $c_4(t)$ is the most likely employed spreading then the outputs of the 4th matched filter are compared to messages 011 and 100. The message that is closest in Euclidean distance to the matched filter outputs is the detected message.

The simulation BER performances of the CDMA system using parity bit selected spreading technique with (6,3) and (7,4) codes in the additive white Gaussian noise (AWGN) channel are shown in Figure 1.4, as is compared to the performance of the CDMA system using conventional method. The generator matrix for (6,3) code is the same as matrix (1.1); and the generator matrix for (7,4) code is given as follow.

$$G = \begin{bmatrix} 1 & 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 \end{bmatrix} \tag{1.4}$$

The comparison results show that the CDMA system using parity bit selected spreading can improve the BER performance. At the BER of 10^{-3}, the parity bit selected spreading technique using (6,3) code provide a gain of approximately 1.2dB over conventional CDMA system, while a gain of approximately 2dB is obtained by using the (7,4) code. The comparison results also show that by increasing the block code length for parity bit selected spreading technique can improve the BER performance. At the BER of 10^{-3}, the (7,4) code system provides a gain of approximately 0.8dB over the system employing (6,3) code.

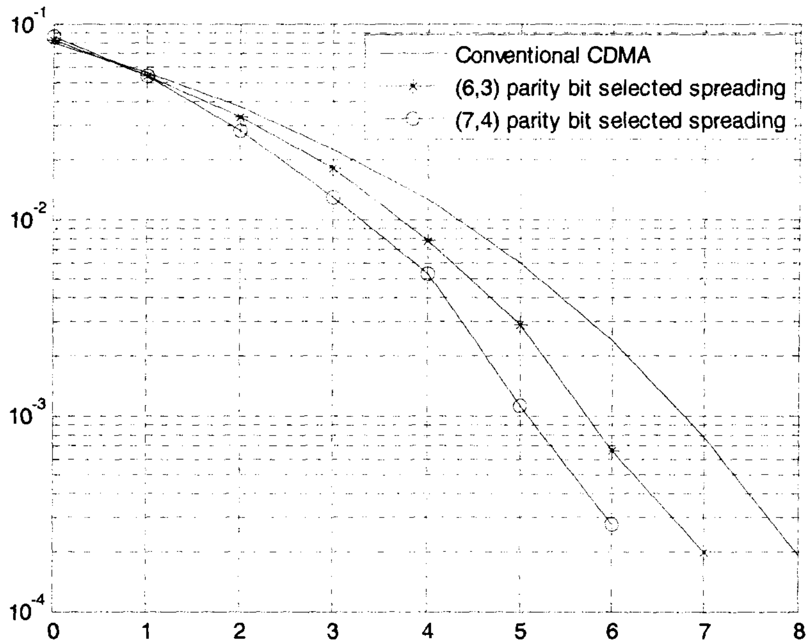

Figure 1.4: Simulation BER Performance of Different CDMA Systems over AWGN Channel

The idea of applying parity bit selected spreading technique to the MIMO-CDMA system was first introduced in [4]. In the MIMO-CDMA system with N_t transmit antennas, N_t symbols are transmitted simultaneously; an *(n,k)* systematic block code having $k= M\times N_t$ would be an excellent choice for the MIMO-CDMA system using parity bit selected spreading. Once the spreading sequence is determined, all the transmit antennas use the selected spreading sequence. The selected spreading sequence would be used for the next M signaling interval; depend on signal mapping, the signaling interval M may be different (eg: if M=2, in BPSK signaling, the signaling interval would be 2; while in QPSK signaling, the signaling interval would be 1). Figure 1.3 shows the transmitter model for the MIMO-CDMA system using parity bit selected spreading.

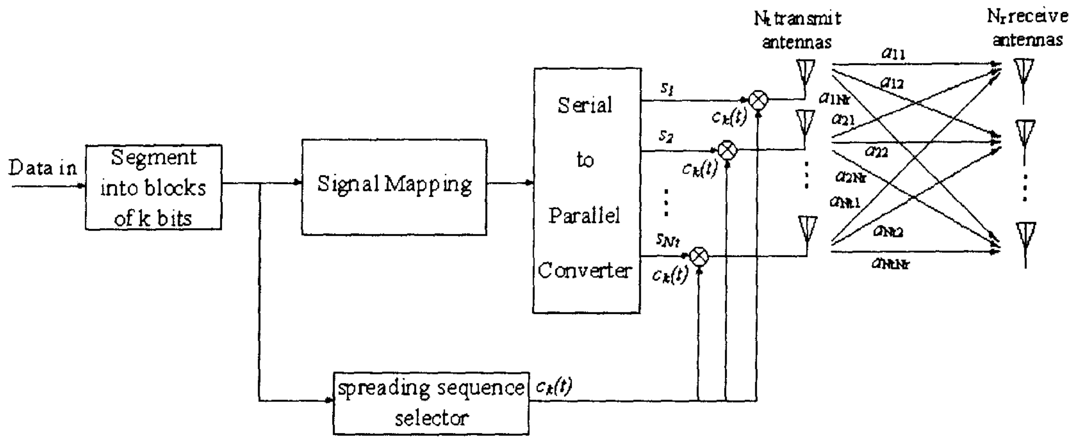

Figure 1.5: Transmitter Model of Parity Bit Selected Spreading MIMO-CDMA System

The advantage of MIMO-CDMA is to let multiple data to be transmitted simultaneously. If all the transmit antennas use the same spreading sequence, limited diversity would be provided at transmitter. This is one of the disadvantages for the MIMO-CDMA system using parity bit selected spreading.

Thus, [4] also introduces another similar technique: permutation spreading technique. In the permutation spreading technique, the parity bits are used to select N_t different spreading sequences, and each antenna would use one of the N_t spreading sequence at a given time interval.[4] also shows a permutation table is required in order to select a unique permutation spreading sequence using given parity bits. Though this technique is more complicated than parity bit selected spreading technique, it can significantly improve the BER performance.

In this thesis, all three techniques, conventional method, parity bit selected spreading, and permutation spreading techniques are applied for MIMO-CDMA system under the frequency non-selective, slowly fading channel. The performances are analyzed in both single user and multi-user system. In the multi-user system, a single-user detector [12] is used for the MIMO-CDMA system. It is simple to implement, and considered that the power control can solve the near-far problem [13].

1.2 Contribution of the Thesis

The following are the main contributions and original researches of this thesis:

- The theoretical analysis of BER performance for single user MIMO-CDMA system over frequency non-selective fading channel is first time provided in this thesis. The theoretical analysis is done for conventional method, parity bit selected spreading, and permutation spreading technique. The closed form bit error probability expressions are given for the BPSK modulated MIMO-CDMA system employing the above three techniques.

- We introduce new design strategies for the MIMO-CDMA system using parity bit selected spreading and permutation spreading techniques. The design strategy for parity bit selected spreading technique is similar to the one given in [11], but with some modifications so that it can be used in MIMO-CDMA system. For the permutation spreading technique, two methods are used to design the permutation tables: space time block code permutation and T-design permutation. The permutation tables for 2, 3 and 4 transmit antennas are given as well.

- We analyze for the first time the theoretical BER performance for asynchronous MIMO-CDMA system with multiple access interference (MAI). The theoretical analysis is done for all the three techniques through simulations. In the MIMO-CDMA system with MAI, each user is assigned a random scrambling code. The scrambling code is added before the orthogonal spreading sequences, so that the spreading sequences are similar to the pseudo-noise (PN) sequences between different users.

- Performance evaluation and simulation comparison for MIMO-CDMA system for all three techniques are done through simulations. The simulation performances are analyzed under the frequency non-selective flat fading channel for both single-user and multi-user systems.

1.3 Thesis Organization

The rest of the thesis is organized as follows:

Chapter 2 defines the conventional method for MIMO-CDMA system. The theoretical expression for BPSK modulated MIMO-CDMA system using conventional method is given under the flat fading channels. The BER performances for MIMO-CDMA systems through simulation are evaluated. We compare the theoretical expressions with the simulation performances.

Chapter 3 introduces the parity bit selected spreading technique for MIMO-CDMA system. The design strategy for the MIMO-CDMA system using parity bit selected spreading is given. The closed form bit error probability expressions for BPSK modulated MIMO-CDMA system are given. We evaluate the simulation performances for the MIMO-CDMA systems; and we also verify the accuracy of the theoretical expression.

Chapter 4 introduces the permutation spreading technique for MIMO-CDMA system. Two design strategies for permutation spreading technique are given: the space time block code permutation and T-design. The closed form bit error probability expressions for BPSK modulated MIMO-CDMA system using permutation spreading is given. We evaluate the system performances through simulation, and we verify the accuracy of theoretical expressions The BER performances comparison between conventional method, parity bit selected spreading, and permutation spreading techniques are done as well.

Chapter 5 introduces all the three techniques to the multi-user MIMO-CDMA system. We give the theoretical analysis for these three techniques by finding the signal-to-interference-noise ratio (SINR). We evaluate the BER performances through simulation and compare the BER performances for three techniques.

Chapter 6 gives the summary of conclusions; and suggestion for the future research.

Chapter 2

Single User Conventional MIMO-CDMA System

2.1 Introduction

In CDMA system, multiple users share the same bandwidth at the same time. Each user is assigned a unique, large bandwidth spreading sequence. The number of simultaneous users in the system is a function of the number of spreading sequences [14]. In CDMA system, if the spreading is done by direct sequence spreading that is called the direct sequence spread spectrum CDMA (DS-SS CDMA) or DS-CDMA [15].

The wireless communication system with multiple transmit and receive antennas (MIMO) has been shown to provide an effective way to increase transmission rate and capacity gain over the fading channel without increasing the bandwidth [9], [10].

The combination of CDMA and MIMO system can provide the advantages of both systems. The ideas of spatial multiplexing and transmit diversity have been applied to systems and also are now being used in the third generation (3G) CDMA standards [10]. Several diversity transmission techniques have been proposed for the wireless MIMO systems. Alamouti introduced a simple space time code for transmit diversity technique in [16]. Bell laboratory introduced the V-BLAST for spatial multiplexing (SM) technique in [17]. In general, the transmit diversity techniques 'spread' bit stream over space and/or time to see multiple channel gains [10].

The MIMO-CDMA system using conventional method only has space diversity at receiver; each transmit antenna uses a unique spreading sequence. Since all the data are transmitted synchronously, Walsh-Hadamard codes can be used in the conventional MIMO-CDMA system. In the Walsh-Hadamard code matrix, all the rows and columns are mutually orthogonal to each other, and it can be used as an optimum orthogonal set [18]. Therefore, using Walsh-Hadamard codes in the conventional MIMO-CDMA system can protect the transmit data from interfering with each other in the flat fading channel.

2.2 System Model

2.2.1 Transmitter Model

The transmitter model for MIMO-CDMA system using conventional method is given in Figure 2.1. The input message bits are grouped and mapped into symbols by signal mapping. Then the symbols are converted into parallel data streams through a serial-to-parallel converter. The information data (s_1~s_{Nt}) is directly multiplied with the spreading sequences ($c_1(t)$~$c_{Nt}(t)$) before transmission. A unique, orthogonal spreading sequence is assigned for each transmit antenna. If there are N_t transmit antennas; accordingly, N_t different spreading sequences are required.

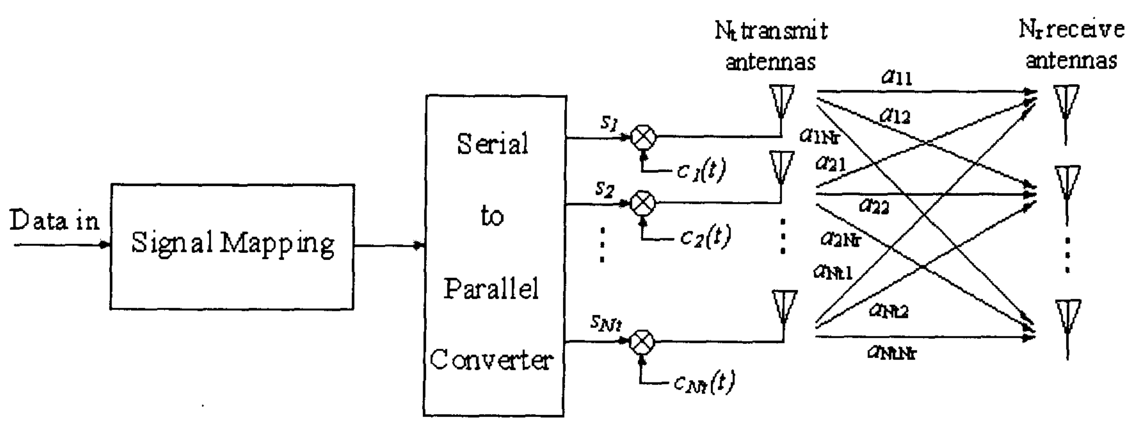

Figure 2.1: Transmitter Model of Conventional MIMO-CDMA System

2.2.2 Receiver Model

The receiver model for MIMO-CDMA system using conventional method is given in Figure 2.2. The received symbols are determined through optimal receivers at receiver. The optimal receiver consists of the optimal detector, which has a set of matched filters, and the decision device. Each receive antenna is connected to an optimal detector. If there are N_t transmit antennas, the total number of matched filters for each optimal receiver are N_t as well. Each matched filter filters and samples the received signal corresponding to one of the spreading sequences given from $\{c_1(t), c_2(t), \ldots, c_{Nt}(t)\}$. In Figure 2.2, $r_{11}, r_{12}, \ldots, r_{NrNt}$ are the decision variables output from the matched filters. The maximal ratio combiner (MRC) combines the decision variables from the same transmit antennas together; and the decision device determines the message bits $\{\tilde{b}_1, \tilde{b}_2, \ldots, \tilde{b}_k\}$.

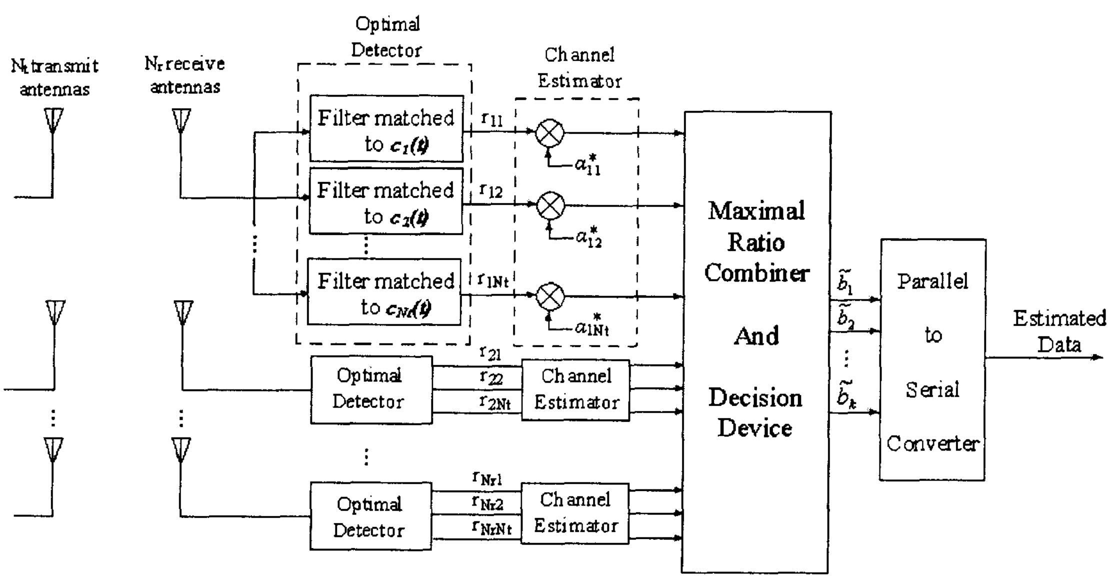

Figure 2.2: Receiver Model of Conventional MIMO-CDMA System

2.3 Bit Error Probability

2.3.1 Multiple Input Single Output (MISO)

Before we give the bit error probability expression for the MIMO system case directly, we consider the case of the MISO system. MISO system is the simplified model for MIMO system, which does not have the space diversity at receiver part.

Consider a BPSK modulated MISO-CDMA system with N_t transmit antennas and 1 receive antenna, the received signal is the sum of all transmit signals multiplied by their corresponding channel gains. Since there is only one receive antenna, the number of optimal detector is one as well. Each matched filter corresponds to one of the spreading sequence from the set $\{c_1(t), c_2(t), \ldots, c_{Nt}(t)\}$. The transmit message symbols can be separated by the optimal detector. And the estimated output message bits can be determined directly from the decision device. Figure 2.3 shows the optimal receiver for the conventional MISO-CDMA system.

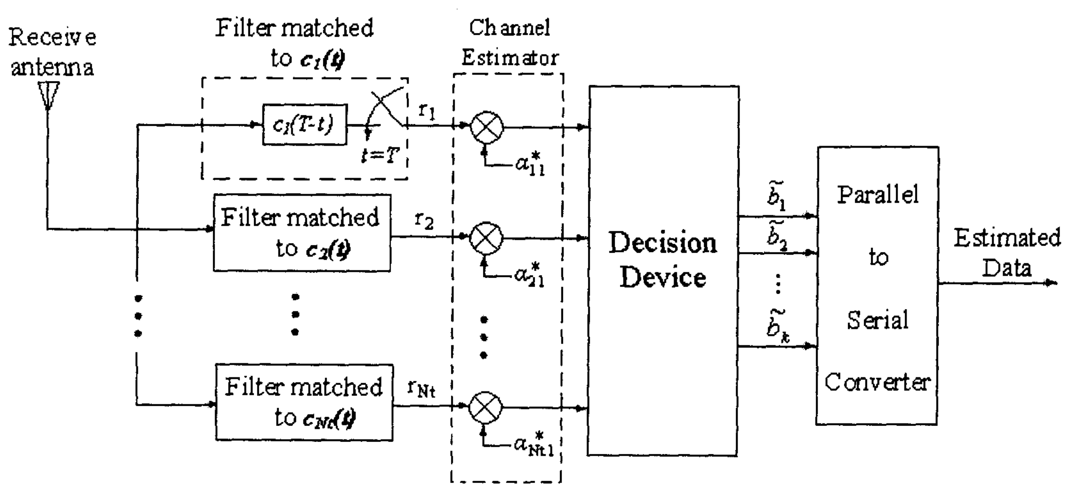

Figure 2.3: Optimal Receiver

i. Decision Variable

The received signal can be expressed as

$$Rx = \alpha_{11} \cdot b_1 \cdot c_1(t) + \alpha_{21} \cdot b_2 \cdot c_2(t) + \ldots + \alpha_{Nt1} \cdot b_{Nt} \cdot c_{Nt}(t) + n \tag{2.1}$$

where n is the total noise at receiver; and α_{k1} is the complex channel gain from the k^{th} transmit antenna.

The output from the k^{th} matched filter is given as

$$r_k = \frac{1}{T}\int_T [\alpha_{11} \cdot b_1 \cdot c_1(t) + \ldots + \alpha_{k1} \cdot b_k \cdot c_k(t) + \ldots + \alpha_{Nt1} \cdot b_{Nt} \cdot c_{Nt}(t) + n] c_k(T-t)dt \tag{2.2}$$

Since the spreading sequences we using are Walsh-Hadamard codes, the spreading sequences are orthogonal to each other, we would have

$$\frac{1}{T}\int c_i(t) \cdot c_j(T-t)dt = \begin{cases} 1 & \mathrm{j} = \mathrm{i} \\ 0 & \mathrm{j} \neq \mathrm{i} \end{cases} \tag{2.3}$$

Then, the output from the k^{th} matched filter would be

$$r_k = \frac{1}{T}\int_T [\alpha_{k1} b_k \cdot c_k(t) \cdot c_k(T-t) + n \cdot c_k(T-t)]dt$$

$$r_k = \alpha_{k1} b_k + w_n \tag{2.4}$$

where w_n is the sampled noise from the matched filter, and is given by

$$w_n = \frac{1}{T}\int_T n \cdot c_k(T-t)dt \tag{2.5}$$

The decision variable can be expressed as

$$\tilde{b}_k = \mathrm{sign}[r_k \cdot (\alpha_{k1})^*] \tag{2.6}$$

where $(\alpha_{k1})^*$ is the complex conjugate of the channel gain α_{k1}.

ii. Bit Error Probability

Equation (2.6) shows, in the MISO-CDMA system using conventional method, the parallel data stream are independent to each other and can be decoded separately. This implies the bit error probability expression would be equivalent to the CDMA system in the single path flat fading channel.

The bit error probability for BPSK modulated CDMA system in the single path flat fading channel is given in [19]. Then, the bit error probability for BPSK modulated MISO-CDMA system using conventional method is given as

$$P_{2b,conventional,MISO}(r_b) = \frac{1}{2}\left[1 - \sqrt{\frac{\bar{\gamma}_b}{1+\bar{\gamma}_b}}\right] \qquad (2.7)$$

where $\bar{\gamma}_b$ is the average signal-to-noise ratio (SNR) given in [19]. It is defined as

$$\bar{\gamma}_b = \frac{E_b}{N_o} \qquad (2.8)$$

2.3.2 Multiple Input Multiple Output (MIMO)

Consider a BPSK modulated MIMO-CDMA system with N_t transmit and N_r receive antennas. Each receive antenna has an optimal detector similar to figure 2.2; MRC is also used for decision variable combining.

i. Decision Variable

The output from the k^{th} matched filter in the j^{th} receive antenna would be given as

$$r_{jk} = \alpha_{jk} b_k + w_{nj} \qquad (2.8)$$

The estimated message bit can be expressed as

$$\tilde{b}_k = \text{sign}[\sum_{j=1}^{Nr} r_{jk} \cdot (\alpha_{jk})^*] \qquad (2.9)$$

ii. Bit Error Probability

The bit error probability expression for BPSK modulated MIMO-CDMA system using conventional method is equivalent to BPSK modulated CDMA system with multiple receive antennas in the flat fading channel. The expression is given in [19], which is expressed as

$$P_{2b,conventional,MIMO}(r_k) = \frac{1}{2}\left[1 - \sqrt{\frac{\bar{\gamma}_b / Nr}{1 + \bar{\gamma}_b / Nr}} \sum_{i=0}^{Nr-1} \binom{2i}{i} \left(\frac{1}{4(1 + \bar{\gamma}_b / Nr)} \right)^i \right] \tag{2.10}$$

2.4 Simulation Results and Discussion

The following assumptions are used for the simulation performances in this thesis

1) All the MIMO-CDMA systems use BPSK signal mapping only.

2) All the orthogonal spreading sequences used in this thesis are Walsh-Hadamard codes, the length of the code is 2^4=16.

3) In order to simplify the simulations, all the MIMO-CDMA systems only consider the cases with either 1 receive antenna, or with the numbers of receive antennas equaling to the number of transmit antennas, N_t=N_r.

4) The fading channel is frequency nonselective (flat fading) channel, and there is no channel induced inter-symbol interference (ISI).

5) The channel impulse response slowly changes over many symbol durations. In other words, the channel is a slowly fading channel.

6) The channel gain between transmit and receive link are uncorrelated.

7) It is assumed that perfect channel state information (CSI) is available at the receiver .

The following sections verify the accuracy of the bit error probability expressions given in section 2.3. MATLAB is used for getting the simulation results; and the simulation message bits are long enough to ensure that there are sufficient numbers of errors to be counted (i.e. at least 100 errors). It is assumed that all the channel paths are uncorrelated, the fading channels are frequency non-selective, and the channel gains are slowly varying complex Gaussian variable with zero mean and unit variance.

A RANDN Method (RANDM), by directly using the MATLAB function *randn*, is used for generating the flat fading channel gain. Due to its simplicity and excellent approximation accuracy, this method is widely employed by many researchers [22].

Figure 2.4 shows the BER performance of theoretical expression result vs. simulation result for BPSK modulated MISO-CDMA system. Because the bit error probability expression given in (2.7) is an exact form; it is reasonable to observe a good matching between the theoretical bit error probability expression and the simulation result. Figure 2.5 shows the BER performance comparison for BPSK modulated MIMO-CDMA system. It gives the same comparison results as Figure 2.4, a good matching between the theoretical expression and simulation result.

