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A Reduced Complexity Detection Algorithm Employing Adaptive LMS Filters for CDMA/MIMO Systems Using Permutation Spreading in Slowly Varying Rayleigh Fading Channels

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A Reduced Complexity Detection Algorithm Employing Adaptive LMS Filters for CDMA/MIMO Systems Using Permutation Spreading in Slowly Varying Rayleigh Fading Channels

by

Jing Luo

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Abstract

In wireless communications, research in the area of advanced detection techniques and adaptive filter algorithms for CDMA and MIMO systems in Rayleigh fading channels has been of a great interest in the past several years. On one hand, most detection algorithms can acquire satisfactory performance. On the other hand, however, the performance improvement can be achieved at the cost of an increase in computational complexity. In this thesis, we present a reduced complexity detection technique based on adaptive Least-mean-square (LMS) filtering for CDMA/MIMO systems using permutation spreading in slowly varying Rayleigh fading channels. By simulating and comparing the BER performance of 27 different models related to 4 different detections techniques (Wiener, Maximum likelihood detection (MLD), LMS, conventional method) in different Rayleigh fading channels and by analyzing and evaluating the computational complexity of Wiener, MLD, and LMS tracking detection solutions, it is not difficult to find that the proposed LMS tracking detection algorithm for CDMA/MIMO systems with permutation spreading has shown its outstanding advantages: lower complexity, without sacrificing too much BER performance, and dynamic tracking of frequency non-selective Rayleigh fading channels.

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List of Acronyms

3G	Third Generation
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
CDMA	Code Division Multiple Access
DMI	Direct Matrix Inversion
DS-SS	Directs Sequence Spread Spectrum
DS-CDMA	Direct Sequence CDMA
ISI	Inter-symbol Interference
LMMSE	Linear Minimum Mean Square Error
LMS	Least Mean Squares
LOS	Line of Sight
LS	Least Squares
MAN	Metropolitan Area Network
MAP	Maximum a Posteriori Probability
MIMO	Multiple Input Multiple Output
MLD	Maximum Likelihood Detection

MSE	Mean Square Error
OFDM	Orthogonal Frequency Division Multiplexing
PS	Permutation Spreading
PSAM	Pilot Symbol Assisted Modulation
RLS	Recursive Least Square
SIC	Successive Interference Canceling
SNR	Signal-to-noise Ratio
TDMA	Time Division Multiple Access
UMTS	Universal Mobile Telecommunications System
WCDMA	Wideband CDMA
WLAN	Wireless Local Area Network
WLL	Wireless Local Loop
WMAN	Wireless Metropolitan Area Network
WSS	Wide-sense Stationary

List of Symbols

α_{ij}	Complex channel gain on the link between transmit *i* and receive antenna *j*
$\alpha(\tau)$	Rayleigh fading channel gain generated at time τ
μ	LMS weight step-size parameter
λ_{max}	The largest eigenvalue of the correlative matrix
A	Carrier amplitude of signal
$\boldsymbol{b}$	Information bit in bipolar format
$\hat{\boldsymbol{b}}$	Receive estimate of information bit $\boldsymbol{b}$
bpoint	The training/pilot bound value of the LMS weight vector
B_d	The Doppler shift in Rayleigh fading channels
$C_{mi}(t-nT)$	Spreading waveform
$c_i^{(n)}(t)$	A set of mutually orthogonal spreading waveforms
$d(n)$	Desired response at time n
DS	Doppler power spectral density in fading channels
$e(n)$	The estimation error or error signal
err_lms	The error between the desired variables and actual message sequences of LMS tracking detection
f_d	Maximum Doppler shift

$\boldsymbol{H}$	$N_t * N_r$ channel transfer matrix
$J_0(x)$	Bessel function of the first kind
L	Number of taps
M_i	A coset subset of the set off all possible message vectors
$\boldsymbol{n}$	Complex additive white Gaussian noise (AWGN) vector
$n_{jk}^{(n)}$	The response of the jth receive antenna's kth matched filter to the input noise
N_t	The number of transmit antennas
N_r	The number of receive antennas
$\boldsymbol{Pb_j}$	Correlation matrix of decision variables and desire variables for j receivers
$\boldsymbol{R}$	Correlation matrix of decision variables
R_b	Bit rate
$\boldsymbol{Ri}$	Correlation matrix of decision variables for i receivers
R_f	Raleigh fading factor or Rayleigh fading parameter
$\boldsymbol{Ri}_{Mj}$	Sub correlation matrix of decision variables related to different coset M_j
T	Symbol interval
$\boldsymbol{u}$	The vector consisted of MLD decision variables
$\mathfrak{u}$	Made up of all of the rest of MLD decision variables not in $\boldsymbol{u}$
$\boldsymbol{U\_W_{jk}}$	Initial decision variables of Wiener algorithm with permutation spreading

$\tilde{U}\_W_{ij}$	Final decision variables of Wiener algorithm with permutation spreading
U_LMS_{jk}	Initial decision variables of LMS tracking detection algorithm
$\tilde{U}\_LMS_{ij}(n)$	Updated decision variables of LMS tracking algorithm at time n
v	The frequency shift relative to the carrier frequency
w_0	Optimum tap-weight vector of Wiener filters
$w_i^{(n)}(t)$	Spreading waveform used to spread the data transmitted by antenna i on the time interval n
$\ddot{w}_{ij}(n)$	Weight coefficients of Wiener filters with permutation spreading
$\hat{W}_{NrN}^{*}(n)$	Filters weight coefficients of proposed LMS tracking detection
x	A complex Gaussian random variable with 0 mean and variance 1
$\boldsymbol{x}$	Signal vector at the transmit antenna array
$\boldsymbol{y}$	Signal vector at the receiver array

Chapter 1 Introduction

1.1 Background

Wireless communications has become one of the most active fields of technology development in recent years. With the rapid development of wireless communications, a great many advanced wireless networks and techniques have been developed: wireless local area network (WLAN)[1][2][3], wireless metropolitan area network (WMAN)[1, 4, 5, and 6], wireless local loop (WLL) systems, multiple input multiple output (MIMO), wideband code division multiple access (WCDMA), and universal mobile telecommunications system (UMTS), etc. Accordingly, some important access or support technologies, such as time-division multiple access (TDMA), code-division multiple access (CDMA), orthogonal frequency-division multiplexing (OFDM), and MIMO techniques have been widely researched and applied in modern wireless systems.

In wireless systems, using direct sequence CDMA (DS-CDMA), different users can share the same time slot and/or the same bandwidth. As a result, the communication resources can be exploited in a more efficient way.

Also, in wireless communications, MIMO technology has been developed to provide better coverage and improved performance in multipath wireless fading channels by using multiple antennas at the transmitter and receiver. A typical feature of MIMO systems is the ability to turn multipath propagation into a benefit for the user. Actually, MIMO can effectively take advantage of random fading [7 - 9] and, when available, multipath delay spread [10, 11] can be used for linear combination of the inputs with partially corrupted bits. It is shown in [12, 13] that there are other advantages in using multiple antennas. For instance, the capacity of a MIMO system increases linearly with the number of transmit and receive antennas without adding additional energy. Also, it has been shown that the use of MIMO systems can improve systems capacity and spectral efficiency in wireless channels

[14 - 16]. Clearly, MIMO has recently emerged as one of the most significant technical breakthroughs in modern wireless communications.

In order to take full advantage of benefits of CDMA and MIMO techniques, in this thesis, we will combine CDMA and MIMO systems. In wireless systems, a common phenomenon, multipath means that multiple copies of a transmitted signal are received at the receiver, due to the presence of multiple radio paths/channels between the transmitter and receiver. These multiple paths arise owing to reflections from objects in the radio channels. Multipath from scattering, which is spaced pretty close together, will cause a random change of in the amplitude of the received signal. Due to the central-limit theory, the resulting fading process is often modeled as being a complex Gaussian random variable. As a result, the envelope of the received signal has a Rayleigh distribution, and this phenomenon is thus called Rayleigh fading. Other fading distributions might also arise, depending on the physical configuration. There exists a very useful Rayleigh fading model. That is, the fading process related to fading rate and the data rate, can be categorized as flat, slow (frequency nonselective) fading where the fading process is assumed to remain constant over one symbol interval and to vary from symbol to symbol. As we know, wireless CDMA/MIMO communications for narrowband voice and data can be modeled as signaling over flat, i.e. frequency nonselective, Rayleigh fading channels. Thus, in this thesis, we will focus on slowly varying /flat Rayleigh fading channels.

The development of wireless communications is being driven primarily by the medium transformation techniques from supporting traditional voice to carrying other services, such as data, images, and video. Accordingly, one solution to the demand for enlarging data capacity can be acquired by increasing frequency power and channel bandwidth. However, the two resources are among the most severely limited in the development of wireless networks: bandwidth because of the limitation with regard to useful radio spectrum, and transmitter power because mobile and other portable services need the use of battery power. On the other hand, the development of novel advanced received signal processing methods and effective detection schemes allow for significant increases in wireless capacity without requiring increases in bandwidth or power requirements. In particular, many new technologies, such as WCDMA and 3G have also spurred considerable research in detection techniques for wireless communications.

In wireless systems, the application of advanced detection techniques and adaptive filters algorithms can not only provide a significant performance improvement but also offer new signal processing capabilities over the use of conventional methods. Hence, adaptive filters have been widely employed in diverse fields such as adaptive beamforming, channel equalization, signal enhancement, noise cancel, and other aspects. For various detection techniques and filters schemes, two important aspects always need to be involved: facilitate BER performance and reduce complexity. Among the popular detection solutions, maximum likelihood detection (MLD) has attracted many researchers due to its better BER performance feature. Nevertheless, the BER performance improvement of most of MLD detection algorithms for CDMA/MIMO systems can be only achieved at the expense of an increase in computational complexity. Thus, in this thesis, we will try to find a lower computational complexity detection algorithm without sacrificing too much BER performance for CDMA/MIMO systems in frequency non-selective Rayleigh fading channels.

1.2 Motivation

In CDMA systems, CDMA assigns a different code to each user. This allows multiple users access to the same frequency band and time slot by encoding their transmissions. This works well because all other users look like noise to everyone else. However, this basic type of CDMA system is difficult to support high data rates and high capacity. In order to increase capacity, we need to combine MIMO and CDMA techniques. Actually, MIMO technology is essential to achieve high spectrum efficiency, enlarge system coverage, and support high data rates. Thus, CDMA/MIMO systems will be one of the focuses in this thesis. Note that we assume that the number of CDMA users will not go well beyond the number of virtual users/antennas in a single MIMO link in this thesis.

Meanwhile, based on CDMA/MIMO systems, in order to obtain additional diversity, increase performance and acquire more power gain, we need to further consider CDMA/MIMO systems with permutation spreading techniques [17]. However, many traditional detection algorithms such as popular MLD with permutation spreading for CDMA/MIMO systems involve higher computational complexity. Accordingly, in CDMA/MIMO systems, as demands for increased data rate and reliability grow, lower computational complexity detection technique for exploiting CDMA/MIMO systems with permutation spreading over fading channels need to be developed.

In particular, most advanced detection schemes for system operating in wireless channels employ signal processing techniques. Researchers still need to focus on low complexity algorithm for ease of practical implementation. Hence, it is anticipated that the detection techniques with lower complexity can be readily applied in real wireless communication systems.

On the other hand, adaptive filter techniques constitute an important part of detection and signal processing in CDMA/MIMO systems. Particularly, as an optimum linear filter for a stationary environment, Wiener filter provides a framework and reference for the other linear adaptive filters. As well, adaptive Least-mean-square (LMS) filters are based upon a transversal structure with simpler design and highly effective in performance, which has made it greatly popular in various applications.

Overall, in order to develop promising detection techniques, not only performance but also computational complexity needs to be considered. To make detection algorithms employing for CDMA/MIMO systems more effective, simpler computations, better BER performance, and the tracking of fading channels are desired. As stated in previous section, a great number of detection algorithms for CDMA/MIMO systems in Rayleigh fading channels have been developed in recent years. Most of them can acquire better BER performance gains. However, the performance improvement of most detection techniques such as MLD can be achieved at the cost of an increase of computational complexity. Therefore, in this thesis, we will focus on to develop a reduced complexity detection algorithm with reasonable performance and tracking function based on LMS adaptive filtering for CDMA/MIMO systems with permutation spreading in slowly varying Rayleigh fading channels.

1.3 Thesis Contributions

This thesis provides the following contributions to the field of wireless CDMA/MIMO systems in Rayleigh fading channels with, including:

The primary contribution is that applying adaptive filters techniques to produce decision variables for CDMA/MIMO systems employing permutation spreading. Compared to MLD, the proposed LMS tracking solution is a reduced complexity detection technique especially for CDMA/MIMO systems since it does not need channel estimation and channel transform matrix while simpler linear computations are involved.

Meanwhile, the comparison of BER simulation of 27 different application models related to 4 different detection algorithms, 3 different Rayleigh fading channels, 3 different LMS weight step-size parameters, and 4 different number of receive antennas for CDMA/MIMO systems in slowly varying Rayleigh fading channels can provides the users with very valuable references on BER performance comparison of the four detection solutions in different Rayleigh fading environments.

Also, the analysis of computational complexity of three detection techniques (MLD, Wiener filters, LMS tracking) can provide the users with useful reference in the future research.

1.4 Thesis Organization

The thesis is organized as follows:

Chapter 2 starts with a literature survey on various detection techniques for CDMA/MIMO systems in fading Channels. In this chapter, several typical detection algorithms are analyzed and discussed with respect to the key techniques and computational complexity.

In Chapter 3, we design and analyze a detection algorithm using Wiener filters with permutation spreading technique for CDMA/MIMO systems in slow Rayleigh fading channels, including its algorithm implementation, weight calculation, along with its complexity.

In Chapter 4, in order to reduce computational complexly and ease of implementation without sacrificing BER performance, a reduced complexity detection algorithm employing adaptive LMS filters for CDMA/MIMO systems with permutation spreading technique in slowly varying Rayleigh fading channels, is proposed, including its algorithm, weight iteration, tracking technique, and other related details.

In chapter 5, we examine the BER simulation performance of 4 different detection algorithms (Wiener algorithm, MLD, conventional approach, and the proposed LMS tracking algorithm), which are related to 27 different application models. Also, we compare the complexity of 3 different detection algorithms (Wiener algorithm, MLD, and the proposed LMS tracking algorithm). Related results are also presented.

Chapter 6 concludes the thesis and discusses future research directions.

Chapter 2 Literature Review on Detection Techniques for CDMA/MIMO Systems

With the striking development of wireless communications, the very rapid pace of improvements in detection and signal processing applications had led to the justifiable view of advanced detection and signal processing as a key, which can aggressively enhance systems reliability and escalate capacity demands in emerging wireless systems. Accordingly, more and more researchers have put a very widespread effort to develop various novel detection techniques and signal processing algorithms that can fulfill this promise. Next, a brief literature survey on a variety of detections techniques for CDMA/MIMO systems will be presented in the following.

2.1 MLD for CDMA/MIMO Systems with Permutation Spreading in Frequency Nonselective Rayleigh Fading Channels

Recently a lot of attention has been paid to MLD algorithms and CDMA/MIMO systems. In this section a detailed look is taken at the solution employing maximum likelihood detection (MLD) with permutation spreading for CDMA/MIMO systems in frequency nonselective Rayleigh fading channels [17]. The MIMO channel model will be introduced first. And then the typical model of CDMA/MIMO transmitter and receiver will be shown in Figure 2.1.

2.1.1 MIMO Channel Model

A typical MIMO channel model can be defined below. In MIMO wireless systems with N_t transmit antennas and N_r receive antennas, the signals collected at the receiver are related to the signals outgoing from the transmitter through the following relation:

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n} \tag{2.1}$$

where $\boldsymbol{y}$ is the $N_r \times 1$ signal vector at the receiver array, $\mathbf{x}$ is the $N_t \times 1$ signal vector at the transmit antenna array, $\boldsymbol{n}$ is the $N_r \times 1$ complex additive white Gaussian noise (AWGN) vector and **H** is the $N_t \times N_r$ channel transfer matrix.

2.1.2 Typical CDMA/MIMO Transmitter and Receiver Network Architecture

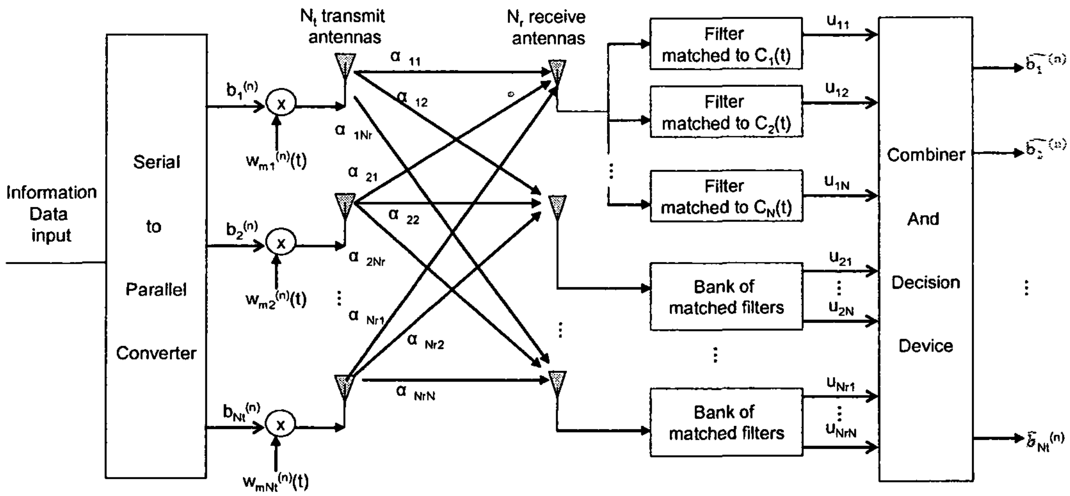

Figure 2.1 Typical CDMA/MIMO transmitter and receiver

In Figure 2.1, several major parameters are specified below:

- $\mathbf{b}^{(n)} = [b_1^{(n)}, b_2^{(n)}, b_3^{(n)}, \ldots, b_{Nt}^{(n)}] = 2*\mathrm{m}^{(n)} - 1$; where $\mathbf{m}^{(n)} = [m_1^{(n)}, m_2^{(n)}, m_3^{(n)}, \ldots, m_{Nt}^{(n)}]$ is the transmitted message on signaling interval n, $m_k^{(n)} = 0$ or 1 with equal probability and independence of each other;
- α_{ij} is the complex channel gain on the link between transmit antenna i and receive antenna j;
- $w_{mi}^{(n)}(\mathrm{t})$ is the spreading waveform used to spread the data transmitted by antenna i on the interval n;
- $c_i^{(n)}(t)$ is a set of mutually orthogonal spreading waveforms;
- U_{ij} denotes the ith matched filter output on the jth receive antenna;
- N_t is the number of transmit antenna and N_r is the # of receive antenna;
- $\hat{b}^{(n)}$ denotes the receive estimate of message $\mathbf{b}^{(n)}$;

The typical transmit and receive model for MIMO-CDMA systems with permutation spreading is shown in Figure 2.1. After being grouped and mapped/modulated, the input message bits with bit rate R_b, become input symbols and then are converted into parallel data streams through a serial to parallel converter. The input information ($b_1^{(n)}$, $b_2^{(n)}$, $b_3^{(n)}$, ... , $b_{Nt}^{(n)}$) is multiplied by the spreading waveforms ($w_{mi}^{(n)}(t)$) before accessing the transmit antennas. That is, different orthogonal spreading sequences ($w_{m1}^{(n)}(t)$ - $w_{mNt}^{(n)}(t)$) will be assigned to different transmitters at a given time interval n. The ith data stream of user m is conveyed by spreading waveform $w_{mi}(t)$, which is an antipodal signal and is selected from a set of mutually orthogonal spreading waveforms $\{w_{m1}(t), w_{m2}(t), \ldots, w_{mNt}(t)\}$. Secondly, at the transmitter, on signaling interval n, the message is transmitted through using Binary Phase Shift Keying (BPSK) or antipodal modulation, so we have $\mathbf{b}^{(n)} = [b_1^{(n)}, b_2^{(n)}, \ldots, b_{Nt}^{(n)}] = 2\mathbf{m}^{(n)}-1$. Also, at the receiver, the output of each receive antenna is related to different spreading waveforms. The data on different antennas are spread by a unique permutation of spreading waveform. After passing through transmit diversity and wireless channels, the related decision variables (U_{ij}) at the receiver will be generated. Finally, the receive estimate ($\hat{b}^{(n)}$) will be acquired by using the corresponding MLD rules.

2.1.3 Permutation Spreading Scheme

In [17], the MLD detection solution is employed for CDMA/MIMO systems with permutation spreading (PS) technique. Let's take 4 transmit antennas and 1 through 4 receive antennas as an example. In the system, each permutation employs 4 of the N spreading waveforms and each permutation has one or two in common. Meanwhile, each spreading waveform can be used only once by arbitrary given antenna i in different permutations. In other words, when a spreading waveform is used by antenna j in certain permutation, it cannot be applied by antenna j in any other permutation. In fact, the design scheme of the different spreading permutations is based on t-designs [18]. Let M be the sets of all possible message vectors, M_1 be a subset of M which is closed under modulo-2 addition, and let M_2, M_3, ..., M_8 be the cosets of M_1. Also, let $w_i^{(n)}(t)$ be the spreading waveform used to convey the data streams transmitted by antenna i on the time interval n. For more details of permutation spreading technique, see [17]. In this thesis, we will directly use the spreading permutations for CDMA/MIMO systems with 4 transmitters given in Table 2.1 [17].

Table 2.1 Spreading permutations for CDMA/MIMO system with 4 transmit antennas

Coset	Message Vectors	$w_{m1}^{(n)}(t)$	$w_{m2}^{(n)}(t)$	$w_{m3}^{(n)}(t)$	$w_{m4}^{(n)}(t)$
M_1	0000,1111	$C_1(t-nT)$	$C_3(t-nT)$	$C_5(t-nT)$	$C_7(t-nT)$
M_2	0001, 1110	$C_8(t-nT)$	$C_1(t-nT)$	$C_4(t-nT)$	$C_5(t-nT)$
M_3	0010, 1101	$C_2(t-nT)$	$C_4(t-nT)$	$C_3(t-nT)$	$C_8(t-nT)$
M_4	0011, 1100	$C_5(t-nT)$	$C_2(t-nT)$	$C_6(t-nT)$	$C_3(t-nT)$
M_5	0100, 1011	$C_6(t-nT)$	$C_7(t-nT)$	$C_1(t-nT)$	$C_4(t-nT)$
M_6	0101, 1010	$C_3(t-nT)$	$C_6(t-nT)$	$C_8(t-nT)$	$C_1(t-nT)$
M_7	0110, 1001	$C_7(t-nT)$	$C_8(t-nT)$	$C_2(t-nT)$	$C_6(t-nT)$
M_8	0111, 1000	$C_4(t-nT)$	$C_5(t-nT)$	$C_7(t-nT)$	$C_2(t-nT)$

The advantage to applying permutation spreading is mainly that the different spreading patterns can not only generate dependence between the parallel data systems but also keep orthogonal between the streams.

2.1.4 The Decision Variables

The decision variables of MLD solution [17] are expressed below:

$$U_{jk}^{(n)} = \begin{cases} ATb_i^{(n)}\alpha_{ij}^{(n)} + n_{jk}^{(n)}, & \text{if } C_{mk}(t-nT) \text{ is used} \\ n_{jk}^{(n)}, & \text{if } C_{mk}(t-nT) \text{ is not used} \end{cases} \quad (2.2)$$

where A is the carrier amplitude, $\alpha_{ij}^{(n)}$ is the complex channel gain on the link between transmit antenna i and receive antenna j over the time interval n, $n_{jk}^{(n)}$ is the response of the jth receive antenna's kth matched filter to the input noise. $C_{mk}(t-nT)$ is a set of mutually orthogonal spreading waveforms. More details can be found in [17].

2.1.5 MLD Detection Rules

The maximum likelihood detection rule [17] is:

$$\hat{b}^{(n)} = \min_{b\in B}(\sum_{i=1}^{N_t}\left|\mathbf{u}_i - b_i^{(n)}\boldsymbol{h}_i^{(n)}\right|^2 + \|\bar{u}\|^2)$$

(2.3)

where $\hat{b}^{(n)}$ denotes the receive estimate of message $\mathbf{b}^{(n)}$, **u** is viewed as the vector consisted of decision variables corresponding to the spreading waveform used by vector **b**, $\bar{u}$ is made up of all of the rest of decision variables not in u. To take 4 receivers as an example, $\boldsymbol{u}_i = [u_{i1}, u_{i2}, u_{i3}, u_{i4}]$, $\bar{u}$ is the vector including all of the decision variables not in $\mathbf{u}_1$, $\mathbf{u}_2$, $\mathbf{u}_3$ and $\mathbf{u}_4$, and $\mathbf{h}_i^{(n)}$ is the *i*th row vector of $\mathbf{H}^{(n)}$, which is $N_t \times N_r$ channel matrix on the *n*th signaling interval [17].

$$\mathbf{H}^{(n)} = \begin{bmatrix} \alpha_{11}^{(n)} & \alpha_{12}^{(n)} & \cdots & \alpha_{1N_r}^{(n)} \\ \vdots & & \ddots & \vdots \\ \alpha_{N_t1}^{(n)} & \alpha_{N_t2}^{(n)} & \cdots & \alpha_{N_tN_r}^{(n)} \end{bmatrix} \quad (2.4)$$

where α_{ij} is the complex channel gain on the link between transmit antennas i and receive antenna j.

The maximum likely detection rule is used to estimate $b_k^{(n)}$. That is, the receive information estimate $\hat{b}^{(n)}$ can be obtained by using maximum likely detection at the receiver.

2.1.6 The Simulation Results of MLD for CDMA/MIMO with Permutation Spreading

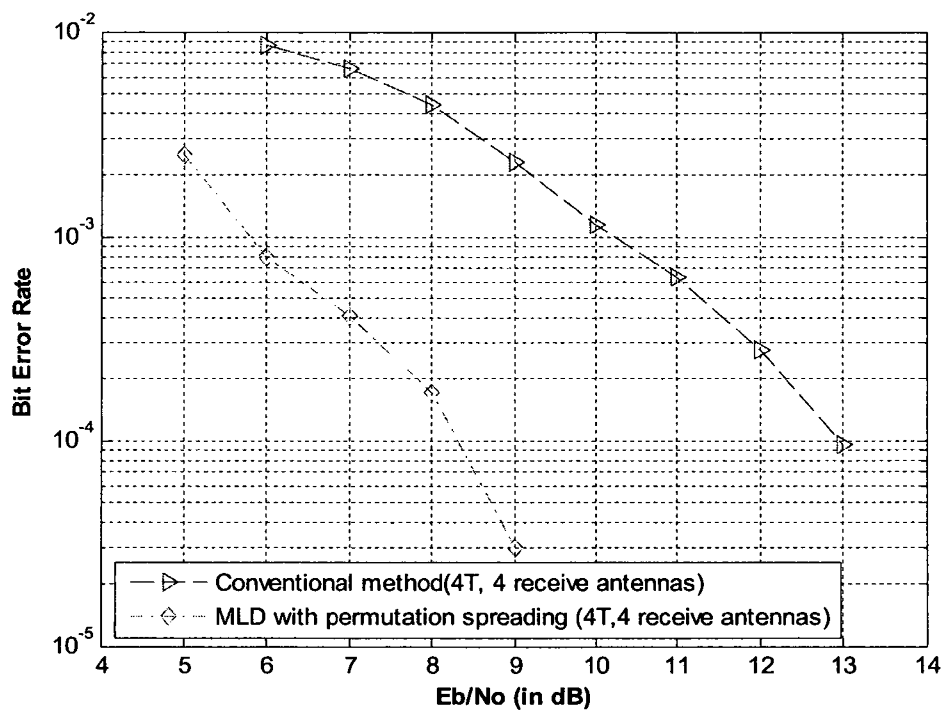

Figure 2.2 BER of MLD/Conventional method for CDMA/MIMO Systems with N_t=4 and N_r=4.

Figure 2.2 shows the BER simulation results of conventional method and MLD with permutation spreading for CDMA/MIMO with 4 transmit antennas and 4 receive antennas. At a BER of 10^{-3}, the MLD detection for CDMA/MIMO with permutation spreading can acquire about 4.5 dB gain improvement over conventional method. Clearly, the MLD with permutation spreading technique can achieve outstanding BER performance improvement over conventional approach.

2.1.7 Comment on the MLD Detection for CDMA/MIMO Systems with Permutation Spreading

As shown in Figure 2.1, the combination of CDMA and MIMO systems can achieve spatial multiplexing and larger capacity gains. With the permutation spreading, additional diversity can be obtained. Also, the MLD detection algorithm for CDMA/MIMO systems with permutation spreading can markedly improve and facilitate the BER performance. In other words, its BER performance is dominated over many detection algorithms for CDMA/MIMO systems. On the other hand, however, this technique has higher computational complexity compared to the conventional method. It will be more and more complicated with the number increase of receive antennas.

2.2 Multiuser Detection for CDMA/MIMO Systems in Slow Fading Channels

In fading channels, two typical statistical modeling are: frequency nonselective and frequency selective fading channels. A considerable amount of recent research has addressed the problem of data detection in slow/flat Rayleigh fading channels. Specially, various MLD techniques [19, 20, and 21] in slowly varying fading channels have been developed. However most of them can acquire desired performance at the cost of pretty high complexity.