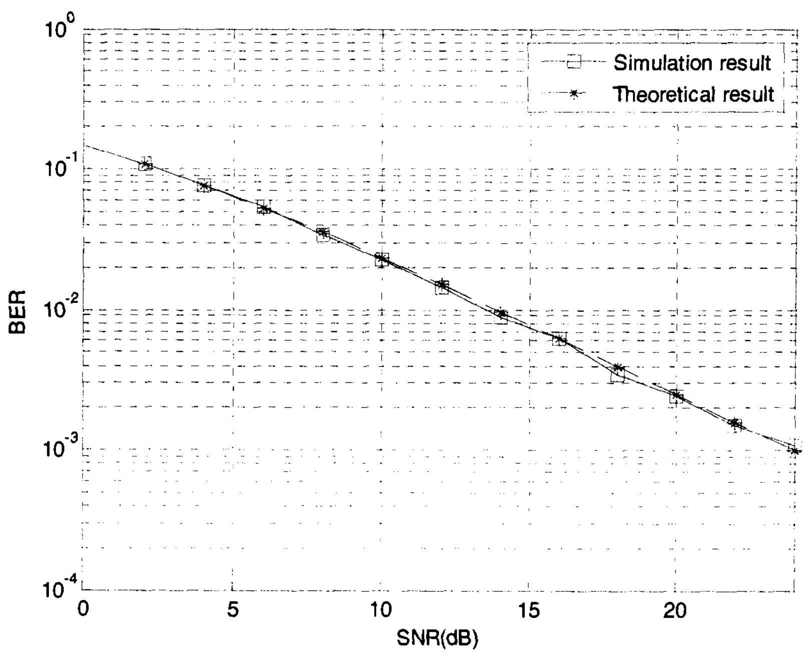

Figure 2.4: Conventional BPSK MISO-CDMA System over Flat Fading Channel

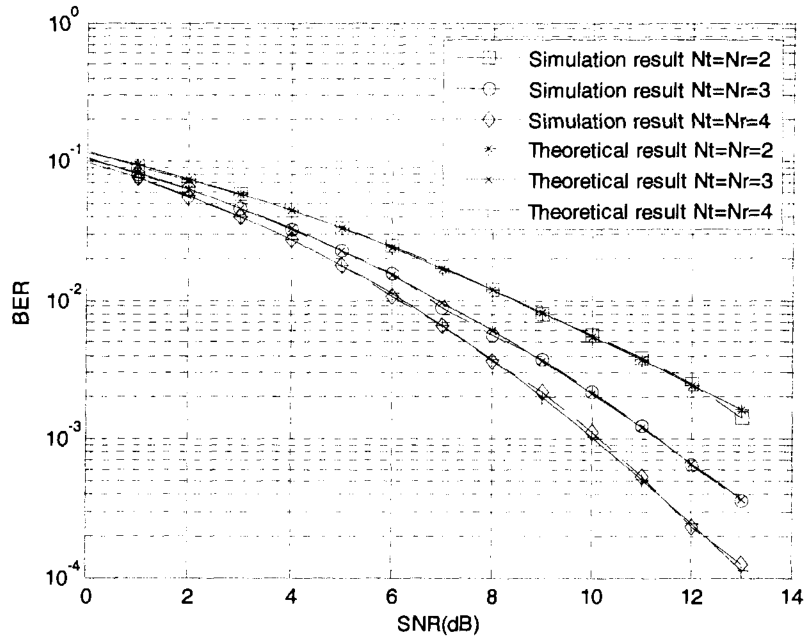

Figure 2.5: Conventional BPSK MIMO-CDMA System over Flat Fading Channel

Chapter 3

Single User Parity-Bit-Selected Spreading MIMO-CDMA System

3.1 Introduction

The parity bit selected spreading technique was first introduces in [11]. Unlike the DS-SS CDMA system using conventional method, for parity bit selected spreading technique, the spreading sequence is selected by the calculated parity bits. The message data block is spread by the selected spreading sequence. Since in this system, the parity bits are used to determine the spreading sequence instead of appending at the end of information block sequence, the system improves the BER performance without the loss of any code rate.

After the parity bit selected spreading technique was proposed in [11], some further researches have been done to analyze the BER performance. The BER performance for multi-user DS-CDMA system was analyzed in [23]; a Log likelihood detection for parity bit selected DS-SS CDMA system is proposed in [24].

So far, the researchers only analyzed the BER performance of parity bit selected DS-CDMA system in AWGN channels. [4] first uses this technique in the MIMO-CDMA system. The simulation results show that the parity bit selected spreading technique improves the BER performance for MIMO-CDMA system over frequency non-selective channels. This thesis does some further research, including providing the closed form bit error probability expression for MIMO-CDMA system employing parity bit selected spreading technique. The simulation results for different number of transmit/receive antenna systems are also included.

Though the main idea of parity bit selected spreading technique is the same for both SISO-CDMA and MIMO-CDMA system. In the MIMO-CDMA system, some modifications may be required. The length of message data block equal to the number of transmit antennas N_t; every 2 message vectors with largest minimum distance share the same spreading sequence (eg: for N_t=2, the message vectors 00 and 11 would share the same spreading sequence), and these 2 message vectors form a coset; and the maximum likelihood (ML) detection is used to determine the decision variable. All those modifications are used in order to simplify the system model. The detailed design strategy at the transmitter and decision variable at receiver are given in section 3.3 and 3.4.

3.2 System Model

3.2.1 Transmitter Model

The transmitter model for MIMO-CDMA system using parity bit selected spreading is given in Figure 3.1. Different from SISO-CDMA system given in [11], in the MIMO-CDMA system, the length of message group equals to the number of transmit antennas N_t. Thus, the input message bit length k should satisfy the equation $k=\log_2(M)\times N_t$. where M is the same number as the M-ary signal mapping.

Then, the message symbols are converted to parallel data stream; and at the same time the spreading sequence selector chooses the spreading sequence according to the input message vector. The message symbols ($s_1 \sim s_{Nt}$) are multiplied with the selected spreading sequences before transmission, where the spreading sequence is chosen from the orthogonal spreading sequence set $\{c_1(t), c_2(t), \ldots, c_i(t)\}$. We shall notice that unlike conventional method, the spreading sequence depends on the transmission data, and all the transmit antennas use the same spreading sequence. The total number of spreading sequences is different from the conventional method. With N_t transmit antennas, if we assign every 2 message vectors with the same spreading sequence, and with M-PSK signal mapping, the minimum number of spreading sequences would be $i=2^{(Nt \times M/2)-1}$.

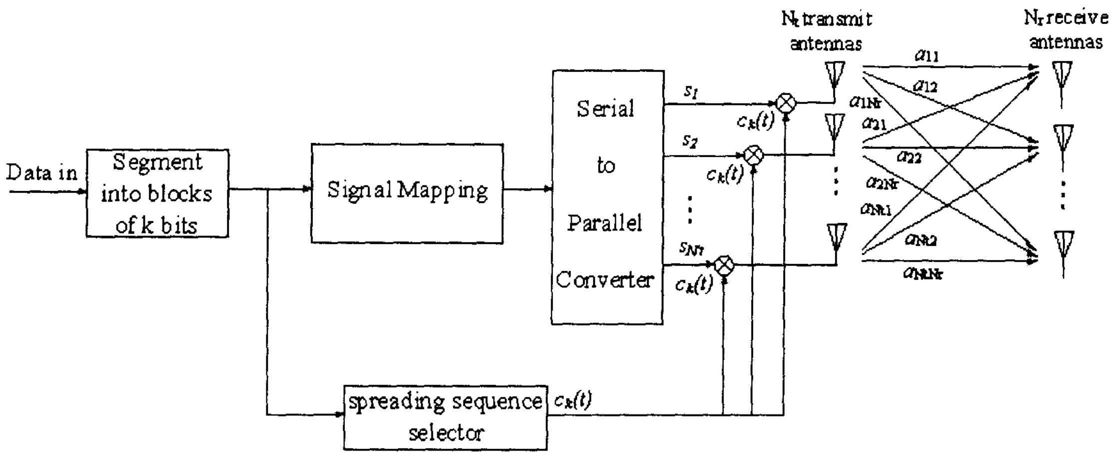

Figure 3.1: Transmitter Model of Parity Bit Selected Spreading MIMO-CDMA System

3.2.2 Receiver Model

The receiver model for MIMO-CDMA system using parity bit selected spreading is given in Figure 3.2. The received symbol messages are determined through optimal receiver at the receiver. Each receive antenna is connected to an optimal detector, where each optimal detector consists of i numbers of matched filters. Each matched filter corresponds to one of the spreading sequence given from $\{c_1(t), c_2(t), ..., c_i(t)\}$. The estimated output message bits are determined by finding the minimum Euclidean distance in the decision device. But unlike the conventional method, for the parity bit selected spreading technique, the channel estimation is part of the decision device. The method of determining the decision variable will be given in section 3.4.

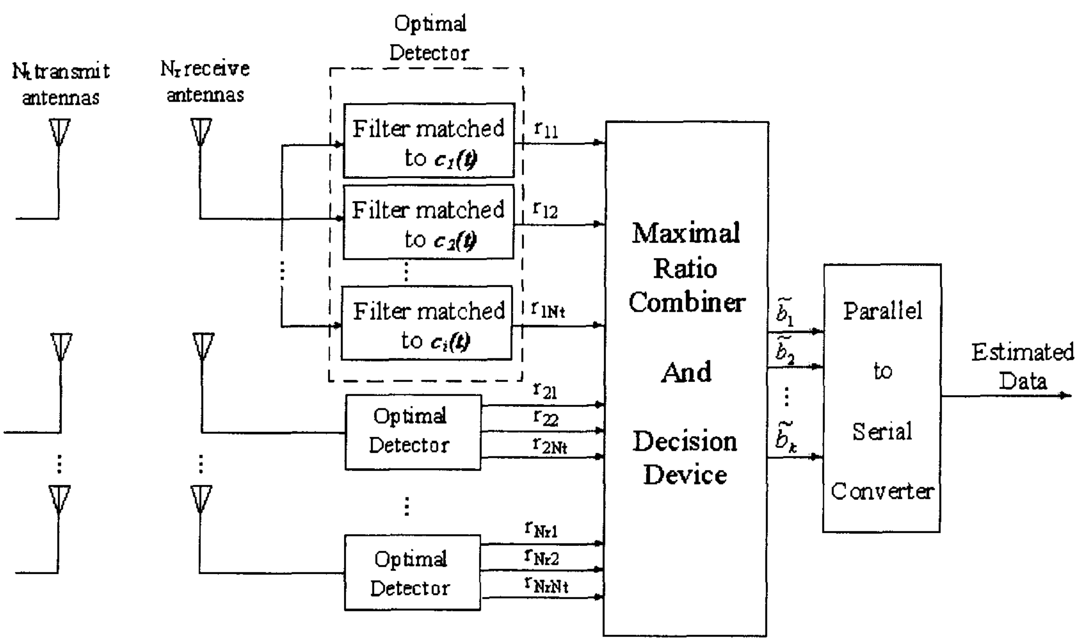

Figure 3.2: Receiver Model of Parity Bit Selected Spreading MIMO-CDMA System

3.3 Design Strategy

In the MIMO-CDMA system using parity bit selected spreading, we assign every 2 transmit message vectors with largest minimum distance to share the same spreading sequence; and they belong to the same coset. Similar to parity bit selected CDMA system given in [11], different cosets have different spreading sequences. If there are N_t transmit antennas, in the BPSK modulated system, the total number of transmit message bits per message vector is N_t, and the total number of spreading sequences would be 2^{N_t-1}.

Consider a BPSK modulated CDMA system with 2 transmit antennas, the parity bit selected spreading table is given in Table 3.1.

Table 3.1: BPSK Parity Bit Selected Spreading Table with N_t=2

Coset	Message vector	N_{t1}	N_{t2}
M_1	00 11	$c_1(t)$	$c_1(t)$
M_2	01 10	$c_2(t)$	$c_2(t)$

Note: the length of orthogonal spreading sequences is 2^4=16. Under the flat fading channel, the length of the orthogonal spreading sequence would not change the simulation performances for the single-user system.

3.4 Bit Error Probability

The original research by providing the theoretical analysis and the bit error probability expressions for the parity bit selected spreading techniques is given in this section.

3.4.1. Multiple Input Single Output (MISO)

Consider a BPSK modulated MISO-CDMA system with N_t transmit antennas and 1 receive antenna, the received signal is the sum of all transmit signals multiplied by their corresponding channel gains. An optimal detector with a set of matched filters is used at the receiver. Unlike conventional method, each matched filter corresponds to one of the spreading sequences chosen from $\{c_1(t), c_2(t),...,c_i(t)\}$ with its corresponding transmit message cosets chosen from $\{ M_1, M_2,...,M_L\}$.

i. Decision Variable

The spreading sequences used for transmission depend on the transmit message cosets, the received signal from k^{th} message group is the sum of all the message bits in k^{th} group multiplied by the channel gain. The expression uses similar expression as equation (2.1). The received signal can be expressed as

$$Rx = \alpha_{11}.b_1^{(k)} \cdot c_k(t) + \alpha_{12}.b_2^{(k)} \cdot c_k(t) + \ldots + \alpha_{1Nt}.b_{Nt}^{(k)} \cdot c_k(t) + n \tag{3.4}$$

Where α_{1i} is the complex channel gain from the i^{th} transmit antenna; $b_i^{(k)}$ is the message bit for the k^{th} message vector to be transmitted from the i^{th} transmit antenna, and its corresponding spreading sequence is $c_k(t)$; n is the total noise at the receiver.

The decision variable for the k^{th} matched filter would be given as

$$r_k = \frac{1}{T}\int_T Rx \cdot c_k(t)dt$$

$$r_k = \frac{1}{T}\int_T \left[\alpha_{11}.b_1^{(k)} \cdot c_k(t) + \alpha_{12}.b_2^{(k)} \cdot c_k(t) + \ldots + \alpha_{1Nt}.b_{Nt}^{(k)} \cdot c_k(t) + n\right] c_k(T-t)dt \tag{3.5}$$

The output from the k^{th} matched filter would be given as

$$r_k = \alpha_{11}.b_1^{(k)} + \alpha_{21}.b_2^{(k)} + \ldots + \alpha_{1Nt}.b_{Nt}^{(k)} + w_n \tag{3.6}$$

where w_n is the sampled noise after matched filter, the expression is given in equation (2.5).

The detected message is selected by ML detection, which finds the minimum Euclidean distance between the received signal message vectors. The expression is given as

$$U = \min_{k=1}^{M}\left\| Rx - \sum_{i=1}^{Nt} \alpha_{1i} \cdot b_i^{(k)} \cdot c_k(t) \right\|^2 \tag{3.7}$$

where M is the total numbers of message groups.

ii. Bit Error Probability

The probability of selecting the correct message vector bits is given in [8], which can be expressed as:

$$P(U = u_1) = P(u_1 < u_2, u_1 < u_3, \ldots, u_1 < u_M / u_1) \tag{3.8}$$

where u_i is the squared distance (decision variable) between the received signal and output from the i^{th} matched filter, which corresponds to the i^{th} message vector, and the equation is given in (3.7).

If we assume all the decision variables are independent of each other, (3.8) can also be expressed as

$$P(U = u_1) = P(u_1 < u_2 / u_1) P(u_1 < u_3 / u_1) \ldots P(u_1 < u_M / u_1) \tag{3.9}$$

Since the probability of selecting the correct message vector bits plus the probability of selecting the incorrect message vector bits equals to 1; the probability of selecting of the incorrect message vector bits u_i would be given as

$$P(U = u_i) = P(u_1 > u_i / u_1) = 1 - P(u_1 < u_i / u_1) \tag{3.10}$$

By rearranging (3.10), we can get

$$P(u_1 < u_i / u_1) = 1 - P(u_1 > u_i / u_1) \tag{3.11}$$

By substituting (3.11) into (3.9), we can get the symbol error probability

$$P(U = u_1) = (1 - P(u_1 > u_2))(1 - P(u_1 > u_3)) \ldots (1 - P(u_1 > u_M)) \tag{3.12}$$

The bit error probability for MIMO-CDMA system using parity bit selected spreading can be expressed as

$$P_{2b,parity}(r_k) \approx 1 - p_1 P(U = u_1)$$

$$P_{2b,parity}(r_k) \approx 1 - (1 - p_1 P(u_1 > u_2))(1 - p_2 P(u_1 > u_3)) \ldots (1 - p_{m-1} P(u_1 > u_M)) \tag{3.13}$$

where p, $p_1 \sim p_{m-1}$ are the coefficients which equal to the number of different bits over the number of total bits for each message vector.

The bit error probability consists of two parts $P_{2b,same}(r_k)$ and $P_{2b,diff}(r_k)$. $P_{2b,same}(r_k)$ is the bit error probability for selecting the correct spreading sequence but incorrect transmit message group (eg: from table 3.1, transmit 00 (belonging to coset M_1), but receive 00 (belonging to coset M_1)); and $P_{2b,diff}(r_k)$ is the bit error probability for selecting the incorrect spreading sequence (eg: from table 3.1, transmit 00 (belonging to coset M_1), but receive 10 (belonging to coset M_2)). From (3.10) we can have the following assumption.

$$P_{2b,same}(r_k) = p_1 P(u_1 > u_2) \tag{3.14}$$

$$P_{2b,diff}(r_k) \approx p_2 P(u_1 > u_3) = \ldots = p_{m-1} P(u_1 > u_M) \tag{3.15}$$

Bit error probability when receiver determines the correct spreading sequence ($P_{2b,same}(r_k)$)

Since every 2 transmit message vector shares the sàme spreading sequence, the symbol error probability for selecting the correct spreading sequence equals to the bit error probability with BPSK signaling transmission in the flat Rayleigh fading channel. The expression is given in [19]. It can be expressed as

$$P_{2m,same}(r_k) = P(u_1 > u_2) = \frac{1}{2}\left[1 - \sqrt{\frac{\bar{\gamma}_s}{1+\bar{\gamma}_s}}\right] \tag{3.16}$$

where $\bar{\gamma}_s$ is the total SNR for each message set, if the SNR per bit is given by $\bar{\gamma}_b$, with N_t transmit antennas, $\bar{\gamma}_s$ is given by

$$\bar{\gamma}_s = N_t \cdot \bar{\gamma}_b \tag{3.17}$$

Since the minimum distance between 2 transmit message vectors is the largest, the bit error probability $P_{2b,same}(r_k)$ would be equal to the symbol error probability $P_{2m,same}(r_i)$;

the coefficient p_1 given in (3.13) would be 1. Thus the bit error probability for selecting the correct spreading sequence can be expressed as

$$P_{2b,same}(r_k) = P_{2m,same}(r_k) = \frac{1}{2}\left[1 - \sqrt{\frac{Nt \cdot \bar{\gamma}_b}{1 + Nt \cdot \bar{\gamma}_b}}\right] \tag{3.18}$$

Bit error probability when receiver determines the incorrect spreading sequence ($P_{2b,diff}(r_k)$)

Once the transmission message vector is determined, the spreading sequences for all the transmit antennas are the same. In [16], it is shown that in such case, there would be no diversity at transmitter, and it is equivalent to the case of transmitting over 1 transmit antenna. Then, the received message for the matched filter corresponding to the correct message vector (assume is the 1st message vector, and the output from the 1st matched filter is r_1) would be given as

$$r_1 = \left(\alpha_{11}.b_1^{(1)} + \alpha_{12}.b_2^{(1)} + \ldots + \alpha_{1Nt}.b_{Nt}^{(1)}\right) \cdot c_1(t) + n \tag{3.19}$$

where $b_1^{(1)}$ is the message bit from the 1st message vector, and its corresponding spread sequence is $c_1(t)$; n is the total noise at the receiver; and α_{1k} is the complex channel gain for the k^{th} transmit antenna.

The received message for the matched filter corresponding to the incorrect message vector (assume is the k^{th} message vector, and the output from the k^{th} matched filter is r_k) would be given as

$$r_k = \left(\alpha_{11}.b_1^{(k)} + \alpha_{12}.b_2^{(k)} + \ldots + \alpha_{1Nt}.b_{Nt}^{(k)}\right) \cdot c_k(t) + n \tag{3.20}$$

We notice that although the channel gain for equation (3.19) and (3.20) are the same, the message vectors $b_1^{(1)} \sim b_{Nt}^{(1)}$ and $b_1^{(k)} \sim b_{Nt}^{(k)}$ are not the same. If we have the following setting

$$\alpha_1' = \alpha_{11}.b_1^{(1)} + \alpha_{12}.b_2^{(1)} + \ldots + \alpha_{1Nt}.b_{Nt}^{(1)} \tag{3.21}$$

$$\alpha_k' = \alpha_{11}.b_1^{(k)} + \alpha_{12}.b_2^{(k)} + \ldots + \alpha_{1Nt}.b_{Nt}^{(k)} \tag{3.22}$$

Both α_1' and α_k' can be viewed as equivalent channel gain for the 1st message vector and the k^{th} message vector.

If 2 message vectors share the same spreading sequence, then $\alpha_1' = -\alpha_k'$. In the coherent detection it can be expressed as

$$\|\alpha_1'\|^2 = \|\alpha_k'\|^2 \tag{3.23}$$

(3.23) indicates that there is no diversity gain if 2 message vectors share the same spreading sequence. And it would give the same expression as equation (3.18).

If 2 message vectors have different spreading sequence, we would have $\|\alpha_1'\|^2 \neq \|\alpha_k'\|^2$. Because all the transmit bits are BPSK signals, α_1' and α_k' would be correlated. However, different transmit message vectors would give different cross-correlation coefficients; and as the number of message vector increases, the complexity of determining the cross-correlation coefficient increases as well.

In order to simplify the calculation, we would use a closed form to express the error probability. In the closed form, we assume the equivalent channel gain between two message vectors (α_1' and α_k') are uncorrelated.

By substituting (3.21) and (3.22) into (3.19) and (3.20), we would have

$$r_1 = \alpha_1' \cdot c_1(t) + n \tag{3.24}$$

$$r_k = \alpha_k' \cdot c_k(t) + n \tag{3.25}$$

The symbol error probability of selecting the incorrect message vector would be given as

$$P(u_1 > u_k) = P(r_1 < r_k) = P(\alpha_1 \cdot c_1 + n < \alpha_k \cdot c_k + n) \tag{3.26}$$

Since all the spreading sequences are orthogonal to each other, equation (3.26) can be viewed as the error probability of binary orthogonal signalling over 2-path fading channel. As previously mentioned, we assume the channel gains are uncorrelated; it can be regarded as a 2-path independent fading channel with MRC.

The expression for 2-FSK signaling with L-path MRC is given [19], which is expressed as

$$P_{2m,diff}(r_k) \approx \frac{1}{2}\left[1-\mu\sum_{i=0}^{L-1}\binom{2i}{i}\left(\frac{1-\mu^2}{4}\right)^i\right] \tag{3.27}$$

Where μ for 2-FSK is given in [19], which can be expressed as

$$\mu = \sqrt{\frac{\bar{\gamma}_c}{2+\bar{\gamma}_c}} = \sqrt{\frac{\bar{\gamma}_s / L}{2+\bar{\gamma}_s / L}} = \sqrt{\frac{Nt\cdot\bar{\gamma}_b / L}{2+Nt\cdot\bar{\gamma}_b / L}} \tag{3.28}$$

With 2-path fading, equation (3.27) can be simplified as

$$P_{2m,diff}(r_k) = P(u_1 > u_k) \approx \frac{1}{2}\left[1-\sqrt{\frac{Nt\cdot\bar{\gamma}_b/2}{2+Nt\cdot\bar{\gamma}_b/2}}\sum_{i=0}^{1}\binom{2i}{i}\left(\frac{1}{2(2+Nt\cdot\bar{\gamma}_b/2)}\right)^i\right] \tag{3.29}$$

[1] shows the coefficient p_2~p_m given in (3.13) would be approximately equal to 0.5. Then, the bit error probability for selecting the incorrect spreading sequence can be expressed as

$$P_{2b,diff}(r_k) \approx \frac{1}{2}P_{2m,diff}(r_k) \approx \frac{1}{4}\left[1-\sqrt{\frac{Nt\cdot\bar{\gamma}_b/2}{2+Nt\cdot\bar{\gamma}_b/2}}\sum_{i=0}^{1}\binom{2i}{i}\left(\frac{1}{2(2+Nt\cdot\bar{\gamma}_b/2)}\right)^i\right] \tag{3.30}$$

By substituting (3.18) and (3.30) into (3.13), the closed form bit error probability for BPSK modulated MISO-CDMA system using parity bit selected spreading can be expressed as

$$P_{2b,parity,MISO}(r_k)$$
$$\approx 1-\left\{1-\frac{1}{2}\left[1-\sqrt{\frac{Nt\cdot\bar{\gamma}_b}{1+Nt\cdot\bar{\gamma}_b}}\right]\right\}\left\{1-\frac{1}{4}\left[1-\sqrt{\frac{Nt\cdot\bar{\gamma}_b/2}{2+Nt\cdot\bar{\gamma}_b/2}}\sum_{i=0}^{1}\binom{2i}{i}\left(\frac{1}{2(2+Nt\cdot\bar{\gamma}_b/2)}\right)^i\right]\right\}^{M-2} \tag{3.31}$$

Where M is the total number of message groups, for N_t=2, M=4; N_t=3, M=8; and N_t=4, M=16.