2.3 Blind Multiuser Detection for CDMA/MIMO Systems

There are two primary approaches to blind multiuser detection: the direct matrix inversion (DMI) method and the subspace approach. 3 main blind multiuser detections based on direct methods are: LMS [22], Recursive Least-squares (RLS) [22], and QR-RLS algorithm [22 –25]. 3 typical subspace tracking algorithms could be: PASTd algorithm, NAHJ subspace tracking algorithm, and QR-Jacobi methods [26 -32]. Although most of them can achieve promising performance, they involve lots of complicated computations.

2.4 Group-Blind Multiuser Detection for CDMA systems

There are several main group-blind multiuser detections: Linear and nonlinear group-blind multiuser detection for synchronous CDMA, Group-Blind Multiuser Detection for uplink CDMA systems, and Group-blind multiuser detection in multipath channels. In [33], although the group-blind linear multiuser detection techniques offer substantial performance gains over the blind linear multiuser detection methods in a CDMA uplink, it generates higher complexity.

2.5 Robust Multiuser Detection for CDMA systems

In this detection, there are two typical robust regression techniques. One is Least-squares regression and linear decorrelator. The other is robust multiuser detection via M-regression. In

[34], although the proposed robust blind multiuser detection approach has a comparable computational complexity over the traditional blind multiuser detection algorithms, its higher computational complexity is stilled involved.

2.6 Space-time Multiuser Detection for CDMA systems

In wireless systems, various space-time multiuser detection techniques have been widely focused. For example, based on sufficient statistic, the optimal space-time detection adopts maximum-likelihood multiuser sequence detection, which has been used in many cases [19, 20, 21, 35, and 36]. As we investigate, most of space-time multiuser detections for CDMA/MIMO systems are not very efficient due to their high complexity.

2.7 Turbo Multiuser Detection for CDMA Systems

Recently, many multiuser detection schemes have been derived from Turbo technique. In [37], Turbo multiuser detection with unknown interferers is depicted. Also, Turbo multiuser receiver can be used for Turbo-coded CDMA in multipath fading channels [38]. Besides, typical examples of space-time turbo multiuser detection for coded MC-CDMA can be found in [39, 40]. Nevertheless, most of them are lack of efficiency due to involving huge computations.

2.8 CDMA-SIC Multiuser Detection for CDMA/MIMO Systems

In [41], the CDMA-SIC (successive interference canceling) multiuser detection is proposed for CDMA systems employing the iterative nulling and canceling approach. The detection technique seems to be useful because it can be extended to MIMO systems if the input of the MIMO systems is seen as virtual users. However, its complexity is pretty high.

2.9 Joint Antenna Multiuser Detection for MIMO Systems

In [42], a joint antenna multiuser detection using the Krylov subspace method for MIMO systems in time varying channels is proposed. In the detection, the LMMSE filters, the Krylov subspace algorithm, and the inverse operation are involved at each of iteration. In other words, the joint antenna multiuser detection for MIMO systems has still expensive complexity.

2.10 Soft Detection for MIMO Systems

Recently, the optimum soft-input soft-output detector for MIMO wireless systems has been researched. In [43], a suboptimal soft detection schemes still has no outstanding improvement in reducing complexity since its computational complexity is exponential in the number of bits transmitted simultaneously on each of symbol interval.

2.11 Chapter Summary

In this chapter, we systematically reviewed related literature on various detection techniques for CDMA/MIMO systems in fading Channels: MLD detection techniques with permutation spreading, blind multiuser detection, group-blind multiuser detection, robust multiuser detection, space-time multiuser detection, Turbo multiuser detection, as well as soft multiuser detection, etc. It is easy to see that most of the detection algorithms discussed in this chapter can achieve promising performance. However, the improvement of performance is achieved at the expense of an increase in computational complexity. Therefore, in the following two chapters, we will explore a low complexity detection algorithm for CDMA/MIMO systems with permutation spreading technique in slow varying Rayleigh fading channels.

Chapter 3 A Novel Detection Algorithm Employing Wiener Filters for CDMA/MIMO Systems Using Permutation Spreading in Slowly Varying Rayleigh Fading Channels

As we will notice, in general, Wiener filter can be used as an important framework and reference for other adaptive filters, such as traditional LMS filters in a stationary and wide-sense stationary (WSS) environment. Accordingly, in this thesis, the proposed LMS filters weight vectors can converge to the Wiener filter solution in slowly varying Rayleigh fading channels.

To determine the training/pilot sequence bound of LMS tracking detection, we need to take advantage of the important feature of Wiener filter along with some particular adjustments for employing in frequency non-selective Rayleigh fading channels environment. Besides, we also need to compare the computational complexity between derived Wiener algorithm described in this Chapter and proposed LMS tracking solution, which will be deliberated in Chapter 4. So this chapter will focus on a novel Wiener filter detection algorithm with permutation spreading technique for CDMA/MIMO systems in slow Rayleigh fading channels.

3.1 Network Architecture of the Detection Algorithm Employing Wiener Filters for CDMA/MIMO Systems Using Permutation Spreading

Derived from MLD with permutation spreading solution, the Wiener filter with permutation spreading solution is an improved detection technique. The proposed 4 networking models using for CDMA/MIMO systems with 1 to 4 receive antennas are shown in Figure 3.1 and Figure 3.2, respectively. As we will see below, the new Wiener filter solution with permutation spreading will bring about several different adjustments, which can be employed in slowly varying Rayleigh fading channels.

- 1 receiver

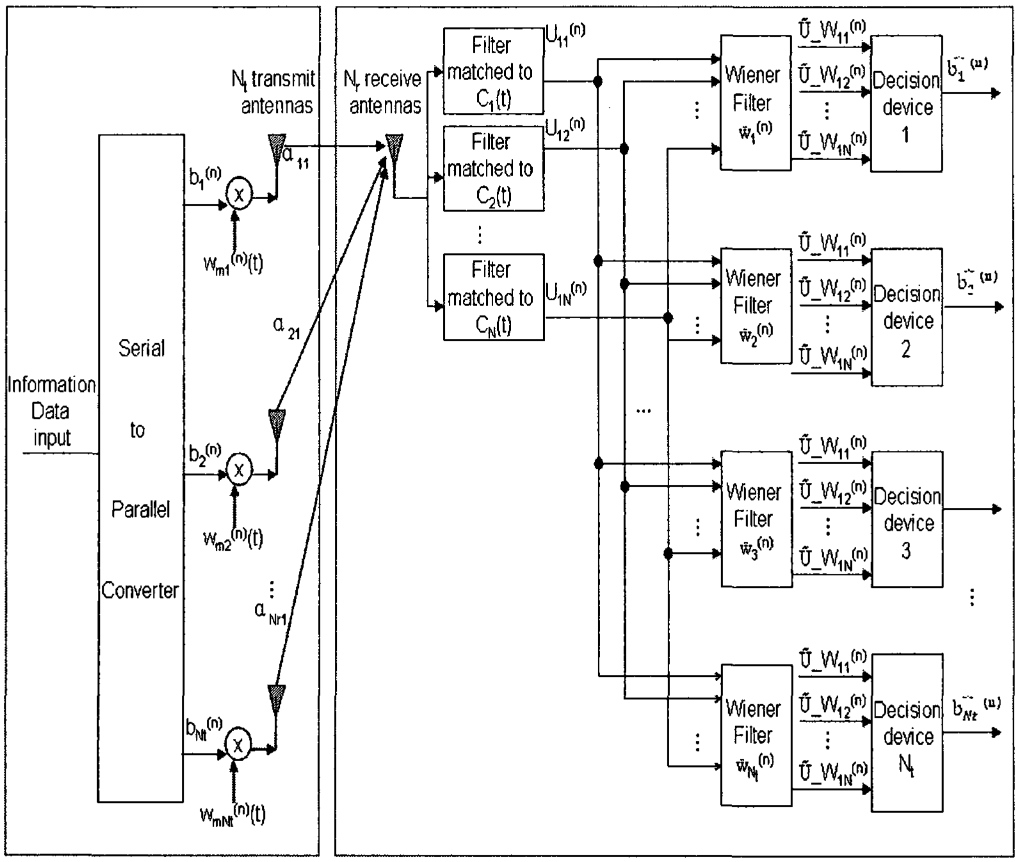

Figure 3.1 A Networking Model Employing Wiener Filters of CDMA/MIMO with Permutation Spreading in Slowly Varying Rayleigh Fading Channels (N_t = 4, N_r =1, and N=8)

In Figure 3.1 and Figure 3.2, several major parameters are notes below:

- $\mathbf{b}^{(n)} = [b_1^{(n)}, b_2^{(n)}, b_3^{(n)}, \ldots, b_{Nt}^{(n)}] = 2*\mathrm{m}^{(n)} - 1$; where $\mathbf{m}^{(n)} = [m_1^{(n)}, m_2^{(n)}, m_3^{(n)}, \ldots, m_{Nt}^{(n)}]$ is the transmitted message on signaling interval n, $m_k^{(n)} = 0$ or 1 with equal probability and keeping independent each other;
- α_{ij} is the complex channel gain on the link between transmit antenna i and receive antenna j;
- $w_{mi}^{(n)}(\mathrm{t})$ is the spreading waveform used to spread the data transmitted by antenna i on the interval n;

- $c_i^{(n)}(t)$ is a set of mutually orthogonal spreading waveforms;
- $\ddot{\mathbf{w}}_{ij}(n)$ is the Wiener filter weight coefficients;
- U_{ij} (U_W_{ij}) is initial decision variable, and $\tilde{U}\_W_{ij}$ is the final decision variable;
- N_t is the number of transmit antenna and N_r is the # of receive antenna;

➢ 2, 3, or 4-receiver case

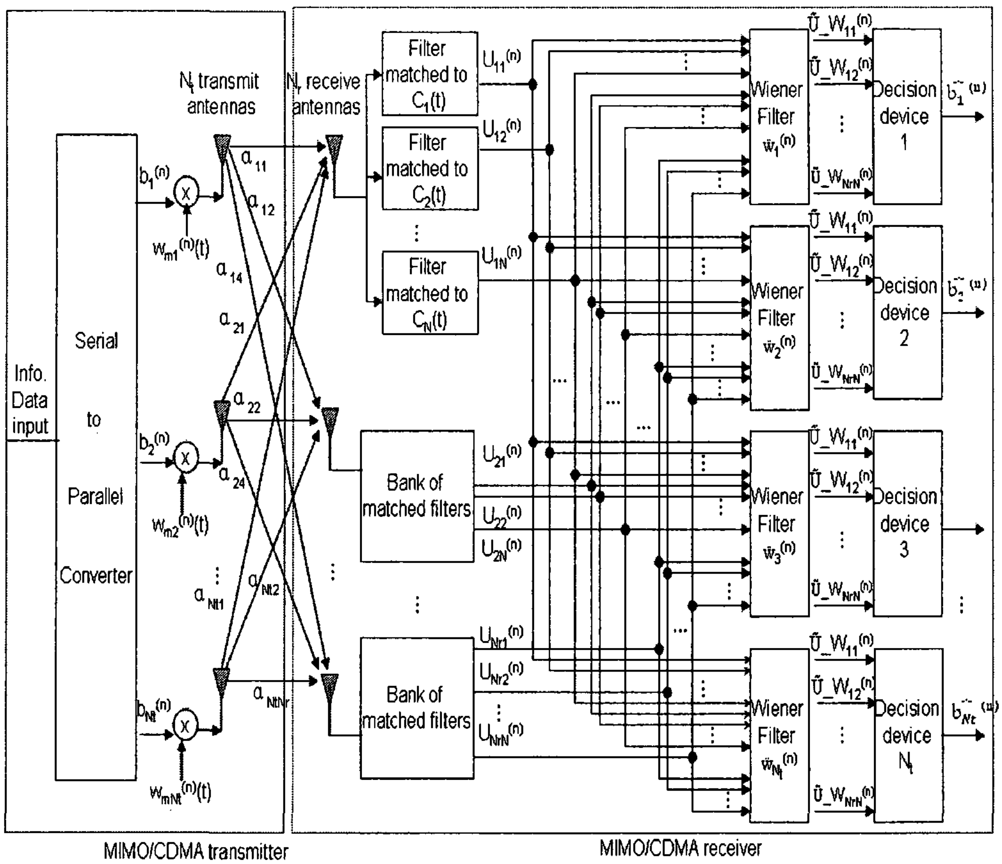

Figure 3.2 A Networking Model Employing Wiener Filters of CDMA/MIMO with Permutation Spreading in Slowly Varying Rayleigh Fading Channels (N_t = 4, N_r =2 to 4, and N=8*N_r)

3.2 Summary of the Detection Algorithm Using Wiener Filters for CDMA/MIMO Systems with Permutation Spreading

The main steps of Wiener filter algorithm using for CDMA/MIMO systems with permutation spreading in slow varying fading channels is described below:

Table 3.1 Summary of Wiener filter algorithm with PS for CDMA/MIMO systems

- Determine permutation spreading scheme used;
- Generate slowing varying complex channel gains;
- Generate complex noise variables;
- Calculate initial decision variables;
- Find out correlation matrix of decision variables;
- Find out cross-matrix of decision variables and desire response;
- Compute the dynamic Wiener weight coefficients;
- Update the final decision variables;
- Apply new Wiener detection rules

Next, we will introduce these basic steps in the following sections.

3.3 Spreading Permutation Scheme

The spreading permutation scheme of Wiener filter algorithm is the same as that of MLD detection algorithm (see Table 2.1) using for CDMA/MIMO systems with 1 to 4 transmit antennas in slowing varying Rayleigh fading channels.

3.4 Rayleigh Channel Gain Variables

In the Wiener filter detection algorithm, the channel gains (α_{ij}) will be slowing varying circularly complex Gaussian random variables.

For each iteration, the dynamic complex channel gains consist of 4*Nr slowing varying channel gain sub vectors. For instance, in CDMA/MIMO systems with 1 receive antenna, there are 4 slowing varying channel gain sub vectors each of time-varying iteration. For more details about how to generate Rayleigh channel gain variables, please see Section 4.6.

3.5 Noise Variables

In the new slow time-varying CDMA/MIMO systems, the noise variables are white complex random variables.

3.6 The Initial Decision Variables

For the Wiener filter detection model, the initial decision variables (U_W_{jk}) before inputting Wiener filters are formulated below:

$$U\_W_{jk} = \begin{cases} ATb_i^{(n)}\alpha_{ij}^{(n)} + n_{jk}^{(n)}, & \text{if } C_{mk}(t-nT) \text{ is used} \\ n_{jk}^{(n)}, & if \text{ if } C_{mk}(t-nT) \text{ is not used} \end{cases} \tag{3.1}$$

where A is the carrier amplitude, $\alpha_{ij}^{(n)}$ is the complex channel gain on the link between transit antenna i and receive antenna j over the time interval n, $n_{jk}^{(n)}$ is the response of the jth receive antenna's kth matched filter to the input noise. $C_{mk}(t-nT)$ is a set of mutually orthogonal spreading waveforms.

Accordingly, we obtain:

- 1 receiver case

  $\mathbf{U}_i = [U_{i1}, U_{i2}, U_{i3}, \ldots, U_{iN}]^T$ (where N =8): (3.2)

  For coset M_1, b_1=b_2=b_3=b_4, which is related to 0000/1111;

  For coset M_2, b_1=b_2=b_3=-b_4 (related to 0001/1110);

  Similarly, for coset M_3, b_1=b_2=-b_3=b_4 (related to 0010/1101), and so forth.

So, all of the initial decision variables related to 1 receiver with permutation spreading are listed in Table 3.2.

Table 3.2 The initial decision variables related to 1 receive antenna

Ui	U_{ij}	Decision variables	*Ui*	U_{ij}	Decision variables	*Ui*	U_{ij}	Decision variables	*Ui*	U_{ij}	Decision variables
U_1	U_{11}	$b_1*a_{11}+n_{11}$	U_2	U_{21}	$b_2*a_{21}+n_{11}$	U_3	U_{31}	n_{11}	U_4	U_{41}	n_{11}
	U_{12}	n_{21}		U_{22}	n_{21}		U_{32}	$b_1*a_{11}+n_{21}$		U_{42}	$b_2*a_{21}+n_{21}$
	U_{13}	$b_2*a_{21}+n_{31}$		U_{23}	n_{31}		U_{33}	$b_3*a_{31}+n_{31}$		U_{43}	$b_4*a_{41}+n_{31}$
	U_{14}	n_{41}		U_{24}	$b_3*a_{31}+n_{41}$		U_{34}	$b_2*a_{21}+n_{41}$		U_{44}	n_{41}
	U_{15}	$b_3*a_{31}+n_{51}$		U_{25}	$b_4*a_{41}+n_{51}$		U_{35}	n_{51}		U_{45}	$b_1*a_{11}+n_{51}$
	U_{16}	n_{61}		U_{26}	n_{61}		U_{36}	n_{61}		U_{46}	$b_3*a_{31}+n_{61}$
	U_{17}	$b_4*a_{41}+n_{71}$		U_{27}	n_{71}		U_{37}	n_{71}		U_{47}	n_{71}
	U_{18}	n_{81}		U_{28}	$b_1*a_{11}+n_{81}$		U_{38}	$b_4*a_{41}+n_{81}$		U_{48}	n_{81}
U_5	U_{51}	$b_3*a_{31}+n_{11}$	U_6	U_{61}	$b_4*a_{41}+n_{11}$	U_7	U_{71}	n_{11}	U_8	U_{81}	n_{11}
	U_{52}	n_{21}		U_{62}	n_{21}		U_{72}	$b_3*a_{31}+n_{21}$		U_{82}	$b_4*a_{41}+n_{21}$
	U_{53}	n_{31}		U_{63}	$b_1*a_{11}+n_{31}$		U_{73}	n_{31}		U_{83}	n_{31}
	U_{54}	$b_4*a_{41}+n_{41}$		U_{64}	n_{41}		U_{74}	n_{41}		U_{84}	$b_1*a_{11}+n_{41}$
	U_{55}	n_{51}		U_{65}	n_{51}		U_{75}	n_{51}		U_{85}	$b_2*a_{21}+n_{51}$
	U_{56}	$b_1*a_{11}+n_{61}$		U_{66}	$b_2*a_{21}+n_{61}$		U_{76}	$b_4*a_{41}+n_{61}$		U_{86}	n_{61}
	U_{57}	$b_2*a_{21}+n_{71}$		U_{67}	n_{71}		U_{77}	$b_1*a_{11}+n_{71}$		U_{87}	$b_3*a_{31}+n_{71}$
	U_{58}	n_{81}		U_{68}	$b_3*a_{31}+n_{81}$		U_{78}	$b_2*a_{21}+n_{81}$		U_{88}	n_{81}

Note:

- U_1 related to Coset M_1 ($b_1=b_2=b_3=b_4$, 0000/ 1111);
- U_2 related to Coset M_2 ($b_1=b_2=b_3=-b_4$, 0001/ 1110);

- U_3 related to Coset M_3 (b_1=b_2=-b_3=b_4, 0010/ 1101);
- U_4 related to Coset M_4 (b_1=b_2=-b_3=-b_4, 0011/ 1100);
- U_5 related to Coset M_5 (b_1=-b_2=b_3=b_4, 0100/ 1011);
- U_6 related to Coset M_6 (b_1=-b_2=b_3=-b_4, 0101/ 1010);
- U_7 related to Coset M_7 (b_1=-b_2=-b_3=b_4, 0110/ 1001);
- U_8 related to Coset M_8 (b_1=-b_2=-b_3=-b_4, 0111/ 1000);

❖ 2-receiver case

$$\mathbf{U}_i = [U_{i1}, U_{i2}, U_{i3}, \ldots, U_{iN}]^T \quad \text{(where N =16)} \tag{3.3}$$

For coset M_1, b_1=b_2=b_3=b_4, which is related to 0000/1111;

Similarly, for coset M_2, b_1=b_2=b_3=-b_4 (related to 0001/1110), and so forth.

So, all of the initial decision variables related to 2 receivers with permutation spreading are listed in Table 3.3.

❖ 3-receiver case

$$\mathbf{U}_i = [U_{i1}, U_{i2}, U_{i3}, \ldots, U_{iN}]^T \quad \text{(where N =24)} \tag{3.4}$$

Similar to 1 or 2-receiver case, the initial decision variables related to 3 receive antennas can be obtained.

❖ 4-receiver case

$$\mathbf{U}_i = [U_{i1}, U_{i2}, U_{i3}, \ldots, U_{iN}]^T \quad \text{(where N =32)} \tag{3.5}$$

Similar to 1 or 2-receiver case, the initial decision variables related to 4 receive antennas can also be derived.

Table 3.3 The initial decision variables related to 2 receive antennas

Ui	U_{ij}	Decision variables	*Ui*	U_{ij}	Decision variables	*Ui*	U_{ij}	Decision variables	*Ui*	U_{ij}	Decision variables
U_1	$U_{1,01}$	$b_1*a_{11}+n_{011}$	U_2	$U_{2,01}$	$b_2*a_{21}+n_{011}$;	U_3	$U_{3,01}$	n_{011}	U_4	$U_{4,01}$	n_{011}
	$U_{1,02}$	n_{021}		$U_{2,02}$	n_{021}		$U_{3,02}$	$b_1*a_{11}+n_{021}$;		$U_{4,02}$	$b_2*a_{21}+n_{021}$
	$U_{1,03}$	$b_2*a_{21}+n_{031}$		$U_{2,03}$	n_{031}		$U_{3,03}$	$b_3*a_{31}+n_{031}$		$U_{4,03}$	$b_4*a_{41}+n_{031}$
	$U_{1,04}$	n_{041}		$U_{2,04}$	$b_3*a_{31}+n_{041}$		$U_{3,04}$	$b_2*a_{21}+n_{041}$		$U_{4,04}$	n_{041}
	$U_{1,05}$	$b_3*a_{31}+n_{051}$		$U_{2,05}$	$b_4*a_{41}+n_{051}$		$U_{3,05}$	n_{051}		$U_{4,05}$	$b_1*a_{11}+n_{051}$
	$U_{1,06}$	n_{061}		$U_{2,06}$	n_{061}		$U_{3,06}$	n_{061}		$U_{4,06}$	$b_3*a_{31}+n_{061}$
	$U_{1,07}$	$b_4*a_{41}+n_{071}$		$U_{2,07}$	n_{071}		$U_{3,07}$	n_{071}		$U_{4,07}$	n_{071}
	$U_{1,08}$	n_{081}		$U_{2,08}$	$b_1*a_{11}+n_{081}$		$U_{3,08}$	$b_4*a_{41}+n_{081}$		$U_{4,08}$	n_{081}
	$U_{1,09}$	$b_1*a_{12}+n_{091}$		$U_{2,09}$	$b_2*a_{22}+n_{091}$		$U_{3,09}$	n_{091}		$U_{4,09}$	n_{091}
	$U_{1,10}$	n_{101}		$U_{2,10}$	n_{101}		$U_{3,10}$	$b_1*a_{12}+n_{101}$		$U_{4,10}$	$b_2*a_{22}+n_{101}$
	$U_{1,11}$	$b_2*a_{22}+n_{111}$		$U_{2,11}$	n_{111}		$U_{3,11}$	$b_3*a_{32}+n_{111}$		$U_{4,11}$	$b_4*a_{42}+n_{111}$
	$U_{1,12}$	n_{121}		$U_{2,12}$	$b_3*a_{32}+n_{121}$		$U_{3,12}$	$b_2*a_{22}+n_{121}$		$U_{4,12}$	n_{121}
	$U_{1,13}$	$b_3*a_{32}+n_{131}$		$U_{2,13}$	$b_4*a_{42}+n_{131}$		$U_{3,13}$	n_{131}		$U_{4,13}$	$b_1*a_{12}+n_{131}$
	$U_{1,14}$	n_{141}		$U_{2,14}$	n_{141}		$U_{3,14}$	n_{141}		$U_{4,14}$	$b_3*a_{32}+n_{141}$
	$U_{1,15}$	$b_4*a_{42}+n_{151}$		$U_{2,15}$	n_{151}		$U_{3,15}$	n_{151}		$U_{4,15}$	n_{151}
	$U_{1,16}$	n_{161}		$U_{2,16}$	$b_1*a_{12}+n_{161}$		$U_{3,16}$	$b_4*a_{42}+n_{161}$		$U_{4,16}$	n_{161}
U_5	$U_{5,01}$	$b_3*a_{31}+n_{011}$	U_6	$U_{6,01}$	$b_4*a_{41}+n_{011}$	U_7	$U_{7,01}$	n_{011}	U_8	$U_{8,01}$	n_{011}
	$U_{5,02}$	n_{021}		$U_{6,02}$	n_{021}		$U_{7,02}$	$b_3*a_{31}+n_{021}$		$U_{8,02}$	$b_4*a_{41}+n_{021}$

Ui	U_{ij}	Decision variables	Ui	U_{ij}	Decision variables	Ui	U_{ij}	Decision variables	Ui	U_{ij}	Decision variables
	$U_{5,03}$	n_{031}		$U_{6,03}$	$b_1*a_{11}+n_{031}$		$U_{7,03}$	n_{031}		$U_{8,03}$	n_{031}
	$U_{5,04}$	$b_4*a_{41}+n_{041}$		$U_{6,04}$	n_{041}		$U_{7,04}$	n_{041}		$U_{8,04}$	$b_1*a_{11}+n_{041}$
	$U_{5,05}$	n_{051}		$U_{6,05}$	n_{051}		$U_{7,05}$	n_{051}		$U_{8,05}$	$b_2*a_{21}+n_{051}$
	$U_{5,06}$	$b_1*a_{11}+n_{061}$		$U_{6,06}$	$b_2*a_{21}+n_{061}$		$U_{7,06}$	$b_4*a_{41}+n_{061}$		$U_{8,06}$	n_{061}
	$U_{5,07}$	$b_2*a_{21}+n_{071}$		$U_{6,07}$	n_{071}		$U_{7,07}$	$b_1*a_{11}+n_{071}$		$U_{8,07}$	$b_3*a_{31}+n_{071}$
	$U_{5,08}$	n_{081}		$U_{6,08}$	$b_3*a_{31}+n_{081}$		$U_{7,08}$	$b_2*a_{21}+n_{081}$		$U_{8,08}$	n_{081}
	$U_{5,09}$	$b_3*a_{32}+n_{091}$		$U_{6,09}$	$b_4*a_{42}+n_{091}$		$U_{7,09}$	n_{091}		$U_{8,09}$	n_{091}
	$U_{5,10}$	n_{101}		$U_{6,10}$	n_{101}		$U_{7,10}$	$b_3*a_{32}+n_{101}$		$U_{8,10}$	$b_4*a_{42}+n_{101}$
	$U_{5,11}$	n_{111}		$U_{6,11}$	$b_1*a_{12}+n_{111}$		$U_{7,11}$	n_{111}		$U_{8,11}$	n_{111}
	$U_{5,12}$	$b_4*a_{42}+n_{121}$		$U_{6,12}$	n_{121}		$U_{7,12}$	n_{121}		$U_{8,12}$	$b_1*a_{12}+n_{121}$
	$U_{5,13}$	n_{131}		$U_{6,13}$	n_{131}		$U_{7,13}$	n_{131}		$U_{8,13}$	$b_2*a_{22}+n_{131}$
	$U_{5,14}$	$b_1*a_{12}+n_{141}$		$U_{6,14}$	$b_2*a_{22}+n_{141}$		$U_{7,14}$	$b_4*a_{42}+n_{141}$		$U_{8,14}$	n_{141}
	$U_{5,15}$	$b_2*a_{22}+n_{151}$		$U_{6,15}$	n_{151}		$U_{7,15}$	$b_1*a_{12}+n_{151}$		$U_{8,15}$	$b_3*a_{32}+n_{151}$
	$U_{5,16}$	n_{161}		$U_{6,16}$	$b_3*a_{32}+n_{161}$		$U_{7,16}$	$b_2*a_{22}+n_{161}$		$U_{8,16}$	n_{161}

3.7 Wiener Weight Coefficients

3.7.1 Correlation Matrix of Decision Variables

Step 1: Compute all of sub correlation matrix of decision variables related to different cosets M_i for different number of receive antenna cases;

$$\mathbf{R}_{\mathrm{M}j} = \mathrm{E}[U_j * U_j^H]; \text{ where } j = 1, 2, \ldots, 8; \quad (3.6)$$

Step 2: Compute final correlation matrix of decision variables for different number of receive antenna cases;

$$\mathbf{R} = \sum_{j=0}^{8} \frac{1}{8} * \boldsymbol{R}_{Mj} \tag{3.7}$$

Next we take 1 receiver and 2 receiver cases as 2 examples to deduce the algorithm. Accordingly, we deduce the following expressions:

- 1 receiver case

For 1 receiver case, the sub correlation matrix of decision variables related to coset M_j, $\mathbf{R1}_{Mj}$ can be expressed as:

$$\mathbf{R1}_{Mj} = E[U_j * U_j^H]; \text{ where } j = 1, 2, \ldots, 8; \tag{3.8}$$

So, for 1 receiver with coset M_1, related message vectors are 0000 or 1111, and the sub correlation matrix of decision variables related to coset M_1, $\mathbf{R1}_{M1}$ can be given below:

- $\mathbf{R1}_{M1} = E[U_1 * U_1^H] =$

$$\begin{bmatrix} |\alpha_{11}|^2+\sigma^2 & 0 & \alpha_{11}*\alpha_{21}^* & 0 & \alpha_{11}*\alpha_{31}^* & 0 & \alpha_{11}*\alpha_{41}^* & 0 \\ 0 & \sigma^2 & 0 & 0 & 0 & 0 & 0 & 0 \\ \alpha_{21}*\alpha_{11}^* & 0 & |\alpha_{21}|^2+\sigma^2 & 0 & \alpha_{21}*\alpha_{31}^* & 0 & \alpha_{21}*\alpha_{41}^* & 0 \\ 0 & 0 & 0 & \sigma^2 & 0 & 0 & 0 & 0 \\ \alpha_{31}*\alpha_{11}^* & 0 & \alpha_{31}*\alpha_{21}^* & 0 & |\alpha_{31}|^2+\sigma^2 & 0 & \alpha_{31}*\alpha_{41}^* & 0 \\ 0 & 0 & 0 & 0 & 0 & \sigma^2 & 0 & 0 \\ \alpha_{41}*\alpha_{11}^* & 0 & \alpha_{41}*\alpha_{21}^* & 0 & \alpha_{41}*\alpha_{31}^* & 0 & |\alpha_{41}|^2+\sigma^2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \sigma^2 \end{bmatrix} \tag{3.9}$$

where $\boldsymbol{\sigma}^2$ corresponds the variance of the noise sample values in 1 receiver case and α_{ij} $(i, j = 1, 2, 3, 4)$ are slowing varying complex random variables and $\mathbf{R1}_{M1}$ is a 8*8 matrix;

Similarly, for 1 receiver with coset M_2, related message vectors are 0001 or 1110, and the sub correlation matrix of decision variables related to coset M_2, $\mathbf{R1}_{M2}$ can be computed as below:

- $\mathbf{R1}_{M2} = E[U_2 * U_2^H] =$

$$\begin{bmatrix} |\alpha_{21}|^2+\sigma^2 & 0 & 0 & \alpha_{21}*\alpha_{31}^* & -\alpha_{21}*\alpha_{41}^* & 0 & 0 & \alpha_{21}*\alpha_{11}^* \\ 0 & \sigma^2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \sigma^2 & 0 & 0 & 0 & 0 & 0 \\ \alpha_{31}*\alpha_{21}^* & 0 & 0 & |\alpha_{31}|^2+\sigma^2 & -\alpha_{31}*\alpha_{41}^* & 0 & 0 & \alpha_{31}*\alpha_{11}^* \\ \alpha_{41}*\alpha_{21}^* & 0 & 0 & -\alpha_{41}*\alpha_{31}^* & |\alpha_{41}|^2+\sigma^2 & 0 & -\alpha_{41}*\alpha_{11}^* & 0 \\ 0 & 0 & 0 & 0 & 0 & \sigma^2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \sigma^2 & 0 \\ \alpha_{11}*\alpha_{21}^* & 0 & 0 & \alpha_{11}*\alpha_{31}^* & -\alpha_{11}*\alpha_{41}^* & 0 & 0 & |\alpha_{11}|^2+\sigma^2 \end{bmatrix} \quad (3.10)$$

where σ^2 corresponds the variance of the noise sample values in 1 receiver case;

Likewise, we can deduce the expressions of $\mathbf{R1}_{M3}$ through $\mathbf{R1}_{M8}$. Then we can figure out the following correlation matrix expression of decision variables used for 1 receiver.