3.4.2. Multiple Input Multiple Output (MIMO)

Consider a BPSK modulated MIMO-CDMA system with N_t transmit antennas and N_r receive antennas, the received signal is the sum of all transmit signals multiplied by their corresponding channel gains. An optimal detector with a set of match filters is used for each receive antenna. And each match filter corresponds to one of the spreading sequence chosen from $\{c_1(t), c_2(t),...,c_i(t)\}$ with its corresponding transmit message vector.

i. Decision Variable

Similar to the MISO system, the output from the k^{th} matched filter in the j^{th} receive antenna would be given as

$$r_{jk} = \alpha_{j1}.b_1^{(k)} + \alpha_{j2}.b_2^{(k)} + \ldots + \alpha_{jNt}.b_{Nt}^{(k)} + n_j \tag{3.32}$$

The received message vector is detected using maximum likelihood (ML) detection and use maximal ratio combining (MRC). The decision variable is expressed as

$$U = \min_{k=1}^{M} \left\| Rx - \sum_{j=1}^{Nr} \sum_{i=1}^{Nt} \alpha_{ji} \cdot b_i^{(k)} \cdot c_k \right\|^2 \tag{3.33}$$

where M is the total numbers of message groups.

ii. Bit Error Probability

Similar to the bit error probability expression for the MISO-CDMA system using the parity bit selected spreading, the bit error probability for the MIMO-CDMA system employing parity bit selected spreading also consists of two parts, $P_{2b,same,MIMO}(r_k)$ and $P_{2b,diff,MIMO}(r_k)$. $P_{2b,same,MIMO}(r_k)$ is the bit error probability for selecting the correct spreading sequence, and $P_{2b,diff,MIMO}(r_k)$ is the bit error probability for selecting the incorrect spreading sequence.

Bit error probability when receiver determines the correct spreading sequence ($P_{2b,same,MIMO}(r_k)$)

Similar to the MISO system, the symbol error probability for choosing the correct spreading sequence equals to the error probability with BPSK singaling transmission with Nr-path MRC diversity technique

$$P_{2m,same,MIMO}(r_k) = P(u_1 > u_2) = \frac{1}{2}\left[1 - \sqrt{\frac{\bar{\gamma}_c}{1+\bar{\gamma}_c}} \sum_{i=0}^{Nr-1} \binom{2i}{i} \left(\frac{1}{4(1+\bar{\gamma}_c)}\right)^i\right] \tag{3.34}$$

where $\bar{\gamma}_c$ is the total SNR per channel per each message vector, with N_t transmit antennas and N_r receive antennas, $\bar{\gamma}_c$ is given by

$$\bar{\gamma}_c = \frac{Nt}{Nr}\bar{\gamma}_b \tag{3.35}$$

Since we only consider the MIMO-CDMA system with N_t=N_t, we woul have $\bar{\gamma}_c = \bar{\gamma}_b$. Similar to MISO system, the bit error probability $P_{2b,same,MIMO}(r_k)$ would be equal the symbol error probability $P_{m,same,diversity}(r_i)$. The bit error probability for selecting the correct spreading sequence can be expressed as

$$P_{2b,same,MIMO}(r_k) = P_{2m,same,MIMO}(r_k) = \frac{1}{2}\left[1 - \sqrt{\frac{\bar{\gamma}_b}{1+\bar{\gamma}_b}} \sum_{i=0}^{Nr-1} \binom{2i}{i} \left(\frac{1}{4(1+\bar{\gamma}_b)}\right)^i\right] \tag{3.36}$$

Bit error probability when receiver determines the incorrect spreading sequence ($P_{2b,diff,MIMO}(r_k)$)

Similar to MISO system, the received message for all the matched filters corresponding to the correct message vector (assume is 1st message vector) would be given as

$$r_1 = \sum_{j=1}^{Nr} \left[\left(\alpha_{j1} b_1^{(1)} + \alpha_{j2} b_2^{(1)} + \ldots + \alpha_{jNt} b_{Nt}^{(1)} \right) \cdot c_1(t) + n_j \right] \tag{3.37}$$

The received message for all the matched filters corresponding to the incorrect message vector (assume is the k^{th} message vector) would be given as

$$r_k = \sum_{j=1}^{Nr} \left[\left(\alpha_{j1} b_1^{(k)} + \alpha_{j2} b_2^{(k)} + \ldots + \alpha_{jNt} b_{Nt}^{(k)} \right) \cdot c_k(t) + n_j \right] \tag{3.38}$$

Since additional received antennas would be equivalent to multi-path fading channels, the received signal at different receive antennas would be independent to each other. By using the similar approach as for equation (3.21) and (3.22), we would have the equivalent channel gains for j^{th} received antennas, which is expressed as

$$\alpha'_{j1} = \alpha_{j1} b_1^{(1)} + \alpha_{j2} b_2^{(1)} + \ldots + \alpha_{jNt} b_{Nt}^{(1)} \tag{3.39}$$

$$\alpha'_{jk} = \alpha_{j1} b_1^{(k)} + \alpha_{j2} b_2^{(k)} + \ldots + \alpha_{jNt} b_{Nt}^{(k)} \tag{3.40}$$

By substituting (3.39) and (3.40) into equation (3.37) and (3.38), we would have

$$r_1 = \left(\alpha'_{11} + \alpha'_{21} + \ldots + \alpha'_{Nr1} \right) \cdot c_1(t) + \sum_{j=1}^{Nr} n_j \tag{3.41}$$

$$r_k = \left(\alpha'_{1k} + \alpha'_{2k} + \ldots + \alpha'_{Nrk} \right) \cdot c_k(t) + \sum_{j=1}^{Nr} n_j \tag{3.42}$$

Note: $\alpha'_{11} \sim \alpha'_{Nr1}$ are the equivalent channel gains for 1st message vector from the 1st to the N_r^{th} receive antennas; and $\alpha'_{1k} \sim \alpha'_{Nrk}$ are the equivalent channel gains for the k^{th}

message vector from the 1st to the N_rth receive antennas.

The symbol error probability for selecting the incorrect message vector would be given as

$$P(u_1 > u_k) = P(r_1 < r_k)$$
$$P(u_1 > u_k) = P((\alpha_{11} + \alpha_{21} + \ldots + \alpha_{Nr1}) \cdot c_1 + n < (\alpha_{1k} + \alpha_{2k} + \ldots + \alpha_{Nrk}) \cdot c_k + n) \quad (3.43)$$

We notice that equation (3.43) is similar to equation (3.26) given in MISO-CDMA system. Since equation (3.26) can be viewed as the error probability of binary orthogonal signaling over 2-path fading channel, equation (3.43) can be viewed as the error probability of binary orthogonal signaling over $2 \times Nr$-path fading channels.

Then, the expression for $P_{2b,diff,MIMO}(r_k)$ with N_r received antennas would be approximately equal to the bit error probability of binary orthogonal signaling over $2 \times N_r$-path fading channel with MRC technique, which is given as

$$P_{2m,diff,MIMO}(r_k) = P(u_1 > u_k) \approx \frac{1}{2}\left[1 - \sqrt{\frac{Nt \cdot \bar{\gamma}_b / 2Nr}{2 + Nt \cdot \bar{\gamma}_b / 2Nr}} \sum_{i=0}^{2Nr-1} \binom{2i}{i} \left(\frac{1}{2(2 + Nt \cdot \bar{\gamma}_b / 2Nr)}\right)^i\right] \quad (3.44)$$

In the case of $N_t = N_r$, equation (3.44) would be simplified as

$$P_{2m,diff,MIMO}(r_k) = P(u_1 > u_k) \approx \frac{1}{2}\left[1 - \sqrt{\frac{\bar{\gamma}_b / 2}{2 + \bar{\gamma}_b / 2}} \sum_{i=0}^{2Nr-1} \binom{2i}{i} \left(\frac{1}{2(2 + \bar{\gamma}_b / 2)}\right)^i\right] \quad (3.45)$$

[1] shows the coefficient $p_2 \sim p_m$ given in (3.13) would be approximately equal to 0.5. Then, the bit error probability for selecting the incorrect spreading sequence can be expressed as

$$P_{2b,diff,MIMO}(r_k) \approx \frac{1}{2} P_{2m,diff,MIMO}(r_k) \approx \frac{1}{4}\left[1 - \sqrt{\frac{\bar{\gamma}_b / 2}{2 + \bar{\gamma}_b / 2}} \sum_{i=0}^{2Nr-1} \binom{2i}{i} \left(\frac{1}{2(2 + \bar{\gamma}_b / 2)}\right)^i\right] \quad (3.46)$$

By substitute (3.36) and (3.46) into (3.13), the closed form bit error probability for BPSK modulated MIMO-CDMA system using parity bit selected spreading would be approximately equal to

$$P_{2b,parity,MIMO}(r_k) \approx$$

$$1-\left\{1-\frac{1}{2}\left[1-\sqrt{\frac{\bar{\gamma}_b}{1+\bar{\gamma}_b}}\sum_{i=0}^{Nr-1}\binom{2i}{i}\left(\frac{1}{4(1+\bar{\gamma}_b)}\right)^i\right]\right\}\times \left\{1-\frac{1}{4}\left[1-\sqrt{\frac{\bar{\gamma}_b/2}{2+\bar{\gamma}_b/2}}\sum_{i=0}^{2Nr-1}\binom{2i}{i}\left(\frac{1}{2(2+\bar{\gamma}_b/2)}\right)^i\right]\right\}^{M-2} \quad (3.47)$$

where M is the number of message vectors in total, for N_t=2, M=4; N_t=3, M=8; and N_t=4, M=16.

And we also notice that in equations (3.31), and (3.47), the bit error probability for selecting the correcting spreading sequence $P_{b,same}(r_k)$ has a lower diversity order than bit error probability for selecting the incorrect spreading sequence $P_{b,diff}(r_k)$. This implies, as we increases the SNR value, eventually, $P_{b,same}(r_k)$ would dominate the system performance.

Since $P_{b,same}(r_k)$ dominates the overall system performance, the design strategy given in section 3.4 gives the optimal BER performance. Increasing or decreasing the number of messages vectors in each coset would degrade the BER performance. In other words, the design strategy given in section 3.4 is an optimally designed strategy.

3.5 Simulation Results and Discussion

The following sections verify the accuracy of the bit error probability expressions given in section 3.4. The simulation environment is the same as those given in chapter 2. It is assume all the channel paths are uncorrelated and frequency non-selective channels, as well.

3.5.1 BPSK MISO-CDMA System

Figures 3.3, 3.4, and 3.5 show the BER performance of theoretical expression results vs. simulation results with 2, 3, and 4 of transmit antennas; Figure 3.6 compares the simulation BER performance of different transmit antennas systems. Figures 3.3, 3.4, and 3.5 show, when the SNR is high, the theoretical bit error probability expression matches the simulation results quite well.

The equation (3.31) also indicated the MISO-CDMA system using parity bit selected spreading has less than 2nd order transmit diversity, and the diversity order is independent of the number of transmit antennas. Figure 3.6 verifies this result; as the number of transmit antennas increases, though the BER performances improve, the diversity gains remain the same.

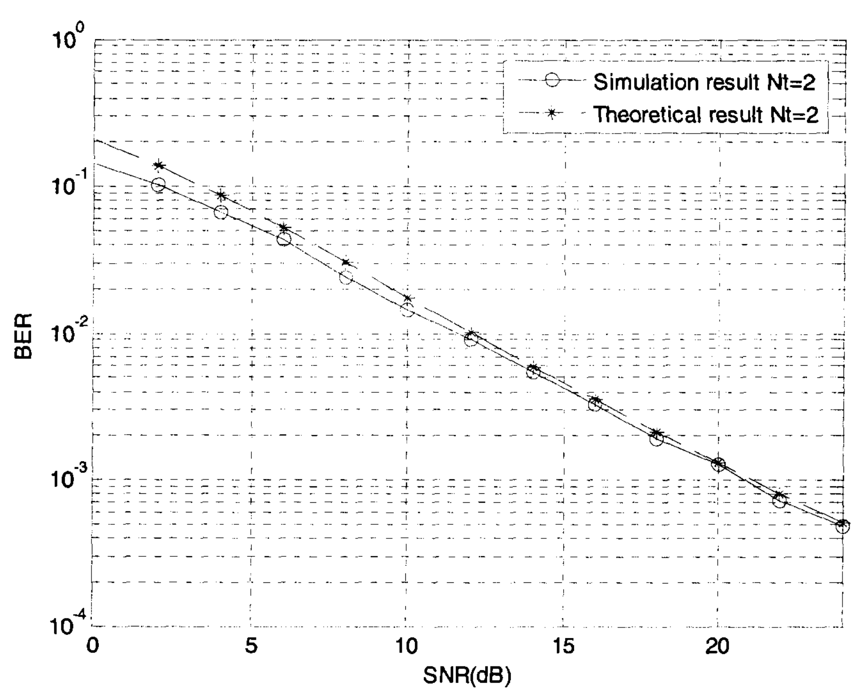

Figure 3.3: Parity Bit Selected Spreading BPSK MISO-CDMA System with N_t=2; N_r=1 over Flat Fading Channel

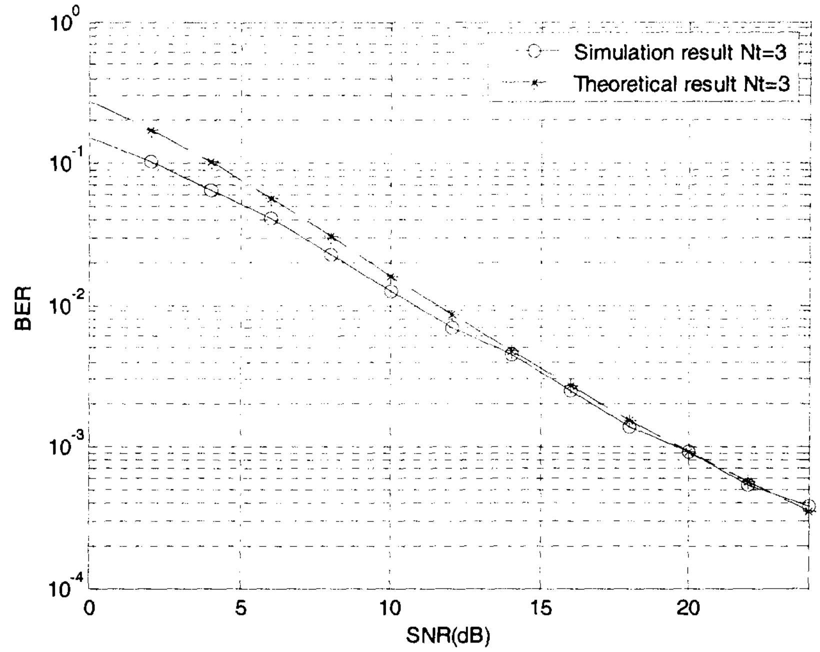

Figure 3.4: Parity Bit Selected Spreading BPSK MISO-CDMA System with N_t=3; N_r= over Flat Fading Channel

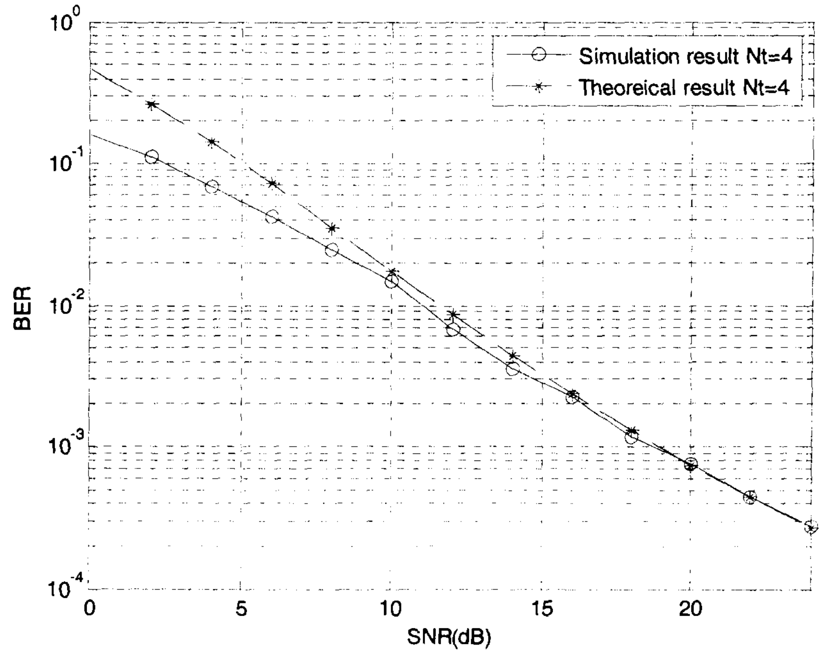

Figure 3.5: Parity Bit Selected Spreading BPSK MISO-CDMA System with N_t=4; N_r=1 over Flat Fading Channel

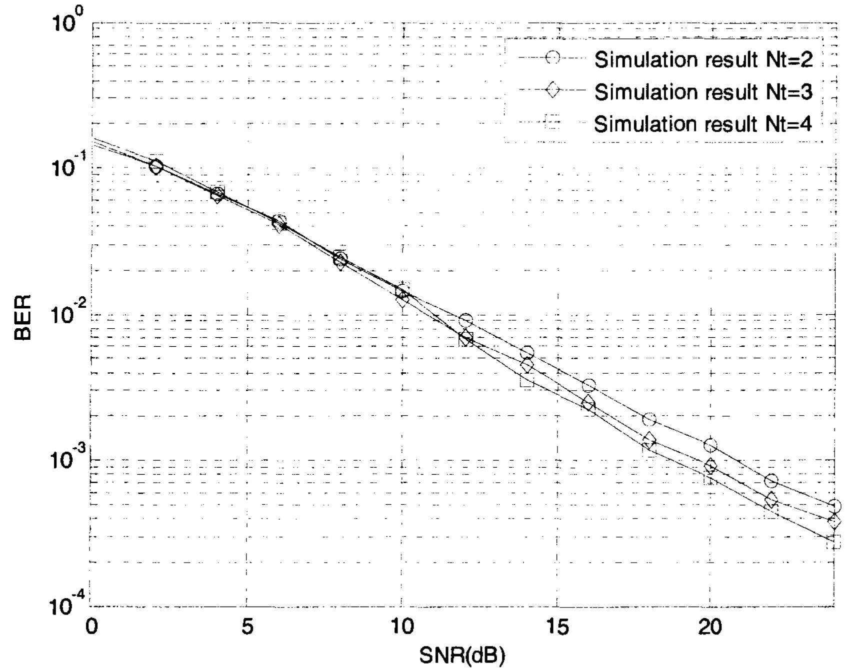

Figure 3.6: Comparison of Parity Bit Selected Spreading BPSK MISO-CDMA Systems over Flat Fading Channel

3.5.2 BPSK MIMO-CDMA System

Figures 3.7, 3.8, and 3.9 show the BER performance of theoretical expression results vs. simulation results with 2, 3, and 4 transmit and receive antennas. Figure 3.10 compares the simulation BER performances of different transmit and receive antennas systems. Similar to the MISO-CDMA system, the theoretical bit error probability expression results has a good matching with the simulation results when the SNR value is high.

Since equation (3.47) is the expansion of equation (3.31) to the MIMO system, the additional diversity gains showing in Figure 3.12 are due to the increasing of receive antennas.

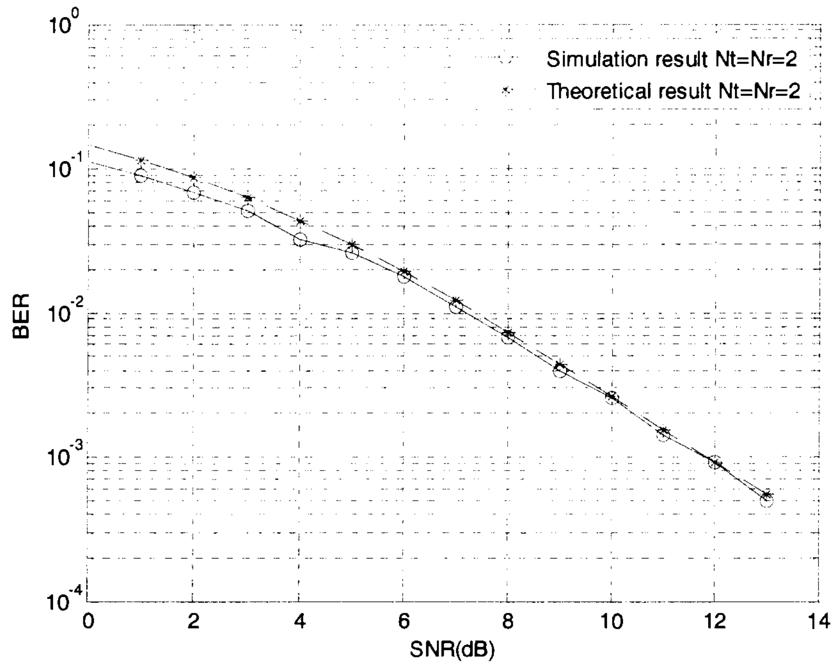

Figure 3.7: Parity Bit Selected Spreading BPSK MIMO-CDMA System with N_t=2; N_r=2 over Flat Fading Channel

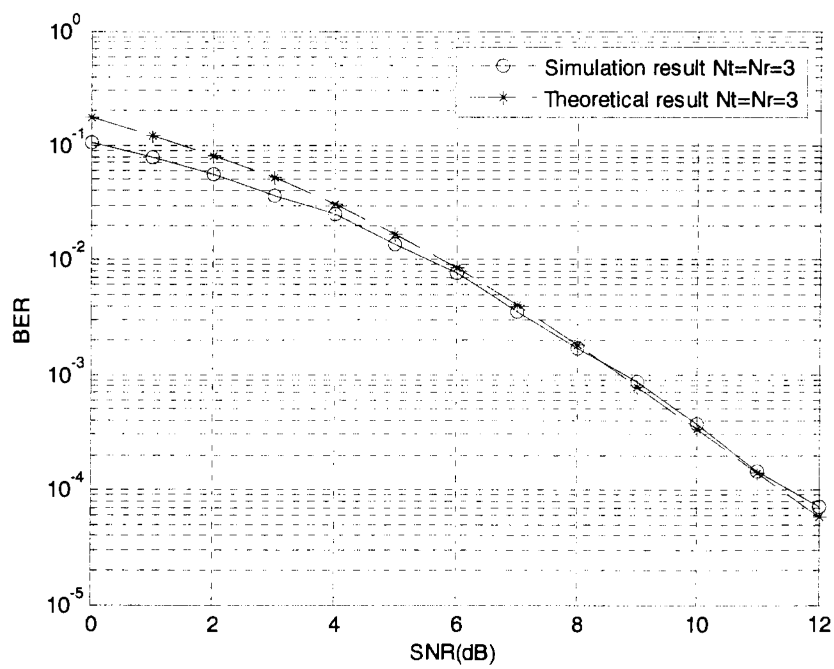

Figure 3.8: Parity Bit Selected Spreading BPSK MIMO-CDMA System with N_t=3; N_r=3 over Flat Fading Channel

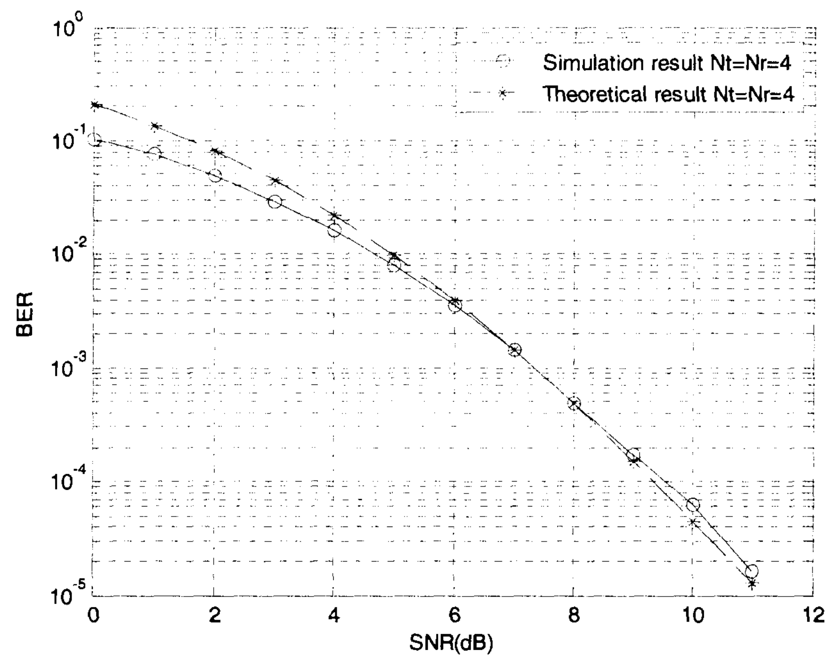

Figure 3.9: Parity Bit Selected Spreading BPSK MIMO-CDMA System with N_t=4; N_r=4 over Flat Fading Channel

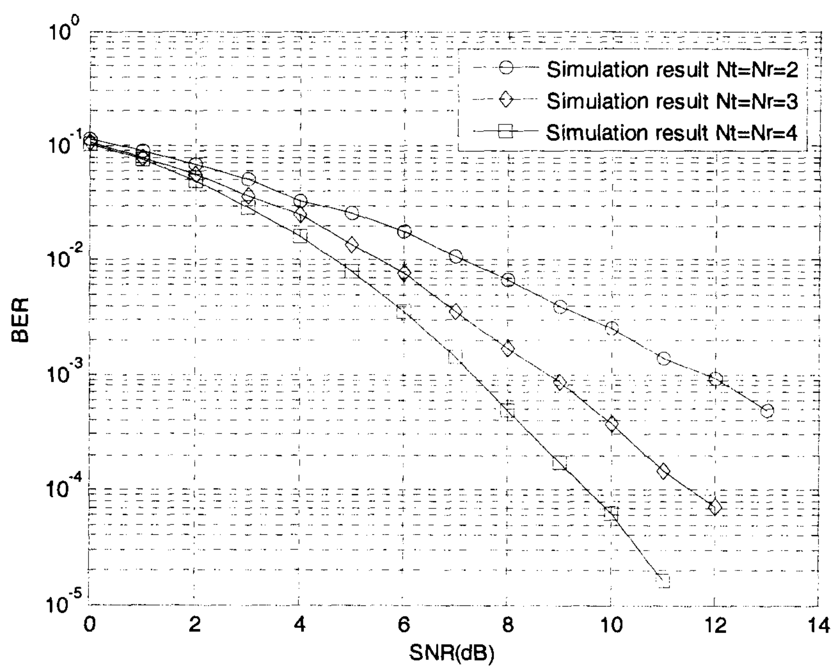

Figure 3.10: Comparison of Parity Bit Selected Spreading BPSK MIMO-CDMA Systems over Flat Fading Channel

Chapter 4
Single User Permutation Spreading MIMO -CDMA System

4.1 Introduction

The permutation spreading technique was first introduced in [4]. The permutation spreading technique is so-called due to its similarity to permutation modulation presented in [26]. As shown in Chapter 3, the parity bit selected spreading technique selects one spreading sequence, each signaling interval, to spread the data on each transmit antenna depending on the coset that the message vector belongs to. In the permutation spreading technique, N_t different spreading sequences from the spreading sequence set $\{c_1, c_2, \ldots, c_i\}$ are selected depending on the coset to which the message vector belongs to; and each transmit antenna uses one of the selected spreading sequences.

The spreading sequence permutations are unique for each message coset. Furthermore, the technique presented in [4] specified that if a spreading sequence is used by antenna j in one permutation, it cannot be used by antenna j in any other permutation. There are many methods to design the spreading sequence permutations. In [4] they use the T-design method. However, the T-design method does not provide the best BER performance among all the permutation design methods. In this thesis, we for the first time introduce a permutation design method based on space time block code (STBC).

Through all the permutation methods we used (T-design permutation, cyclic permutation, and STBC permutation), the space time block code permutation gives the best BER performance.

4.2 System Model

4.2.1 Transmitter Model

The transmitter model for a MIMO-CDMA system using permutation spreading is given in Figure 4.1. The input message bits are segmented into a message vector of length k; where k satisfies the equation $k=M\times N_t$. Then, the message bits are mapped into symbols while the spreading sequence permutation is selected as a function of the input message. The message symbols are then converted into parallel data streams through a serial-to-parallel converter. The information data ($s_1 \sim s_{Nt}$) is multiplied with the selected spreading sequences ($w_1(t) \sim w_{Nt}(t)$) before transmission. The spreading sequences employed on a given signaling interval $\{w_1(t) \sim w_{Nt}(t)\}$ are chosen from the set of orthogonal spreading sequences $\{c_1(t), c_2(t), \ldots, c_i(t)\}$. On each signaling interval, the spreading sequence permutation used depends on the coset to which the input message vector belongs. This process is repeated every signaling interval, thus the spreading sequence used by each transmit antenna usually changes every signaling interval.

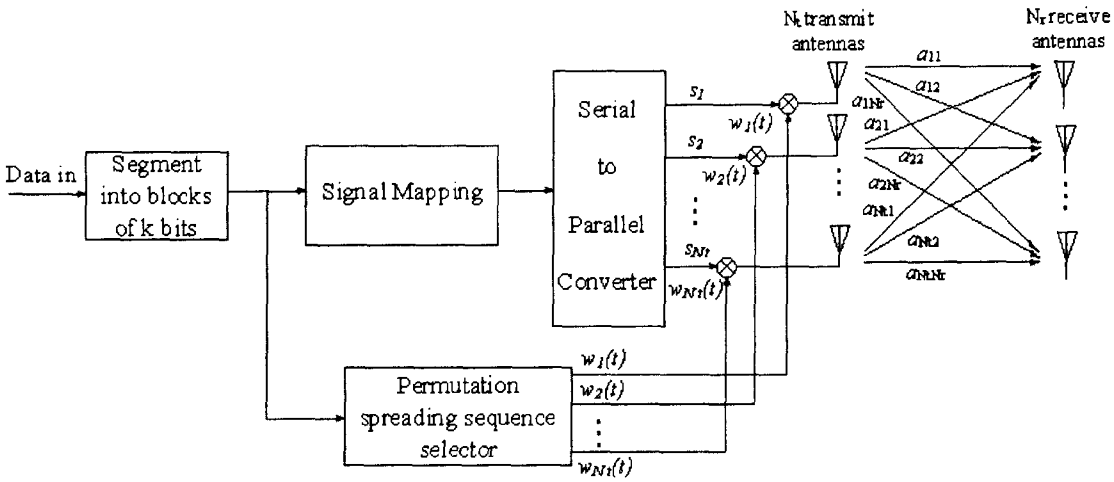

Figure 4.1: Transmitter Model of Permutation Spreading MIMO-CDMA System

4.2.2 Receiver Model

The receiver model for a MIMO-CDMA system using permutation spreading is given in Figure 4.2. This block diagram is the same as the one for a MIMO-CDMA system using parity bit selected spreading as shown in Figure 3.4. The optimal detector for permutation spreading technique is the same as parity bit selected spreading technique, because both techniques use the same number of spreading sequences. However, the decision device for permutation technique is different from the decision device for parity bit selected spreading technique. The detailed decision method is given in section 4.4. Thus, we notice that though the block diagram for permutation spreading technique is the same as the one for parity bit selected spreading technique, the actual model is different.

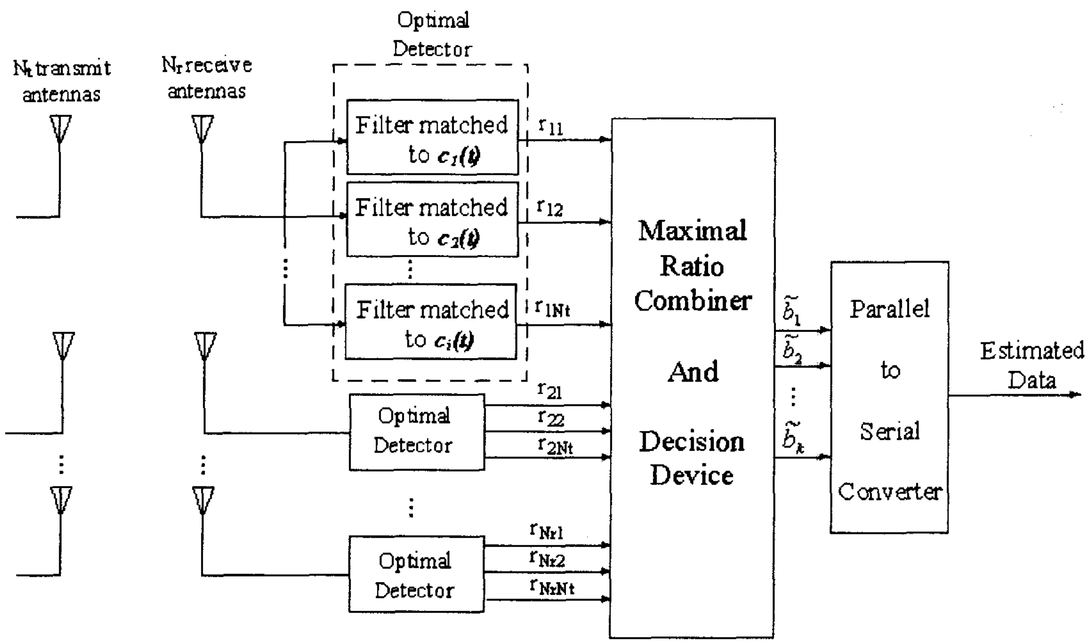

Figure 4.2: Receiver Model of Permutation Spreading MIMO-CDMA System

4.3 Design Strategy

Since space time block codes (STBC) for two-transmit antennas were first introduced in [16], much research has been done on STBCs employing a larger number of transmit antennas [put example references]. The advantage of STBC is to give transmit diversity by providing orthogonality between the transmit message cosets. In this thesis, for the first time, we show that the code matrices of STBCs can also be used to design the spreading sequence permutations, in the case of 2 transmit message vectors per coset (STBC based design). Designed properly, spreading sequence permutations based on STBC matrices (design strategy 1) can give the same diversity order as STBC.

4.3.1 STBC Design (G=2)

A. Two-transmit Antennas

In the STBC designed system, we assign 2 transmit message vectors with the minimum distance equal to the message length ($d_{min}=N_t$) to the same spreading sequence permutation (G=2). These two message vectors form a coset. It is possible to design such a permutation table so that all the transmit message cosets are orthogonal to each other.

The spread message bit for the l^{th} message vector to be transmitted from the k^{th} antenna is given by the following expression:

$$b_k^{(l)} \cdot w_k^{(l)}(t) \tag{4.1}$$

where $b_k^{(l)}$ is the bit for the l^{th} message vector to be transmitted from the kth antenna; and $w_k^{(l)}$ is the corresponding spreading sequence for that bit, which is chosen from $\{c_1(t), c_2(t), \ldots, c_i(t)\}$.

Let us consider a multiple transmit antenna CDMA system with 2 transmit antennas that uses BPSK modulation. The spreading sequence permutation table is given as follows.

Table 4.1: STBC Design (G=2) BPSK Permutation Spreading Table with N_t=2

Coset	Message vector	N_{t1}	N_{t2}
M_1	00 11	$c_1(t)$	$c_2(t)$
M_2	01 10	$c_2(t)$	$c_1(t)$

For example, if the message vector 00 (which belongs to coset M_1) is transmitted, then the transmit symbol from 1st transmit antenna N_{t1}, is given by

$$b_1^{(1)} \cdot w_1^{(1)}(t) = -c_1(t) \tag{4.2}$$

And the transmit symbol from 2nd transmit antenna N_{t2} is given by

$$b_2^{(1)} \cdot w_2^{(1)}(t) = -c_2(t) \tag{4.3}$$

If the message vector 01 (belonging to coset M_2) is transmitted, then the transmit signal from N_{t1} is given by

$$b_1^{(3)} \cdot w_1^{(3)}(t) = -c_2(t) \tag{4.4}$$

And the transmit signal from N_{t2} is given by

$$b_2^{(3)} \cdot w_2^{(3)}(t) = c_1(t) \tag{4.5}$$

Then, by using the expression given above, we can write a transmit signal table for 2 transmit antennas.

Table 4.2: STBC Design (*G*=2) BPSK Transmit Signal Table with N_t=2

Coset	Message vector	N_{t1}	N_{t2}
M_1	00	$c_1(t)$	$c_2(t)$
	11	$-c_1(t)$	$-c_2(t)$
M_2	01	$-c_2(t)$	$c_1(t)$
	10	$c_2(t)$	$-c_1(t)$

From table 4.2, we notice that rows 1 and 2 are orthogonal to rows 3 and 4. Then, M_1 and M_2 are considered to be orthogonal to each other over 2 transmit antennas. Therefore orthogonality is achieved between transmit message cosets. Also, different rows corresponding to messages of the same coset are simply the negative of one another. For example, row 2 is simply -1×row 1.

We also notice table 4.2 is similar to the Alamouti's space time block code (STBC) matrix with two-transmit antennas given in [16], which is expressed as

$$\begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix} \tag{4.6}$$

where s_n^* is the complex conjugate. In BPSK signaling $s_n^* = s_n$. It is a full rate (code rate equals to 1) STBC. Thus one method of designing the spreading sequence permutations can be derived from space time block code matrices.

B. Extension to More than Two-transmit Antennas

By using the above principle, we can find the permutation table for systems using more than two-transmit antennas by using the proper space time block code matrix.

i. Three-transmit Antennas

The space time block code with three-transmit antennas is given in [27]

$$\begin{bmatrix} s_1 & s_2 & s_3 \\ -s_2 & s_1 & -s_4 \\ -s_3 & s_4 & s_1 \\ -s_4 & -s_3 & s_2 \\ s_1^* & s_2^* & s_3^* \\ -s_2^* & s_1^* & -s_4^* \\ -s_3^* & s_4^* & s_1^* \\ -s_4^* & -s_3^* & s_2^* \end{bmatrix} \tag{4.7}$$

The STBC matrix in (4.7) is a rate 1/2 code.

For our 3 transmit antenna system, there are only 4 message cosets. Based on the matrix in (4.7), we design the following permutation table for a system with 3 transmit antennas:

Table 4.3: STBC Design (G=2) BPSK Permutation Spreading Table with N_t=3

Coset	Message vector	N_{t1}	N_{t2}	N_{t3}
M_1	000 111	$c_1(t)$	$c_2(t)$	$c_3(t)$
M_2	001 110	$c_4(t)$	$c_3(t)$	$c_2(t)$
M_3	010 101	$c_2(t)$	$c_1(t)$	$c_4(t)$
M_4	011 100	$c_3(t)$	$c_4(t)$	$c_1(t)$

The transmit signal table for 3 transmit antennas is given as follows

Table 4.4: STBC Design (G=2) BPSK Transmit Signal Table with N_t=3

Coset	Message vector	N_{t1}	N_{t2}	N_{t3}
M_1	000	$-c_1(t)$	$-c_2(t)$	$-c_3(t)$
	111	$c_1(t)$	$c_2(t)$	$c_3(t)$
M_2	001	$-c_4(t)$	$-c_3(t)$	$c_2(t)$
	110	$c_4(t)$	$c_3(t)$	$-c_2(t)$
M_3	010	$-c_2(t)$	$c_1(t)$	$-c_4(t)$
	101	$c_2(t)$	$-c_1(t)$	$c_4(t)$
M_4	011	$-c(t)_3$	$c_4(t)$	$c_1(t)$
	100	$c_3(t)$	$-c_4(t)$	$-c_1(t)$

From the above table, we can see that rows 2, 3, 5, 7 are respectively equivalent to rows 1, 4, 3, 2 of the matrix in (4.7).. Thus we maintain orthogonality between messages of different cosets. Also, like Table 4.2, different rows corresponding to messages of the same coset are simply the negative of one another.

ii. Four-transmit antennas

In the case of four-transmit antennas, the number of message coset is 8; the space time block code matrix we need to design our spreading sequence permutations should have 8 symbols. A full rate (code rate equals to 1) 8×8 space time block code matrix is given in [28], which can be used for designing the permutation table for a four-transmit antenna system.

$$\begin{bmatrix} s_1 & s_2 & s_3 & s_4 & s_5 & s_6 & s_7 & s_8 \\ -s_2 & s_1 & s_4 & -s_3 & s_6 & -s_5 & -s_8 & s_7 \\ -s_3 & s_4 & s_1 & s_2 & s_7 & s_8 & -s_5 & -s_6 \\ -s_4 & s_3 & s_2 & s_1 & s_8 & -s_7 & s_6 & -s_5 \\ -s_5 & s_6 & s_7 & -s_8 & s_1 & s_2 & s_3 & s_4 \\ -s_6 & s_5 & s_8 & s_7 & -s_2 & s_1 & -s_4 & s_3 \\ -s_7 & s_8 & s_5 & -s_6 & -s_3 & s_4 & s_1 & -s_2 \\ -s_8 & s_7 & s_6 & s_5 & -s_4 & -s_3 & s_2 & s_1 \end{bmatrix} \quad (4.8)$$

Based on the matrix of (4.8), the permutation table for the 4 transmit antenna system is given as follow.

Table 4.5: STBC Design (*G*=2) BPSK Permutation Spreading Table with N_t=4

Coset	Message vector	N_{t1}	N_{t2}	N_{t3}	N_{t4}
M_1	0000 1111	$c_1(t)$	$c_5(t)$	$c_8(t)$	$c_6(t)$
M_2	0001 1110	$c_2(t)$	$c_6(t)$	$c_7(t)$	$c_5(t)$
M_3	0010 1101	$c_3(t)$	$c_7(t)$	$c_6(t)$	$c_8(t)$
M_4	0011 1100	$c_4(t)$	$c_8(t)$	$c_5(t)$	$c_7(t)$
M_5	0100 1011	$c_5(t)$	$c_1(t)$	$c_4(t)$	$c_2(t)$
M_6	0101 1010	$c_6(t)$	$c_2(t)$	$c_3(t)$	$c_1(t)$
M_7	0110 1001	$c_7(t)$	$c_3(t)$	$c_2(t)$	$c_4(t)$
M_8	0111 1000	$c_8(t)$	$c_4(t)$	$c_1(t)$	$c_3(t)$

The transmit signal table for 4 transmit antennas is given as follows

Table 4.6: STBC Design (*G*=2) BPSK Transmit Signal Table with N_t=4

Coset	Message vector	N_{t1}	N_{t2}	N_{t3}	N_{t4}
M_1	0000	$-c_1(t)$	$-c_5(t)$	$-c_8(t)$	$-c_6(t)$
	1111	$c_1(t)$	$c_5(t)$	$c_8(t)$	$c_6(t)$
M_2	0001	$-c_2(t)$	$-c_6(t)$	$-c_7(t)$	$c_5(t)$
	1110	$c_2(t)$	$c_6(t)$	$c_7(t)$	$-c_5(t)$
M_3	0010	$-c_3(t)$	$-c_7(t)$	$c_6(t)$	$-c_8(t)$
	1101	$c_3(t)$	$c_7(t)$	$-c_6(t)$	$c_8(t)$
M_4	0011	$-c_4(t)$	$-c_8(t)$	$c_5(t)$	$c_7(t)$
	1100	$c_4(t)$	$c_8(t)$	$-c_5(t)$	$-c_7(t)$
M_5	0100	$-c_5(t)$	$c_1(t)$	$-c_4(t)$	$-c_2(t)$
	1011	$c_5(t)$	$-c_1(t)$	$c_4(t)$	$c_2(t)$
M_6	0101	$-c_6(t)$	$c_2(t)$	$-c_3(t)$	$c_1(t)$
	1010	$c_6(t)$	$-c_2(t)$	$c_3(t)$	$-c_1(t)$
M_7	0110	$-c_7(t)$	$c_3(t)$	$c_2(t)$	$-c_4(t)$
	1001	$c_7(t)$	$-c_3(t)$	$-c_2(t)$	$c_4(t)$
M_8	0111	$-c_8(t)$	$c_4(t)$	$c_1(t)$	$c_3(t)$
	1000	$c_8(t)$	$-c_4(t)$	$-c_1(t)$	$-c_3(t)$

Note: we choose only 4 columns from matrix (4.8) to design the permutation table for 4 transmit antenna system. Since in space time block codes, all the columns and rows are orthogonal to each other, we still maintain the orthogonality between the message cosets.

4.3.2 T- Design (*G*=4)

In [4], a T-design is used for permutation technique; it can also be used in the permutation spreading system with more than 2 number of message vectors per coset (in this thesis we choose 4 number of message vector per coset, or *G*=4), which is a sub-optimal design strategy

The BER performance of the T-design (*G*=4) system is inferior to that of the STBC based designed (*G*=2) system for the following reasons: first, the minimum distance between 2 message vectors in the same coset would be smaller than N_t ($d_{min} < N_t$); second, not all the transmit message cosets are orthogonal to each other. Thus, diversity gain may be lost in the T- design (G=4) system. And its BER performance would be affected by the decreased minimum distance between 2 message vectors in the same coset. Table 4.7 shows a T- design (G=4) system employing 3 transmit antennas, and table 4.8 shows a 4 transmit antenna sub-optimally designed system.

Table 4.7: T- Design (G=4) BPSK Spreading Permutation Table with N_t=3

Co-set	Message group	N_{t1}	N_{t2}	N_{t3}
M_1	000 011 101 110	$c_1(t)$	$c_3(t)$	$c_2(t)$
M_2	001 010 100 111	$c_4(t)$	$c_1(t)$	$c_3(t)$

Note: the minimum distance between 2 message vectors is 2. Different message cosets share a maximum of 2 spreading sequences to reduce the cross correlation between message cosets.

Table 4.8: T- Design (G=4) BPSK Permutation Spreading with Table N_t=4

Co-set	Message group	N_{t1}	N_{t2}	N_{t3}	N_{t4}
M_1	0000 0111 1011 1110	$c_1(t)$	$c_3(t)$	$c_5(t)$	$c_7(t)$
M_2	0001 1010 0110 1101	$c_8(t)$	$c_1(t)$	$c_4(t)$	$c_5(t)$
M_3	0010 0101 1001 1100	$c_2(t)$	$c_4(t)$	$c_3(t)$	$c_8(t)$
M_4	0100 1000 0011 1111	$c_5(t)$	$c_2(t)$	$c_6(t)$	$c_3(t)$

Note: the minimum distance between 2 message vectors of the same coset is 2; and different message cosets also share a maximum of 2 spreading sequences to reduce the cross correlation between message cosets.

4.4 Bit Error Probability

The original research by providing the theoretical analysis and the bit error probability expressions for the permutation spreading techniques is given in this section.

4.4.1 STBC Design (*G*=2) Bit Error Probability

As previously mentioned in section 4.3, for the optimally designed system, each message coset is made up of 2 message vectors; and $d_{min}= N_t$. Though several different permutation methods exist, such as T-design permutation [30] and cyclic permutation [31], the STBC permutation presented in section 4.3.1 gives the best BER performance. This is because the space time block code based permutations produce orthogonality between the different cosets of message vectors while other permutation methods cannot guarantee this orthogonality.

A. Multiple Input Single Output (MISO)

Consider a BPSK modulated MISO-CDMA system with N_t transmit antennas and 1 receive antenna. The received signal is the sum of all the transmit signals multiplied by their corresponding channel gains. An optimal receiver with a set of matched filters is used at the receiver. Similar to the parity bit selected spreading method, each matched filter corresponds to one of the spreading sequence choosing from $\{c_1(t), c_2(t), \ldots, c_i(t)\}$ with its corresponding transmit message choosing from $\{M_1, M_2, \ldots, M_L\}$.

i. Decision Variable

The received signal from the l^{th} message group is the sum of all the message bits in the l^{th} group multiplied by the channel gain. The expression would be similar to equation (4.1); the received signal can be expressed as

$$Rx = \alpha_{11}.b_1^{(l)} \cdot w_1^{(l)}(t) + \alpha_{12}.b_2^{(l)} \cdot w_2^{(l)}(t) + \ldots + \alpha_{1Nt}.b_{Nt}^{(l)} \cdot w_{Nt}^{(l)}(t) + n \tag{4.9}$$

where α_{1i} is the complex channel gain from the i^{th} transmit antenna; $b_k^{(l)}$ is the k^{th} message bits in the l^{th} message group, and its corresponding spread sequence is $w_k^{(l)}$; and n is the total noise at received part.