Accordingly, the final correlation matrix of decision variables in 1 receiver case can be expressed as:

$$\mathbf{R1} = \sum_{j=0}^{8} \frac{1}{8} * \boldsymbol{R1}_{Mj} \quad (3.11)$$

$$\mathbf{R1} = \begin{bmatrix} R1_{11} & R1_{12} & R1_{13} & R1_{14} & R1_{15} & R1_{16} & R1_{17} & R1_{18} \\ R1_{12}^* & R1_{22} & R1_{23} & R1_{24} & R1_{25} & R1_{26} & R1_{27} & R1_{28} \\ R1_{13}^* & R1_{23}^* & R1_{33} & R1_{34} & R1_{35} & R1_{36} & R1_{37} & R1_{38} \\ R1_{14}^* & R1_{24}^* & R1_{34}^* & R1_{44} & R1_{45} & R1_{46} & R1_{47} & R1_{48} \\ R1_{15}^* & R1_{25}^* & R1_{35}^* & R1_{45}^* & R1_{55} & R1_{56} & R1_{57} & R1_{58} \\ R1_{R_{24}^*} & R1_{26}^* & R1_{36}^* & R1_{46}^* & R1_{56}^* & R1_{66} & R1_{67} & R1_{68} \\ R1_{17}^* & R1_{27}^* & R1_{37}^* & R1_{47}^* & R1_{57}^* & R1_{76}^* & R1_{77} & R1_{78} \\ R1_{18}^* & R1_{28}^* & R1_{38}^* & R1_{48}^* & R1_{58}^* & R1_{86}^* & R1_{87}^* & R1_{88} \end{bmatrix} \quad (3.12)$$

where * denotes complex conjugate and related sub vector mapping value of **R1** can be given in Table 3.4.

Table 3.4 Sub vector mapping value of correlation matrix R1

Sub vectors mapping value of **R1**	
$\mathbf{R1}_{11} = \mathbf{R1}_{22} = \mathbf{R1}_{33} = \ldots = \mathbf{R1}_{88} = \lvert\alpha_{11}\rvert^2 + \lvert\alpha_{21}\rvert^2 + \lvert\alpha_{31}\rvert^2 + \lvert\alpha_{41}\rvert^2 + 8var$	
$\mathbf{R1}_{12} = 0$	$\mathbf{R1}_{13} = \alpha_{11}*\alpha_{21}^* - \alpha_{41}*\alpha_{11}^*$
$\mathbf{R1}_{14} = \alpha_{21}*\alpha_{31}^* + \alpha_{31}*\alpha_{41}^*$	$\mathbf{R1}_{15} = \alpha_{11}*\alpha_{31}^* - \alpha_{21}*\alpha_{41}^*$
$\mathbf{R1}_{16} = \alpha_{31}*\alpha_{11}^* + \alpha_{41}*\alpha_{21}^*$	$\mathbf{R1}_{17} = \alpha_{11}*\alpha_{41}^* - \alpha_{31}*\alpha_{21}^*$
$\mathbf{R1}_{18} = \alpha_{21}*\alpha_{11}^* - \alpha_{41}*\alpha_{31}$	$\mathbf{R1}_{23} = -\alpha_{11}*\alpha_{31}^* - \alpha_{21}*\alpha_{41}^*$
$\mathbf{R1}_{24} = \alpha_{11}*\alpha_{21}^* - \alpha_{41}*\alpha_{11}^*$	$\mathbf{R1}_{25} = \alpha_{21}*\alpha_{11}^* + \alpha_{41}*\alpha_{21}^*$
$\mathbf{R1}_{26} = -\alpha_{21}*\alpha_{31}^* - \alpha_{31}*\alpha_{41}^*$	$\mathbf{R1}_{27} = -\alpha_{31}*\alpha_{11}^* + \alpha_{41}*\alpha_{31}^*$
$\mathbf{R1}_{28} = \alpha_{11}*\alpha_{41}^* + \alpha_{31}*\alpha_{21}^*$	$\mathbf{R1}_{34} = -\alpha_{31}*\alpha_{21}^*$
$\mathbf{R1}_{35} = \alpha_{21}*\alpha_{31}^* - \alpha_{41}*\alpha_{11}^*$	$\mathbf{R1}_{36} = \alpha_{41}*\alpha_{31}^* - \alpha_{11}*\alpha_{21}^*$
$\mathbf{R1}_{37} = \alpha_{21}*\alpha_{41}^*$	$\mathbf{R1}_{38} = -\alpha_{31}*\alpha_{41}^* + \alpha_{11}*\alpha_{31}^*$
$\mathbf{R1}_{45} = -\alpha_{31}*\alpha_{41}^* - \alpha_{11}*\alpha_{21}^*$	$\mathbf{R1}_{46} = \alpha_{41}*\alpha_{11}^*$;
$\mathbf{R1}_{47} = -\alpha_{41}*\alpha_{21}^* - \alpha_{11}*\alpha_{31}^*$	$\mathbf{R1}_{48} = \alpha_{31}*\alpha_{11}^* + \alpha_{21}*\alpha_{41}^*$
$\mathbf{R1}_{56} = -\alpha_{11}*\alpha_{31}^*$	$\mathbf{R1}_{57} = \alpha_{31}*\alpha_{41}^* + \alpha_{21}*\alpha_{31}^*$
$\mathbf{R1}_{58} = -\alpha_{41}*\alpha_{11}^*$	$\mathbf{R1}_{67} = -\alpha_{11}*\alpha_{21}^* - \alpha_{41}*\alpha_{11}^*$
$\mathbf{R1}_{68} = -\alpha_{21}*\alpha_{31}^* - \alpha_{41}*\alpha_{21}^*$	$\mathbf{R1}_{78} = -\alpha_{11}*\alpha_{21}^*$

❖ 2 receivers

Similarly, we can use similar method used in 1 receiver to compute the correlation matrix of initial decision variables in 2-receive case. That is, for 2-receiver case, the sub correlation matrix of decision variables related to coset M_j, $\mathbf{R2}_{\mathrm{Mj}}$ can be expressed as:

$$\mathbf{R2}_{\mathrm{Mj}} = \mathrm{E}[U_j * U_j^H]; \text{ where } j = 1, 2, \ldots, 8; \tag{3.13}$$

So, for 2-receiver case with coset M1, related message vectors are 0000 or 1111, and the sub correlation matrix of decision variables related to coset M_1, $\mathbf{R2}_{\mathrm{M1}}$ can be calculated as below:

$$\mathbf{R2}_{\mathrm{M1}} = \mathrm{E}[U_1 * U_1^H]; \text{ where it is a 16*16 matrix;} \tag{3.14}$$

Likewise, we can deduce the expressions of $\mathbf{R2}_{\mathrm{M2}}$ through $\mathbf{R2}_{\mathrm{M8}}$. Then we can figure out the following correlation matrix expression of decision variables used for 2 receivers.

Accordingly, the final correlation matrix of decision variables in 2-receiver case can be expressed as:

$$\mathbf{R2} = \sum_{j=0}^{8} \frac{1}{8} * \boldsymbol{R2}_{Mj} \tag{3.15}$$

- 3 receivers

$$\mathbf{R3}_{\mathrm{Mj}} = \mathrm{E}[U_j * U_j^H]; \tag{3.16}$$

where it is a 24*24 matrix and $j = 1, 2, 3, \ldots, 8$;

Similar to 1 or 2-receiver case, we can deduce the expressions of $\mathbf{R3}_{\mathrm{M1}}$ through $\mathbf{R3}_{\mathrm{M8}}$. Then we can figure out the following correlation matrix expression of decision variables used for 3 receivers:

Accordingly, the final correlation matrix of decision variables in 3-receiver case can be expressed as:

$$\mathbf{R3} = \sum_{j=0}^{8} \frac{1}{8} * \boldsymbol{R3}_{Mj} \tag{3.17}$$

- 4 receivers

$$\mathbf{R4}_{\mathrm{Mj}} = \mathrm{E}[U_j * U_j^H]; \tag{3.18}$$

where it is a 32*32 matrix and $j = 1, 2, 3, \ldots, 8$;

Likewise, we can deduce the expressions of $\mathbf{R4}_{\mathrm{M1}}$ through $\mathbf{R4}_{\mathrm{M8}}$. Then we can figure out the following correlation matrix expression of decision variables used for 4 receivers:

Accordingly, the final correlation matrix of decision variables in 4-receiver case can be expressed as:

$$\mathbf{R4} = \sum_{j=0}^{8} \frac{1}{8} * \boldsymbol{R4}_{Mj} \tag{3.19}$$

3.7.2 Correlation Matrix of Decision Variables and Desire Variables

$$\mathbf{Pb}_j = E[\mathbf{U}_j * d^*] = E[\mathbf{U}_j * b^*]; \tag{3.20}$$

Specifically,

$$\mathbf{Pb}_1 = \sum_{j=1}^{16} 1/16 * \mathbf{Pb}_{1j}; \tag{3.21}$$

$$\mathbf{Pb}_2 = \sum_{j=1}^{16} 1/16 * \mathbf{Pb}_{2j}; \tag{3.22}$$

$$\mathbf{Pb}_3 = \sum_{j=1}^{16} 1/16 * \mathbf{Pb}_{3j}; \tag{3.23}$$

$$\mathbf{Pb}_4 = \sum_{j=1}^{16} 1/16 * \mathbf{Pb}_{4j}; \tag{3.24}$$

Accordingly, we can compute the correlation matrix of decision variables and desire values for 1 through 4 receive antennas.

3.7.3 Wiener Filter Weight Coefficients

$$\mathbf{w}_0 = \mathbf{R}^{-1} * \mathbf{Pb}; \tag{3.25}$$

where:

- $\mathbf{R}^{-1}$ denotes the inverse matrix of correlation matrix **R**; For example, for 1 receiver case, it is $\mathbf{R1}^{-1}$, and for 2-receiver case, it is $\mathbf{R2}^{-1}$, and so forth;
- $\mathbf{w}_0$ is Wiener filter weight coefficients, which consists of 4 sub vectors: $\mathbf{w}_{01}$, $\mathbf{w}_{02}$, $\mathbf{w}_{03}$, and $\mathbf{w}_{04}$.

And the sub vectors can be computes as below:

$$\mathbf{w}_{01} = \mathbf{R}^{-1} * \mathbf{Pb}_1; \tag{3.26}$$

$$\mathbf{w}_{02} = \mathbf{R}^{-1} * \mathbf{Pb}_2; \tag{3.27}$$

$$\mathbf{w}_{03} = \mathbf{R}^{-1} * \mathbf{Pb}_3; \tag{3.28}$$

$$\mathbf{w}_{04} = \mathbf{R}^{-1} * \mathbf{Pb}_4; \tag{3.29}$$

3.8 Final Decision Variables

The final decision variables after passing through Wiener filters can be expressed in the following:

$$\tilde{U}\_W_{ij}(1,i) = (\mathbf{w}_{01})^H * \mathbf{U\_W}_{ij}; \quad (3.30)$$

$$\tilde{U}\_W_{ij}(2,i) = (\mathbf{w}_{02})^H * \mathbf{U\_W}_{ij}; \quad (3.31)$$

$$\tilde{U}\_W_{ij}(3,i) = (\mathbf{w}_{03})^H * \mathbf{U\_W}_{ij}; \quad (3.32)$$

$$\tilde{U}\_W_{ij}(4,i) = (\mathbf{w}_{04})^H * \mathbf{U\_W}_{ij}; \quad (3.33)$$

where:

- $\mathbf{U\_W}_{ji}$ is initial decision variable stated in Section 3.6;
- i is the iteration number;
- H denotes complex conjugate, and
- $\tilde{U}\_W_{ij}$ is final decision variables.
- $\mathbf{w}_{01}$, $\mathbf{w}_{02}$, $\mathbf{w}_{03}$, and $\mathbf{w}_{04}$ can be computed in Eq.3.26 – Eq.3.29.

Next, let's take **b**= [-1 -1 -1 -1] as an example to compute the final decision variables in 1 to 4 receiver antennas cases, respectively.

❖ 1 receiver case

$$\mathbf{U01}_{ij} = [U01_{(1,i)}, U01_{(2,i)}, U01_{(3,i)}, \ldots, U01_{(8,i)}]^T; \quad (3.34)$$

where:

- i is the iteration number;
- $\mathbf{U01}_{ij}$ denotes initial decision variables related to 1 receiver case;
- $U01_{(j,i)}$ is the jth sub variable of $\mathbf{U01}_{ij}$;
- T denotes the transpose of a matrix;

Accordingly, the final decision variables for 1 receiver case can be computed as follows:

$$U01\_new_{(1,i)} = (\mathbf{w}_{01})^H * \mathbf{U01}_{ij}; \quad (3.35)$$

$$U01\_new_{(2,i)} = (\mathbf{w}_{02})^H * \mathbf{U01}_{ij}; \quad (3.36)$$

$$U01\_new_{(3,i)} = (\mathbf{w}_{03})^H * \mathbf{U01}_{ij}; \quad (3.37)$$

$$U01\_new_{(4,i)} = (\mathbf{w}_{04})^H * \mathbf{U01}_{ij}; \quad (3.38)$$

where: i is the iteration number;

- $U01\_new_{(j,i)}$ is the jth sub variable of the final decision variable with j = 1, 2, 3, or 4, related to 1 receiver case;
- H denotes complex conjugate of a matrix;
- $\mathbf{w}_{01}$, $\mathbf{w}_{02}$, $\mathbf{w}_{03}$, and $\mathbf{w}_{04}$ can be obtained in Eq.3.26 – Eq.3.29.

❖ 2-receiver case

$$\mathbf{U02}_{ij}=[U02_{(1,q)}, U02_{(2,q)}, U02_{(3,q)}, \ldots, U02_{(16,q)}]^T; \tag{3.39}$$

where: q is the iteration number;

- T denotes the transpose of a matrix;
- $\mathbf{U02}_{ij}$ denotes initial decision variables related to 2-receiver case;
- $U02_{(j,i)}$ is the jth sub variable of $\mathbf{U02}_{ij}$;

Accordingly, the final decision variables for 2-receiver case can be derived as:

$$U02\_new_{(1,q)} = (\mathbf{w}_{01})^H * \mathbf{U02}_{ij}; \tag{3.40}$$

$$U02\_new_{(2,q)} = (\mathbf{w}_{02})^H * \mathbf{U02}_{ij}; \tag{3.41}$$

$$U02\_new_{(3,q)} = (\mathbf{w}_{03})^H * \mathbf{U02}_{ij}; \tag{3.42}$$

$$U02\_new_{(4,q)} = (\mathbf{w}_{04})^H * \mathbf{U02}_{ij}; \tag{3.43}$$

where: q is total iteration number;

- H denotes complex conjugate of a matrix;
- $U02\_new(j,i)$ is the jth sub variable of the final decision variable with j = 1, 2, 3, or 4, related to 2-receiver case;
- $\mathbf{w}_{01}$, $\mathbf{w}_{02}$, $\mathbf{w}_{03}$, and $\mathbf{w}_{04}$ can be obtained in Eq.3.26 – Eq.3.29.

❖ 3 or 4-receiver case

Similarly, we can deduce all of final decision variables corresponding to 3 or 4-receiver case, respectively.

3.9 Detection Rules of Wiener Filter Solution

$$\widetilde{b_1}^{(n)} = \mathrm{sgn}(\mathrm{real}(\tilde{U}\_W_{ij}(1,i))); \tag{3.44}$$

$$\widetilde{b_2}^{(n)} = \mathrm{sgn}(\mathrm{real}(\tilde{U}\_W_{ij}(2,i))); \tag{3.45}$$

$$\widetilde{b_3}^{(n)} = \mathrm{sgn}(\mathrm{real}(\tilde{U}\_W_{ij}(3,i))); \tag{3.46}$$

$$\widetilde{b_4}^{(n)} = \mathrm{sgn}(\mathrm{real}(\tilde{U}\_W_{ij}(4,i))); \tag{3.47}$$

where:

- $\widetilde{b_1}^{(n)}$, $\widetilde{b_2}^{(n)}$, $\widetilde{b_3}^{(n)}$, and $\widetilde{b_4}^{(n)}$ are the estimated receive bits;

- i is the loop number on the time interval n;
- $\tilde{U}\_W_{ij}(j,i)$ denotes the jth variable of final decision variables which can be calculated by Eq.3.30 to Eq.3.33.

Next, let us continue the previous example stated in Section 3.8 (**b** = [-1 -1 -1 -1]).

❖ 1 receiver case

$$\tilde{\mathbf{b}}_1^{(i)} = \text{sign}(\text{real}(U01\_new_{(1,i)})); \tag{3.48}$$

$$\tilde{\mathbf{b}}_2^{(i)} = \text{sign}(\text{real}(U01\_new_{(2,i)})); \tag{3.49}$$

$$\tilde{\mathbf{b}}_3^{(i)} = \text{sign}(\text{real}(U01\_new_{(3,i)})); \tag{3.50}$$

$$\tilde{\mathbf{b}}_4^{(i)} = \text{sign}(\text{real}(U01\_new_{(4,i)})); \tag{3.51}$$

where:

- $U01\_new_{(j,i)}$ denotes the jth sub variable of the final decision variable related to 1 receiver case, which can be computed from Eq.3.35 to Eq.3.38.
- i denotes the ith iteration;
- $\tilde{\mathbf{b}}_j^{(i)}$ with j = 1, 2, 3, or 4 is the jth estimated receive sub vector filtered by Wiener filters in 1 receiver case;

❖ 2-receiver case

$$\tilde{\mathbf{b}}_1^{(q)} = \text{sign}(\text{real}(U02\_new_{(1,q)})); \tag{3.52}$$

$$\tilde{\mathbf{b}}_2^{(q)} = \text{sign}(\text{real}(U02\_new_{(2,q)})); \tag{3.53}$$

$$\tilde{\mathbf{b}}_3^{(q)} = \text{sign}(\text{real}(U02\_new_{(3,q)})); \tag{3.54}$$

$$\tilde{\mathbf{b}}_4^{(q)} = \text{sign}(\text{real}(U02\_new_{(4,q)})); \tag{3.55}$$

where:

- $U02\_new_{(j,i)}$ denotes the jth sub vector of the final decision variable related to 2-receiver case, which can be computed from Eq.3.41 to Eq.3.44.
- q denotes the qth iteration;

- $\widetilde{b_j}^{(q)}$ with j = 1, 2, 3, or 4 are the jth estimated receive sub vectors filtered by Wiener filters in 2-receiver case;

And so forth to deduce the relate results in 3 or 4 receive antennas cases.

3.10 Integrated Analysis of Wiener Filter Solution

3.10.1 Computation Complexity Analysis of Wiener Filter Solution

Clearly, the computational complexity of Wiener filters detection scheme with permutation spreading technique for CDMA-MIMO systems with 1 receiver in slowing varying Rayleigh Fading Channels is not too bigger. However, as the number of receive antennas increase, the computational complexity of the Wiener filter solution will be very high because the correlation matrix of decision variables and cross-correlation vectors between the decision variables and desire response as well as their inversion need to be recomputed at each time slot no matter how complex the matrix structure might be.

3.10.2 BER Performance Analysis

On the whole, Wiener filter solution has better BER performance. And related contents will be stated in Chapter 5.

3.11 Chapter Summary

In chapter 3, we design and analyze the implementation of Wiener filters with permutation spreading technique for CDMA/MIMO systems in slow Rayleigh fading channels. Although the BER performance is promising, which will be shown in Chapter 5, the new Wiener filter algorithm with permutation spreading is still limited by its high complexity, because it involves huge complexity with matrix inversion operation each of iteration with the increase of multiple receiver (for the number of receive antennas > 1).

Chapter 4 Proposed Solution – a Reduced Complexity Detection Algorithm Employing LMS Filters for CDMA/MIMO Systems Using Permutation Spreading in Slowly Varying Rayleigh Fading Channels

In order to reduce computational complexity of detection algorithm used for CDMA/MIMO systems and to obtain fewer current sample errors, least mean squares algorithms draw our great attention. Specifically, the simplicity of LMS algorithm is neither requiring the measurement of the pertinent correlation and cross-matrix nor needing to compute matrix inversion. Also, as it will be seen, when the fading statistics are unknown, they are usually estimated from the data in a training-assisted mode or decision mode. Thus, with related adjustments, a low complexity detection algorithm employing adaptive LMS filters for CDMA/MIMO systems using permutation spreading in slowly varying Rayleigh fading channels will be proposed and represented in this Chapter.

4.1 Proposed LMS Tracking Detection Network Architecture

The proposed detection solution employing adaptive LMS filters and permutation spreading technique is an improved and reduced computational complexity detection algorithm. The proposed 4 network models corresponding 1 to 4 receive antennas are used for CDMA/MIMO systems in slowing varying Rayleigh fading channels and are shown in Figure 4.1, Figure 4.2, and Figure 4.3, respectively. As we will see, the new proposed LMS solution will bring about some important adjustments, which can dramatically reduce the computational complexity. Also, Least-Mean Square adaptive filters, which consist of $\hat{W}_{11}^*(n)$ through $\hat{W}_{NrN}^*(n)$, are employed at the receivers to greatly reduce the sample signal error probability. That is, it does not sacrifice too much BER performance due to the nature advantage of LMS adaptive filter tracking with permutation spreading technique.

➢ 1 receiver networking architecture

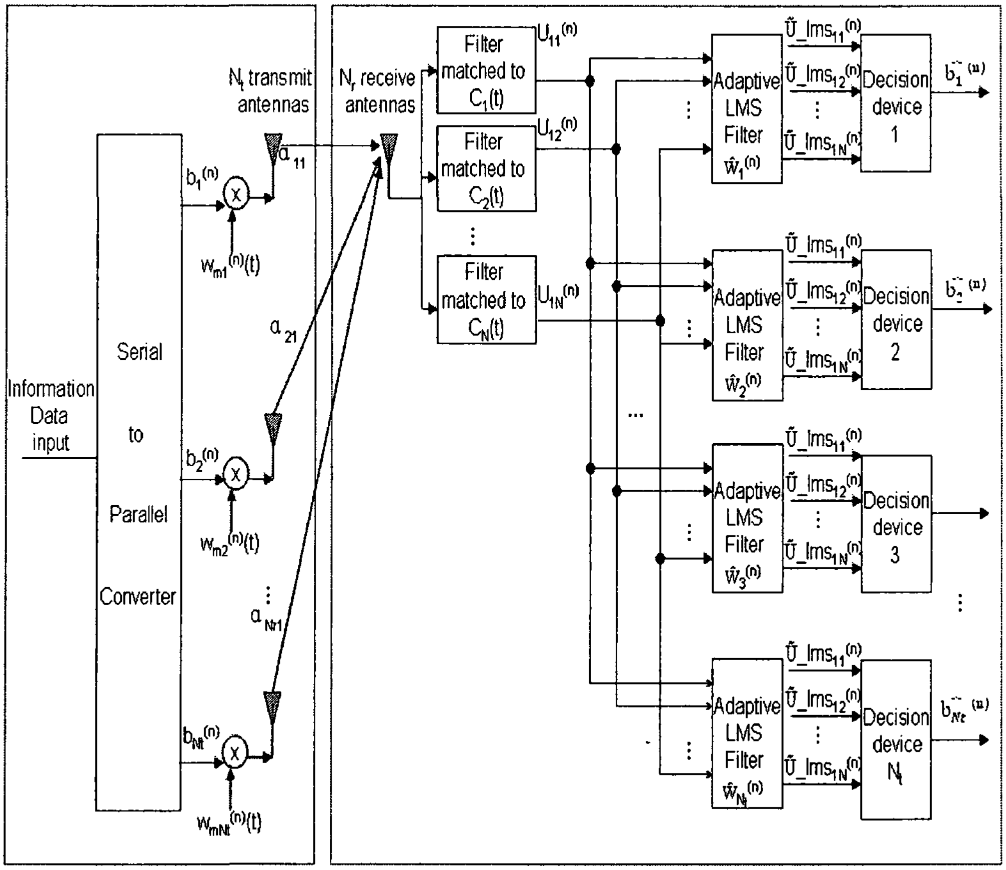

Figure 4.1 Proposed networking model based on LMS tracking detection for CDMA/MIMO with Permutation Spreading in slowly varying Rayleigh fading channels (N_t = 4, N_r =1, and N=8)

In Figure 4.1 to Figure 4.3, several major parameters are specified in the following:

❖ $\mathbf{b}^{(n)} = [b_1^{(n)}, b_2^{(n)}, b_3^{(n)}, \ldots, b_{Nt}^{(n)}] = 2*\mathbf{m}^{(n)} - 1$; where $\mathbf{m}^{(n)} = [m_1^{(n)}, m_2^{(n)}, m_3^{(n)}, \ldots, m_{N_t}^{(n)}]$ is the transmitted message on signaling interval n, $m_k^{(n)} = 0$ or 1 with equal probability and keeping independent each other;

❖ α_{ij} is the complex channel gain on the link between transmit antenna i and receive antenna j;

❖ $w_{mi}^{(n)}(t)$ is the spreading waveform used to spread the data transmitted by antenna i

on the interval n;

- $c_i^{(n)}(t)$ is a set of mutually orthogonal spreading waveforms;
- $\hat{W}_{ij}(n)$ is LMS adaptive filter weight coefficients;
- U_{ij} (U_LMS_{ij}) is initial decision variable;
- $\tilde{U}\_lms_{ij}$ is the final decision variable;
- N_t is the number of transmit antenna and N_r is the number of receive antenna;