The decision variable for the k^{th} matched filter would be given as

$$r_k = \frac{1}{T}\int_T Rx_k \cdot c_k(t)dt$$

$$r_k = \frac{1}{T}\int_T \left[\alpha_{11}.b_1^{(l)} \cdot w_1^{(l)}(t) + \alpha_{12}.b_2^{(l)} \cdot w_2^{(l)}(t) + \ldots + \alpha_{1Nt}.b_{Nt}^{(l)} \cdot w_{Nt}^{(l)}(t) + n\right]c_k(t)dt \tag{4.10}$$

Then, the output from the k^{th} matched filter would be given as

$$r_k = \begin{cases} \alpha_{1i} \cdot b_i^{(l)} + w_n & \text{if } \ w_i^{(l)}(t) = c_k(t) \\ w_n & \text{otherwise} \end{cases} \tag{4.11}$$

The detected message is selected by ML detection, which finds the minimum Euclidean distance between the received signal and all the possible received message vectors in the absence of noise. The expression is given as

$$U = \min_{l=1}^{M}\left\| Rx - \sum_{i=1}^{Nt}\alpha_{1i} \cdot b_i^{(l)} \cdot w_i^{(l)}(t)\right\|^2 \tag{4.12}$$

where M is the total number of message vectors.

ii. Bit Error Probability

The bit error probability expression for permutation spreading MIMO-CDMA system is the same expression as equation (3.13), which is given as

$$P_{2b,permutation}(r_k) \approx 1-(1-p_1P(u_1>u_2))(1-p_2P(u_1>u_3))\ldots(1-p_{m-1}P(u_1>u_M)) \quad (4.13)$$

Where p, $p_1 \sim p_{m-1}$ are the coefficients which equal to the number of bits in error over the number of total bits for each message vector. The bit error probability also consists of two parts; $P_{2b,same}(r_k)$, the bit error probability for selecting the correct spreading permutation sequence but incorrect transmit message (eg: from table 4.1, transmit 00 (belonging to coset M_1), but receive 11 (belonging to coset M_1)); and $P_{2b,diff}(r_k)$, the bit error probability for selecting the incorrect permutation spreading sequence (eg: from table 4.1, transmit 00 (belonging to coset M_1), but receive 10 (belonging to coset M_2)). And we also use the following assumption:

$$P_{2b,same}(r_k) = p_1P(u_1>u_2) \quad (4.14)$$

$$P_{2b,diff}(r_k) \approx p_2P(u_1>u_3) = \ldots = p_{m-1}P(u_1>u_M) \quad (4.15)$$

Bit error probability when receiver determines the correct spreading sequence permutation ($P_{2b,same}(r_k)$)

In the STBC design (G=2), 2 transmit message vectors are assigned the same spreading sequence permutation. With N_t transmit antennas, each transmit antenna uses a unique spreading sequence so that the signals transmitted from different antennas are orthogonal to each other. Thus the bit error probability is approximately equal to the error probability of BPSK signaling transmission with N_t-path maximal ratio combining (MRC) diversity technique. The symbol error probability is given in [19], which can be expressed as

$$P_{2m,same}(r_k) = \frac{1}{2}\left[1-\mu\sum_{k=0}^{Nt-1}\binom{2i}{i}\left(\frac{1-\mu^2}{4}\right)^i\right] \quad (4.16)$$

where for BPSK signalling in a fading channel with N_t paths, μ is given in [19]

$$\mu = \sqrt{\frac{\bar{\gamma}_c}{1+\bar{\gamma}_c}} = \sqrt{\frac{\bar{\gamma}_s / Nt}{1+\bar{\gamma}_s / Nt}} = \sqrt{\frac{\bar{\gamma}_b}{1+\bar{\gamma}_b}} \tag{4.17}$$

$\bar{\gamma}_s$ is the total SNR for each message set, if the SNR per bit is $\bar{\gamma}_b$, then $\bar{\gamma}_s$ is given by

$$\bar{\gamma}_s = Nt \cdot \bar{\gamma}_b \tag{4.18}$$

Since the message group has the largest minimum distance, the bit error probability $P_{2b,same}(r_k)$ would be equal the symbol error probability $P_{2m,same}(r_k)$.

By substitute (4.17) into (4.16), the bit error probability for selecting the correct spreading sequence can be expressed as

$$P_{2b,same}(r_k) \approx P_{2m,same} = \frac{1}{2}\left[1 - \sqrt{\frac{\bar{\gamma}_b}{1+\bar{\gamma}_b}} \sum_{k=0}^{Nt-1} \binom{2i}{i} \left(\frac{1}{4(1+\bar{\gamma}_b)}\right)^i\right] \tag{4.19}$$

Bit error probability when receiver determines the incorrect spreading sequence permutation ($P_{2b,diff}(r_k)$)

As previously mentioned, if properly designed the transmit message cosets can be orthogonal to each other. Then the symbol error probability for selecting the incorrect spreading sequence is approximately equal to the symbol error probability for 2-FSK signaling with N_t-path MRC diversity technique. The expression is given in [19], which is expressed as

$$P_{2m,diff}(r_k) = \frac{1}{2}\left[1 - \mu \sum_{i=0}^{Nt-1} \binom{2i}{i} \left(\frac{1-\mu^2}{4}\right)^i\right] \tag{4.20}$$

where, for 2-FSK, μ is expressed as

$$\mu = \sqrt{\frac{\bar{\gamma}_c}{2+\bar{\gamma}_c}} = \sqrt{\frac{\bar{\gamma}_s / Nt}{2+\bar{\gamma}_s / Nt}} = \sqrt{\frac{\bar{\gamma}_b}{2+\bar{\gamma}_b}} \tag{4.21}$$

By substituting (4.21) into (4.20) the equation can be simplified as

$$P(u_1 > u_k) \approx P_{2m,diff}(r_k) = \frac{1}{2}\left[1 - \sqrt{\frac{\bar{\gamma}_b}{2+\bar{\gamma}_b}} \sum_{i=0}^{Nt-1} \binom{2i}{i} \left(\frac{1}{2(2+\bar{\gamma}_b)}\right)^i\right] \tag{4.22}$$

[1] shows the bit error probability approximately equal to one half of symbol error probability for selecting the incorrect spreading sequences. Then, the coefficient $p_2 \sim p_m$ given in (4.15) would be approximately equal to 0.5; the bit error probability for selecting the incorrect spreading sequence is given as

$$P_{2b,diff}(r_k) \approx \frac{1}{2} P(u_1 > u_k) \approx \frac{1}{4}\left[1 - \sqrt{\frac{\bar{\gamma}_b}{2+\bar{\gamma}_b}} \sum_{i=0}^{Nt-1} \binom{2i}{i} \left(\frac{1}{2(2+\bar{\gamma}_b)}\right)^i\right] \tag{4.23}$$

By substituting (4.19) and (4.23) into (4.13), the closed form bit error probability for BPSK modulated MISO-CDMA system employing STBC designed (G=2) permutation spreading would be given as

$$P_{2b,permutation,MISO}(r_k) \approx$$

$$1 - \left\{1 - \frac{1}{2}\left[1 - \sqrt{\frac{\bar{\gamma}_b}{1+\bar{\gamma}_b}} \sum_{i=0}^{Nt-1} \binom{2i}{i} \left(\frac{1}{4(1+\bar{\gamma}_b)}\right)^i\right]\right\} \left\{1 - \frac{1}{4}\left[1 - \sqrt{\frac{\bar{\gamma}_b}{2+\bar{\gamma}_b}} \sum_{i=0}^{Nt-1} \binom{2i}{i} \left(\frac{1}{2(2+\bar{\gamma}_b)}\right)^i\right]\right\}^{M-2} \tag{4.24}$$

where M is the total number of message vectors, for N_t=2, M=4; N_t=3, M=8; and N_t=4, M=16.

B. Multiple Input Multiple Output (MIMO)

Consider a BPSK modulated MIMO-CDMA system with N_t transmit antennas and N_t receive antennas, the received signal is the sum of all transmit signals multiplied by their corresponding channel gains. An optimal receiver with a set of matched filters is used for each receive antenna.

i. Decision Variable

Similar to the MISO system, the output from the k^{th} matched filter in the j^{th} receive antenna would be given as

$$r_{jk} = \begin{cases} b_i^{(l)} \cdot \alpha_{jk} + w_{nj} & \text{if } w_i^{(l)}(t) = c_k(t) \\ w_{nj} & \text{otherwise} \end{cases} \tag{4.25}$$

The received message vector is detected using maximum likelihood (ML) detection and maximal ratio combining (MRC) from the data at all the received antennas. The expression is given as

$$U = \min_{l=1}^{M} \left\| Rx - \sum_{j=1}^{Nr} \sum_{k=1}^{Nt} \alpha_{jk} \cdot b_k^{(l)} \cdot w_k^{(l)} \right\|^2 \tag{4.26}$$

where M is the total number of message vectors.

ii. Bit Error Probability

The bit error probability for MIMO-CDMA system using permutation spreading also consists of two parts, $P_{2b,same,MIMO}(r_k)$ and $P_{2b,diff,MIMO}(r_k)$; where $P_{2b,same,MIMO}(r_k)$ is the bit error probability for selecting the correct spreading sequence but incorrect transmit message vector, and $P_{2b,diff,MIMO}(r_k)$ is the bit error probability for selecting the incorrect spreading sequence.

Bit error probability when receiver determines the correct spreading sequence permutation ($P_{2b,same,MIMO}(r_k)$)

With N_t transmit antennas and N_r receive antennas, there are $N_t \times N_r$ different channel paths in total. In order to simplify the calculation, we assume all the channel paths are independently. It is approximately equal to the error probability of BPSK signaling transmission with $N_t \times N_r$-path MRC diversity technique. The symbol error probability for choosing the correct spreading sequence can be expressed as

$$P_{2m,same,MIMO}(r_k)=\frac{1}{2}\left[1-\mu\sum_{i=0}^{Nt\cdot Nr-1}\binom{2i}{i}\left(\frac{1-\mu^2}{4}\right)^i\right] \tag{4.27}$$

where μ is given as

$$\mu=\sqrt{\frac{\bar{\gamma}_c}{1+\bar{\gamma}_c}}=\sqrt{\frac{\bar{\gamma}_s/(Nt\cdot Nr)}{1+\bar{\gamma}_s/(Nt\cdot Nr)}}=\sqrt{\frac{\bar{\gamma}_b/Nr}{1+\bar{\gamma}_b/Nr}} \tag{4.28}$$

where $\bar{\gamma}_s$ is the total SNR for each message group, which is the same expression as (4.18).

Since 2 transmit message vectors have the largest minimum distance, the bit error probability $P_{2b,same,MIMO}$ (r_k) would be equal the symbol error probability. Thus, the bit error probability for choosing correct spreading sequence can be expressed as

$$P_{2b,same,MIMO}(r_k)\approx P_{2m,same,MIMO}=\frac{1}{2}\left[1-\sqrt{\frac{\bar{\gamma}_b/Nr}{1+\bar{\gamma}_b/Nr}}\sum_{k=0}^{Nt\cdot Nr-1}\binom{2i}{i}\left(\frac{1}{4(1+\bar{\gamma}_b/Nr)}\right)^i\right] \tag{4.29}$$

Bit error probability when receiver determines the incorrect spreading sequence permutation ($P_{2b,diff,MIMO}(r_k)$)

In the MISO-CDMA system, there are N_t-path channels. Accordingly, in the MIMO-CDMA system, there are $N_t \times N_r$ independent paths in total; the symbol error probability for incorrect spreading sequence is approximately equal to the symbol error probability for 2-FSK signalling with $N_t \times N_r$-path MRC diversity technique. The expression would be similar to equation (4.23), which can be expressed as

$$P_{2m,diff,MIMO}(r_k)=P(u_1>u_k)\approx\frac{1}{2}\left[1-\sqrt{\frac{\bar{\gamma}_b/Nr}{1+\bar{\gamma}_b/Nr}}\sum_{i=0}^{Nt\cdot Nr-1}\binom{2i}{i}\left(\frac{1}{2(2+\bar{\gamma}_b/Nr)}\right)^i\right] \tag{4.30}$$

The coefficient $p_2 \sim p_m$ given in (4.30) would be approximately equal to 0.5 as well;

the bit error probability for selecting the incorrect spreading sequence is given as

$$P_{2b,diff,MIMO}(r_k) \approx \frac{1}{2} P_{2m,diff,MIMO}(r_k) \approx \frac{1}{4}\left[1-\sqrt{\frac{\bar{\gamma}_b / Nr}{1+\bar{\gamma}_b / Nr}} \sum_{i=0}^{Nt \cdot Nr-1} \binom{2i}{i} \left(\frac{1}{2(2+\bar{\gamma}_b / Nr)}\right)^i\right] \tag{4.31}$$

By substituting (4.29), and (4.31) into (4.13), the closed form bit error probability for BPSK modulated MISO-CDMA system employing STBC design (G=2) permutation spreading is given by

$$\begin{aligned} P_{2b,permutation,MIMO}(r_k) \approx \\ 1-\left\{1-\frac{1}{2}\left[1-\sqrt{\frac{\bar{\gamma}_b / Nr}{1+\bar{\gamma}_b / Nr}} \sum_{k=0}^{Nt \cdot Nr-1} \binom{2i}{i} \left(\frac{1}{4(1+\bar{\gamma}_b / Nr)}\right)^i\right]\right\} \times \\ \left\{1-\frac{1}{4}\left[1-\sqrt{\frac{\bar{\gamma}_b / Nr}{1+\bar{\gamma}_b / Nr}} \sum_{i=0}^{Nt \cdot Nr-1} \binom{2i}{i} \left(\frac{1}{2(2+\bar{\gamma}_b / Nr)}\right)^i\right]\right\}^{M-2} \end{aligned} \tag{4.32}$$

where M is the number of message vectors, for N_t=2, M=4; N_t=3, M=8; and N_t=4, M=16.

4.4.2 T- Design (G=4) Bit Error Probability

In this thesis, for the T-design (G=4) system, as the number of message vectors in each message coset increases, the minimum distance becomes smaller, and the message cosets can no longer be orthogonal to one another as well.

In section 4.3.3, only the permutation table for 4 message vectors per coset case is given. Therefore, only the bit error probability expression for such a system is derived here. However, the main idea for deriving the bit error probability expression for permutation spreading system with different number of message vectors per coset would be the same as the one shown in this thesis.

A. Multiple Input Multiple Output (MIMO)

Consider a BPSK modulated MIMO-CDMA system with N_t transmit antennas andN_r receive antenna, the T-designed (G=4) system would be similar to STBC designed (G=2) system, but with fewer numbers of spreading sequences.

i. Decision Variable

The received message vector is detected using maximum likelihood (ML) detection and maximal ratio combining (MRC). The expression is the same as equation (4.26) given as follow

$$U = \min_{l=1}^{M} \left\| Rx - \sum_{j=1}^{Nr} \sum_{k=1}^{Nt} \alpha_{jk} \cdot b_k^{(l)} \cdot w_k^{(l)} \right\|^2 \tag{4.33}$$

ii. Bit Error Probability

In the T-designed (G=4) system, there are two major problems which complicate the expression: 1st, the minimum distance between two message groups is not a fixed value; 2nd, unlike the optimal design, the transmit message cosets are not orthogonal to each other, therefore diversity gain is lost.

In order to simplify the calculation, we assume the minimum distances between message vectors are all equal to the smallest minimum distance d_{min}; and the orthogonality is maintained between the message cosets. Then, we can approximate the bit error probability expression for sub-optimally designed BPSK MIMO-CDMA systems employing permutation spreading.

The bit error probability expression is given as

$$P'_{2b,permutation}(r_k) = 1 - (1 - p_1 P(u_1 > u_2))(1 - p_2 P(u_1 > u_3)) \ldots (1 - p_{m-1} P(u_1 > u_M)) \tag{4.34}$$

where p, $p_1 \sim p_{m-1}$ are the coefficients which equal to the number of different bits over the number of total bits for each message group.

The bit error probability consists of two parts; $P'_{2b,same}(r_k)$, the bit error probability for selecting the correct permutation spreading sequence but incorrect transmit message set(eg: from table 4.8, transmit 000 (belonging to coset M_1), but receive 011, 101, or 110 (which all belonging to coset M_1)); and $P'_{2b,diff}(r_k)$, the bit error probability for selecting the incorrect permutation spreading sequence (eg: from table 4.8, transmit 000 (belonging to coset M_1), but receive 100 (belonging to coset M_2)). And since each message coset has 4 message vectors, the following assumption is used:

$$P'_{2b,same}(r_k) \approx p_1 P(u_1 > u_2) = p_2 P(u_1 > u_3) = p_3 P(u_1 > u_4) \quad (4.35)$$

$$P'_{2b,diff}(r_k) \approx p_4 P(u_1 > u_5) = \ldots = p_{m-1} P(u_1 > u_M) \quad (4.36)$$

Bit error probability when receiver determines the correct spreading sequence permutation ($P'_{2b,same,MIMO}(r_k)$)

Unlike the STBC designed (G=2) system, in the T-designed (G=4) system, the minimum distance is smaller than the length of message vector ($d_{min} < N_t$), it can therefore be considered as BPSK signaling with $d_{min} \times N_r$-path MRC diversity. The bit error probability with correct spreading sequence can be approximately expressed as

$$P'_{2b,same,MIMO}(r_k) = p_1 P(u_1 > u_2) = p_2 P(u_1 > u_3) = p_3 P(u_1 > u_4) \approx \frac{1}{2}\left[1 - \mu \sum_{i=0}^{d\min \cdot Nr-1} \binom{2i}{i} \left(\frac{1-\mu^2}{4}\right)^i\right] \quad (4.37)$$

where N_r is the number of receive antennas, d_{min} is the minimum distance between 2 message groups, for $N_t=3$, and $N_t=4$, $d_{min}=2$; and μ, for BPSK signaling, is given as

$$\mu = \sqrt{\frac{\bar{\gamma}_c}{1+\bar{\gamma}_c}} = \sqrt{\frac{d_{\min}\bar{\gamma}_b/(d_{\min} \cdot Nr)}{1 + d_{\min}\bar{\gamma}_b/(d_{\min} \cdot Nr)}} = \sqrt{\frac{\bar{\gamma}_b/Nr}{1 + d_{\min}\bar{\gamma}_b/Nr}} \quad (4.38)$$

Then equation (4.37) can be simplified as

$$P'_{2b,same,MIMO}(r_k) \approx \frac{1}{2}\left[1 - \sqrt{\frac{\bar{\gamma}_b/Nr}{1+\bar{\gamma}_b/Nr}} \sum_{i=0}^{d\min \cdot Nr-1} \binom{2i}{i} \left(\frac{1}{4(1+\bar{\gamma}_b)}\right)^i\right] \quad (4.39)$$

Bit error probability when receiver determines the incorrect spreading sequence permutation ($P'_{2b,diff,MIMO}(r_k)$)

In the T-designed (G=4) system, the transmit message cosets are no longer orthogonal to each other. Since T-design permutation would minimize the sharing spreading sequences between 2 message cosets, and it may have a small cross-correlation value, and may minimize the loss of BER performance. As previously mentioned, in order to simplify the calculation, we assume all the message cosets are still orthogonal to each other. The bit error probability with incorrect spreading sequence, $P'_{2b,diff,MIMO}(r_k)$, is similar to equation (4.30), which is given as

$$P'_{2b,diff,MIMO}(r_k) \approx \frac{1}{2}P(u_1 > u_k) \approx \frac{1}{4}\left[1 - \sqrt{\frac{\bar{\gamma}_b / Nr}{1+\bar{\gamma}_b / Nr}} \sum_{i=0}^{Nt \cdot Nr-1} \binom{2i}{i} \left(\frac{1}{2(2+\bar{\gamma}_b / Nr)}\right)^i\right] \tag{4.40}$$

By substituting (4.38), and (4.40) into (4.34), the closed form bit error probability for BPSK modulated MIMO-CDMA system employing T-designed (G=4) permutation spreading is given by

$$\begin{aligned} P'_{2b,permutation,MIMO}(r_k) \approx \\ 1-\left\{1-\frac{1}{2}\left[1-\sqrt{\frac{\bar{\gamma}_b / Nr}{1+\bar{\gamma}_b / Nr}} \sum_{i=0}^{d\min \cdot Nr-1} \binom{2i}{i} \left(\frac{1}{4(1+\bar{\gamma}_b)}\right)^i\right]\right\}^3 \times \\ \left\{1-\frac{1}{4}\left[1-\sqrt{\frac{\bar{\gamma}_b / Nr}{1+\bar{\gamma}_b / Nr}} \sum_{i=0}^{Nt \cdot Nr-1} \binom{2i}{i} \left(\frac{1}{2(2+\bar{\gamma}_b / Nr)}\right)^i\right]\right\}^{M-4} \end{aligned} \tag{4.41}$$

where M is the total number of message vectors, for N_t=3, M=8; for N_t=4, M=16.

We notice that, in equation (4.24) and (4.32), the bit error probability for selecting the correct spreading sequence, $P_{b,same}(r_k)$ has same diversity order as the bit error probability of selecting the incorrect spreading sequence, $P_{b,diff}(r_k)$. And, since, in $P_{b,same}(r_k)$, the transmission method is equivalent to BPSK signaling, while in $P_{b,diff}(r_k)$, the transmission method is equivalent to orthogonal signaling, we would have the following conclusion,

$P_{b,same}(r_k)$ $<P_{b,diff}(r_k)$. In other words, unlike parity bit selected spreading technique, for the permutation spreading technique, $P_{b,diff}(r_k)$ dominates the BER performance.

As shown in section 4.4.2, increasing the number of messages vectors in each message coset would degrade the system's BER performance. We also notice that decreasing the number of message vecotrs in each message coset (in other words, let each message coset contain only one message vector) would make all the message vectors orthogonal to each other. Since BPSK signaling has smaller bit error probability than orthogonal signaling, the BPSK signaling bit error probability for $P_{b,same}(r_k)$ in the STBC designed (G=2) system would be smaller than the one in such a system. As a result, such a system has worse BER performance. This is also the main reason that the STBC design with 2 message vectors per coset gives the best BER performance.

4.5 Simulation Results and Discussion

The following sections compare the bit error probability expressions with the simulation results. The simulation environments are the same as those given in chapter 2; and the length of orthogonal spreading sequences is 16. It is assume all the channel gains are uncorrelated and frequency non-selective.

4.5.1 STBC Design (G=2) BPSK MISO-CDMA System

Figures 4.3, 4.4, and 4.5 show the BER performance of theoretical expression results vs. simulation results with 2, 3, and 4 of transmit antennas; Figure 4.6 compares the simulation BER performance of different transmit antennas systems. The space time block code permutation method is used, and the permutation tables are the same as Tables 4.1, 4.3, and 4.5 for 2, 3, and 4 of transmit antennas system.

Figures 4.3, 4.4, and 4.5 show the theoretical bit error probability expressions are about 0.5dB worse than the simulation results. As we showed in section 4.4, all the bit error probability expressions are closed form expressions, and the results would yield approximate values.

Equation (4.24) shows that by using space block code permutation technique, the diversity order increases as the number of transmit antennas increases. Figure 4.6 verifies this result, as the number of transmit antennas increases, we see the additional diversity gain. We noted that since the permutation technique is based on space time block code, given a certain number of transmit antennas, the MISO-CDMA system using permutation spreading would have same diversity order as space time block code with same numbers of transmit antennas. However, we also notice that the permutation spreading MISO-CDMA system does not need to re-transmit the message data at different time interval, and it has higher transmit rate than STBC-CDMA system.