> 2 receivers

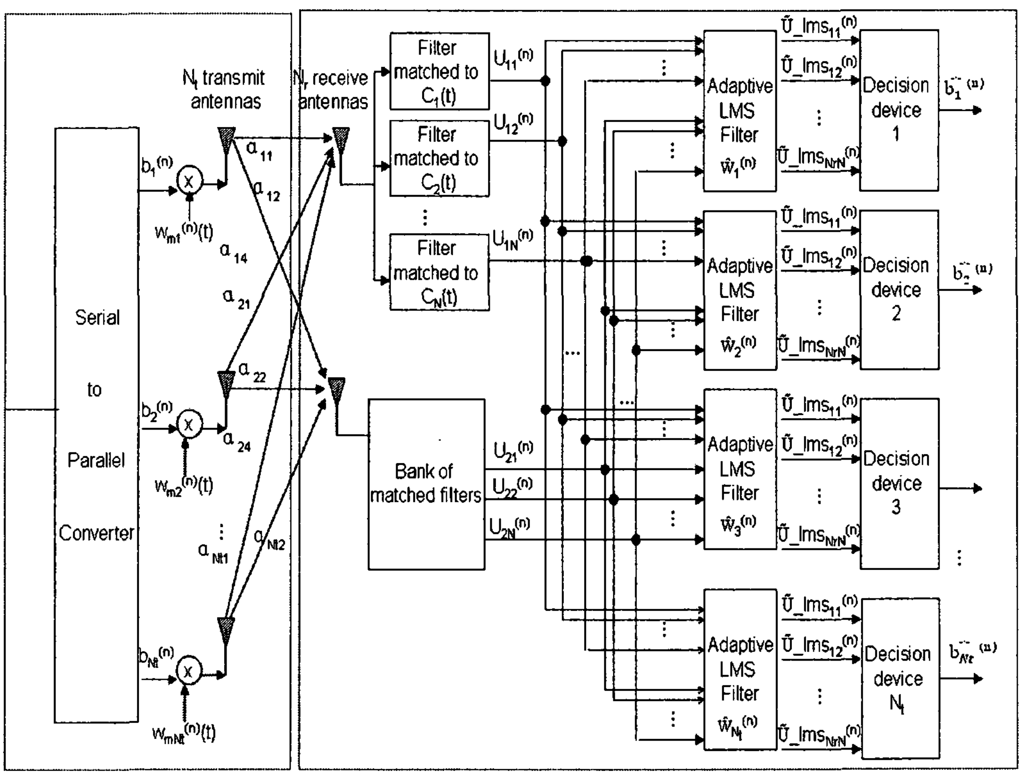

Figure 4.2 Proposed networking model based on LMS tracking detection for CDMA/MIMO with Permutation Spreading in slowly varying Rayleigh fading channels (N_t = 4, N_r =2, and N=16)

- 3, or 4-receiver

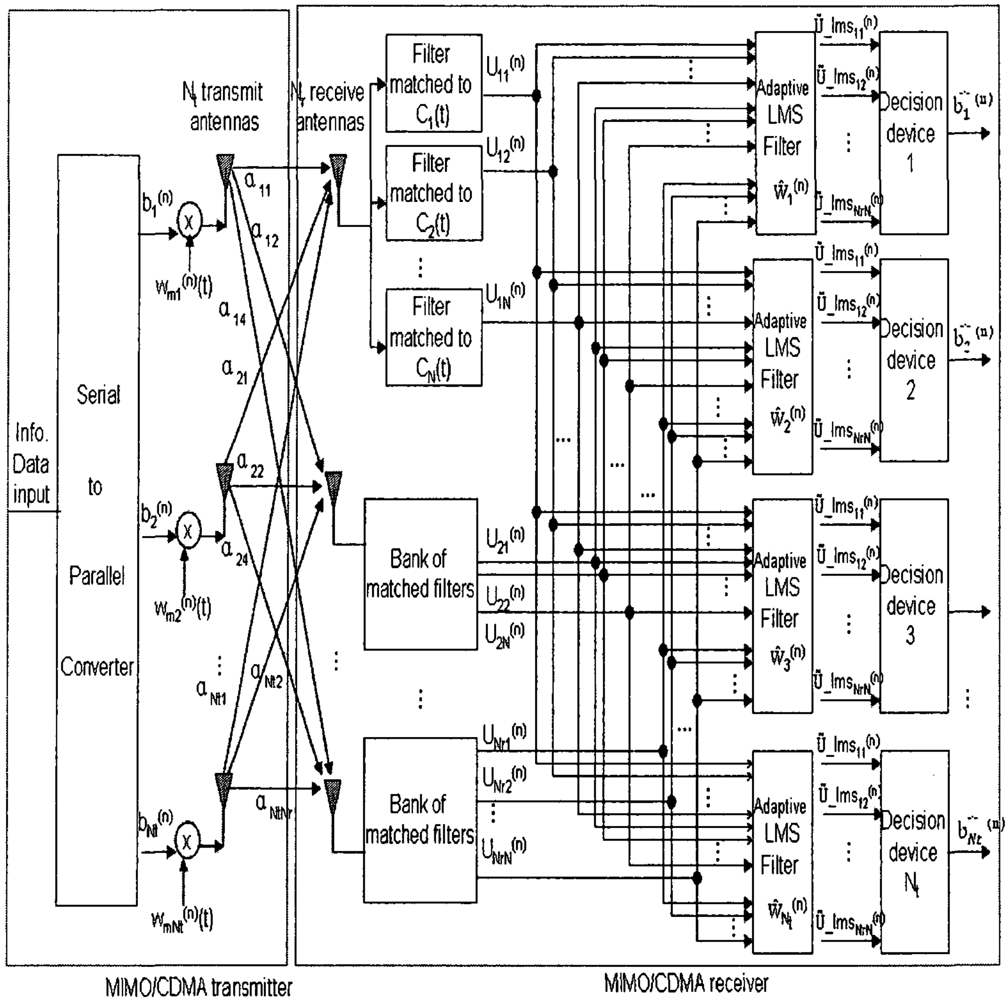

Figure 4.3 Proposed network model employing LMS detection for CDMA/MIMO with Permutation Spreading in slowly varying Rayleigh fading channels (N_t = 4, N_r =3 or 4, and N=8*N_r)

4.2 Summary of Proposed Detection Algorithm Using LMS Filters with Permutation Spreading Techniques for CDMA/MIMO Systems

The main steps of proposed LMS adaptive filter algorithm for CDMA/MIMO systems in slowing varying fading channels is outline as follows:

Table 4.1 Summary of proposed LMS tracking algorithm for CDMA/MIMO systems

- Determine permutation spreading scheme used;
- Set proper parameters: number of taps and weight step-size parameter
- Initialization of tap-weight vectors;
- Generate slowing varying complex channel gains;
- Generate complex noise variables;
- Calculate initial decision variables;
- Find out the training (pilot) bound of LMS tracking filters;
- Figure out desire response and timely tracking variables;
- Compute error difference between desire response / tracking variables and output variables;
- Dynamically update LMS weight estimate per iteration;
- Generate the final decision variables;
- Apply new LMS tracking detection rules

Next, we will state the steps in details in the following sections.

4.3 Spreading Permutation Scheme

In this thesis, we will take advantage of the spreading permutation scheme employed in MLD detection algorithm (see Table 2.1) for CDMA/MIMO systems with 1, 2, 3 or 4 transmit antennas in slowly varying Rayleigh fading channels.

4.4 Parameters

(1) Number of taps: the number of taps L relates to how many tap-input vectors at time n. For instance, take L=8 for 1 receiver.

(2) Step-size parameter:

Step-size parameter μ can be suitably chosen in the range of

$$0 < \mu < 2/\lambda_{max} \quad (4.1)$$

where λ_{max} is the largest eigenvalue of the correlation matrix **R**.

4.5 Initialization of Tap-weight Vectors

At the beginning, set initial tap-weight vectors of adaptive LMS filters as: **wlms**(n) = $[0, 0, \ldots, 0]^T$;

4.6 Rayleigh Channel Gain Variables

4.6.1 Rayleigh Fading

Rayleigh fading is a typical statistical model for the effect of a propagation environment on a radio signal, such as that used by wireless systems devices. In modern wireless networks, Rayleigh fading is viewed as a reasonable model especially for signal propagation as well as the effect of urban environments on radio signals [44][45]. In general, Rayleigh fading is most applicable when there is no dominant propagation along a light of sight (LOS) between the transmitters and receivers. If there is a dominant line of sight, Rician fading or other related fading models might be more applicable.

For CDMA/MIMO systems, Rayleigh fading can be viewed as a very reasonable and useful channel model when there are a lot of objects in the fading environment that scatter the radio signal before it arrives at the receiver, especially in city centers where there is no LOS between the transmitter and receiver and a number of buildings and other objects might attenuate, reflect, refract, and diffract the signal.

As it will be seen below, a Rayleigh fading channel itself can be modeled by generating the real and imaginary parts of a complex number according to independent normal Gaussian variables. In this thesis, the aim of our approach is to produce a signal, which has the Doppler power spectrum and the equivalent autocorrelation properties.

4.6.2 Doppler Power Spectrum

A possible way to generate a signal with the required Doppler power spectrum is to pass a white Gaussian noise signal through a filter with a frequency response equal to the square-root of the Doppler spectrum required.

The Doppler power spectral density of fading channels describers how much spectral broadening it causes. This shows how an impulse in the frequency domain, which is spread out across frequency when it passes through the fading channel. For Rayleigh fading with equal sensitivity receive antenna in all directions, this can be expressed below [45]:

$$DS(v) = \frac{1}{\pi f_d \sqrt{1-\left(\frac{v}{f_d}\right)^2}} \tag{4.2}$$

Where *DS* is Doppler power spectral density of fading channels, v is the frequency shift relative to the carrier frequency. This equation is only valid for values of v between $\pm f_d$; outside this range the spectrum will be zero.

4.6.3 Autocorrelation Function of Rayleigh Fading Channels

The normalized autocorrelation function of a Rayleigh fading channel with motion at a constant velocity is a zeroth-order Bessel function of the first kind [46]:

$$R(\tau) = J_0(2\pi f_d \tau) \tag{4.3}$$

at delay τ when the maximum Doppler shift is f_d. It is periodic in delay and its envelope decays slowly after the initial zero-crossing.

4.6.4 Zeroth-order Bessel Function of the First Kind

Here, we will simply introduce zero*th*-order Bessel function of the first kind, J_0. Bessel functions of the first kind, denoted as $J_\alpha(x)$, are solutions of Bessel's differential equation that are finite at the origin ($x = 0$) for non-negative integer α, and diverge as x approaches zero for negative non-integer α. It is possible to define the function by its Taylor series expansion around $x = 0$ [47].

$$J_a(x) = \sum_{k=0}^{\infty} \frac{(-1)^k}{k!\,\Gamma(k+a+1)} \left(\frac{x}{2}\right)^{2k+a} \tag{4.4}$$

where $\Gamma(z)$ is the gamma function, a generalization of the factorial function to non-integer values.

4.6.3 Channel Gain Model used in the thesis

In this thesis we use a first order autoregressive model to generate the complex fading coefficients. This is done for simplicity if the model is given the following equation:

$$\alpha(\tau) = J_0(2\pi B_d \tau)^* \alpha(\tau\text{-}1) + \sqrt{1 - J_0^2(2\pi B_d \tau)}^* x \tag{4.5}$$

where:

- $\alpha(\tau)$ is Rayleigh fading channel gain generated;
- $J_0(x)$ is Bessel function of the first kind stated in Section 4.6.2;
- B_d is the Doppler shift in Rayleigh fading channels;
- x is a complex Gaussian random variable with 0 mean and variance 1;

However, the simpler generating approach seems to be non-deterministic and bring out some implementation issue. That is, it presents some implementation questions related to needing high-order filters to approximate the irrational square-root function in the response and sampling the Gaussian waveform at an appropriate rate. Thus, to simplify, we introduce Raleigh fading factor R_f as:

$$R_f = J_0(2\pi B_d \tau); \tag{4.6}$$

Please note that R_f termed as Raleigh factor or Rayleigh fading parameter will be used or mentioned hereafter in this thesis.

Accordingly, we get:

$$\alpha(\tau) = R_f * \alpha(\tau\text{-}1) + \sqrt{1 - R_f^2}\; x\,; \tag{4.7}$$

In this thesis, for the proposed LMS filter tracking detection, the channel gains (α_{ij}) are slowing varying circularly complex Gaussian random variables.

For each iteration, the complex channel gains consists of $4{*}N_r$ slowing varying channel gain sub vectors. For example, in CDMA/MIMO systems with 4-receive antennas, there are 16 slowly varying channel gain sub vectors corresponding to each of time-varying iteration.

4.7 Noise Variables

In the new time varying CDMA/MIMO systems, the noise variables are white complex random variables.

4.8 The Initial Decision Variables

The initial decision variables of LMS solution are expressed below:

$$U\_LMS_{jk} = \begin{cases} ATb_i^{(n)}\alpha_{ij}^{(n)} + n_{jk}^{(n)}, & \text{if } C_{mk}(t-nT) \text{ is used} \\ n_{jk}^{(n)}, & if \text{ if } C_{mk}(t-nT) \text{ is not used} \end{cases} \quad (4.8)$$

Accordingly, the related initial decision variables expresses of LMS tracking solution used for CDMA-MIMO systems with 1 to 4 receivers will be same as the expressions stated in Section 3.6.

4.9 LMS Pilot/Training Sequence Bound

The channel measurements can be acquired by sending out known pilot/training symbols periodically from the transmitter to the receiver. The receiver can then use these pilot/training symbols to estimate the channels at different time intervals. This can be called pilot symbol-assisted modulation (PSAM) [48 - 50], and it is a very promising technique for both slowly varying Rayleigh channels and rapidly fading environments.

As the receiver acquires information about the channel, it calculates which LMS adaptive filter weight vector matches the channel the best. The receiver then sends back the index of that latest LMS weight vector for updating in order to accomplish better adaption at each of iteration. By measuring the channel, the proposed adaptive LMS tracking technique can mitigate error estimate per iteration and then increase performance in wireless CDMA/MIMO systems.

In the slow varying fading channels, the Wiener filters can be adequate as the framework and reference of LMS filters. That is, the Wiener filters built on the same tapped-delay structure that is used in the LMS filters provide a meaningful training/pilot bound on the performance of the LMS filters. Before reaching the training/pilot sequence bound, the transmitted pilot bits will be used as required desire bits. After passing by the pilot bound, the decision variables passing through LMS filters will be used as corresponding desire variables. Based on the desire variables, the corresponding difference errors and varying LMS tracking weights will be timely updated and derived.

According to the rules, we will generate the training/pilot bounds of these LMS filtered applied in the 1 to 4 receive antennas cases by comparing and observing the timely varying weights of Wiener filters and LMS filters, respectively. In order to simplify the processing of training/pilot bounds, we mainly concentrate on three important SNR values: 5 dB, 10 dB, and 15 dB. When $SNR < 5$ dB, the training/pilot bound value corresponding $SNR = 5$ dB will add certain amount, which can be estimated by observing the training varying trend. Then the new values will be used as the related training/pilot bound points, respectively. When 5 dB $\leq SNR <$ 10 dB, the training/pilot bound value corresponding to SNR = 5 dB will be used as their training bounds. Similarly, when 10 dB $\leq SNR <$ 15 dB, the training/pilot bound value corresponding to $SNR = 10$ dB will be used as their training value bounds. Likewise, when $SNR \geq 15$ dB, the training/pilot bound value corresponding to $SNR = 15$ dB will be used as their training sequence bounds. Next, we will take some of them to observe and obtain the related training/pilot bound points.

4.9.1 LMS Tracking Training Bound with Middle-scale Step-size Parameter

For LMS weight step-size parameter μ =0.05 and fixed Rayleigh fading factor $R_f = 0.99$, the LMS tracking training/pilot bound is measured in the following:

- 1 receiver

In this case, LMS adaptive filters weight coefficients include 4 sub vectors: $\mathbf{w}_{01}$, $\mathbf{w}_{02}$,

$\mathbf{w}_{03}$, and $\mathbf{w}_{04}$, and each of them insists of 8 sub vectors. For instance, $\mathbf{w}_{01} = [w_{011}, w_{012}, w_{013}, w_{014}, w_{015}, w_{016}, w_{017}, w_{018}]^H$. Then let us measure the training bound points related to *SNR* = 5 dB, *SNR* = 10 dB, and *SNR* = 15 dB, respectively.

- *SNR* = 5 dB case
  - $\mathbf{w}_{01}$

For $\mathbf{w}_{01}$, 8 slowly varying LMS weight figures will be generated at each of iteration. To simplify them, we will only take one of them as examples to compare and analyze.

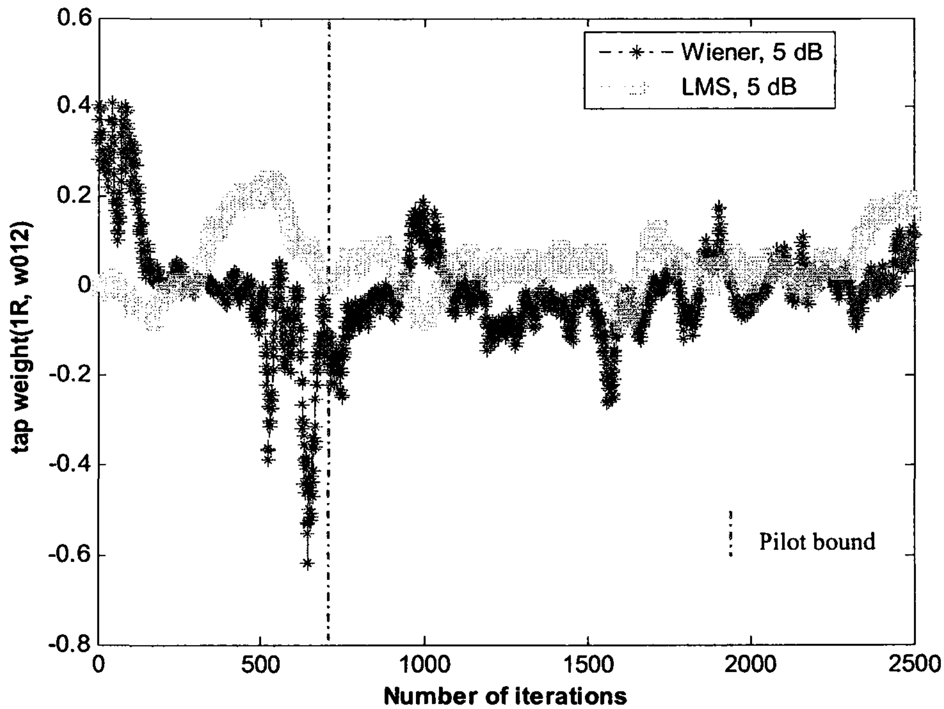

Figure 4.4 Weight varying of LMS and Wiener ($\mathbf{w}_{012}$, *SNR*=5 dB, 1R, μ=0.05)

In Figure 4.4, by observation, it is easy to see that the LMS tracking training bound point value of $\mathbf{w}_{012}$, *n*, will be about 700. Here the "w012" shown in Figure 4.4 is the same as $\mathbf{w}_{012}$. Please note that thereafter "w0ij" shown in the following Figures located in Section 4.9 will be viewed as $\mathbf{w}_{0ij}$.

Similarly, the training bound points of the rest of $\mathbf{w}_{01}$ sub vectors can also be measured and acquired. Then we take the maximum training/pilot bound value from all of the sub-vectors ($\mathbf{w}_{011}$, $\mathbf{w}_{012}$, $\mathbf{w}_{013}$, $\mathbf{w}_{014}$, $\mathbf{w}_{015}$, $\mathbf{w}_{016}$, $\mathbf{w}_{017}$, $\mathbf{w}_{018}$) as the final $\mathbf{w}_{01}$ training/pilot bond value of corresponding SNR = 5 dB case. That is, the training sequence bound of $\mathbf{w}_{01}$ can be maximized as:

$$bpoint\_w_{01} = \max(bpoint\_w_{01j}) \tag{4.9}$$

where $bpoint\_w_{01}$ is the training/pilot bound value of the LMS $\mathbf{w}_{01}$ vector, and j=1,2,...,8.

Similarly, the training bound value of $\mathbf{w}_{02,}$ $\mathbf{w}_{03}$ and $\mathbf{w}_{04}$ can be also obtained by observing. Then the final training/pilot bound values corresponding to the slowing varying fading channels case (1 receiver, SNR = 5 dB) will be:

$$bpoint\_1R\_5dB = \max(bpoint\_w_{0ij}) \tag{4.10}$$

where $bpoint\_1R\_5dB$ is the final training/pilot bound value corresponding to the case, j=1, 2, 3...,8, and i=1, 2, 3, 4.

Likewise, we can determine all the training bound of three different SNR values (SNR=5dB, SNR=10dB, SNR=15dB) related to CDMA/MIMO with 4 transit antennas and 1 receiver antenna.

- Summary of training/pilot bound values for 1 receiver and 3 different SNR values (SNR=5dB, SNR=10dB, and SNR=15dB)

Ideally, for certain dB value, the maximum value will be taken from all of training sequence bound values of weight sub-vectors and be used as the training bound value of the weight vector. Let us take 15 dB as an example, the biggest one will be taken from $\mathbf{w}_{0101}$ to $\mathbf{w}_{0408}$ and will be used as the training/pilot bound value (1250). In practical wireless communication network, bigger values than the ideal bound values need to be considered and employed due to smaller observation difference as well as minor weight varying volatility. Accordingly, we will use 1360 instead of 1250 as the new training sequence bound value.

Table 4.2 Training bound point distribution for 1 receiver and middle scale step-size μ

	Training/pilot bound (1 receiver, $\mu = 0.05$, $R_f = 0.99$)		
Weight #	*SNR = 5dB*	*SNR = 10dB*	*SNR = 15dB*
w_{0101}	800	700	700
w_{0102}	700	1300	1100
w_{0103}	700	800	1000
...	...	...	...
w_{0408}	900	1350	750
Training/Pilot bound values (Ideal)	1400	1350	1250
Training/Pilot bound values (Real)	1520	1440	1360

- other dB cases

As such, we consider other different SNR values related to the 1 receiver case. When *SNR* < 5 dB, their related pilot bound values are based on the pilot bound value corresponding *SNR* = 5 dB adds certain different amount, which can be estimated by observing the varying trend of the training/pilot bound curve. So the new values corresponding to *SNR* < 5dB will be used as their related training/pilot bound points, respectively.

For example, the pilot bound value of *SNR* = 5 dB, *SNR* =10 dB, and *SNR* = 15 dB for 1 receiver is 1520, 1440, and 1360, respectively. By viewing, it is readily to estimate that the adjusted bound varying value for 1 dB scale will be about $\Delta = 16$. Accordingly, in this case, the training bound value of *SNR* = 4 could be 1520+16, and the one of *SNR*=3dB is 1520+32, and so forth.

In this case, when 5 dB <= *SNR* < 10 dB, the training/pilot bound value corresponding to *SNR*=5dB (Δ=1520) will be used as their reference pilot bound values. Additionally, we can also add certain step-size varying pilot bound values by observing in order to more exactly link the different SNR cases respectively. Similarly, when 10 dB <= SNR < 15 dB, the training bound value corresponding to SNR = 10dB will be taken as their training bound values. And so forth.

❖ 2 receivers

In 2 receive antennas cases, the LMS adaptive filter weight $\mathbf{w}_0$ consists of 4 vectors, that is $\mathbf{w}_0 = [w_{01}, w_{02}, w_{03}, w_{04}]^H$, and each of them includes 16 sub vectors. For instance, $\mathbf{w}_{01} = [w_{0101}, w_{0102}, w_{0103}, w_{0104}, w_{0105}, w_{0106}, w_{0107}, w_{0108}, w_{0109}, w_{0110}, w_{0111}, w_{0112}, w_{0113}, w_{0114}, w_{0115}, w_{0116}]^H$.

Next, let us take one of them to examine the training bound corresponding to SNR=10dB for 2-receiver cases.

- SNR = 10 dB

As mentioned in 2-receiver case and SNR = 10 dB case, there are 16 LMS filter tap weight varying figures linked to 4 weight vectors ($\mathbf{w}_{01}$, $\mathbf{w}_{02}$, $\mathbf{w}_{03}$, and $\mathbf{w}_{04}$). Next, we will take one of them, to observe and analyze their pilot bound varying.

➢ $\mathbf{w}_{02}$

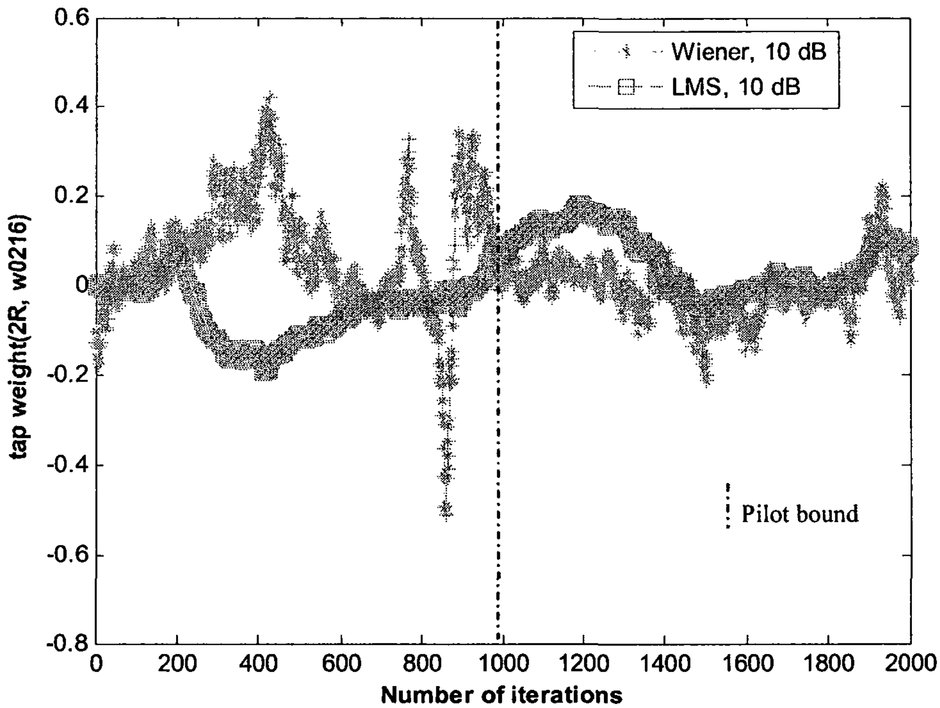

Figure 4.5 Weight varying of LMS and Wiener filters ($\mathbf{w}_{0216}$, *SNR*=10 dB, 2R, μ=0.05)

From Figure 4.5, it is very easy to observe that the training/Pilot bound points of $\mathbf{w}_{0216}$ related to *SNR*=10 dB is 980. Then we can compare and acquire all of these training/pilot bound values of $\mathbf{w}_{0101}$ to $\mathbf{w}_{0416}$ and take the maximum as the training/pilot bound values of $\mathbf{w}_{01}$ through $\mathbf{w}_{04}$ corresponding to *SNR* = 10 dB and 2 receivers case.

Similarly, we can get all of training/pilot bound values of $\mathbf{w}_{01}$, $\mathbf{w}_{02}$, $\mathbf{w}_{03}$, and $\mathbf{w}_{04}$ applied in 2 receivers at *SNR* = 5 dB, 10 dB, and 15 dB slowing varying fading channels case.

- Summary of training/pilot bound values for 2-receiver and 3 different SNR values (*SNR*=5dB, *SNR*=10dB, and *SNR*=15dB, μ=0.05)

Table 4.3 Training bound point distribution for 2 receivers and middle scale step-size μ

	Training/pilot value (2 receivers, μ=0.05, R_f=0.99)		
Training/Pilot bound	SNR = 5dB	SNR = 10dB	SNR = 15dB
bound values (Ideal)	1100	1050	950
bound values (Real)	1200	1120	1040

❖ 3 or 4 receivers

As presented previously, the LMS weight coefficient $\mathbf{w}_0$ insists of 4 weight vectors: $\mathbf{w}_{01}$, $\mathbf{w}_{02}$, $\mathbf{w}_{03}$, and $\mathbf{w}_{04}$. Each of the four weight vectors includes 24 sub weight vectors in 3 receive antennas cases while 32 sub weight vectors in 4 receivers cases. Accordingly, each of sub weight vector relates to a different tap weight varying figure for certain SNR value.

Using similar measurement rule mentioned in 1 or 2 receivers cases, we can further examine and obtain all of corresponding training/pilot bound values of LMS weight vectors, $\mathbf{w}_{01}$, $\mathbf{w}_{02}$, $\mathbf{w}_{03}$, and $\mathbf{w}_{04}$ applied in CDMA/MIMO systems with 3 or 4 receivers related to SNR=5 dB, 10 dB, and 15 dB cases, respectively.

❖ Summary of training/pilot bound values of tap weight varying for 1 to 4 receivers

Next, with middle scale step-size μ =0.05, we summarize all of the estimation of LMS training/pilot bound points stated in Table 4-4.

In Table 4.4, it is not difficult to find one important feature: with the increasing of number of receive antennas or / and SNR values, the pilot bound values estimated will be smaller.

Table 4.4 Pilot bound point distribution for 1 to 4 receivers, μ = 0.05, R_f = 0.99 cases

# of receive antennas	SNR	Pilot bound (Estimate)	Pilot bound (Real)
	5 dB	1400	1520
	10 dB	1350	1440
1R	*15 dB*	1250	1360
	5 dB	1100	1200
	10 dB	1050	1120
2R	*15 dB*	950	1040
	5 dB	800	880
	10 dB	750	800
3R	*15 dB*	650	720
	5 dB	500	560
	10 dB	400	480
4R	*15 dB*	350	400

As we notice, in Table 4-4, all of estimate of LMS weight varying pilot bound value is based upon one basic condition: LMS weight step-size parameter μ =0.05 and Rayleigh fading factor R_f = 0.99.

In Rayleigh fading channel, generally speaking, the Rayleigh fading factor used in measurement might be adjusted with a very smaller scale. However, for LMS adaptive filter algorithm, the weight step-size parameter is often switched with a bigger degree between 0 and 1 as per different requirement, such as convergence rate and misadjustment expectation.