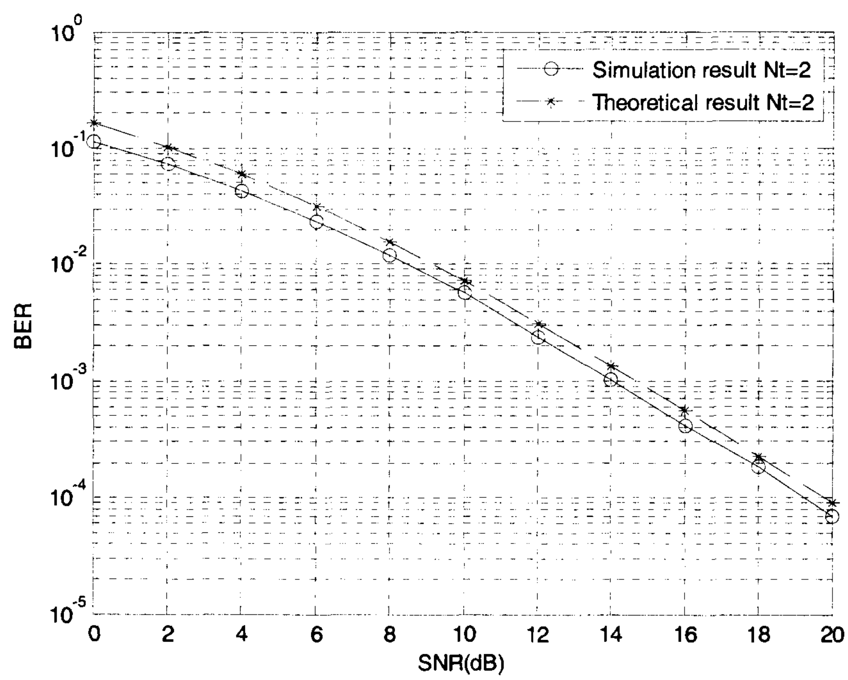

Figure 4.3: STBC Design (G=2) Permutation Spreading BPSK MISO-CDMA System with N_t=2; N_r=1 over Flat Fading Channel

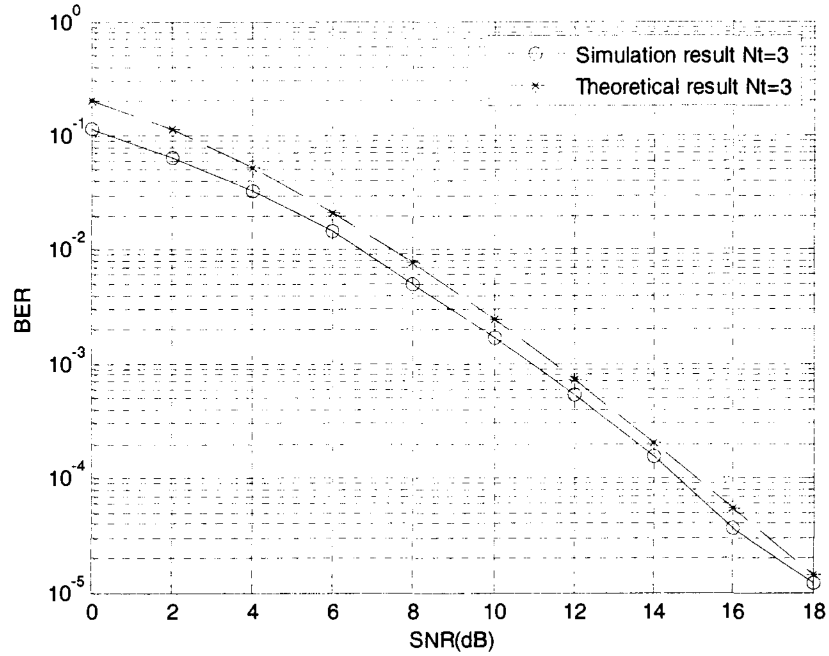

Figure 4.4: STBC Design (G=2) Permutation Spreading BPSK MISO-CDMA System with N_t=3; N_r=1 over Flat Fading Channel

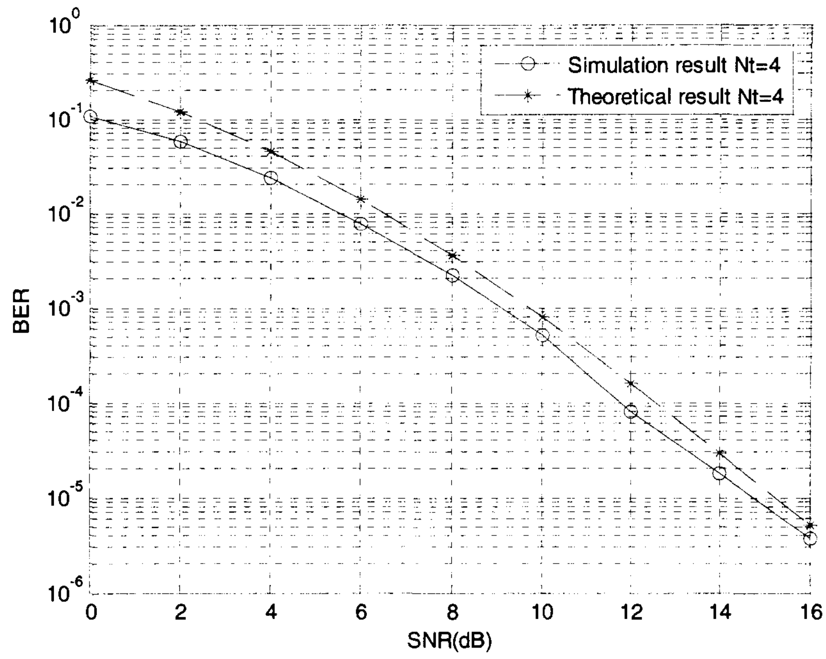

Figure 4.5: STBC Design (G=2) Permutation Spreading BPSK MISO-CDMA System with N_t=4; N_r=1 over Flat Fading Channel

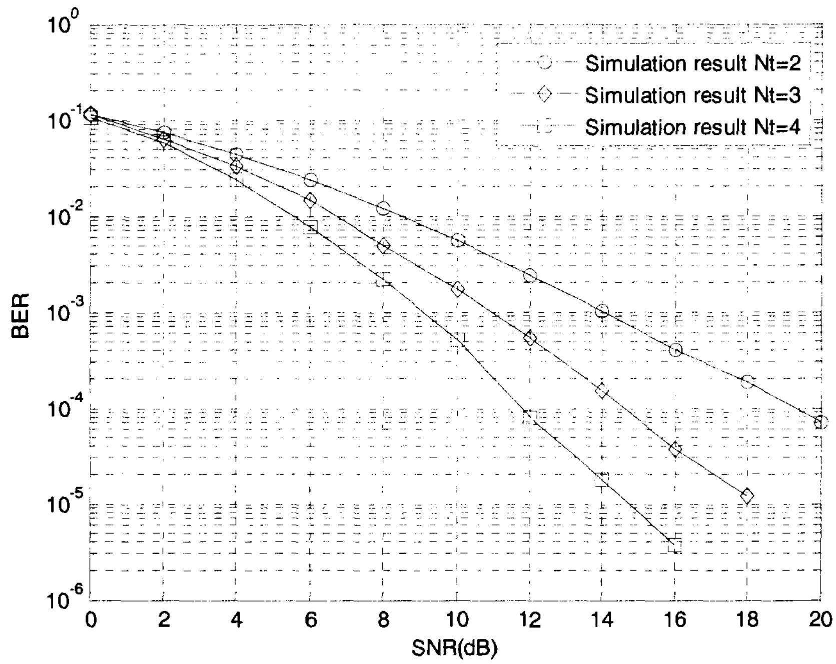

Figure 4.6: Comparison of STBC Design (G=2) Permutation Spreading BPSK MISO-CDMA Systems over Flat Fading Channel

4.5.2 STBC Design (G=2) BPSK MIMO-CDMA System

Figures 4.7, 4.8, and 4.9 show the theoretical BER results vs. the simulated BER results with 2, 3, and 4 transmit and receive antennas. Figure 4.10 compares the simulation BER performances with different transmit and receive antennas systems. Similar to the MISO-CDMA system, the theoretical bit error probability expression is a little worse than the simulation results. But the differences are smaller.

Equation (4.32) shows the number of channel paths equaling to $N_t \times N_r$. In the case of $N_t = N_r$, the number of channel paths increases quadratically as the number of transmit and receive antennas increases. Though, as the number of receive antennas increases, the SNR value per channel decreases, we still have better diversity gain due to the increasing of channel paths. And similar to MIMO-CDMA system, given a certain number of transmit and receive antennas, the MIMO-CDMA system using permutation spreading would have same diversity order as the space time block code with same numbers of transmit and receive antennas.

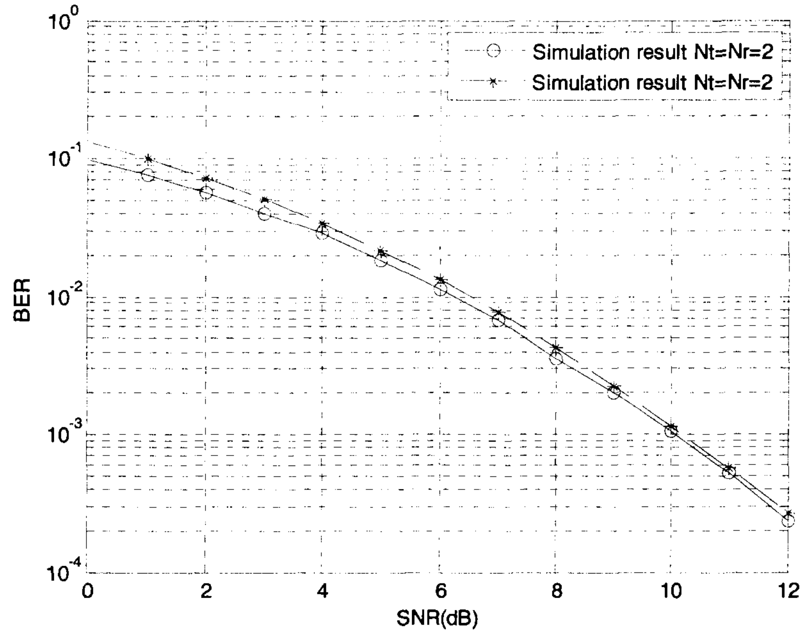

Figure 4.7: STBC Design (G=2) Permutation Spreading BPSK MIMO-CDMA System with N_t=2; N_r=2 over Flat Fading Channel

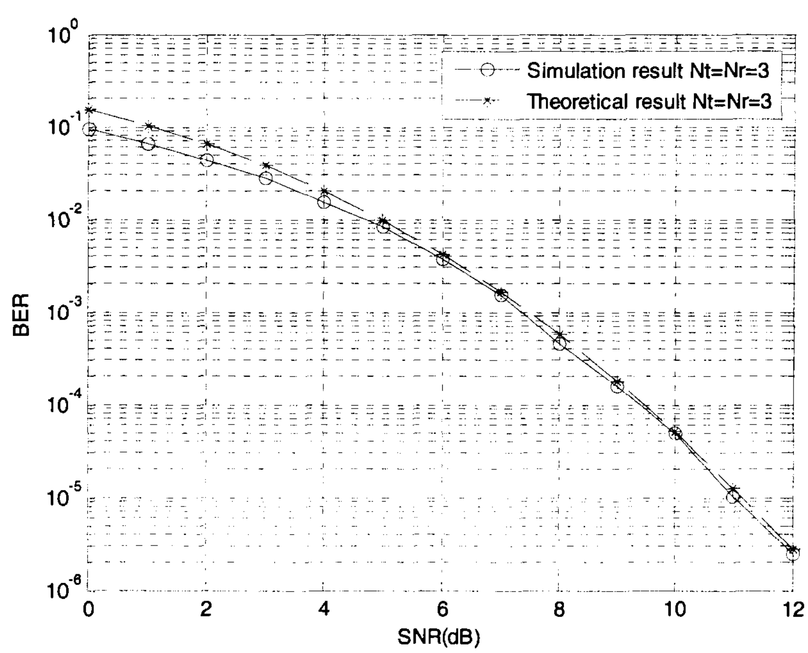

Figure 4.8: STBC Design (G=2) Permutation Spreading BPSK MIMO-CDMA System with N_t=3; N_r=3 over Flat Fading Channel

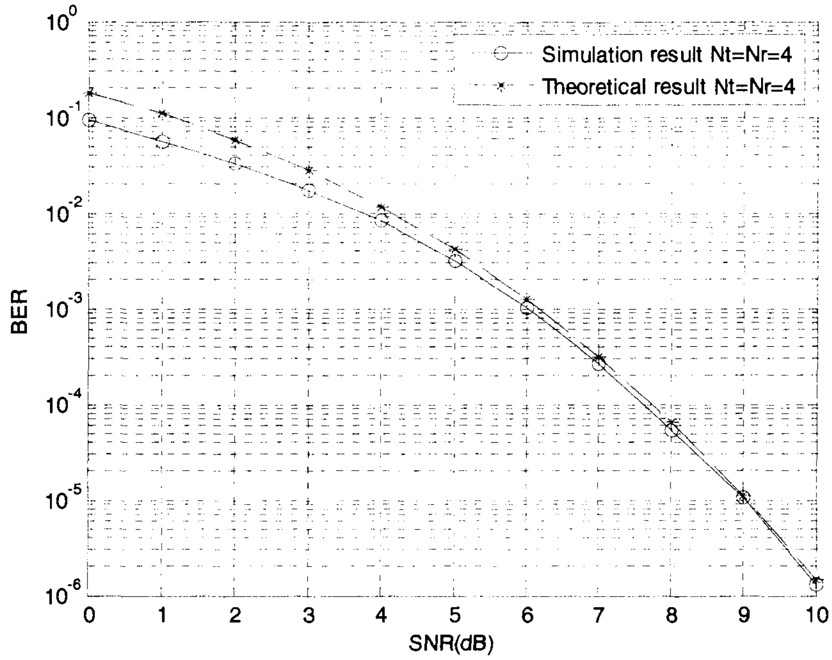

Figure 4.9: STBC Design (G=2) Permutation Spreading BPSK MIMO-CDMA System with N_t=4; N_r=4 over Flat Fading Channel

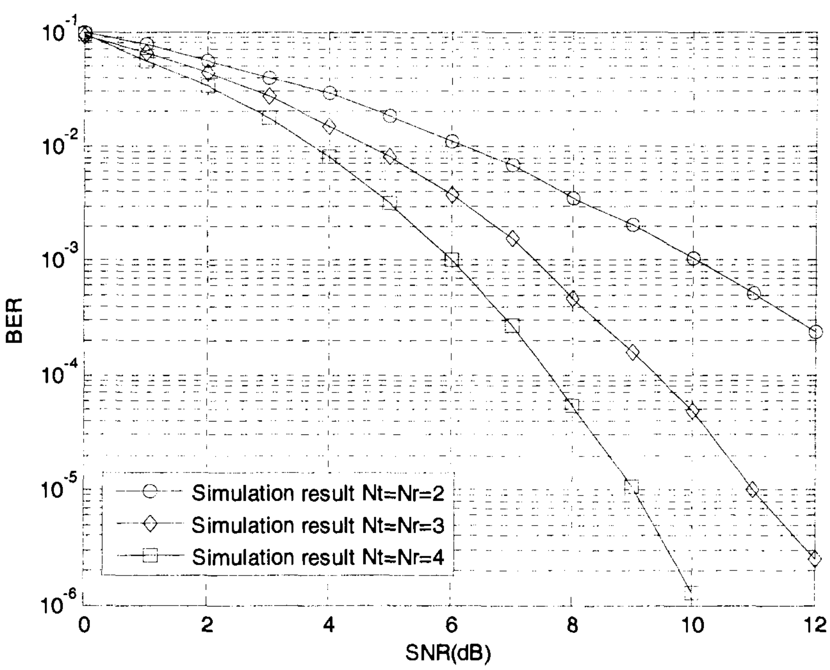

Figure 4.10: Comparison of STBC Design (G=2) Permutation Spreading BPSK MIMO-CDMA Systems over Flat Fading Channel

4.5.3 T-Design (G=4) BPSK MISO-CDMA System

Figures 4.11 and 4.12 show the theoretical BER results vs. the simulated results with 3, and 4 transmit antennas. Figure 4.13 compares the simulation BER performance of different transmit antennas systems. A T-design is used to find the permutation table, and the permutation tables are the same as Tables 4.7, 4.8, for 3, and 4 of transmit antennas system.

Figure 4.11 shows the theoretical expression for N_t=3 is still about 0.5dB worse than simulation result. But Figure 4.12 shows the theoretical expression for N_t=4 is much worse than simulation result, which is about 2dB worse. The major problem is the assumption of minimum distance d_{min} in equation (4.4q). If the minimum distance between any 2 message vectors in the same coset all equals to d_{min}, then, the theoretical expression is very close to the simulation result. However, if the minimum distance between any 2 message vectors in the coset is not a fixed value, then, the theoretical expression would be much worse than the simulation result. Table 4.8 shows the minimum distance between any 2 message vectors in the coset all equals to d_{min} =2; thus, the theoretical expression for N_t=3 is only 0.5dB worse than simulation result. Table 4.9 shows the minimum distance between any 2 message vectors in the coset does not all equal to d_{min} =2; and through analysis, only about 5/12 of the time 2 message vectors has d_{min} =2, in the other 7/12 of the time, 2 message vectors has d_{min} =3. Assume d_{min} =2 as a fixed value would give much worse result. Thus, the theoretical expression for N_t=4 is about 2dB worse than simulation result.

Equation (4.41) also indicates even when d_{min} remains the same, as we increases number of transmit antennas, we still would have better BER performance. And figure 4.13 verifies this result.

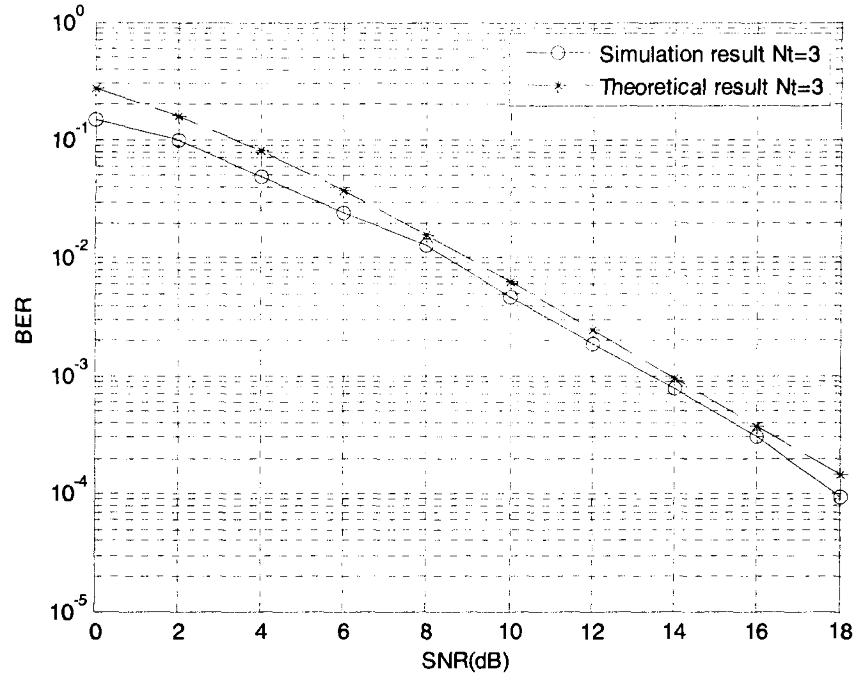

Figure 4.11: T-Design (G=4) Permutation Spreading BPSK MISO-CDMA System with N_t=3; N_r=1 over Flat Fading Channel

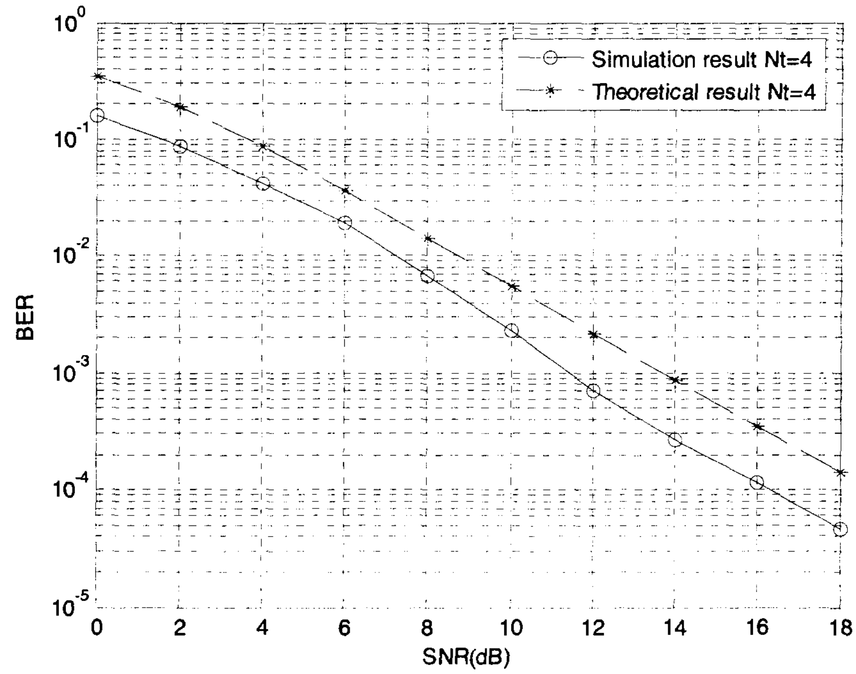

Figure 4.12: T-Design (G=4) Permutation Spreading BPSK MISO-CDMA System with N_t=4; N_r=1 over Flat Fading Channel

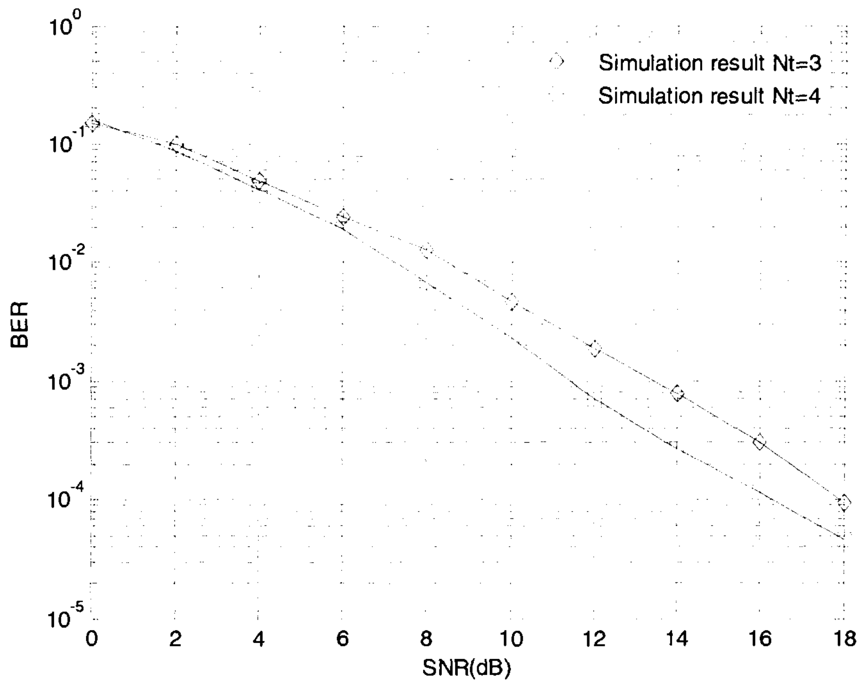

Figure 4.13: Comparison of T-Design (G=4) Permutation Spreading BPSK MISO-CDMA Systems over Flat Fading Channel

4.5.4 T-Design (G=4) BPSK MIMO-CDMA System

Figures 4.14 and 4.15 show the theoretical BER results vs. the simulated results with 3, and 4 transmit and receive antennas. Figure 4.16 compares the simulation BER performance of different transmit antennas systems.

Similar to the T-Design (G=4) MISO-CDMA system, the theoretical expression for N_t=3 compares with the simulation result quite well; the theoretical expression for N_t=4 is about 1dB worse than the simulated result. And Figure 4.16 also gives the same observation results as Figure 4.13.

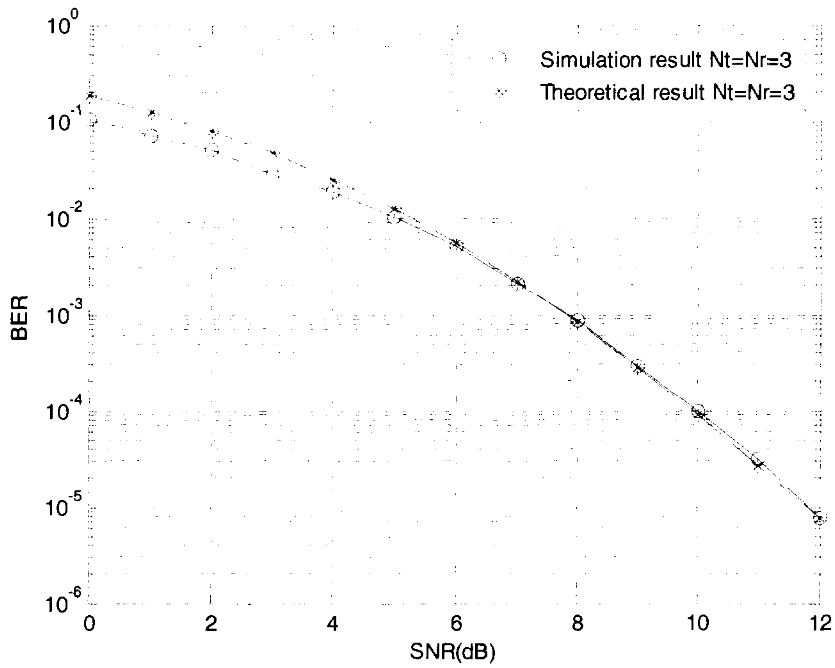

Figure 4.14: T-Design (G=4) Permutation Spreading BPSK MIMO-CDMA System with N_t=3; N_r=3 over Flat Fading Channel

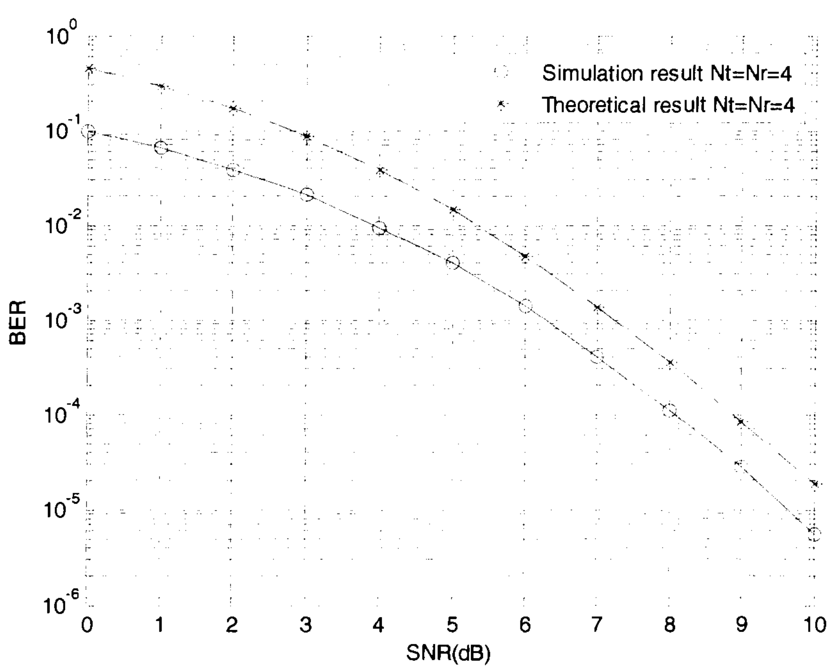

Figure 4.15: T-Design (G=4) Permutation Spreading BPSK MIMO-CDMA System with N_t=4; N_r=4 over Flat Fading Channel

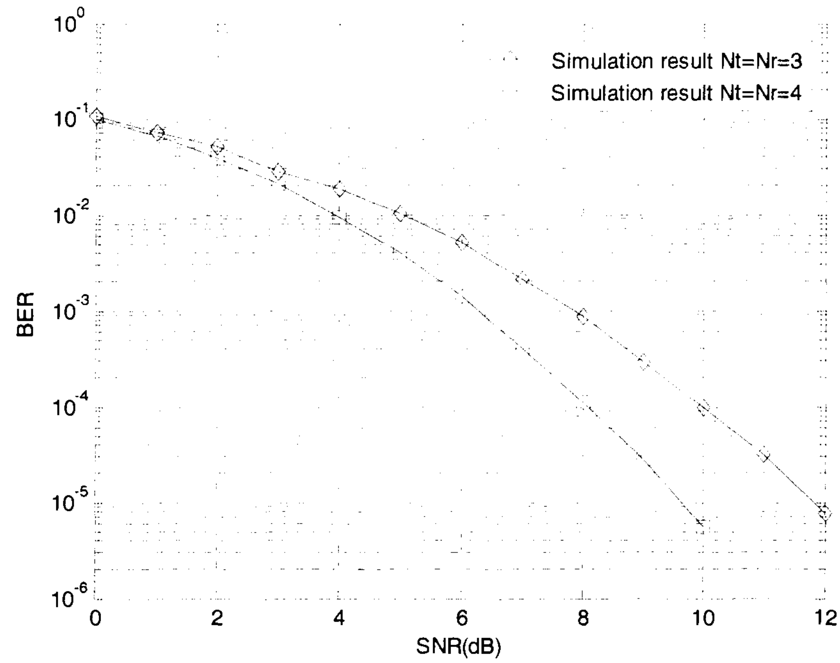

Figure 4.16: Comparison of T-Design (G=4) Permutation Spreading BPSK MIMO-CDMA Systems over Flat Fading Channel

4.6 Simulation Results Comparison

So far, three spreading techniques were proposed for MIMO-CDMA systems, the conventional method, parity bit selected spreading, and permutation spreading techniques. The simulation results comparison is given in this section.

4.6.1 BPSK MISO-CDMA system

Figures 4.17, 4.18, and 4.19 show the simulated BER performances of MISO-CDMA system using conventional method, parity bit selected spreading and permutation spreading techniques with 2, 3 and 4 transmit antennas. All the figures show permutation spreading technique provides the best BER performance; while the parity bit selected spreading technique, although it performs worse than the permutation spreading technique, still outperforms the conventional method.

The parity bit selected spreading technique provides limited transmit diversity; instead it groups the transmit message data together to enhance the total transmit signal energy level. It can improve the system performance, but can only provide limited diversity gain. However, the permutation spreading technique can have the same transmit diversity order as space time block code; as the number of transmit antennas increases, the diversity order increases as well.

We also notice that for the permutation spreading techniques, the sub-optimally designed technique provide less diversity gain than the optimal design while still outperforming the parity bit selected spreading technique. Since the sub-optimally designed permutation spreading technique can provide at least 2nd order transmit diversity for N_t=3 and N_t=4 system, which still has a higher diversity order than parity bit selected spreading technique. Thus, the sub-optimally designed permutation spreading technique given in chapter 4 still has better diversity gain than parity bit selected spreading technique.

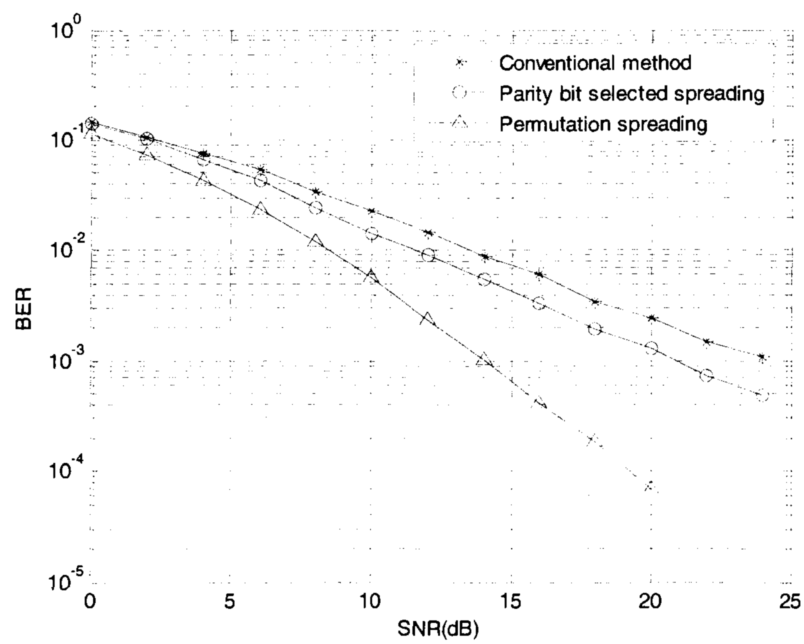

Figure 4.17: BER for Different BPSK MISO-CDMA System with N_t=2; N_r=1 over Flat Fading Channel

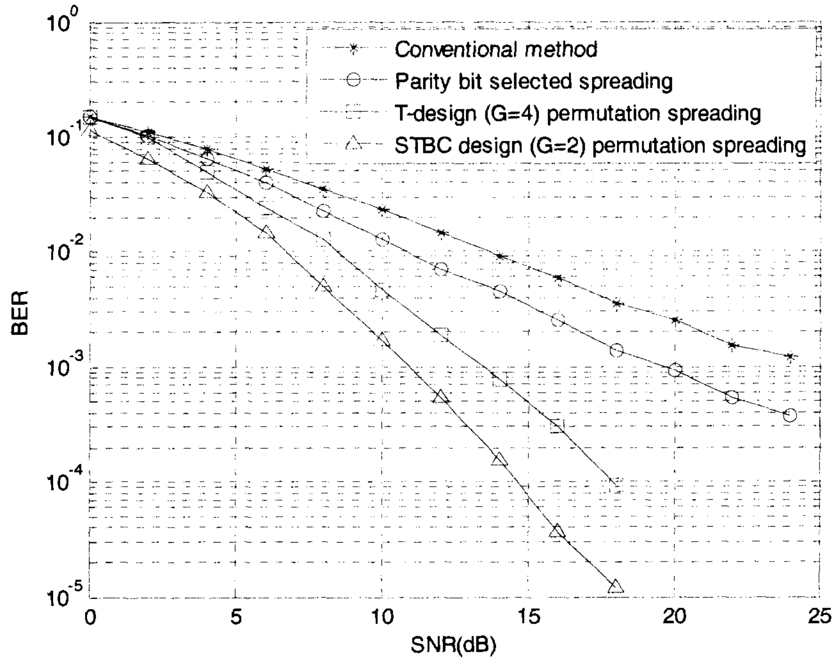

Figure 4.18: BER for Different BPSK MISO-CDMA System with N_t=3; N_r=1 over Flat Fading Channel

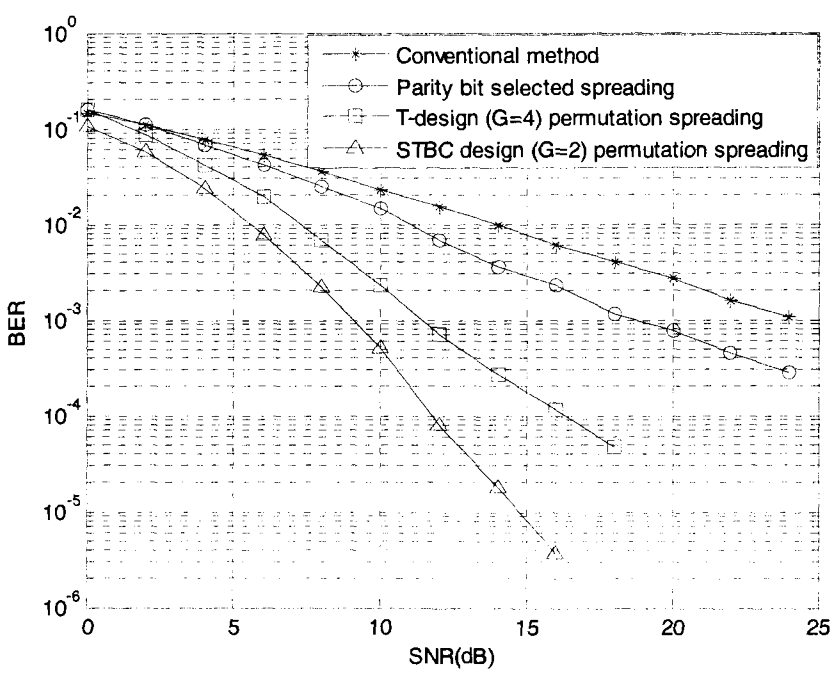

Figure 4.19: BER for Different BPSK MISO-CDMA System with N_t=4; N_r=1 over Flat Fading Channel

4.6.2 BPSK MIMO-MIMO system

Figures 4.20, 4.21, and 4.22 show the simulated BER performance f MISO-CDMA system using conventional method, parity bit selected spreading and permutation spreading techniques with 2, 3 and 4 transmit and receive antennas. Similar to MISO-CDMA systems, permutation spreading has the best performance; parity bit selected spreading is worse than permutation spreading, but still outperforms the conventional method.

We notice that, though permutation spreading still gives the best performance, the diversity gains are less than those in the MISO-CDMA system. And the diversity gain remains almost the same as we increase the number of transmit and receive antennas.

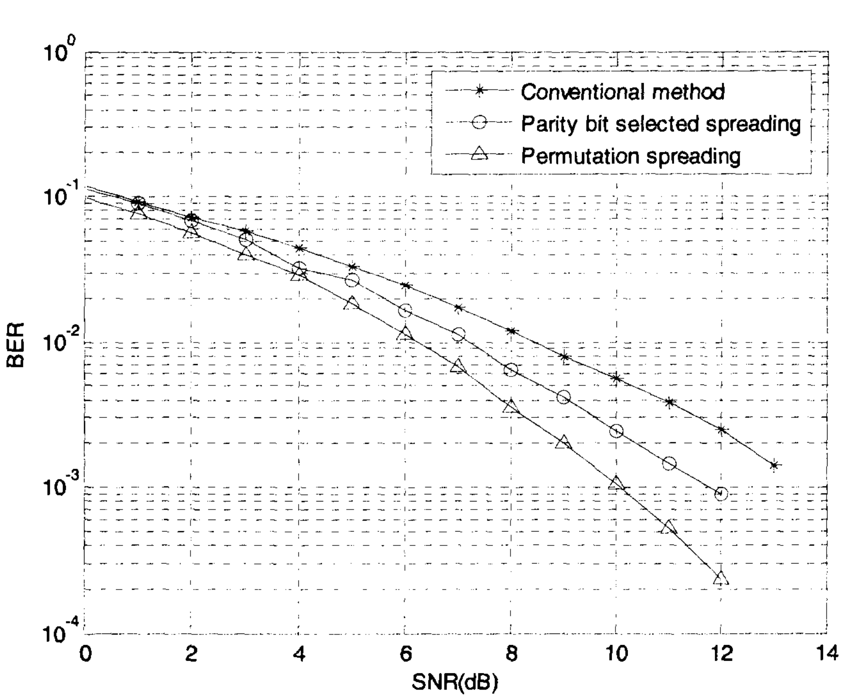

Figure 4.20: BER for Different BPSK MIMO-CDMA System with N_t=2; N_r=2 over Flat Fading Channel

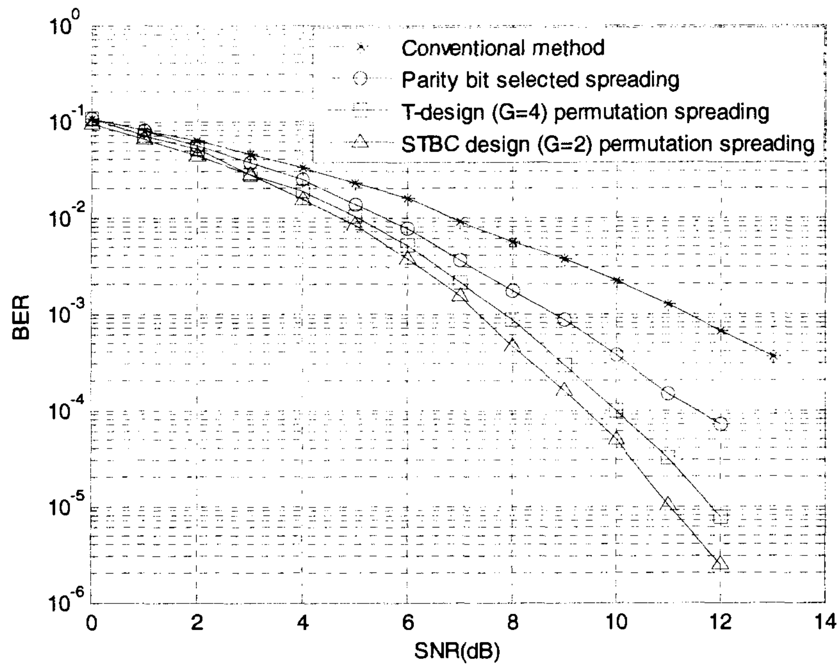

Figure 4.21: BER for Different BPSK MIMO-CDMA System with N_t=3; N_r=3 over Flat Fading Channel

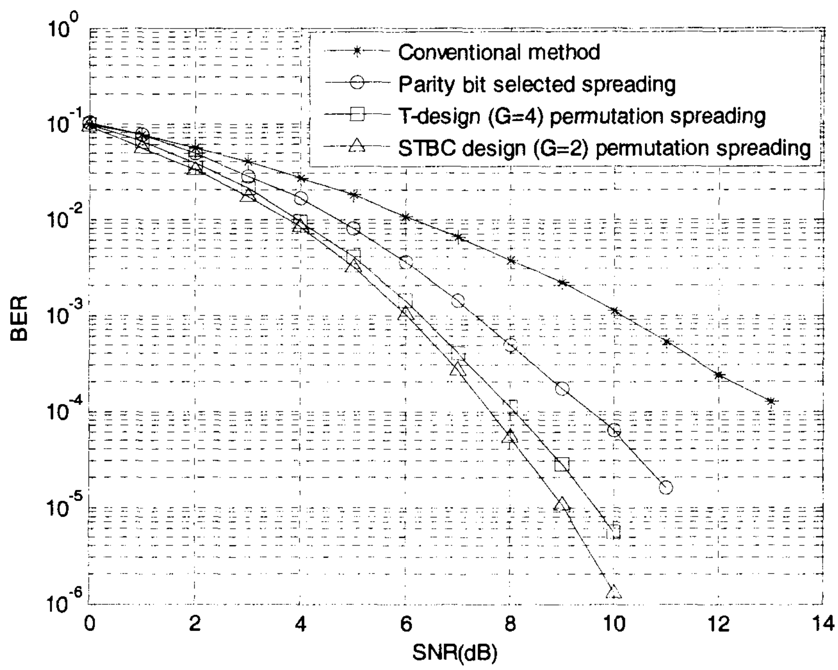

Figure 4.22: BER for Different BPSK MIMO-CDMA System with N_t=4; N_r=4 over Flat Fading Channel

Chapter 5
Asynchronous MIMO-CDMA Multiple Access System

5.1 Introduction

There are some advantages to using DS-CDMA in multiuser environments. For example, spread spectrum can provide bandwidth efficiency as well as communication security [32], and there is no hard limit for the number of users that can simultaneously access the shared channel [33].

In asynchronous CDMA systems, users accessing the shared channel cause interferences to to all other users. Those users closest to the base station will cause a high level of interference compared to the users that are far away from the base station. This is called near far effect [33]. Power control technique can adjusts the users' transmit power to ensure the received power of each user is no more than the minimum level needed for demodulation [5], [33], so that the effect of near-far effect is minimized. Power control can be used to compensate for the channel fading as well.

Pseudo-noise (PN) sequences are also called pseudorandom sequences. In the DS-CDMA system, the information signal is multiplied by the PN sequence so that the transmit signal appears to be similar to Gaussian noise. This protects the information from being decoded by an unintended receiver [5], [13]. A set of shift registers are needed to generate the PN sequence, the number of elements in the shift register determines the length of PN sequence [34]. Different CDMA standards require different length of PN sequences. For example, in the IS-95 standard, a PN sequence of length 2^{15} chips is used [15]. However, in this thesis, in order to simplify the simulation, a scrambling code of length 2^4=16 chips is used to make the spreading sequence similar to the PN sequence.

5.2 System Model

5.2.1 Transmitter Model

The transmitter model for multi-user MIMO-CDMA systems using conventional methods, parity bit selected spreading and permutation spreading techniques are given in Figure 6.1, Figure 6.2 and Figure 6.3 respectively. A scrambling code ($sc_m(t)$) for the m^{th} user is multiplied with the spreading sequence before the signal is transmitted. This is done to provide signal separation between the different users. In order to simply the simulation, the scrambling code used in this thesis has a length of 16 chips, where each chip is a discrete uniformly distributed random variable consists of antipodal value 1 and -1. By using the scrambling code after orthogonal spreading sequence would make the spreading sequence similar to a pseudo-noise (PN) sequence. Since the scrambling code consists of a sequence of chips that are uniformly distributed random variables with value 1 or -1, the probability of two users having the same scrambling code would be equal to $1/2^N$, where N is the length of the scrambling code. In the case of the scrambling code length equals to 16; the probability would be equals to $1/2^{16}$.

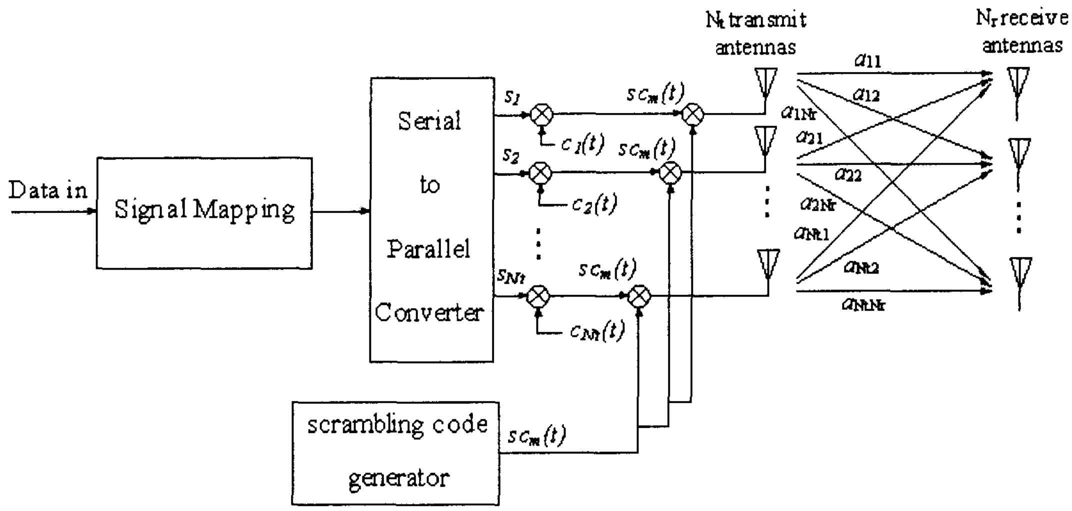

Figure 5.1: Transmitter Model of Multi-user Conventional MIMO-CDMA System

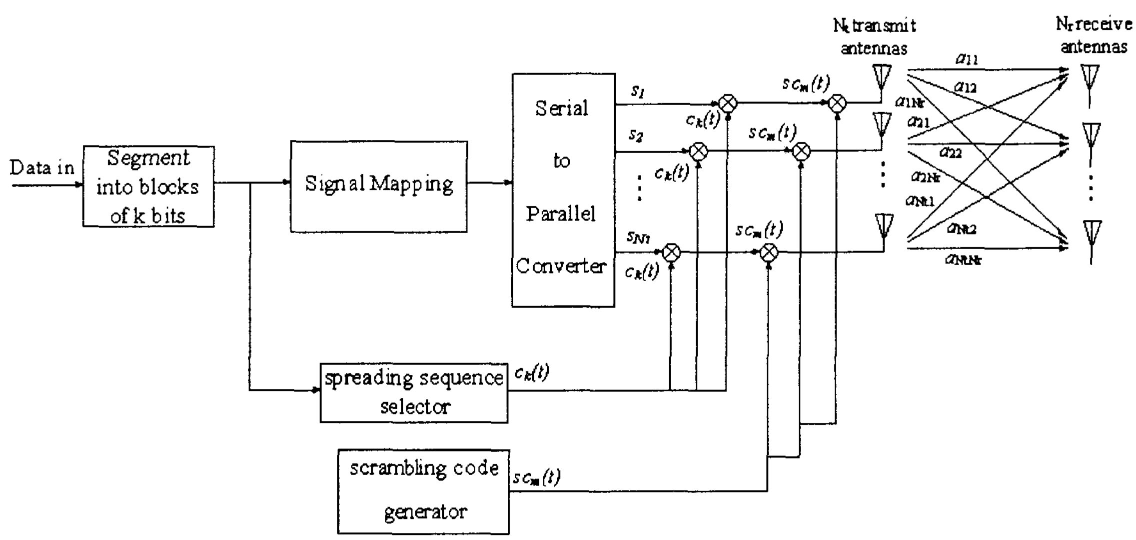

Figure 5.2: Transmitter Model of Multi-user Parity Bit Selected Spreading MIMO-CDMA System

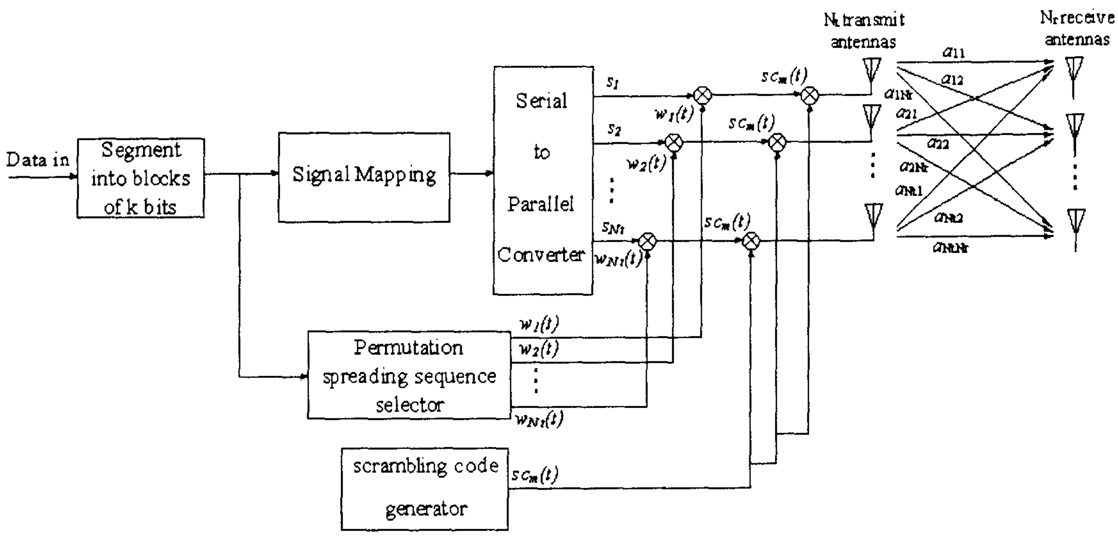

Figure 5.3: Transmitter Model of Multi-user Permutation Spreading MIMO-CDMA system

5.2.2 Receiver Model

The receiver model for multi-user MIMO-CDMA systems using conventional methods, parity bit selected spreading and permutation spreading techniques are given in Figure 6.4, and Figure 6.5 respectively. The scrambling code sequence ($sc_m(t)$) for the m^{th} user is added before the received signals being sent to the optimal receivers at receive part. The scrambling code would only decoded the message signal for the m^{th} user, and treat all the other users' message as interference. Then, the optimal receiver would estimate the transmit message bits by ML detection.