So, if we fix the Rayleigh fading factor (R_f = 0.99) and reduce LMS weight step-size parameter, then how will the weight pilot bound value estimation of LMS filter using for CDMA/MIMO with 1 to 4 receive antennas vary? Next, we will examine the question in the following section.

4.9.2 LMS Tracking Pilot Bound with Small-scale Step-size Parameter

Now we turn to consider the training bound varying by using smaller step-size parameter μ =0.005. For LMS weight smaller step-size parameter μ =0.005 given fixed Rayleigh fading factor R_f = 0.99, the LMS tracking training/pilot bound is then measured in the following. Next, let's view the 2-receiver case first.

❖ 2 receivers

Due to similar measurement method and rule elaborated in Section 4.9.1, we will take some typical pilot bound figures to analyze and compare. Specifically, to simplify the analysis, in the following cases, we will mainly consider the following several constraints:

➢ Focus on 3 typical SNR values: SNR = 5 dB, SNR = 10 dB, SNR = 15dB.

➢ Only take and show some of LMS weight training bound varying figures;

➢ Basic condition: the smaller LMS weight step-size μ =0.005 and fixed Rayleigh fading factor R_f = 0.99.

- SNR = 5 dB case

➢ $\mathbf{w}_{01}$

To simplify them, we take one weight figure from all of 16 ones of $\mathbf{w}_{01}$ sub vectors and show in Figure 4.6.

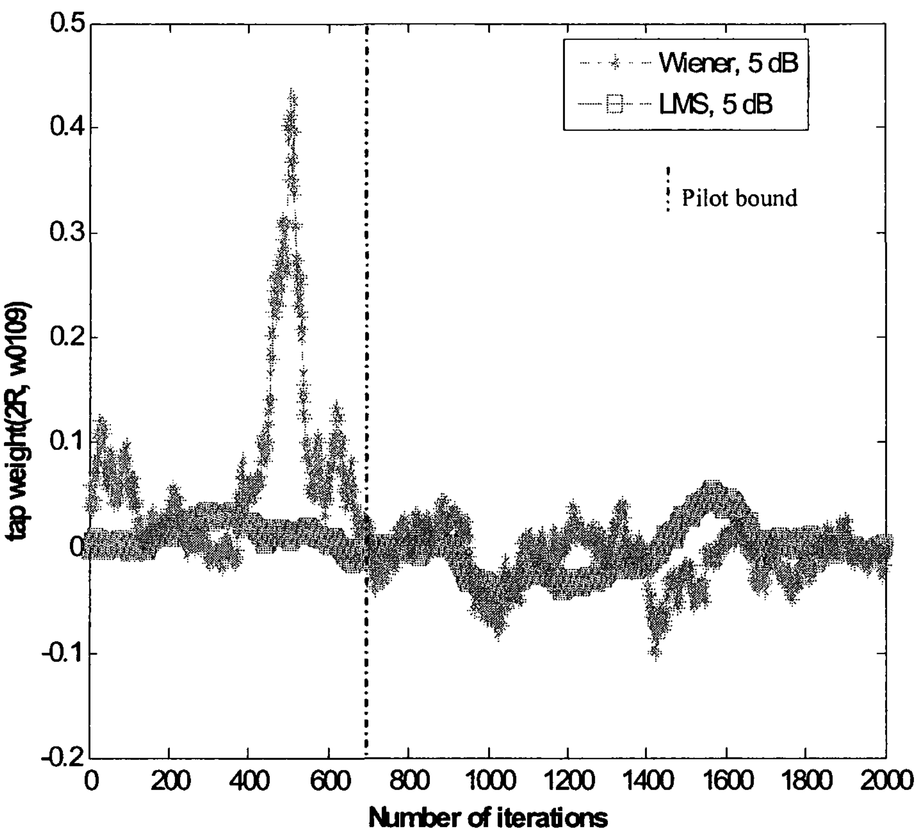

Figure 4.6 Weight varying of LMS and Wiener filter ($\mathbf{w}_{0109}$, *SNR*=5dB, 2R, μ=0.005)

From Figure 4.6, we see that the training bound points of $\mathbf{w}_{0109}$ related to SNR = 5 dB and 2 receivers under new constraint is 700.

Similarly, using same constraint, we can measure the training bound value of the rest weight sub vectors of $\mathbf{w}_{01}$. Then take the maximum one as the pilot bound point of $\mathbf{w}_{01}$.

➢ $\mathbf{w}_{03}$

Next, with new same constraint, we continue the cases related to $\mathbf{w}_{03}$.

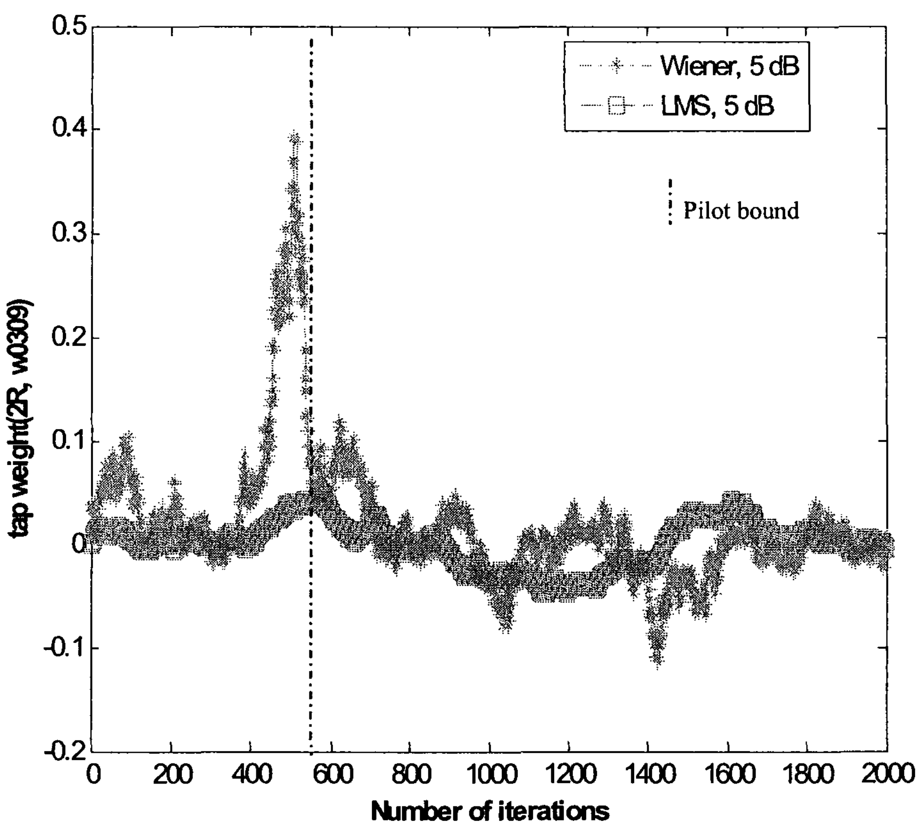

Figure 4.7 Weight varying of LMS and Wiener filter ($\mathbf{w}_{0309}$, SNR=5dB, 2R, μ=0.005)

From Figure 4.7, we see that the training/pilot bound points of $\mathbf{w}_{0309}$ related to SNR = 5 dB and 2 receivers under new constraint is 550.

➢ $\mathbf{w}_{04}$

Next, with new same constraint, we examine the cases related to $\mathbf{w}_{04}$.

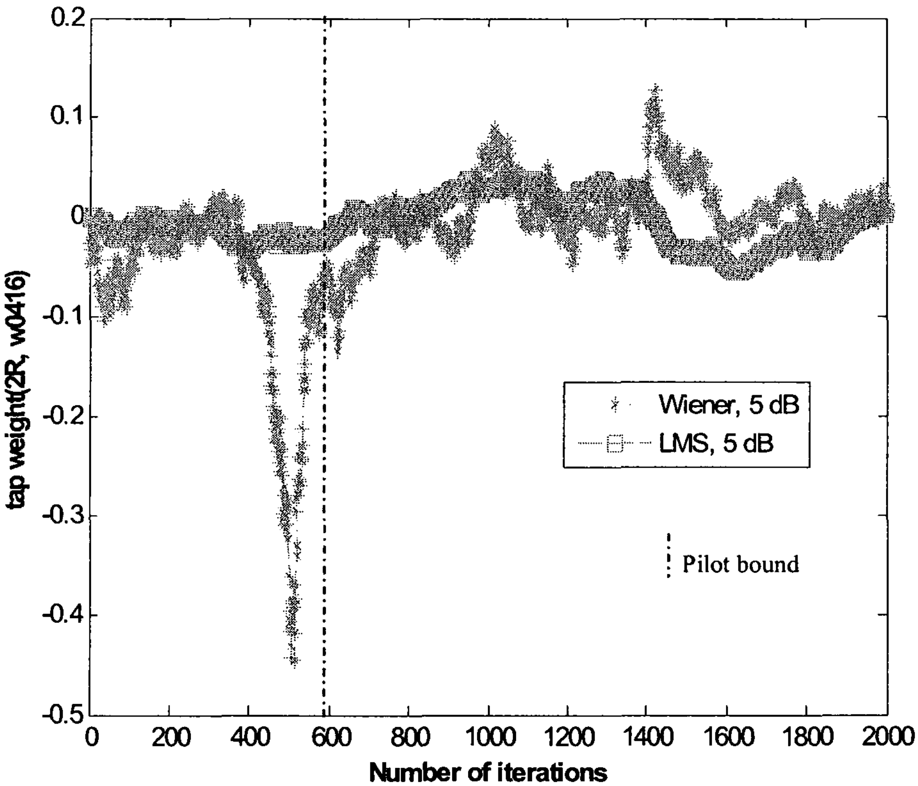

Figure 4.8 Weight varying of LMS and Wiener filter ($\mathbf{w}_{0416}$, *SNR*=5dB, 2R, μ=0.005)

From Figure 4.8, it is clear to observe that the training/pilot bound points of $\mathbf{w}_{0416}$ related to *SNR* = 5 dB and 2 receivers under new constraint is 590.

Similarly, the training/pilot bound points of other weight sub vector of $\mathbf{w}_{01}$, $\mathbf{w}_{02}$, $\mathbf{w}_{03}$, and $\mathbf{w}_{04}$ can be measured by same rule. Then compare all of them and take the maximum one as the final pilot bound point corresponding to *SNR* = 5 dB, 2 receivers, and smaller weight step-size μ=0.005.

Likewise, with the new same training, the training/pilot bound points related to *SNR*

= 10 dB or SNR =15 dB and 2 receivers cases can be measured.

- Summary of training/pilot bound values for 2 receiver and 3 different SNR values (*SNR*=5dB, *SNR*=10dB, and *SNR*=15dB, μ=0.005)

Table 4.5 Pilot bound point distribution for 2 receivers and small scale step-size μ

	Training/pilot value (2 receiver, μ=0.005, R_f=0.99)		
Training/Pilot bound	*SNR = 5dB*	*SNR = 10dB*	*SNR = 15dB*
bound values (Ideal)	1300	1200	1120
bound values (Real)	1400	1320	1240

❖ 1 receiver

Apply the new same constraint for 1-receiver case, and related measurement is depicted below:

- Summary of training/pilot bound values for 1 receiver and 3 different SNR values (*SNR*=5dB, *SNR*=10dB, and *SNR*=15dB, μ=0.005)

Table 4.6 Training bound distribution for 1 receiver and small scale step-size μ

	Training/pilot value (1 receiver, μ=0.005, R_f=0.99)		
Training/Pilot value bound	*SNR = 5dB*	*SNR = 10dB*	*SNR = 15dB*
bound values (Ideal)	1600	1520	1450
bound values (Real)	1720	1640	1560

❖ 3 or 4 receivers

Likewise, with new same constraint, adopting similar measurement method depicted in 1 or 2 receivers cases, we can further examine and obtain all of corresponding training/pilot bound values of LMS weight vectors ($\mathbf{w}_{01}$, $\mathbf{w}_{02}$, $\mathbf{w}_{03}$, and $\mathbf{w}_{04}$) applied in CDMA/MIMO systems with 3 or 4 receivers related to *SNR*=5 dB, 10 dB, and 15 dB cases, respectively.

❖ Summary of training/pilot bound values of tap weight varying for 1 to 4 receivers

With smaller scale step-size μ =0.005, all of pilot bound points estimation of LMS tap weight varying is summarized in Table 4-7.

Table 4.7 Pilot bound point distribution for 1 to 4 receivers, μ = 0.005, R_f = 0.99 cases

# of receive antennas	SNR	Pilot bound (Estimate)	Pilot bound (Real)
	5 dB	1600	1720
	10 dB	1520	1640
1R	*15 dB*	1450	1560
	5 dB	1300	1400
	10 dB	1200	1320
2R	*15 dB*	1120	1240
	5 dB	980	1080
	10 dB	900	1000
3R	*15 dB*	800	920
	5 dB	680	760
	10 dB	600	680
4R	*15 dB*	500	600

4.9.3 The Comparison and Analysis of Training Bound Estimation of LMS Algorithm

❖ <u>Direct conclusion of comparison and analysis</u>

Clearly, it is not difficult to find several important features on training bound distribution by comparing and analyzing them.

From Table 4.4 and Table 4.7, it is easy to see several apparent features:

- As SNR values increase, less training sequences are needed;
- As the number of receivers increase, less training sequences are needed;
- As step size increases, less training sequences are needed;

Compare to the training bound points estimated in Table 4.4, the corresponding values measured in Table 4.7 are relatively bigger. As we know, smaller LMS weight varying can generate smaller misadjustment, which can achieve better BER performance. However, the weight rate of convergence will be relatively bigger. As for this point, the simulation BER performance shown in Chapter 5 will provide us many typical examples and demonstration. Consequently, we need to adjust and acquire the relatively ideal weight step-size parameter according to related real requirement in actual CDMA/MIMO systems.

Also, in this thesis, we should realize that the new proposed LMS tracking detection technique might not be very easy by observing to determine the exact training/pilot bound points corresponding to the LMS weight vectors due to slight weight varying volatility and minor bound point deviation by observing and estimating. A better solution can be adopted is that taking bigger close bound values with some redundancy instead of the smaller values observed and estimated to deploy in practical LMS tracking filters. Then the training/pilot bound points difference could be reduced and controlled within a minor scope.

❖ Indirect conclusion of comparison and analysis

From Table 4.4 and Table 4.7, we further examine and analyze them and explore two very valuable aspects in the following:

- Based on same fading channels with same LMS step-size and same number of receiver, with the 5 dBs increase of SNR, the training bound value will reduce about 80. For example, in Table 4.7, for same constraints ($\mu = 0.005$, $R_f = 0.99$, 4R), the pilot bound value at SNR =5dB is 760, that at SNR=10dB is 680, and that at SNR=15dB is 600. As another example, in Table 4.4, for same constraints ($\mu = 0.05$, $R_f = 0.99$, 4R), the pilot bound value at SNR =5dB is 560, that at SNR=10dB is 480, and that at SNR=15dB is 400. That is, we can see that with the increase of 1 dB, the training bound will be estimated to reduce roughly 16. As such, we can estimate what the training bound related to same constraints except for different SNR values could be.

- Based on same fading channels with same LMS step-size while different number of receiver, with the increase of 1 receiver, the pilot bound value will decrease roughly 320. Let's take *SNR*=10dB as an example. In Table 4.7, for same constraints (μ = 0.005, R_f = 0.99, *SNR*=10 dB), the pilot bound value for 1 receiver is 1640, that for 2 receivers is 1320, that for 3 receivers is 1000, and that for 4 receivers is 680. One more example, in Table 4.4, for same constraints (μ = 0.05, R_f = 0.99, *SNR*=10 dB), the pilot bound value for 1 receiver is 1440, that for 2 receivers is 1120, that for 3 receivers is 800, and that for 4 receivers is 480. Consequently, as such, we can also estimate what the training bound related to same constraints except for different number of receive antennas might be.

According to the two very useful estimate conclusions above, it is not difficult to find a very important fact that we can roughly estimate the LMS tracking training /pilot bound without further using Wiener filters, which can dramatically reduce the complexity of proposed LMS tracking algorithm.

4.10 Updated Decision Variables Filtered by LMS Filters

$$\tilde{\mathbf{U}}\_\mathbf{LMS}_{ij}(n) = \hat{\mathbf{W}}_{ji}^{H}(n) * \mathbf{U}\_\mathbf{LMS}_{ji}(n) \qquad (4.11)$$

where:

- $\mathbf{U}\_\mathbf{LMS}_{ji}(n)$ is initial decision variable at time n;
- $\tilde{\mathbf{U}}\_\mathbf{LMS}_{ji}(n)$ is updated decision variables;
- $\hat{\mathbf{W}}_{ji}^{H}(n)$ denotes the Hermitian transpose of $\hat{\mathbf{W}}_{ji}(n)$;

Next, let's take **b**= [-1 -1 -1 -1] as an example to compute the final decision variables in 1 to 4 receiver antennas cases, respectively.

❖ 1 receiver case

$$ylms01_{(1,i)} = (\mathbf{wlms}_{011})^{H} * \mathbf{U01}_{ji}; \qquad (4.12)$$

$$ylms01_{(2,i)} = (\mathbf{wlms}_{012})^{H} * \mathbf{U01}_{ji}; \qquad (4.13)$$

$$ylms01_{(3,i)} = (\mathbf{wlms}_{013})^{H} * \mathbf{U01}_{ji}; \qquad (4.14)$$

$$ylms01_{(4,i)} = (\mathbf{wlms}_{014})^{H} * \mathbf{U01}_{ji}; \qquad (4.15)$$

where:

- **ylms01** is updated decision variable at time n after passing through LMS filters in 1 receiver case;
- $\mathbf{wlms}_{011}$, $\mathbf{wlms}_{012}$, $\mathbf{wlms}_{013}$, and $\mathbf{wlms}_{014}$ are LMS weight sub vectors at time n relate to 1 receiver case;
- i denotes total iteration number;
- H denotes complex conjugate operation;
- $\mathbf{U01}_{ji}$ is initial decision variables related to 1 receiver at time n, with

$$\mathbf{U01}_{ji}=[U01_{(1,i)}, U01_{(2,i)}, U01_{(3,i)}, \ldots, U01_{(8,i)}]^T; \quad (4.16)$$

where:

- $U01_{(j,i)}$ is the jth sub vectors of the decision variables $\mathbf{U01}_{ji}$ related to

1 receiver case;

- i denotes total iteration number;
- T denotes transpose operation of a matrix;

❖ 2-receiver case

The updated decision variables expression related to 2-receiver case is the same as that of 1 receiver case except for the initial decision variable $\mathbf{U02}_{ji}$. And

$$\mathbf{U02}_{ji}=[U02_{(1,i)}, U02_{(2,i)}, U02_{(3,i)}, \ldots, U02_{(16,i)}]^T; \quad (4.17)$$

where $U02_{(j,i)}$ is the jth sub vectors of the decision variables $\mathbf{U02}_{ji}$ related to 2-receiver case;

❖ 3-receiver case

The updated decision variables expression related to 3-receiver case is the same as that of 1 receiver case except for different initial decision variable $\mathbf{U03}_{ji}$.

$$\mathbf{U03}_{ji}=[U03_{(1,i)}, U03_{(2,i)}, U03_{(3,i)}, \ldots, U03_{(24,i)}]^T; \quad (4.18)$$

where $U03_{(j,i)}$ is the jth sub vectors of the decision variables $\mathbf{U03}_{ji}$ related to 3-receiver case;

❖ 4-receiver case

The updated decision variables expression related to 4-receiver case is the same as that of 1 receiver case except for the initial decision variable $\mathbf{U04}_{ji}$.

$$\mathbf{U04}_{ji}=[U04_{(1,i)}, U04_{(2,i)}, U04_{(3,i)}, \ldots, U04_{(32,i)}]^T; \quad (4.19)$$

where $U04_{(j,i)}$ is the jth sub vectors of the decision variables $\mathbf{U04}_{ji}$ related to 4-receiver case;

4.11 Difference Error of Decision Variables

The difference error of decision variables refers to difference between the desired and the actual signal.

$$err\_lms_{ji}(n) = d_{ji} - \hat{\mathbf{W}}_{ji}^{H}(n) * \mathbf{U\_LMS}_{ji}(n); \quad (4.20)$$

where:

- d_{ji} denotes the desired information variables;
- $\hat{\mathbf{W}}_{ji}(n)$ is the LMS weight variables at time n;
- $\mathbf{U\_LMS}_{ji}(n)$ denotes the initial decision variables before passing through LMS filters at time n;
- $err\_lms_{ji}(n)$ denotes the different error between the desired variables and actual message variables

$$d_{ji} = \begin{cases} b^{(n)}, & \text{if iteration n} < \textit{pilot bound}; \\ sgn(real((\hat{W}_{ij}{}^{H}(n) * U_{ji}(n))), & \text{if iteration n} \geq \text{pilot bound}; \end{cases} \quad (4.21)$$

where:

- $\mathbf{b}^{(n)} = [b_1^{(n)}, b_2^{(n)}, \ldots, b_{Nt}^{(n)}]$ denotes the desire
- The training (pilot) bound has been introduced in Section 4.9;

4.12 LMS Weight Update Algorithm

$$\hat{\mathbf{W}}_{ji}(n+1) = \hat{\mathbf{W}}_{ji}(n) + \mu * \mathbf{U\_LMS}_{ji} * (err\_lms_{ji}(n))^*; \quad (4.22)$$

where:

- $\hat{\mathbf{W}}_{ji}(n)$ is the LMS weight variables at time n;
- **U_LMS**$_{ji}$ denotes the initial decision variables before passing through LMS filters
- $err\_lms_{ji}(n)$ denotes the different error between the desired variables and actual message variables (see Eq.4.20)
- * denotes the complex conjugate operation;

More specifically, we have

$$\hat{\mathbf{W}}_{(1,i+1)} = \hat{\mathbf{W}}_{(1,i)} + \mu * \mathbf{U\_LMS}_{ji} * (err\_lms_{(1,i)})^H; \tag{4.23}$$

$$\hat{\mathbf{W}}_{(2,i+1)} = \hat{\mathbf{W}}_{(2,i)} + \mu * \mathbf{U\_LMS}_{ji} * (err\_lms_{(2,i)})^H; \tag{4.24}$$

$$\hat{\mathbf{W}}_{(3,i+1)} = \hat{\mathbf{W}}_{(3,i)} + \mu * \mathbf{U\_LMS}_{ji} * (err\_lms_{(3,i)})^H; \tag{4.25}$$

$$\hat{\mathbf{W}}_{(4,i+1)} = \hat{\mathbf{W}}_{(4,i)} + \mu * \mathbf{U\_LMS}_{ji} * (err\_lms_{(4,i)})^H; \tag{4.26}$$

where:

- $\hat{\mathbf{W}}_{(x,i+1)}$ denotes the estimate of LMS tap-weight vector at time i+1, and x=1,2,3,4;
- μ is the step-size parameter, which can be suitably chosen as per the related practical requirement; Note that when step size μ is small enough, the estimated weights can tend to the optimal weights. However, if μ is too small, the adaptive estimated weights apparently lag behind the optimal weights required. In general, step size μ will be in the range of

  $0 < \mu < 2/\lambda_{max}$, as stated before.

4.13 Detection Rules of LMS Filter Tracking Solution

$$\hat{b}^{(n)} = \text{sgn}(\text{real}(\hat{\mathbf{W}}_{ij}^H(n) * \mathbf{U\_LMS}_{ji}(n))); \tag{4.27}$$

where $\hat{b}^{(n)}$ is the final received bits after passing by LMS filters at time n.

Next, let us continue the previous example (**b** = [-1 -1 -1 -1]).

- 1 receiver

$$\hat{b}(1,i) = \text{sgn}(\text{real}(ylms01_{(1,i)})); \quad (4.28)$$

$$\hat{b}(2,i) = \text{sgn}(\text{real}(ylms01_{(2,i)})); \quad (4.29)$$

$$\hat{b}(3,i) = \text{sgn}(\text{real}(ylms01_{(3,i)})); \quad (4.30)$$

$$\hat{b}(4,i) = \text{sgn}(\text{real}(ylms01_{(4,i)})); \quad (4.31)$$

where:

- $\hat{b}(j,i)$ is the estimated *j*th sub receive vectors at time *i*;
- $ylms01_{(j,i)}$ denotes the final decision variables at time *i*, which can computed in Eq.4.12 – Eq.4.15.

Likewise, we can compute and obtain all of estimated receive bits in the 2 or 3 or 4-receiver case, respectively.

4.14 Chapter Summary

In this chapter, a reduced complexity detection algorithm employing adaptive LMS filters with permutation spreading technique for CDMA/MIMO systems with 1 to 4 receive antennas in slowly varying Rayleigh fading channels is presented and proposed. In particular, based upon the further investigating of LMS tracking weight pilot bound varying, we acquire a very valuable insight, that is, the LMS tracking training /pilot bound can be roughly estimated without further use of Wiener filters. As a result, the proposed LMS tracking algorithm can not only provide reasonable BER performance but also reduce dramatically computational complexity as well as provides with tracking of fading channels. For more details about the BER performance comparison and computation complexity analysis of the proposed LMS tracking detection technique, please see Chapter 5.

Chapter 5 Simulation Results and Complexity Analysis of the Proposed LMS Tracking Detection Algorithm

5.1 Related Assumptions of Simulation BER Performance

The performed simulations of bit error rate (BER) performance of MLD Solution, Wiener filters detection, LMS tracking solution, as well as conventional approach are stated in this section. The considered systems are CDMA/MIMO with 4 transmit antennas and 1 through 4 receive antennas. These simulation models are based on the following assumptions:

(1) The slowly varying Rayleigh fading channels are applied;

(2) The channel gains are modeled as slowly varying complex Gaussian random variables;

(3) There is no cross-correlation between different receive antenna links due to different and independent transmit antennas.

Next, the BER performance of MLD detection, Wiener filter detection, conventional method, and proposed LMS filter tracking detection schemes with different fading factors and LMS step-size parameter μ over slowing varying Rayleigh fading channels for CDMA/MIMO systems with 1 to 4 receive antennas are shown and analyzed in the following, respectively.

5.2 The BER Performance Comparison of Four Detection Algorithms (MLD, Wiener, LMS tracking, Conventional method) for CDMA/MIMO Systems

First of all, we will examine the BER performance of the four different detection techniques using for CDMA/MIMO systems with 1 to 4 receive antennas over same channels environments. The conventional approach for CDMA/MIMO system can be found in [5]. And several different simulation situations are depicted below.

5.2.1 The BER Performance Comparison of the Four Detection Algorithms for CDMA/MIMO System with 1 Receive Antenna

- Case 1 - 1 receiver with fading factor $R_f = 0.99$ and LMS weight step-size $\mu = 0.05$

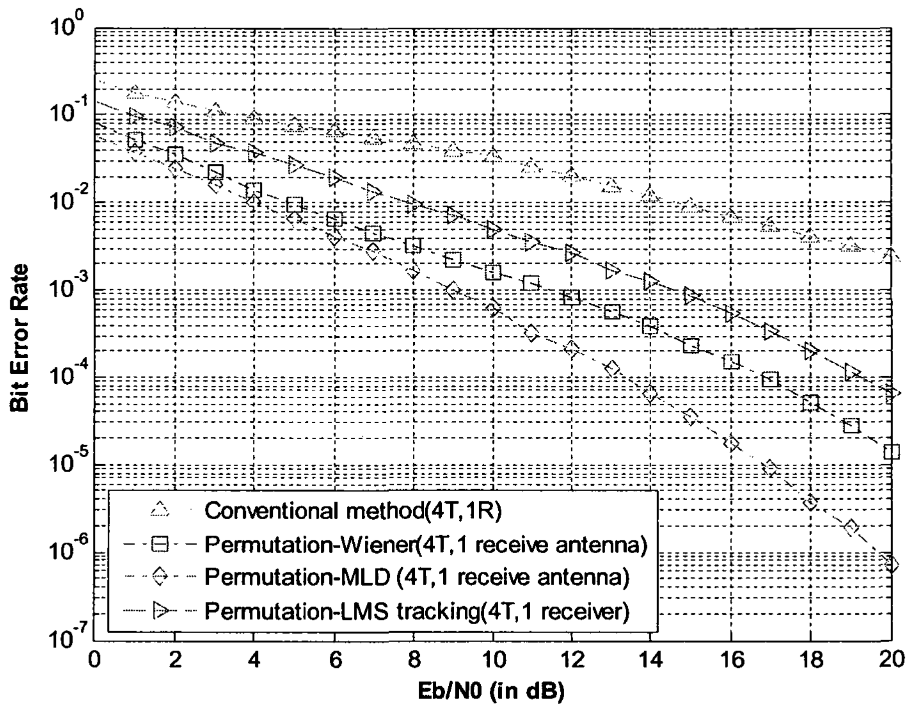

Figure 5.1 BER performance comparison of MLD, Wiener, Conventional method, and LMS solution (4 transmitters, 1 receiver, $R_f = 0.99$, LMS step-size $\mu = 0.05$)

In Figure 5.1, we plot the BER of MLD detection, Wiener filter detection, Conventional method, and proposed LMS tracking detection schemes with fading factor $R_f = 0.99$, LMS step-size $\mu = 0.05$ for CDMA/MIMO systems with 1 receiver. In the figure, we demonstrate the simulation results of the four detection schemes. From the figure, we observe the following four features.

(a) The BER performance of proposed LMS tracking detection is in between that of Conventional method and MLD;

(b) The BER performance of proposed LMS tracking is much better than that of conventional method. For instance, for CDMA/MIMO systems with 4 transmitters and 1 receiver, at a BER of 10^{-2}, LMS scheme provides roughly 7 dB improvements over conventional method, while provides about 10 dB improvement over conventional method at a BER of 10^{-3};

(c) The BER performance of proposed LMS tracking detection is less than that of Wiener or MLD detection scheme but not sacrificing too much. Specifically, at a BER of 10^{-3}, LMS tracking scheme for 1 receiver system produces roughly 5.5 dB and 3 dB losses over MLD and Wiener filter scheme, respectively. Relatively, comparing with MLD and conventional method, the performance of proposed LMS tracking is closer to the MLD detection solution while offers outstanding BER gain over conventional method;

(d) For LMS tracking detection scheme, the bit error rate at $SNR = 14.5$ dB is around 10^{-3}, which can be still reasonable in actual CDMA/MIMO systems over slowly varying Rayleigh fading channels.

- Case 2 - 1 receiver with fading factor = 0.99 and LMS weight step-size $\mu = 0.005$

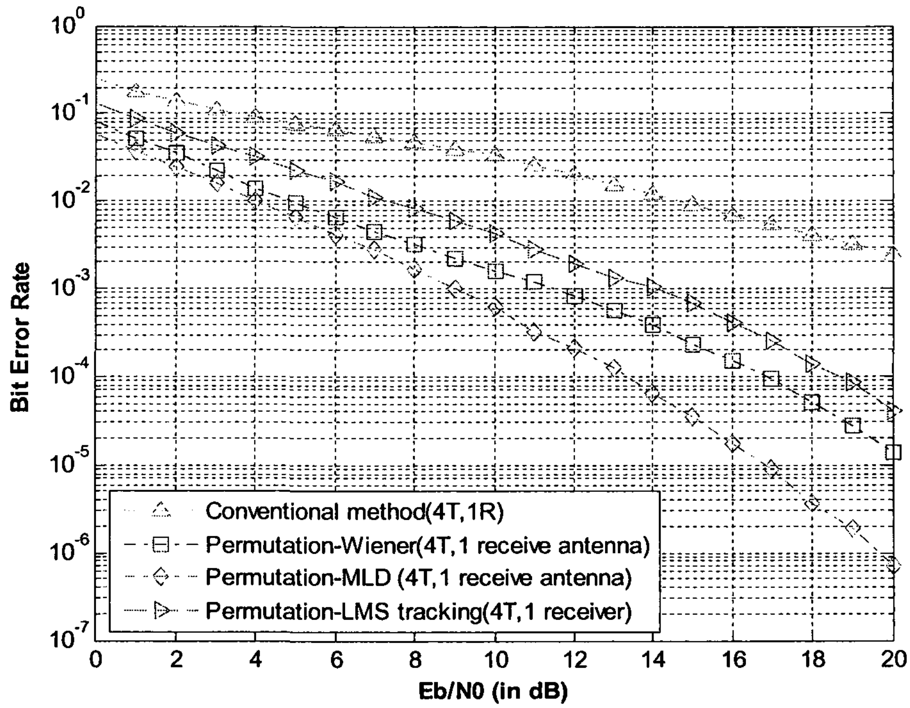

Figure 5.2 BER performance comparison of MLD, Wiener, Conventional method, and LMS solution (1 receiver, R_f = 0.99, LMS step-size μ =0.005)

In Figure 5.2, we plot the BER of MLD detection, Wiener filter detection, Conventional method, and proposed LMS tracking detection schemes with fading factor R_f = 0.99, LMS step-size μ =0.005 for CDMA/MIMO systems with 1 receiver. Compare to Figure 5.1, based on same parameter and conditions except for small LMS weight tap-size μ =0.005 along with fixed fading factor, we see that the better BER improvement can be achieved by using smaller LMS weight tap-size parameter. And more detailed measurement on LMS tracking will be introduced in Section 5.3 to Section 5.5.

- Case 3 - 1 receiver with fading factor = 0.99 and LMS weight step-size μ = 0.001

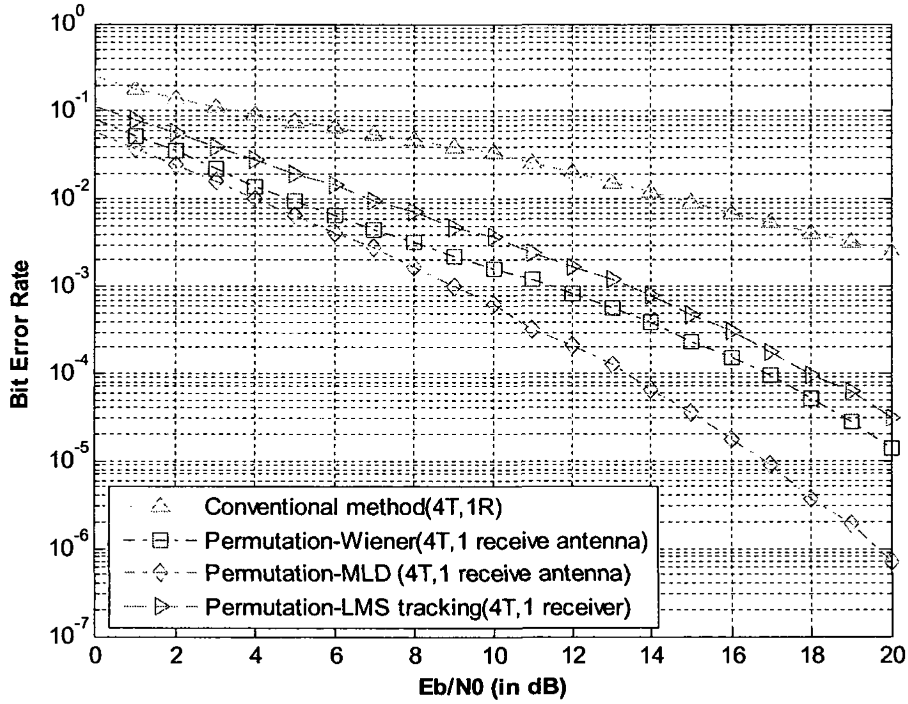

Figure 5.3 BER performance comparison of MLD, Wiener, Conventional method, and LMS solution (1 receiver, R_f = 0.99, LMS step-size μ =0.001)

In Figure 5.3, we plot the BER of MLD detection, Wiener filter detection, Conventional method, and proposed LMS tracking detection schemes with fading factor = 0.99, LMS step-size μ =0.001 for CDMA/MIMO systems with 1 receiver. Compare to Figure 5.1 and Figure 5.2, based on same parameter and conditions except for small LMS weight tap-size μ =0.001 along with fixed fading factor, we see that the better BER improvement can be achieved by employing smaller LMS weight tap-size parameter. And more measurement on LMS tracking detection will be presented in Section 5.3 to Section 5.5.

- Case 4 - 1 receiver with fading factor = 0.995 and LMS weight step-size $\mu = 0.05$

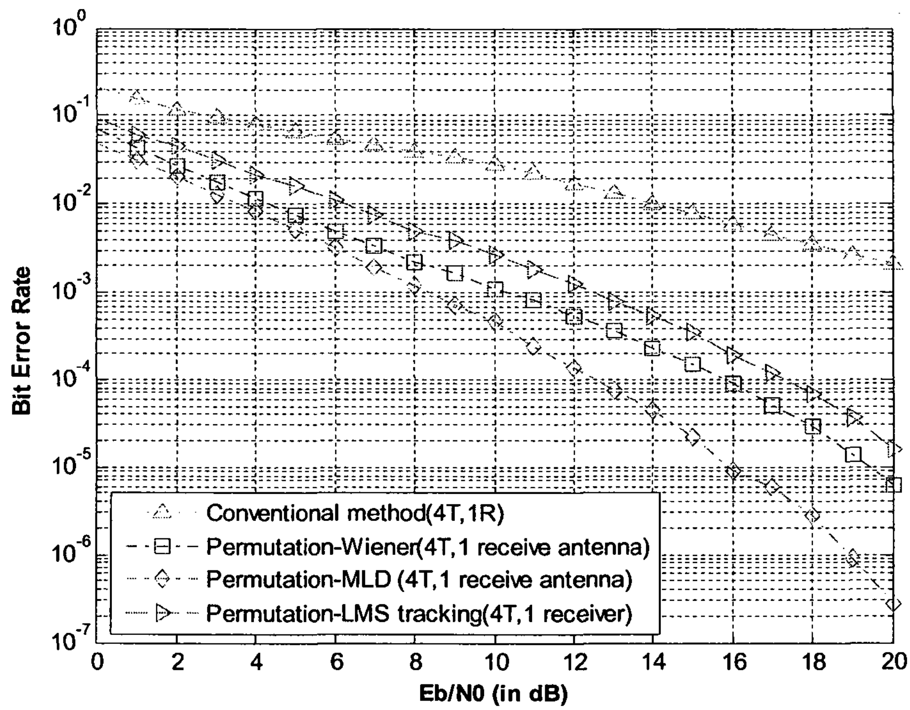

Figure 5.4 BER performance comparison of MLD, Wiener, Conventional method, and LMS solution (1 receiver, R_f = 0.995, LMS step-size μ =0.05).

In Figure 5.4, we demonstrate the BER simulation results of MLD detection, Wiener filter detection, conventional method, and proposed LMS tracking detection schemes with fading factor R_f = 0.995 and LMS step-size μ =0.05 for CDMA/MIMO systems with 1 receiver. Compare to Figure 5.1, their condition and parameters are same except for fading factor =0.995 along with fixed LMS weight tap-size parameter μ.

Clearly, we observe that the BER performance of LMS tracking detection, which is employed in slower varying Rayleigh fading channels (fading factor R_f = 0.995), can acquire apparent BER performance improvement. As for this point, more detailed performance comparison on LMS tracking will be discussed in Section 5.3 to Section 5.5.

- Case 5 - 1 receiver with fading factor = 0.998 and LMS weight step-size μ = 0.05

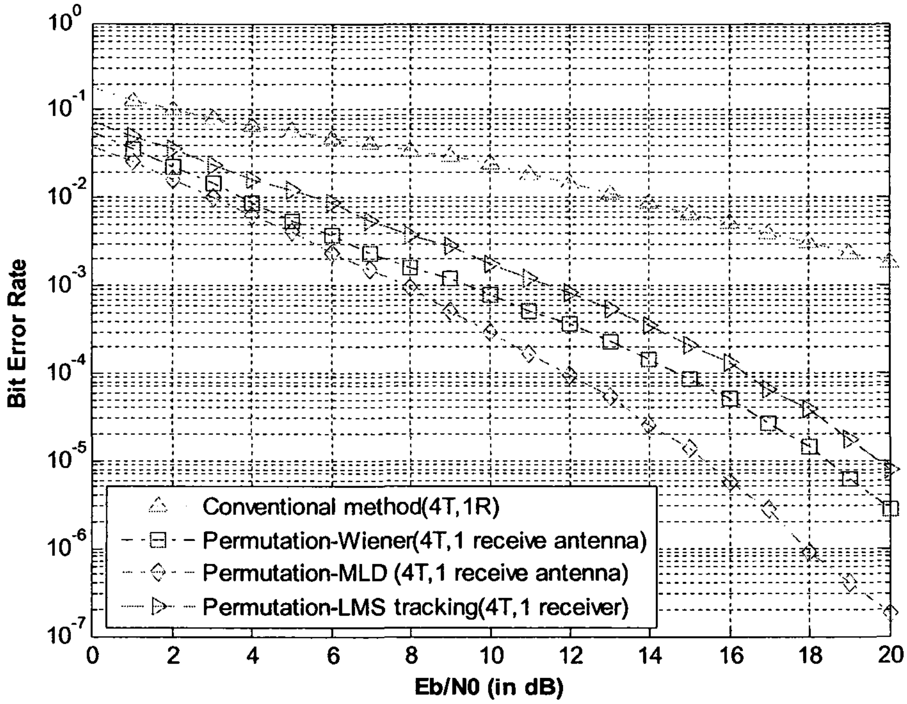

Figure 5.5 BER performance comparison of MLD, Wiener, Conventional method, and LMS solution (1 receiver, R_f = 0.998, LMS step-size μ =0.05).

In Figure 5.5, we plot the BER simulation of MLD detection, Wiener filter detection, conventional method, and proposed LMS tracking detection schemes with fading factor = 0.998 and LMS step-size μ =0.05 for CDMA/MIMO systems with 1 receiver. Compare to Figure 5.1 and Figure 5.4, their condition and parameters are same except for fading factor R_f=0.998 along with fixed LMS weight tap-size parameter μ.

From Figure 5.5, we see that the BER performance of LMS tracking detection, which is employed in slower varying Rayleigh fading channels (fading factor R_f= 0.998), is better than that of the cases related to fading factor R_f= 0.99 or 0.995.

- Case 6 - 1 receiver with fading factor = 0.998 and LMS weight step-size $\mu = 0.001$

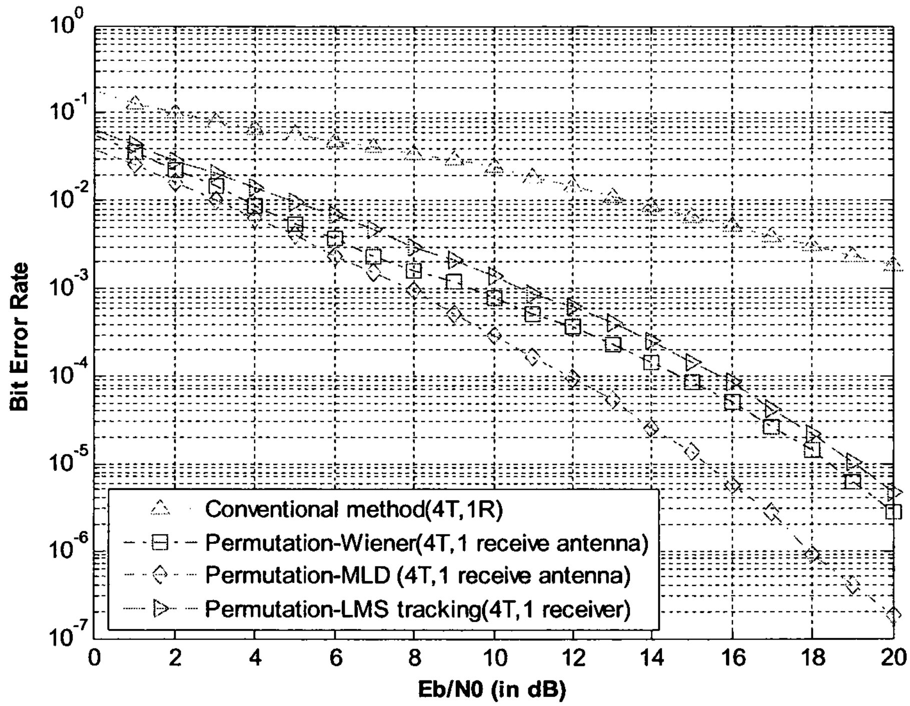

Figure 5.6 BER performance comparison of MLD, Wiener, Conventional method, and LMS solution (1 receiver, R_f = 0.998, LMS step-size μ =0.001)

In Figure 5.6, we demonstrate of the BER simulation result of MLD detection, Wiener filter detection, Conventional method, and proposed LMS tracking detection schemes with fading factor R_f = 0.998, LMS step-size μ =0.001 for CDMA/MIMO systems with 1 receiver.

Compare to Figure 5.5, based on same parameter and conditions except for smaller LMS weight tap-size μ =0.001 along with fixed fading factor R_f = 0.998, we see that the better BER improvement can be achieved by employing smaller LMS weight tap-size parameter. And more measurement on LMS tracking dètection will be further discussed in Section 5.3 to Section 5.5.

5.2.2 The BER Performance Comparison of the Four Detection Algorithms for CDMA/MIMO System with 2 Receive Antennas

- Case 7: 2-receiver with fading factor $R_f = 0.99$ and LMS weight step-size $\mu = 0.05$

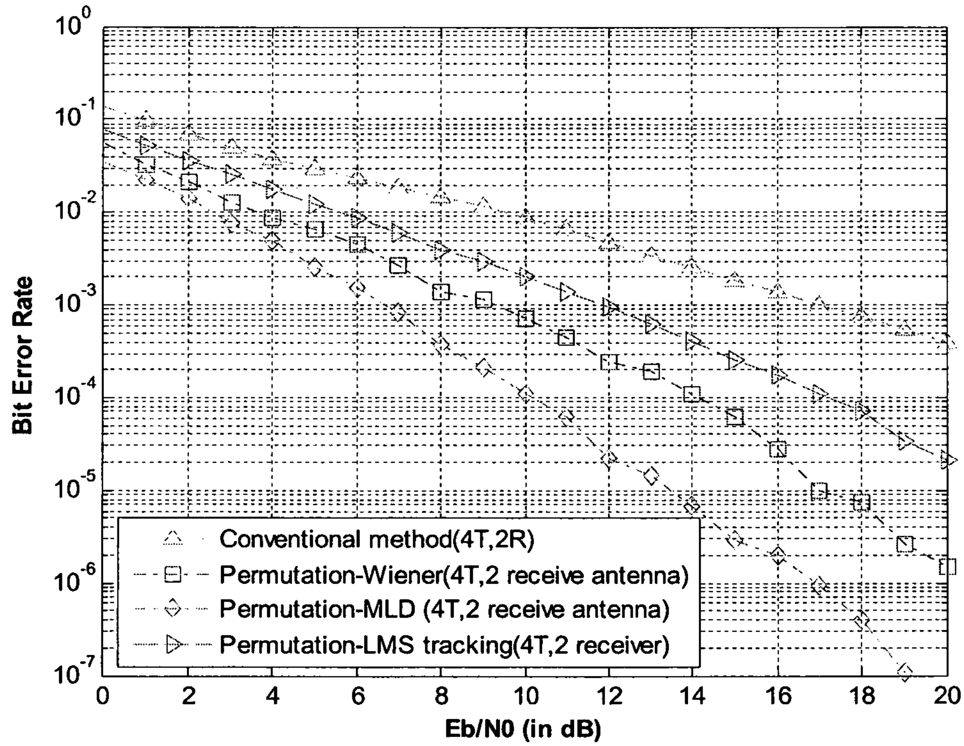

Figure 5.7 BER performance comparison of MLD, Wiener, Conventional method, and LMS solution (2 receivers, $R_f = 0.99$, LMS step-size μ =0.05)

In Figure 5.7, we plot the BER of the four schemes (MLD detection, Wiener filter detection, Conventional approach, and proposed LMS tracking detection schemes) with fading factor R_f = 0.99 and LMS step-size μ =0.05 for CDMA/MIMO systems with 2 receivers.

Compare to Figure 5.1, their condition and parameters are same except for different number of receive antenna. Clearly, we observe that the BER performance of the three detection schemes with 2 receive antennas are apparently better than that with 1 receiver.

- Case 8: 2-receiver with fading factor = 0.99 and LMS weight step-size $\mu = 0.005$

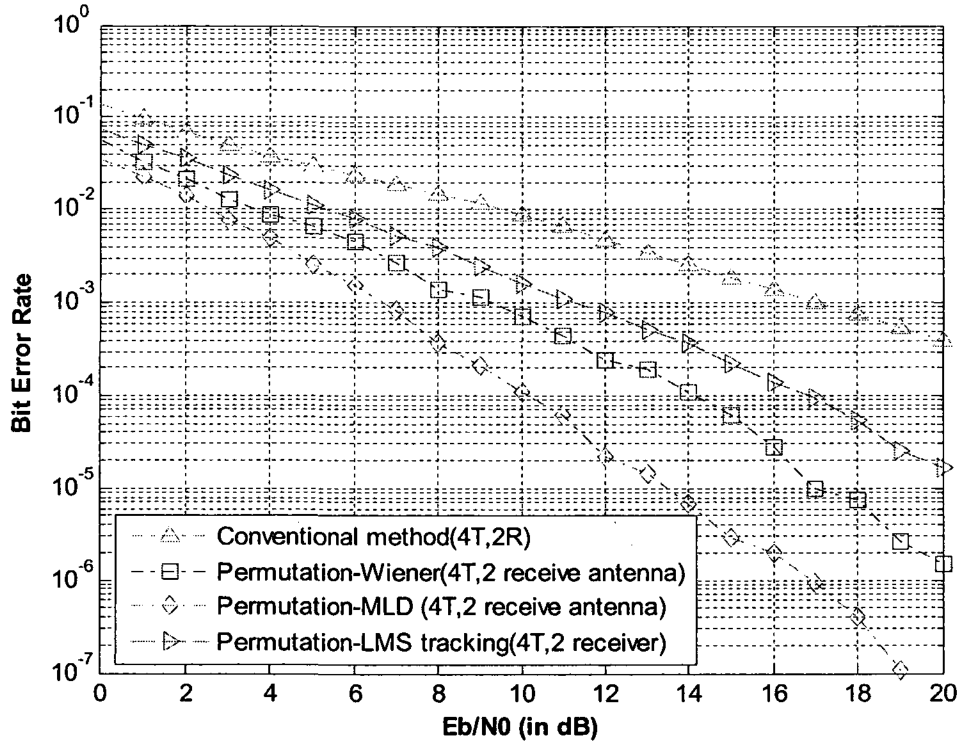

Figure 5.8 BER performance comparison of MLD, Wiener, Conventional method, and LMS solution (2 receivers, R_f = 0.99, LMS step-size μ =0.005)

In Figure 5.8, we demonstrate the BER simulation results of the MLD detection, Wiener filter detection, Conventional method, and proposed LMS tracking detection schemes with fading factor R_f = 0.99 and LMS step-size μ =0.005 for CDMA/MIMO systems with 2 receivers. Compare to Figure 5.2, their parameters along with related condition are same except for different number of receive antennas.

Clearly, compare with Figure 5.2, we see that the BER performance of the four detection solutions with 2 receive antennas are apparently better than that with 1 receiver based upon same parameter and fading channel. Also, compare with Figure 5.7, it is observed that the LMS scheme with smaller weight tap-size parameter can achieve better BER performance improvement.

- Case 9: 2-receiver with fading factor = 0.99 and LMS weight step-size μ = 0.001

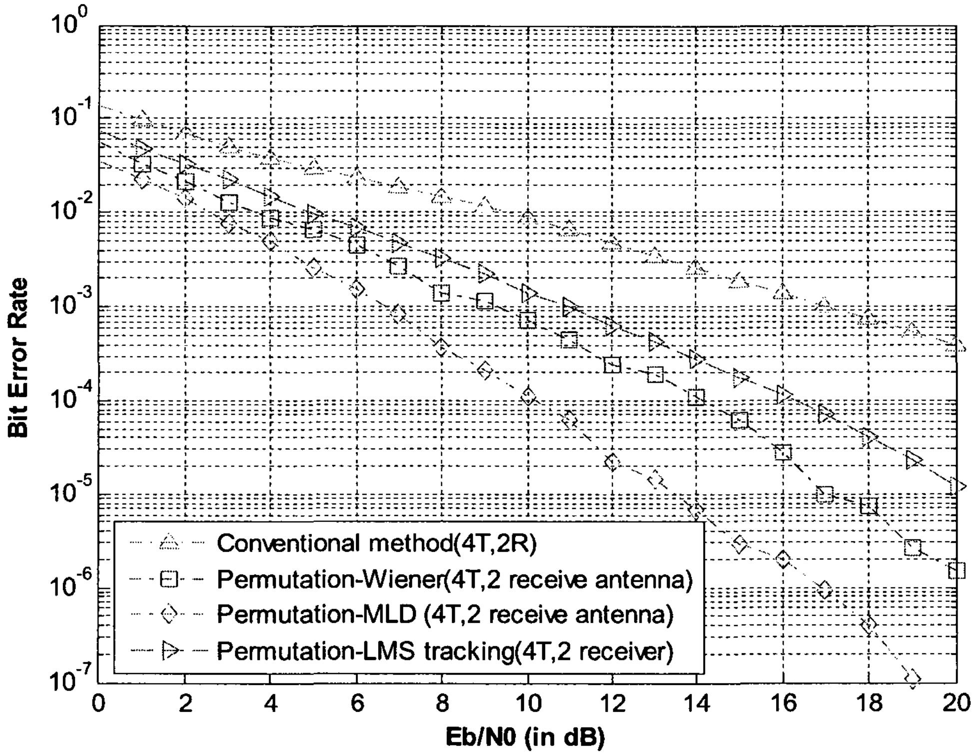

Figure 5.9 BER performance comparison of MLD, Wiener, Conventional method, and LMS solution (2 receivers, R_f = 0.99, LMS step-size μ =0.001)

In Figure 5.9, we demonstrate the BER simulation results of the MLD detection, Wiener filter detection, Conventional method, and proposed LMS tracking detection schemes with fading factor R_f = 0.99 and LMS step-size μ =0.001 for CDMA/MIMO systems with 2 receivers. Compare with Figure 5.3, their parameters along with related condition are same except for different number of receive antennas.

Similarly, in comparison with Figure 5.3, we see that the BER performance of the four detection solutions with 2 receive antennas are clearly better than that with 1 receiver based upon same parameter and fading channel. Also, compare with Figure 5.7 and Figure 5.8, it is observed that the LMS scheme with smaller weight tap-size parameter can achieve better BER performance gain.

- Case 10: 2-receiver with fading factor = 0.995 and LMS weight step-size μ = 0.05

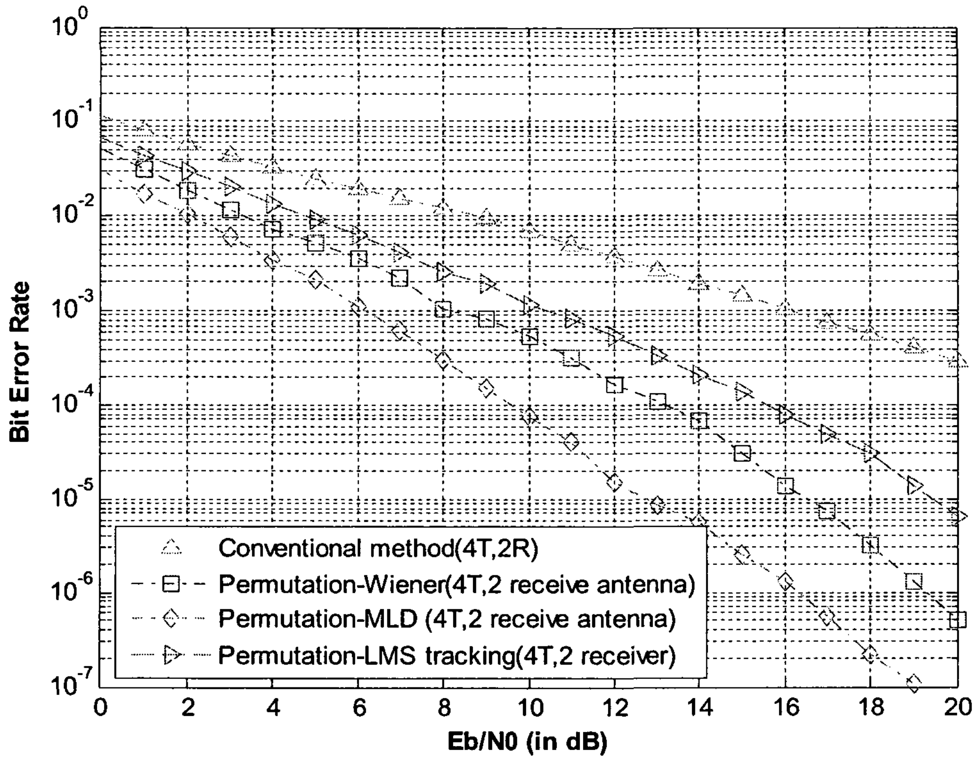

Figure 5.10 BER performance comparison of MLD, Wiener, and LMS solution (2 receivers, R_f = 0.995, LMS step-size μ =0.05)

In Figure 5.10, we plot the BER of the MLD detection, Wiener filter detection, Conventional approach, and proposed LMS tracking detection schemes with fading factor R_f = 0.995 and LMS step-size μ =0.05 for CDMA/MIMO systems with 2 receivers.

Compare with Figure 5.4, they are in the same parameters and condition except for different number of receiver. Clearly, we observe that same feature: the BER performance results of the four detection solutions with 2 receive antennas are obviously better than that with 1 receiver based upon same parameters and fading channels.