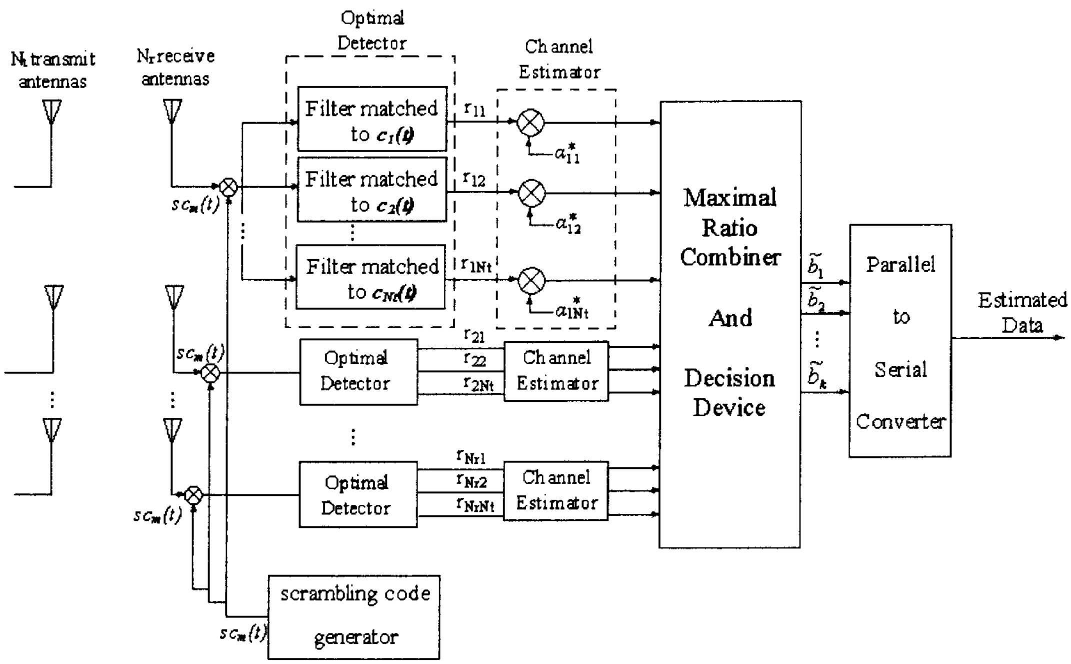

Figure 5.4: Receiver Model of Multi-user Conventional MIMO-CDMA System

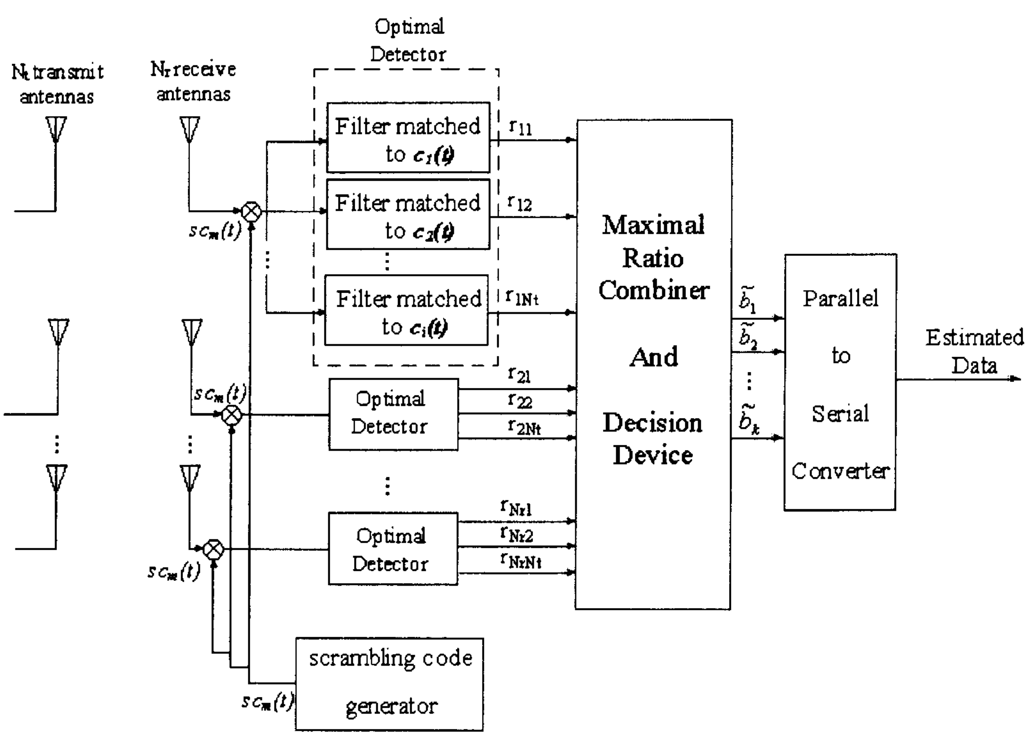

Figure 5.5: Receiver Model of Multi-user Parity Bit selected Spreading and Permutation Spreading MIMO-CDMA System

5.3 Multiple Access Interference Error Probability

A. Power control

In CDMA systems, all users transmit simultaneously on the same range of frequencies. If the correlation coefficient of the different users' spreading codes is nonzero, then multiple access interference (MAI) will be present. If all users transmit at the same power level without taking into account of the fading and the distance between the base station, then the users nearest the base station will create large interference levels to all other users [33]. This is the near-far effect. It limits the amount of users that can simultaneously access the channel.

Power control technique continuously adjusts the users' transmit power to ensure the received power of each user is no more than the minimum level needed for demodulation and same SNR value.

In this thesis we assume the power control is used to ensure the received signal for each user has same average signal-to-noise ratio (SNR) value; but that it does not compensate for the small scale fading. In other words, the power control ensures the system can eliminate the near-far effect, but the system still suffering from flat Rayleigh fading.

B. Signal-to-interference-noise-ratio (SINR) and bit error probability expression

Using the above power control assumption, the signal-to-interference-noise ratio (SINR) of asynchronous multi-user DS-CDMA systems using random signature spreading sequence, is shown in [4], [1], [35] to be:

$$\gamma_b' \approx \frac{\bar{\gamma}_b}{1 + (U' - 1)\left(\frac{2R_b}{3R_c}\right)\bar{\gamma}_b} \tag{5.1}$$

where $\bar{\gamma}_b$ is the SNR per bit, U' is the total numbers of simultaneously transmitting users, R_b/R_c is the spreading factor. We note that equation (5.1) uses the Gaussian approximation. Thus, the resulting γ'_b is an approximate value.

However, equation (5.1) only considers the case of single input single output (SISO) system. In MIMO-CDMA systems, each user would have more than one interfering channels, and the received SNR value would be proportional to the inverse of total numbers of receive antennas. Consider a MIMO-CDMA system with N_t transmit antennas, N_r receive antennas. If the total number of uncorrelated channel paths is L; the message signal transmission rate per antenna is R_b; and the chip rate is R_c; then the signal-to-interference-noise-ratio (SINR) per receive antenna for the MIMO-CDMA system would be expressed as

$$\gamma'_{b,antenna} \approx \frac{\bar{\gamma}_{b,receive}}{1 + L(U-1)\left(\frac{2R_b}{3R_c}\right)\bar{\gamma}_c} \tag{5.2}$$

Where $\bar{\gamma}_{b,receive}$ is the average SNR value per receive antenna, which is given as

$$\bar{\gamma}_{b,receive} = \frac{\bar{\gamma}_b}{Nr} \tag{5.3}$$

$\bar{\gamma}_c$ is the SNR value per channel, which is given as

$$\bar{\gamma}_c = \frac{\bar{\gamma}_b}{L} \tag{5.4}$$

By substituting (5.3) and (5.4) into (5.2), the SINR value per receive antenna for MIMO-CDMA system would be expressed as

$$\gamma'_{b,antenna} \approx \frac{\bar{\gamma}_b / Nr}{1 + L(U-1)\left(\frac{2R_b}{3R_c}\right)\frac{\bar{\gamma}_b}{L}}$$

$$\gamma'_{b,antenna} \approx \frac{\bar{\gamma}_b / Nr}{1+(U-1)\left(\frac{2R_b}{3R_c}\right)\bar{\gamma}_b} \tag{5.5}$$

The SINR value for BPSK modulated MIMO-CDMA system would be given as

$$\gamma'_b = Nr \cdot \gamma'_{b,antenna} \approx \frac{\bar{\gamma}_b}{1+(U-1)\left(\frac{2R_b}{3R_c}\right)\bar{\gamma}_b} \tag{5.6}$$

We notice that equation (5.6) is identical to equation (5.3). Thus the signal-to-interference-noise ratio (SINR) given in [4], [1], [35] is still valid for MIMO-CDMA system.

i. Conventional MIMO-CDMA system

The bit error probability expression for multi-user conventional BPSK MIMO-CDMA system with N_t transmit antennas and N_r receive antennas would be the same as equation (2.10) given in chapter 2, which is given as

$$P_{2b,conventional,MIMO}(r_k) = \frac{1}{2}\left[1-\sqrt{\frac{\gamma'_b / Nr}{1+\gamma'_b / Nr}}\sum_{i=0}^{Nr-1}\binom{2i}{i}\left(\frac{1}{4(1+\gamma'_b / Nr)}\right)^i\right] \tag{5.7}$$

ii. Parity bit selected spreading MIMO-CDMA system

The bit error probability expression for multi-user parity bit selected spreading BPSK MIMO-CDMA system with N_t transmit antennas and N_r receive antennas would be the same as equation (3.47), which is given as

$$P_{2b,parity,MIMO}(r_k) \approx$$

$$1-\left\{1-\frac{1}{2}\left[1-\sqrt{\frac{\gamma'_b}{1+\gamma'_b}}\sum_{i=0}^{Nr-1}\binom{2i}{i}\left(\frac{1}{4(1+\gamma'_b)}\right)^i\right]\right\}\times \left\{1-\frac{1}{4}\left[1-\sqrt{\frac{\gamma'_b/2}{2+\gamma'_b/2}}\sum_{i=0}^{2Nr-1}\binom{2i}{i}\left(\frac{1}{2(2+\gamma'_b/2)}\right)^i\right]\right\}^{M-2} \tag{5.8}$$

iii. Permutation spreading MIMO-CDMA system

The bit error probability expression for multi-user permutation spreading BPSK MIMO-CDMA system with N_t transmit antennas and N_r receive antennas would be the same as equation (4.32), which can be expressed as

$$P_{2b,permutation,MIMO}(r_k) \approx$$
$$1-\left\{1-\frac{1}{2}\left[1-\sqrt{\frac{\gamma_b'/Nr}{1+\gamma_b'/Nr}}\sum_{k=0}^{Nt\cdot Nr-1}\binom{2i}{i}\left(\frac{1}{4(1+\gamma_b'/Nr)}\right)^i\right]\right\}\times \tag{5.9}$$
$$\left\{1-\frac{1}{4}\left[1-\sqrt{\frac{\gamma_b'/Nr}{1+\gamma_b'/Nr}}\sum_{i=0}^{Nt\cdot Nr-1}\binom{2i}{i}\left(\frac{1}{2(2+\gamma_b'/Nr)}\right)^i\right]\right\}^{M-2}$$

Where γ_b' showing in equation (5.7), (5.8) and (5.9) are all the same expression as equation (5.6).

5.4 Simulation Results and Discussion

The following sections show the simulated BER performance. The simulation environment is the same as those in chapter 2. The length of orthogonal spreading sequence and scrambling code are both 16. We assume the received signal for each user has same averaging signal-to-noise ratio (SNR) value.

5.4.1 Conventional BPSK MIMO-CDMA System

Figure 5.6 shows the simulated BER performances for multi-user BPSK modulated MIMO-CDMA system using conventional method with 4 transmit and receive antennas. The processing gain using in the simulation is R_c/R_b= 16, where R_c is the chip rate, and R_b is the message transmission rate per transmit antenna.

From the graph, it can be observed the error floor for 2-user system occurs around BER value of 10^{-4}, and the error floor for 3-user system occurs around BER value of 4.5×10^{-4}. Adding more users to the system, the interference would increase as well, and as a result, the error floor would occur at higher BER value. We also notice that as the number of interference increases, the BER performance gets worse, and we lose some diversity gain as well.

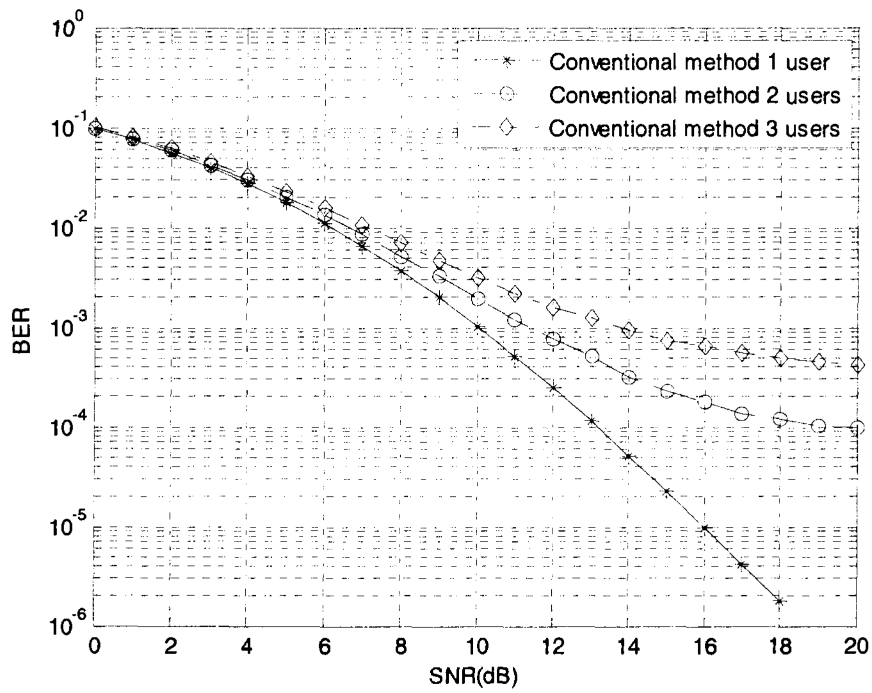

Figure 5.6: BER for Multi-user Conventional BPSK MIMO-CDMA System with N_t=4; N_r=4 over Flat Fading Channel

5.4.2 Parity Bit Selected Spreading BPSK MIMO-CDMA System

Figure 5.7 shows the simulation BER performances for multi-user BPSK modulated MIMO-CDMA system using parity bit selected spreading with 4 transmit and receive antennas. The processing gain using in the simulation is R_c/R_b= 16 as well.

From the graph, it can be observed the error floor for 2-user system occurs around BER value of 4×10^{-5}, and the error floor for 3-user system occurs around BER value of 1.6×10^{-4}. The parity bit selected spreading technique provides the same comparison results as conventional method.

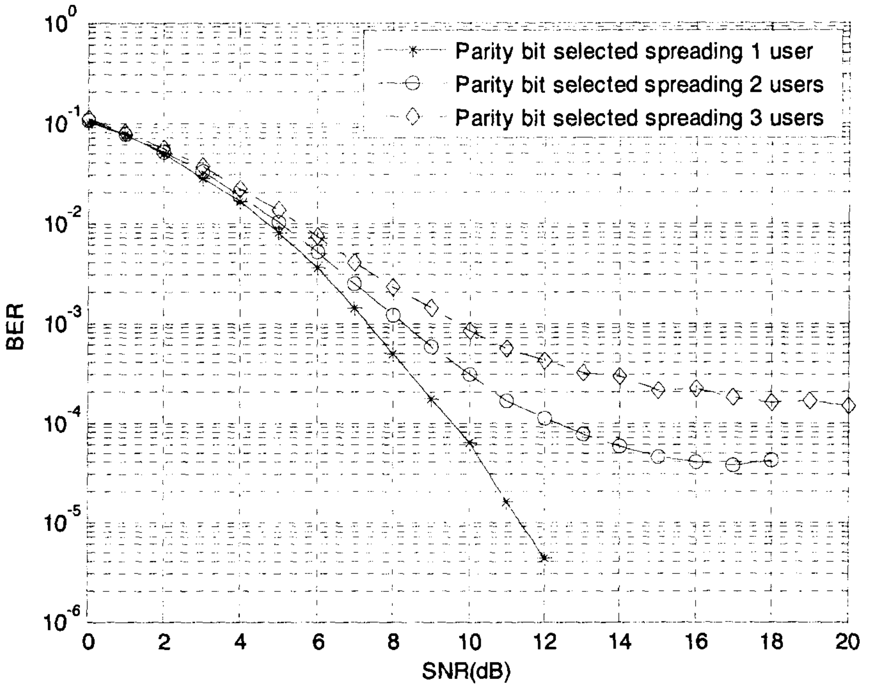

Figure 5.7: BER for Multi-user Parity Selected Spreading BPSK MIMO-CDMA System with N_t=4; N_r=4 over Flat Fading Channel

5.4.3 Permutation Spreading BPSK MIMO-CDMA System

Figure 5.8 shows the simulation BER performances for multi-user MIMO-CDMA system using permutation spreading with 4 transmit and receive antennas. The processing gain using in the simulation is R_c/R_b= 16 as well.

From the graph, it can be observed the error floor for 2-user system cannot be clearly observed even at the SNR value of 10^{-6}, and the error floor for 3-user system occurs around BER value of 1.6×10^{-6}. It provides the same comparison results as parity bit selected spreading technique and conventional method.

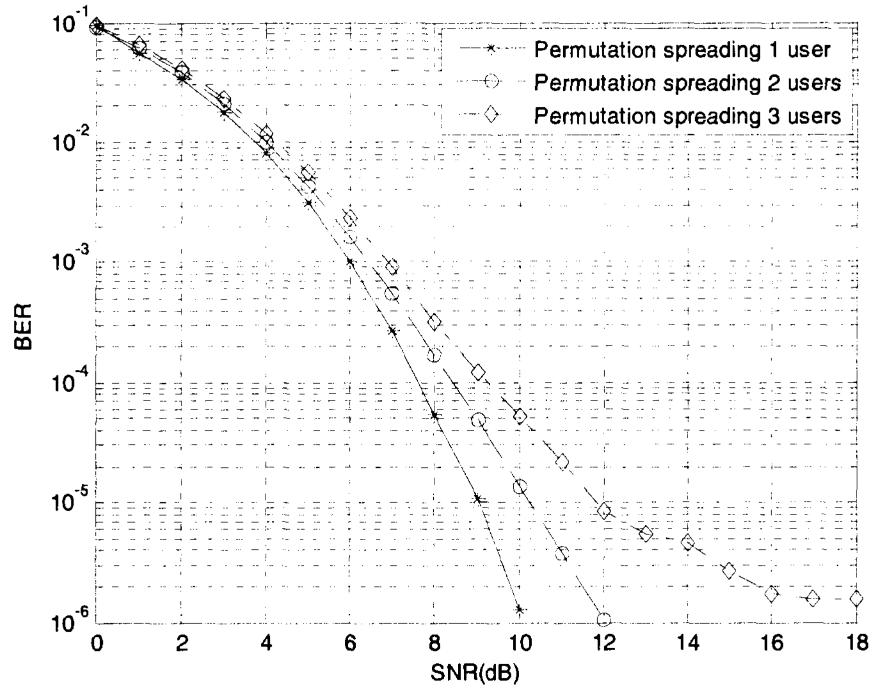

Figure 5.8: BER for Multi-user Permutation Spreading MIMO-CDMA System with N_t=4; N_r=4 over Flat Fading Channel

5.4.4 Simulation Results Comparison

Figure 5.9 shows the simulation BER performances of multi-user BPSK modulated MIMO-CDMA system using conventional method, parity bit selected spreading, and permutation spreading techniques with 4 transmit and receive antennas.

The parity bit selected spreading technique can improve the BER performances in the multi-user MIMO-CDMA system. But, similar to the single user MIMO-CDMA system, the improvements in the diversity gain and error floor are limited. The 2-user parity bit selected spreading system is better than 1-user conventional system when the BER value is greater than 10^{-4}, then the error floor occurs, and the 2-user parity bit selected spreading system becomes worse than 1-user conventional system. The 3-user parity bit selected spreading system is better than 2-user conventional system when the

BER value is below 2×10^{-4}, because the 3-user parity bit selected spreading system has a lower error floor.

Unlike the parity bit selected spreading technique, the permutation spreading technique provides very good BER performance in the multi-user systems. The 2-user MIMO-CDMA system using permutation spreading has the error floor lower than BER value of 10^{-6}, and it is about 1dB better than single-user MIMO-CDMA system using parity bit selected spreading. The 3-user MIMO-CDMA system employing permutation spreading is still better than single-user MIMO-CDMA system employing parity bit selected spreading when the BER value is greater than 10^{-4}; it is also better than single-user conventional MIMO-CDMA system when BER value is greater than 2×10^{-6}.

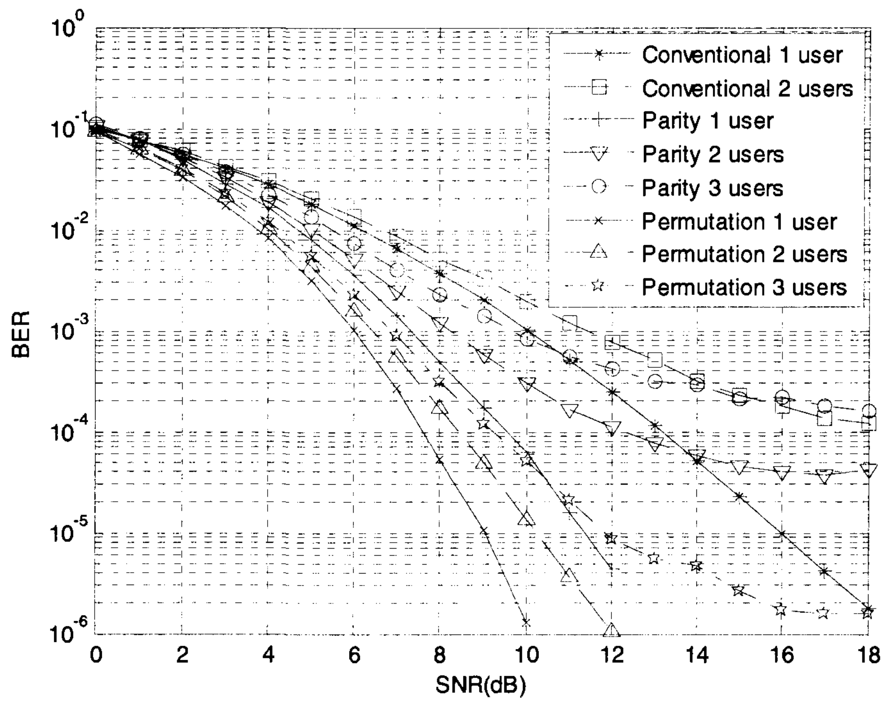

Figure 5.9: BER for Different Multi-user MIMO-CDMA System with N_t=4; N_r=4 over Flat Fading Channel

Chapter 6
Conclusions and Suggestions for Future Research

6.1 Conclusions

The MIMO-CDMA system is currently used in the third generation (3G) wireless communication systems. Many improvements are being proposed. In this thesis such two new techniques that can improve the system performance are analyzed and discussed for selecting the spreading sequences for the DS MIMO-CDMA system.

We have provided design strategies for parity bit selected spreading and permutation spreading techniques. It has been shown that, by using space time block code permutation, all the transmit message vectors can be orthogonal to each other, and permutation spreading can achieve same transmit diversity order as space time block code.

We have evaluated and compared the BER performances of conventional method, parity bit selected spreading, and permutation spreading techniques over frequency non-selective fading channels. We showed that the parity bit selected spreading technique can improve the BER performance, but with a limited improvement in the diversity gain; and the permutation spreading can provide significant improvements in both BER performance and diversity gain.

In addition, the performances for the asynchronous MIMO-CDMA systems are also evaluated. With a single-user detector, 2-user MIMO-CDMA system using permutation spreading is better than single-user MIMO-CDMA system using parity bit selected spreading, and the error floor cannot clearly be observed even when BER=10^{-6}. 3-user MIMO-CDMA system employing permutation spreading is still better than single-user MIMO-CDMA system employing conventional method when BER<2×10^{-6}; and has the error floor around BER=2×10^{-6}.

6.2 Suggestions for Future Research

There are various possible further researches that can be considered in the future.

One interesting area is the system's BER performance in frequency selective fading channel. Frequency selective fading channel is caused by multi-path delay; though it is more difficult to model, it corresponds to many practical operating scenarios in the wireless mobile communication system. The two techniques we have studied are expected to have less degraded performances under the frequency selective fading channels than the conventional method.

Another area of the future research would be Orthogonal Frequency-Division Multiple Access (OFDMA) system. OFDMA system has some attractive advantages, such as robust against multi-path fading channel and high spectral efficiency, and it is also one of the strong candidates for the fourth generation (4G) communication system. In the OFDMA system, instead of selecting the orthogonal spreading sequences, the parity bits can be used to select the assigned subcarriers.

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