- Case 11: 2-receiver with fading factor = 0.998 and LMS weight step-size μ = 0.05

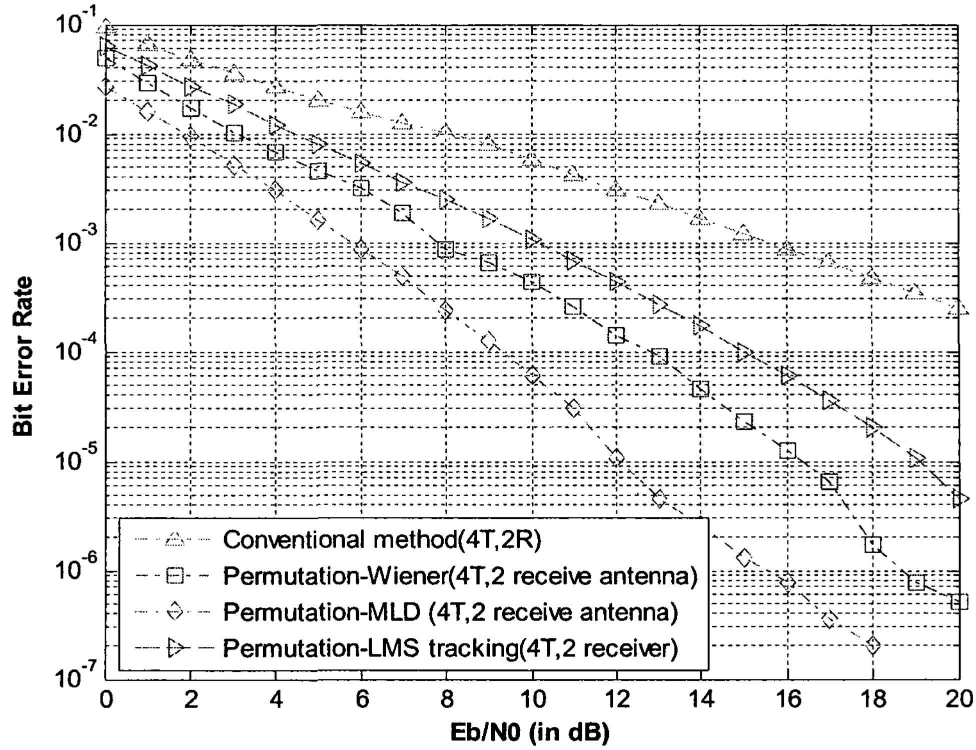

Figure 5.11 BER performance comparison of MLD, Wiener, and LMS solution (2 receivers, R_f = 0.998, LMS step-size μ =0.05)

In Figure 5.11, we show the BER simulation result of the MLD detection, Wiener filter detection, Conventional approach, and proposed LMS tracking detection schemes with fading factor R_f = 0.998 and LMS step-size μ =0.05 for CDMA/MIMO systems with 2 receivers.

In comparison with Figure 5.5, they are in the same parameters and condition except for different number of receiver. Apparently, we see that same feature: the BER performance results of the four detection solutions with 2 receive antennas are better than that with 1 receiver based upon same parameters and fading channels.

- Case 12: 2-receiver with fading factor = 0.998 and LMS weight step-size μ = 0.001

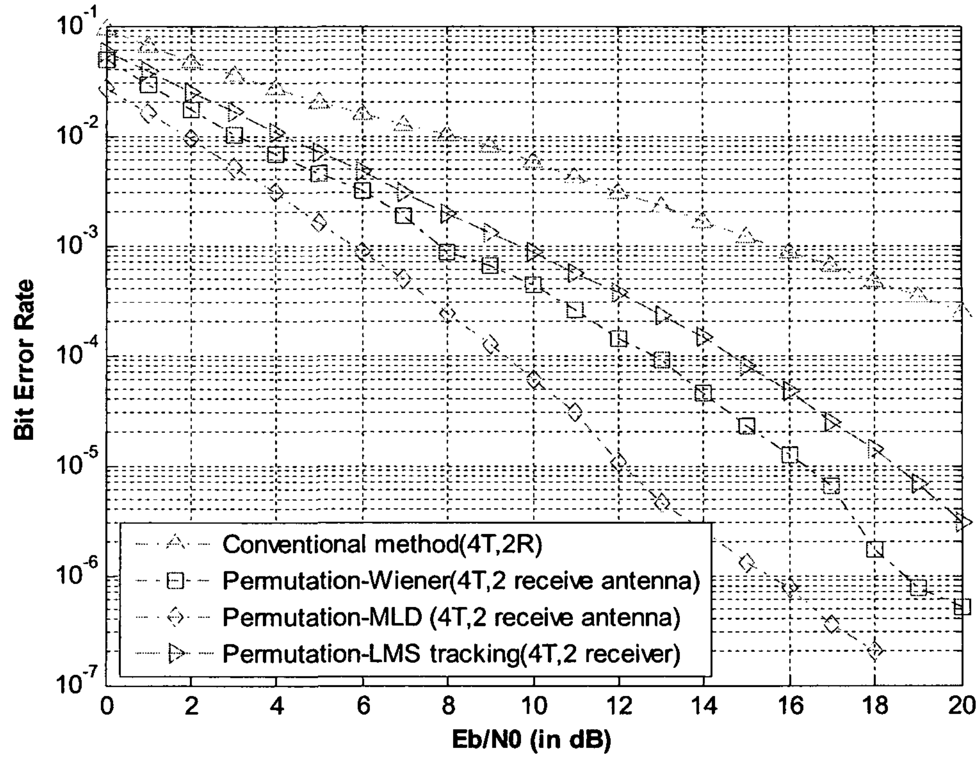

Figure 5.12 BER performance comparison of MLD, Wiener, Conventional method, and LMS solution (2 receivers, R_f = 0.998, LMS step-size μ =0.001)

In Figure 5.12, we demonstrate the BER simulation results of the MLD detection, Wiener filter detection, Conventional method, and proposed LMS tracking detection schemes with fading factor R_f = 0.998 and LMS step-size μ =0.001 for CDMA/MIMO systems with 2 receivers.

Compare with Figure 5.6, their parameters along with related condition are same except for different number of receive antennas. Similarly, in comparison with Figure 5.6, we see that the BER performance of the four detection solutions with 2 receive antennas are apparently better than that with 1 receiver based upon same parameter and fading channel. Also, compare with Figure 5.11, it is observed that the LMS scheme with smaller weight tap-size parameter can achieve better BER performance gain.

5.2.3 The BER Performance Comparison of the Four Detection Algorithms for CDMA/MIMO System with 3 Receive Antennas

In this section, similar to Section 5.2.1 and Section 5.2.2, we show the BER simulation results of the four detections (MLD detection, Wiener filter detection, Conventional method, and proposed LMS tracking detection schemes) with different fading factors and different LMS step-size μ for CDMA/MIMO systems with 3 receivers.

As will be seen from Figure 5.13 to Figure 5.18, an apparent feature is outlined below:

Based upon same fading channels and same related conditions, the BER performance of the four detection algorithms using for CDMA/MIMO systems with 3 receivers is clearly better than that for CDMA/MIMO with 1 or 2 receiver cases.

For example, in Figure 5.18, we demonstrate the BER simulation results of the four detections (MLD detection, Wiener filter detection, and proposed LMS tracking detection schemes) with fading factor $R_f = 0.998$ and LMS step-size $\mu = 0.001$ for CDMA/MIMO systems with 3 receivers. Compare to Figure 5.6 and Figure 5.12, their parameters along with related condition are same except for different number of receive antenna. Apparently, it is easy to observe that the BER performance of the four detection schemes with 3 receive antennas are much better than that with 1 receiver or 2 receivers based upon same parameter and fading channels.

- Case 13: 3-receiver with fading factor = 0.99 and LMS weight step-size $\mu = 0.05$

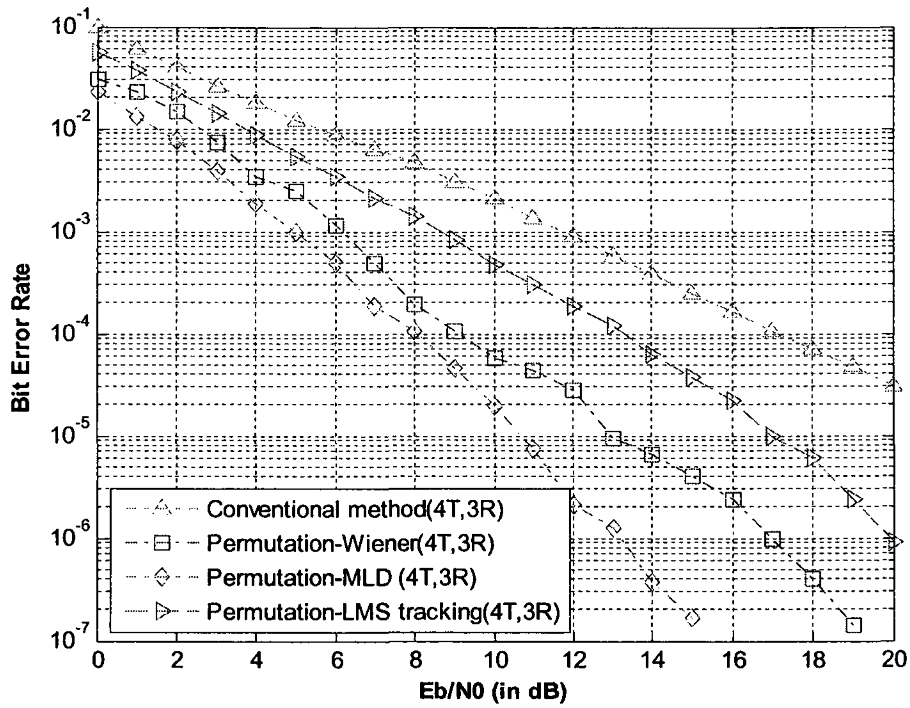

Figure 5.13 BER performance comparison of MLD, Wiener, Conventional method, and LMS solution (3 receivers, R_f = 0.99, LMS step-size μ =0.05)

- Case 14: 3-receiver with fading factor = 0.99 and LMS weight step-size $\mu = 0.005$

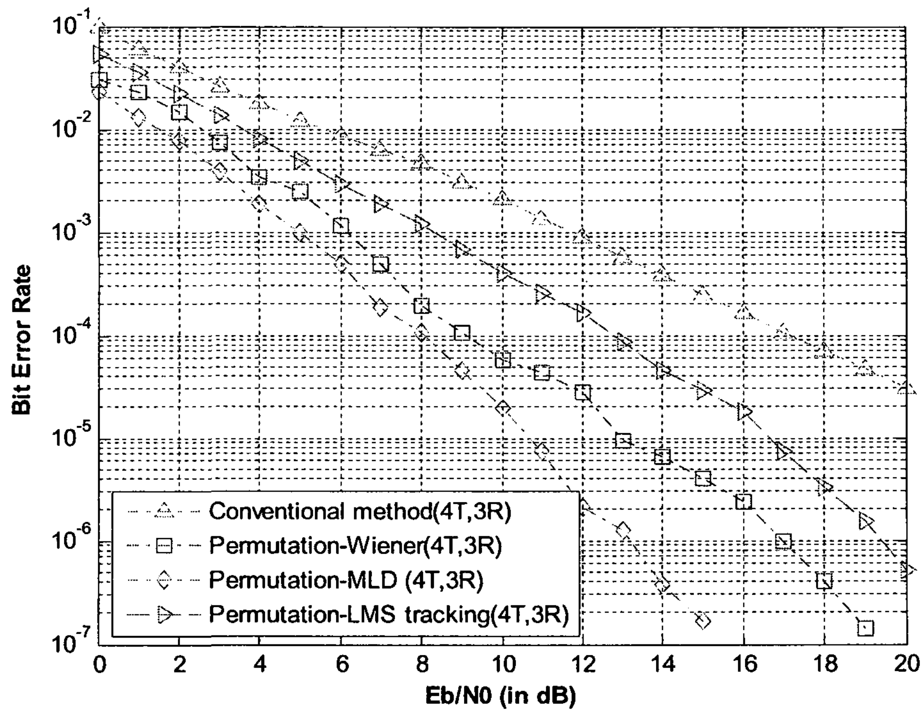

Figure 5.14 BER performance comparison of MLD, Wiener, Conventional method, and LMS solution (3 receivers, $R_f = 0.99$, LMS step-size $\mu = 0.005$)

- Case 15: 3-receiver with fading factor = 0.99 and LMS weight step-size $\mu = 0.001$

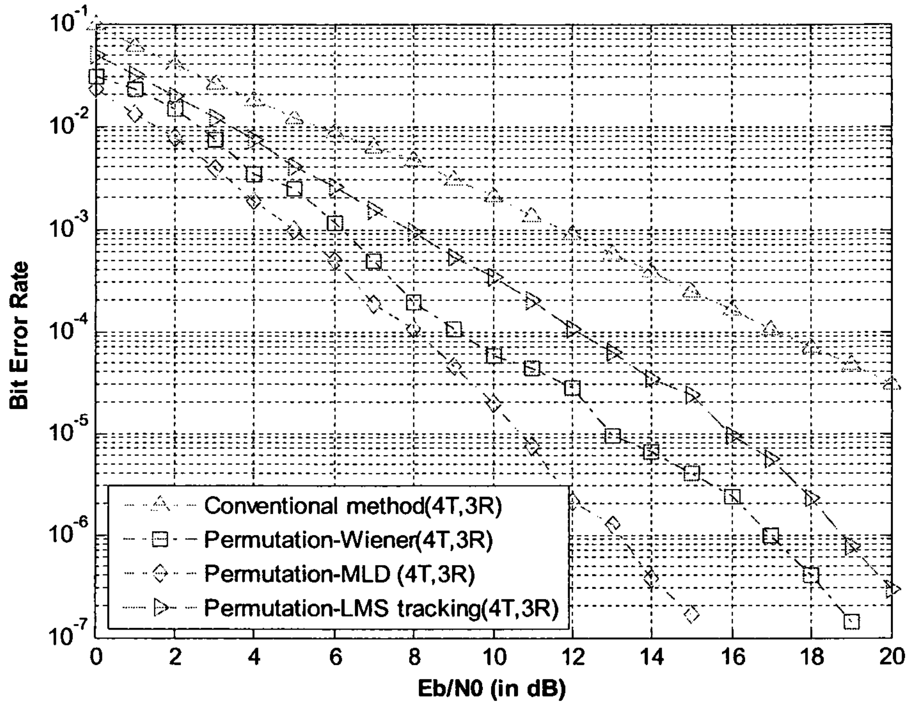

Figure 5.15 BER performance comparison of MLD, Wiener, Conventional method, and LMS solution (3 receivers, R_f = 0.99, LMS step-size μ =0.001)

- Case 16: 3-receiver case with fading factor = 0.995 and LMS weight step-size μ = 0.05

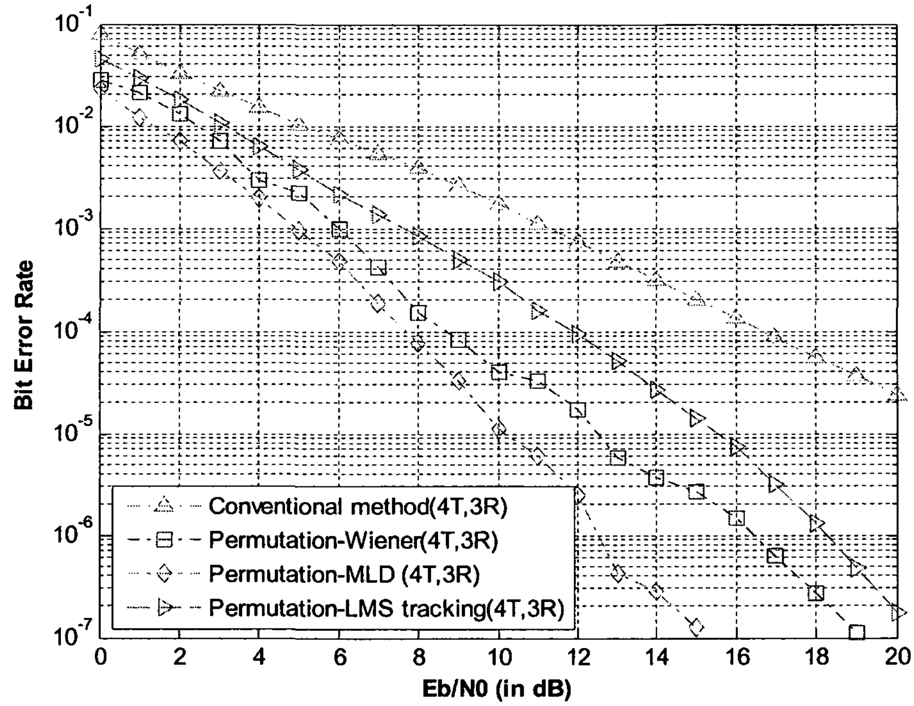

Figure 5.16 BER performance comparison of MLD, Wiener, Conventional method, and LMS solution (3 receivers, R_f = 0.995, LMS step-size μ =0.05)

- Case 17: 3-receiver case with fading factor = 0.998 and LMS weight step-size μ = 0.05

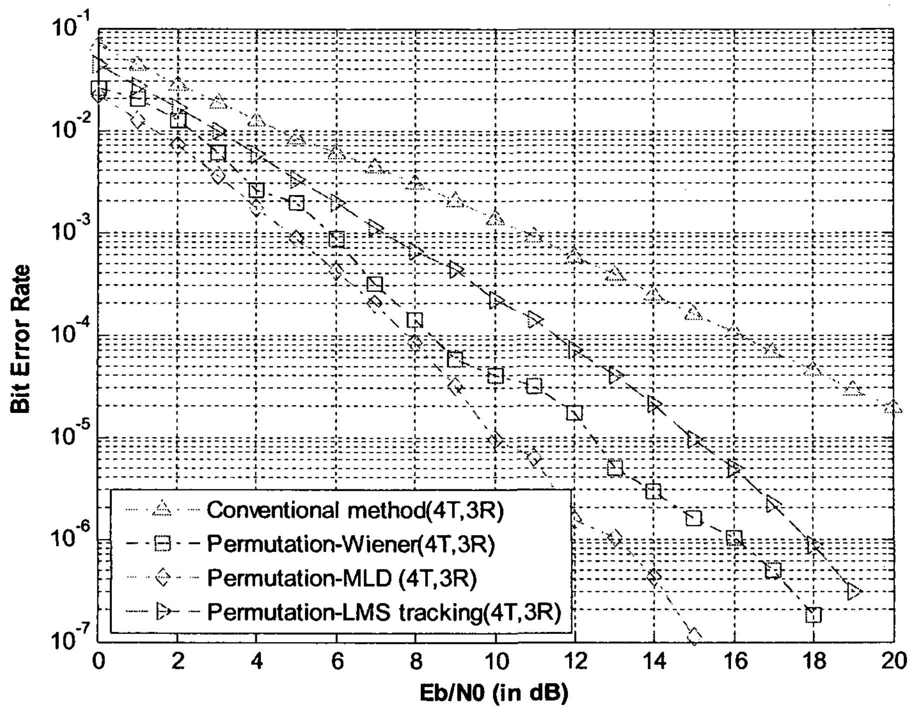

Figure 5.17 BER performance comparison of MLD, Wiener, Conventional method, and LMS solution (3 receivers, R_f = 0.998, LMS step-size μ =0.05)

- Case 18: 3-receiver case with fading factor = 0.998 and LMS weight step-size μ = 0.001

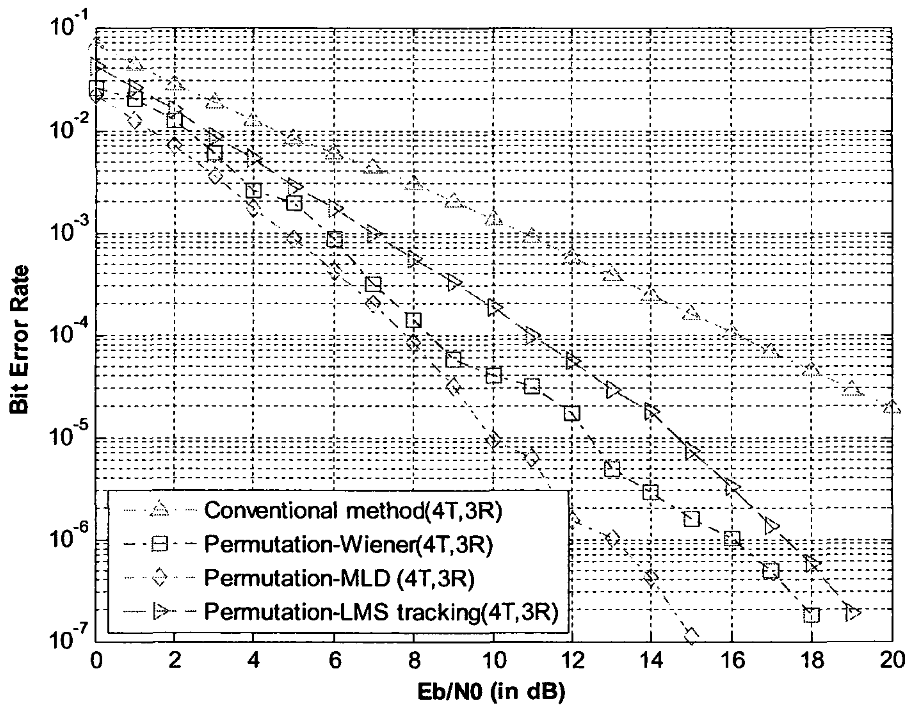

Figure 5.18 BER performance comparison of MLD, Wiener, Conventional method, and LMS solution (3 receivers, R_f = 0.998, LMS step-size μ =0.001)

5.2.4 The BER Performance Comparison of the Four Detection Algorithms for CDMA/MIMO System with 4 Receive Antennas

In this section, again, we demonstrate the BER simulation results of the four detections (MLD detection, Wiener filter detection, Conventional method, and proposed LMS tracking detection schemes) with different fading factors and different LMS step-size μ for CDMA/MIMO systems with 4 receive antennas.

As will be seen from Figure 5.19 to Figure 5.24, again, we see the same feature mentioned in Section 5.2.3. That is, when the four detection algorithms with same parameter and conditions are employed for CDMA/MIMO systems with different number of receive antennas in same fading channels, the BER performance related to 4 receivers is better than that related to 1, 2, or 3 receive antennas.

- Case 19: 4-receiver with fading factor = 0.99 and LMS weight step-size μ = 0.05

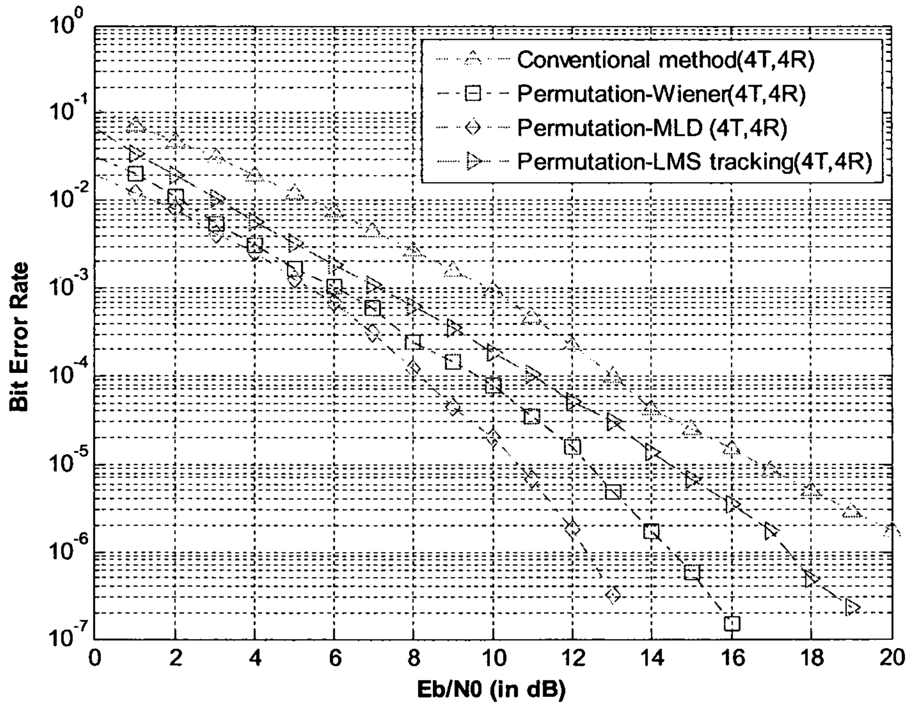

Figure 5.19 BER performance comparison of MLD, Wiener, Conventional method, and LMS solution (4 receivers, R_f = 0.99, LMS step-size μ =0.05)

- Case 20: 4-receiver with fading factor = 0.99 and LMS weight step-size $\mu = 0.005$

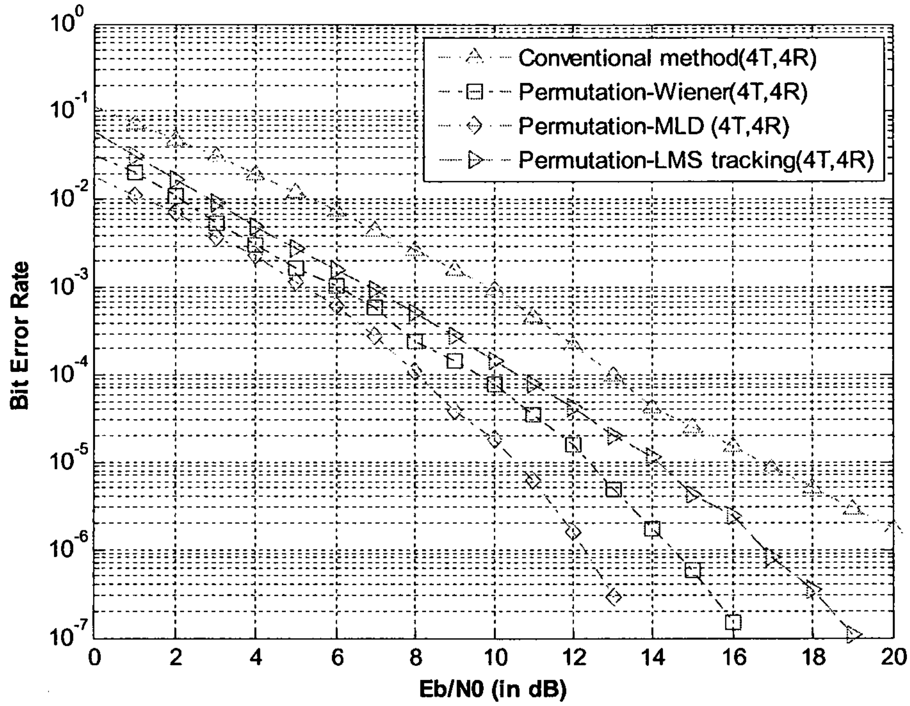

Figure 5.20 BER performance comparison of MLD, Wiener, Conventional method, and LMS solution (4 receivers, R_f = 0.99, LMS step-size μ =0.005)

- Case 21: 4-receiver with fading factor = 0.99 and LMS weight step-size μ = 0.001

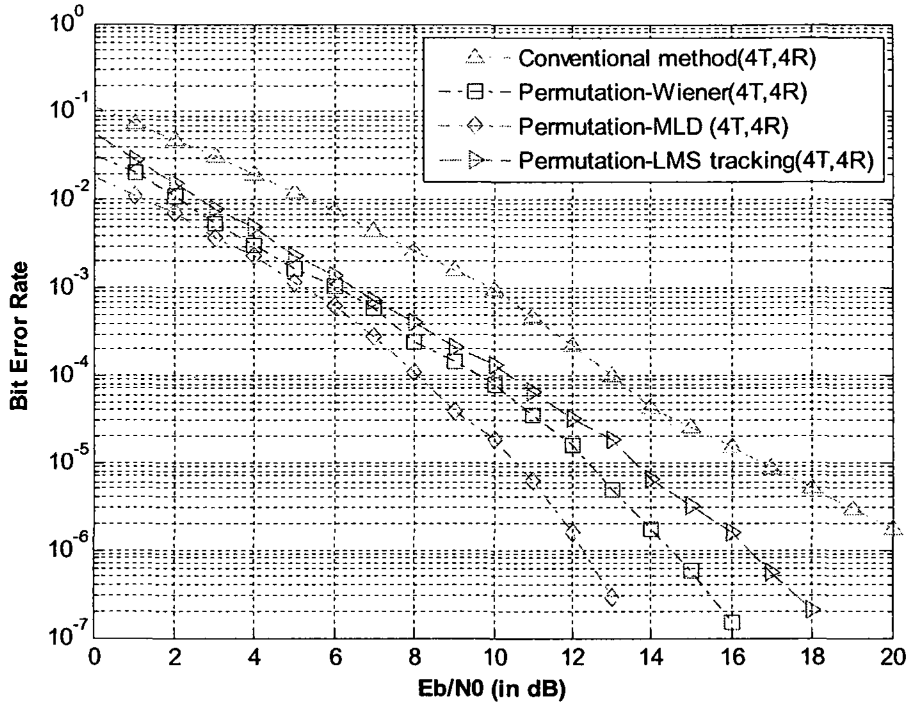

Figure 5.21 BER performance comparison of MLD, Wiener, Conventional method, and LMS solution (4 receivers, R_f = 0.99, LMS step-size μ =0.001)

- Case 22: 4-receiver case with fading factor = 0.995 and LMS weight step-size μ = 0.05

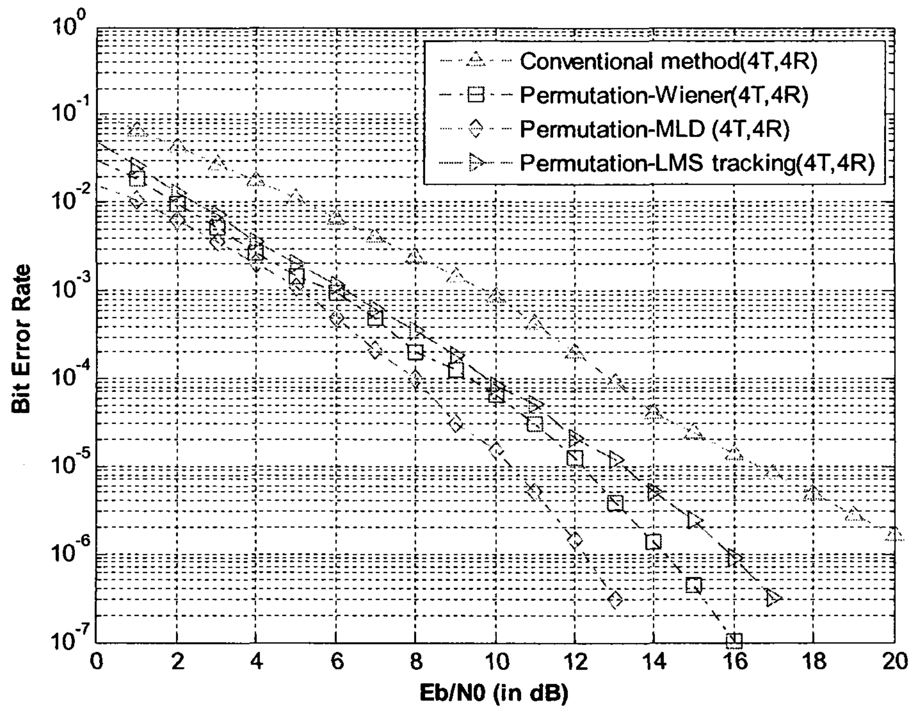

Figure 5.22 BER performance comparison of MLD, Wiener, Conventional method, and LMS solution (4 receivers, R_f = 0.995, LMS step-size μ =0.05)

- Case 23: 4-receiver case with fading factor = 0.998 and LMS weight step-size μ = 0.05

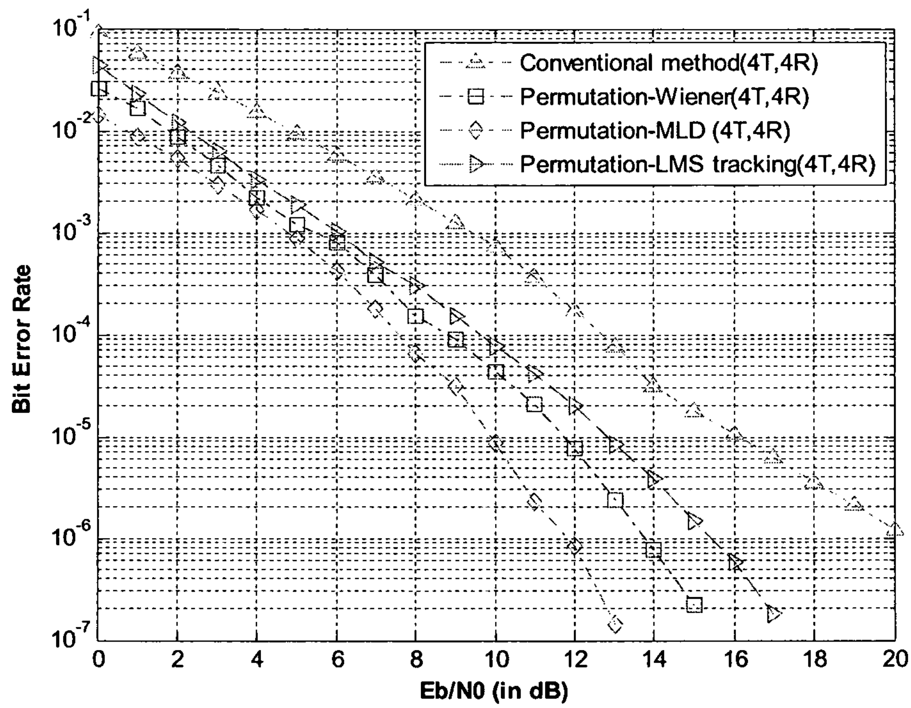

Figure 5.23 BER performance comparison of MLD, Wiener, Conventional method, and LMS solution (4 receivers, R_f = 0.998, LMS step-size μ =0.05)

- Case 24: 4-receiver case with fading factor = 0.998 and LMS weight step-size μ = 0.001

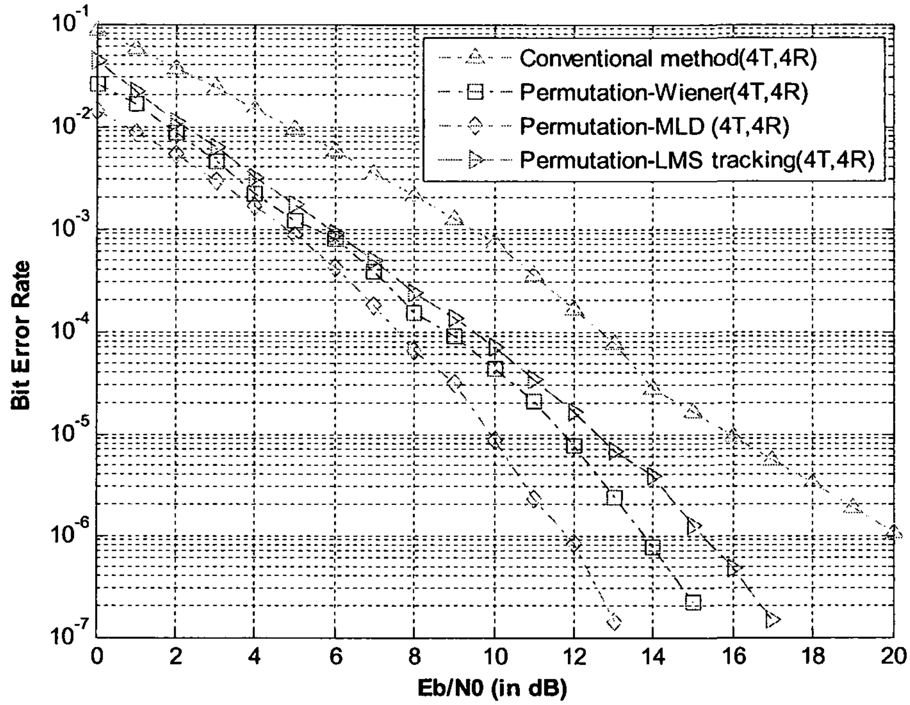

Figure 5.24 BER performance comparison of MLD, Wiener, Conventional method, and LMS solution (4 receivers, R_f = 0.998, LMS step-size μ =0.001)

5.3 The BER Performance Comparison of LMS Tracking Detection Algorithm with Different Step-size for CDMA/MIMO Systems in the same Rayleigh Fading Channels

In this section, we will examine the BER performance comparison of proposed tracking detection algorithm with three different step-size (μ_1 = 0.05, μ_2 = 0.005, μ_3 = 0.001) over same Rayleigh fading channels. Here, we take fading factor R_f = 0.99 and 1 receiver as an example.

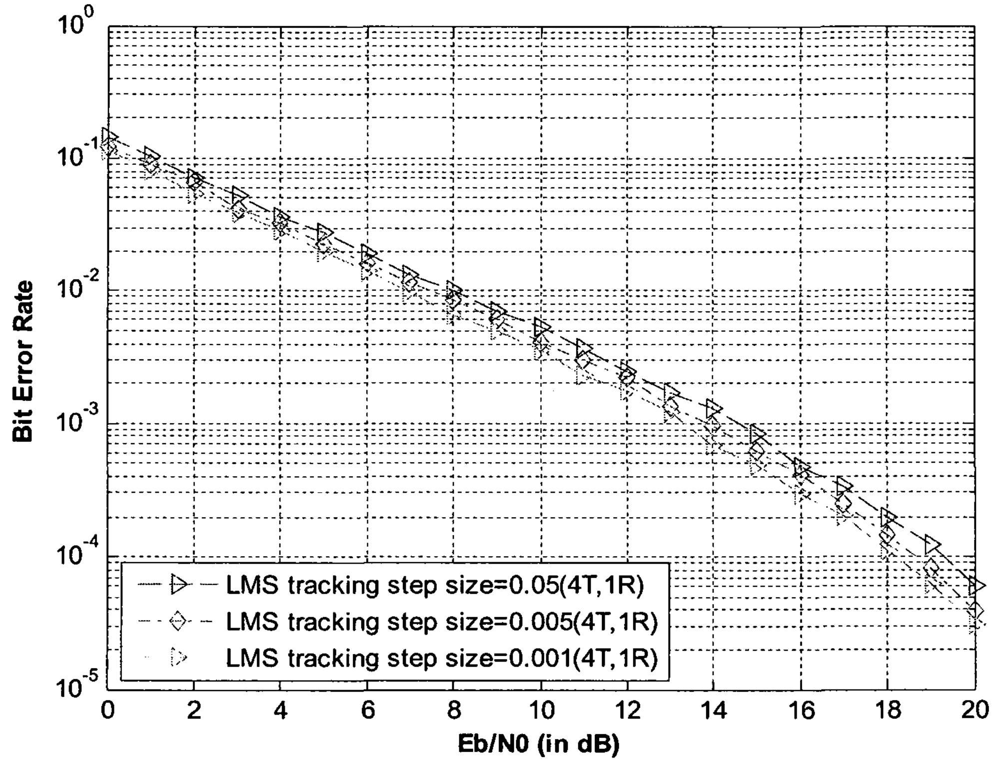

Figure 5.25 BER performance comparison of proposed LMS tracking detection with different step-size over same fading channels (4T, 1R, R_f = 0.99, μ_1 =0.05, μ_2 =0.005, and μ_3 =0.001)

In Figure 5.25, we demonstrate the BER simulation results of proposed LMS tracking detection schemes with different LMS step-size μ_1 =0.05, μ_2 =0.005, and μ_3 =0.001 for CDMA/MIMO systems with 1 receive antenna in the same Rayleigh fading channels.

From this figure, we see that the proposed LMS tracking detection algorithm with smaller step-size parameter can achieve minor BER improvement. For example, at a BER of 10^{-4}, the LMS tracking scheme with step-size μ_3 =0.001 for CDMA/MIMO with 1 receiver can generate about 0.4 dB improvement over that with μ_2 =0.005 while about 1 dB gain improvement over that with μ_1 =0.05.

5.4 The BER Performance Comparison of LMS Tracking Detection Algorithm with Same Step-size for CDMA/MIMO Systems in Different Rayleigh Fading Channels

Next, we will compare the BER performance of proposed tracking detection algorithm with same step-size parameter (μ = 0.05) over different Rayleigh fading channels. Here, we take 1 receiver, fading factor 1 = 0.99, fading factor 2 = 0.995, and fading factor 3 = 0.998 as an example.

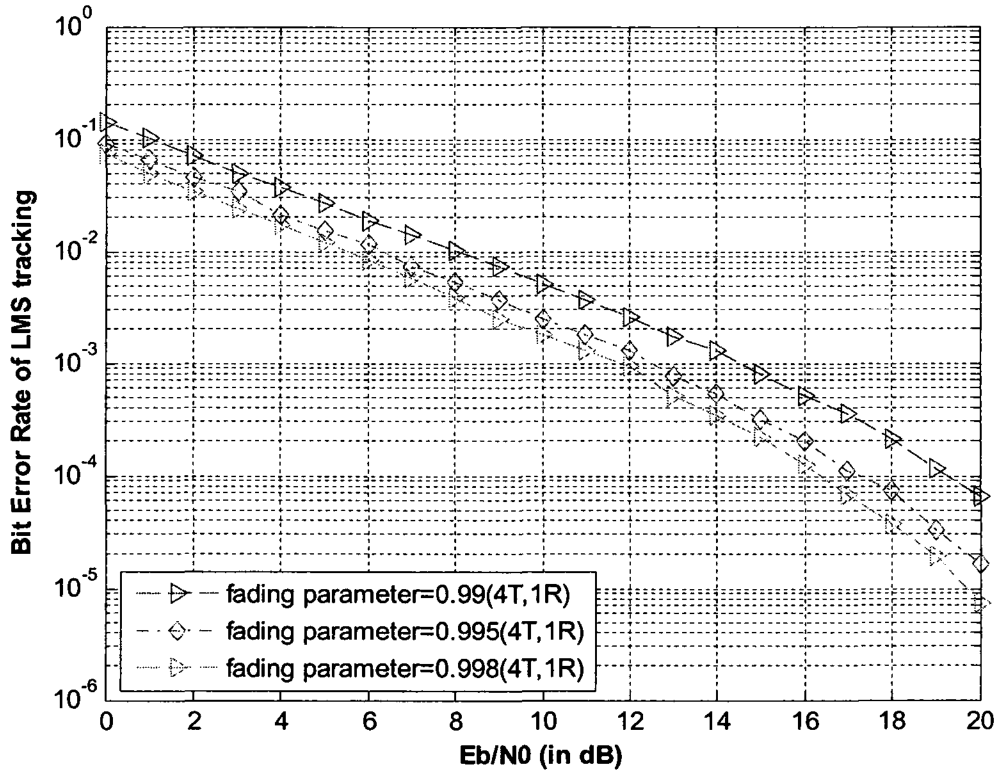

Figure 5.26 BER performance comparison of proposed LMS tracking detection with same step-size over different fading channels (4T, 1R, μ =0.05, R_{f1} = 0.99, R_{f2} = 0.995, and R_{f3} = 0.998)

In Figure 5.26, we plot the BER performance of proposed LMS tracking detection schemes with same LMS step-size μ =0.05 for CDMA/MIMO systems with 1 receive antenna in the different Rayleigh fading channels. Note that the fading parameter is the fading factor (R_f).

From this figure, we view that the BER performance of proposed LMS tracking detection algorithm with same LMS step-size parameter in slower varying Rayleigh fading channels is better than that in faster varying Rayleigh fading channels. For instance, at a BER of 10^{-4}, the LMS tracking scheme with same step-size is employed for CDMA/MIMO with 1 receiver in Rayleigh fading factor $R_{f3} = 0.998$ can generate about 1 dB improvement over that in fading factor $R_{f2} = 0.995$ while about 3 dB gain improvement over that in fading factor $R_{f1} = 0.99$.

5.5 The BER Performance Comparison of LMS Tracking Detection with Same Step-size for CDMA/MIMO Systems with Different Number of Receive Antennas in Same Rayleigh Fading Channels

Finally, we will compare the BER performance of proposed tracking detection algorithm with same step-size parameter (μ = 0.05) for CDMA/MIMO systems in the same Rayleigh fading channels. Here, we take step-size parameter $\mu = 0.05$, $R_f = 0.99$, and 1, 2, 3, or 4 receive antennas as an example.

Figure 5.27 shows the BER simulation results of proposed LMS tracking detection schemes with same LMS step-size μ =0.05 for CDMA/MIMO systems with 1 to 4 receive antennas in the same varying Rayleigh fading channels ($R_f = 0.99$).

From this figure, it is readily to observe that the BER performance of proposed LMS tracking detection algorithm with same LMS step-size parameter for CDMA/MIMO with 4 receivers in same slow varying Rayleigh fading channels is much better than that for 1, 2, or 3 receivers.

For instance, at a BER of 10^{-4}, the LMS tracking scheme with same step-size (μ =0.05) is used for CDMA/MIMO with 4 receivers in same Rayleigh fading channels ($R_f = 0.99$) can acquire about 3 dB gain improvement over that for 3 receivers, roughly 6 dB improvement for 2 receivers, or about 9 dB gain improvement for 1 receive antenna case.

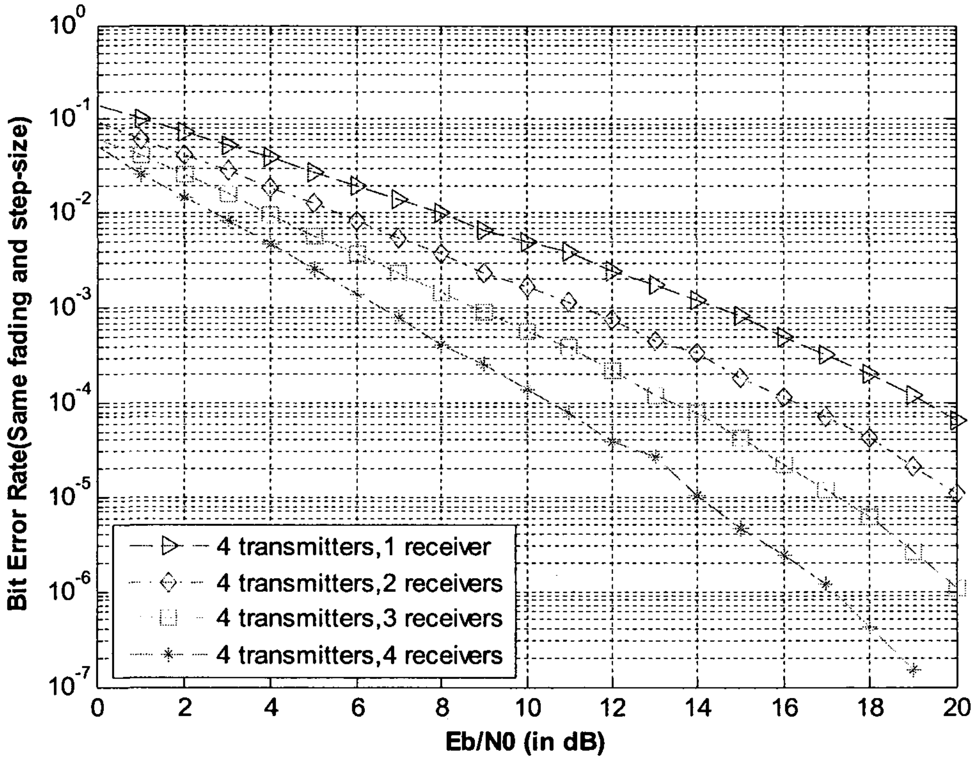

Figure 5.27 BER performance comparison of proposed LMS tracking detection with same step-size over different fading channels (4T, 1 to 4R, μ = 0.05, R_f = 0.99)

In brief, based on same fading channels and same LMS step-size, the more the number of receive antennas are, the better the BER performance achieved will be.

5.6 BER Simulation Results Summary

As discussed in Section 5.2 to Section 5.5, we summarize several typical features of BER simulation results as follows:

(a) The BER performance of proposed LMS tracking detection scheme is in between Conventional approach and MLD detection algorithm. Relatively speaking, the BER performance of proposed LMS tracking detection is closer to that of MLD and Wiener filter scheme, especially for CDMA/MIMO systems with 4 receivers in slower varying Rayleigh fading channels. For example, in Figure 5.24, at a BER of

10^{-4}, the BER performance of proposed LMS tracking detection algorithm with step-size μ =0.001 for CDMA/MIMO systems with 4 receivers in same slow varying Rayleigh fading channels generate only roughly 0.8 dB loss over Wiener filter scheme, about 2 dB loss over MLD detection solution, while acquires roughly 3.4 dB gain improvement over Conventional method.

(b) Although the BER performance of proposed LMS tracking detection scheme seems to be less than that of Wiener filter or MLD detection algorithm, the BER simulation results of proposed LMS tracking solution can be reasonable and be used in CDMA/MIMO systems in practical wireless CDMA/MIMO systems. For instance, from Figure 5.1 to Figure 5.24, for LMS tracking detection scheme, the bit error rate at *SNR* = 16 dB shown is less than or much less than 10^{-3}. More specifically, in Figure 5.23, when *SNR* >10.5 dB, the bit error rate will be less or much less than 10^{-4}, which is a satisfaction BER performance result. Hence it is readily to see that the BER performance of proposed LMS tracking detection algorithm is reasonable and can be employed in actual CDMA/MIMO systems especially in slowly varying Rayleigh fading channels.

(c) Based upon same fading channels and parameters except for different number of receive antennas, the BER performance of the four detection solutions (MLD detection, Wiener filter detection, conventional method, and proposed LMS tracking detection scheme) will be better and better with the number increase of receive antennas.

(d) Based on same Rayleigh fading channels along with same parameters except for different LMS weight step-size parameter, the smaller the LMS step-size parameter is, the better BER performance gain improvement of proposed LMS tracking detection algorithm with slower rate of convergence can acquire.

(e) Compare to adjusting LMS weight tap-size parameter, the Rayleigh fading rate affects BER performance more apparently. However, as for this point, it is a little bit hard to reduce Rayleigh fading rate in real CDMA/MIMO systems.

Thus, based on the BER comparing and analysis of four detection schemes, we can draw a clear conclusion. The four detection algorithms can be employed for CDMA/MIMO systems over slow Rayleigh fading environment because their BER performance can be reasonable at middle or higher SNR such as *SNR*>10 dB although MLD detection can achieve relatively better BER performance improvement over the Wiener or LMS tracking detection scheme. In other words, it is pretty useful to employ proposed LMS tracking detection with relatively ideal weight tap-size factor as well as the other related parameters for actual CDMA/MIMO systems with 4 or more receive antennas in slowly varying Rayleigh fading channels because of its reasonable BER performance and its lower computational complexity. As for this point, it will be represented next.

5.7. Discussion of Computational Complexity of Proposed Solution

Next let us examine the computational complexity of the three solutions (MLD, Wiener, and proposed LMS tracking algorithm). First of all, look into the MLD detection solution. On one hand, for the system with fewer receivers (i.e. not more than 4 receive antennas) using simpler modulation such as BPSK, the maximum likelihood detection rule (Eq. 2.3) has relatively reasonable computational complexity compare to conventional method or proposed LMS solution. On the other hand, however, for the system with more receivers (more than 4 receivers) using high order modulation such as 32 QAM and 64 QAM, the MLD algorithm will involve larger or prohibitive computational complexity. There are two main reasons. One is that it always needs channel transfer matrix and channel estimation at each time slot. The other reason is that it also involves complex matrix and vectors calculations each time. More specifically, for the maximum likelihood detection rule, in Eq.2.3, at each of iteration it needs to compute two complex parts: $\sum_{i=1}^{N_t}\left|\mathbf{u}_i - b_i^{(n)}\boldsymbol{h}_i^{(n)}\right|^2$ and $\|\bar{u}\|^2$, (where $\boldsymbol{u}$ consisted of MLD decision variables, and $\bar{u}$ is made up of all of the rest of MLD decision variables not in $\boldsymbol{u}$), and brings about a great deal of second power calculation and comparing. For instance, if we consider b from M_6 in Eq. 2.3, and take $N_t = 4$, then $\mathbf{u}_1=[u_{13}, u_{23}, u_{33}, u_{43}]$, $\mathbf{u}_2=[u_{16}, u_{26}, u_{36}, u_{46}]$, $\mathbf{u}_1=[u_{18}, u_{28}, u_{38}, u_{48}]$,

$\mathbf{u}_1=[u_{11}, u_{21}, u_{31}, u_{41}]$, and $\bar{u}=[u_{12}, u_{22}, u_{32}, u_{42}, u_{14}, u_{24}, u_{34}, u_{44}, u_{15}, u_{25}, u_{35}, u_{45}, u_{17}, u_{27}, u_{37}, u_{47}]$, which causes much matrix operation and calculations as per the MLD rule. As such, we further consider high order modulation such as 64 QAM, and corresponding computational complexity of the MLD rule will be quite high. As a result, the nonlinear growing high computational complexity of the MLD rule will become an apparent defect especially for the system with more receivers using high order modulation.

As for the Wiener filter solution, it is unnecessary to check its computational complexity due to the following two reasons. First of all, it is not practical to apply Wiener filter solution in real CDMA/MIMO systems. Also, should the Wiener filter algorithm be used, it would involve huge matrix computations at each time slot for more receive antennas case. To take $N_r = 4$ as an example, the correlation matrix $\mathbf{R}$ of input vectors will be a 64*64 matrix and the correlation matrix and its inversion will be recomputed at each time slot, which would get very complex.

Eventually, let's evaluate the computational complexity of the proposed LMS detection technique. Clearly, a significant feature of the proposed LMS tracking detection algorithm with permutation spreading technique is its computation simplicity. Actually, it does not need to measure the pertinent correlation matrix and matrix inversion, nor does it require channel transfer matrix and channel estimate at each time slot. More exactly, the proposed LMS tracking detection solution requires only $2L+1$ complex multiplications and $2L$ complex additions each time, where L is the number of the LMS tap weight used. Accordingly, the computational complexity of the permutation spreading and LMS tracking detection algorithm is $O(L)$. Basically, the LMS detection algorithm only requires fewer and simpler linear computations even though the number of the receiver is increasing more and more. Also, as investigated in Section 4.9.3, the LMS tracking training/pilot bound can be roughly estimated without further using Wiener filters, which can dramatically reduce the complexity of Proposed LMS tracking algorithm. Meanwhile, when the LMS algorithm is employed for the systems using higher order modulation, it requires only simpler linear computations, which makes its computational complexity small in this case.

Hence, compare to MLD and Wiener filter solution, the proposed LMS detection algorithm is dominated with respect to lower computational complexity especially for the systems with more receivers using high order modulation.

5.8. Integrated Analysis of Proposed Solutions

As discussed above, we prefer to employ the proposed LMS tracking scheme with permutation spreading technique for CDMA/MIMO systems with 1 to 4 receivers in slowly varying Rayleigh fading channels because proposed LMS tracking algorithm can not only generate reasonable BER performance but also has lower computational complexity.

On one hand, all of the three detection schemes (MLD, Wiener filters, and LMS tracking detection algorithms) can achieve reasonable or better BER performance results for practical CDMA/MIMO systems with 1 through 4 receive antennas in frequency-nonselective fading channels although the BER performance of MLD solution apparently outperforms Wiener adaptive filers and the proposed LMS tracking algorithm. Moreover, more exactly, the BER performance of proposed LMS tracking detection is actually closer to that of MLD and Wiener filter scheme, especially for CDMA/MIMO systems with 4 receivers in slower Rayleigh fading channels. For instance, in Figure 5.24, at a BER of 10^{-4}, the BER performance of proposed LMS tracking detection algorithm with step-size μ =0.001 for CDMA/MIMO systems with 4 receivers generate only roughly 2 dB loss over MLD detection solution in same slowly varying Rayleigh fading channels.

On the other hand, LMS tracking detection technique requires much fewer computations than Wiener filter algorithm and MLD detection solution especially for the systems with more receive antennas using high order modulation. In other words, and LMS tracking algorithm with permutation spreading technique has outstanding advantage over MLD algorithm and Wiener filter detection solution with respect to low computational complexity. Moreover, in particular, the LMS tracking training /pilot bounds can be roughly estimated without the use of Wiener filters, which further simplify the complexity of the LMS tracking scheme. Besides, the proposed LMS detection algorithm also allows the dynamic tracking of fading channels at each of time variations, which can be fully employed for CDMA/MIMO systems with more receivers in frequency nonselective Rayleigh fading channels.

Therefore, on the whole, the proposed LMS tracking algorithm will be viewed as a better choice over MLD and Wiener filters detection algorithms to be used for CDMA/MIMO systems with more receivers using high order modulation in slowly varying Rayleigh fading channels due to its outstanding advantages, such as lower computational complexity, not sacrificing too much BER performance, as well as dynamic tracking of Rayleigh fading channels.

Chapter 6 Conclusions and Future Work

6.1 Conclusions

In this thesis, first of all, we briefly review related literature on various detection techniques for CDMA and MIMO systems in fading channels. In particular, we introduce maximum likelihood detection algorithm with permutation spreading technique for CDMA/MIMO systems in respect to its BER performance along with its computational complexity. Then, we state a novel detection technique using Wiener filter for CDMA/MIMO systems with permutation spreading technique. We see that most of the detection techniques and the designed Wiener detection algorithm have higher complexity.

In order to reduce the computational complexity, a lower complexity detection algorithm employing adaptive LMS filters with permutation spreading technique for CDMA/MIMO systems in slowly varying Rayleigh fading channels is represented and proposed in Chapter 4.

We further examined the BER performance of the proposed LMS tracking detection algorithm in Chapter 5. By simulating and comparing 27 different models related to 4 different detection schemes (MLD, Wiener, Conventional method, and the proposed LMS tracking detection), 3 different fading channels, 3 different LMS weight step-size, and 4 different number of receive antennas, we observed that the BER performance of the proposed LMS tracking algorithm does not sacrifice too much over that of MLD while its BER performance apparently outperforms that of conventional approach especially using for CDMA/MIMO systems with more receive antennas.

Furthermore, we compared and analyzed the computational complexity of the proposed LMS tracking detection technique, the Wiener filter algorithm with permutation spreading, and MLD with permutation spreading technique. Compared with MLD, LMS tracking algorithm does not require channel transform matrix and channel estimation, and only requires simpler linear computations instead of second power calculations used in MLD algorithm. Moreover, the computational complexity of the proposed LMS algorithm is intuitively lower than that of MLD for the system with more receivers using high order modulation, such as 64 QAM. As for the computational complexity of Wiener filter algorithm, it will not be further considered in this thesis due to its non practical application and its huge matrix calculations involved at each time slot. As the number of receive antennas increase and higher order modulation is adopted, the proposed LMS algorithm only required lower linear computations. In particular, the tracking training /pilot sequence bound of LMS detection algorithm can be roughly estimated without the further presence of Wiener filters, which dramatically reduce the complexity of the proposed LMS detection solution. Consequently, it is easy to see that the proposed LMS detection algorithm needs much less computations than MLD and Wiener filter solution for the systems with more receive antennas using higher order modulation.

Also, the LMS filters with permutation spreading technique allows to process the dynamic tracking of fading channels each of iterations, which can be effectively employed for frequency non-selective CDMA/MIMO systems with many receivers environment.

Therefore, as discussed and analyzed above, it is not difficult to see that the proposed lower complexity detection algorithm using adaptive LMS filters with permutation spreading can be employed for practical CDMA/MIMO systems with 1 to 4 receive antennas or more receivers in slowly varying Rayleigh fading channels, due to its outstanding advantages: lower computational complexity, not sacrificing too much BER performance, as well as dynamic tracking of Rayleigh fading channels.

Last but not least, please note that the proposed LMS tracking algorithm has some application scope limitation. More specifically, on one hand, the proposed LMS tracking detection is very useful to transmit longer information streams such as voice and image messages in CDMA/MIMO systems over slow Rayleigh fading channels. On the other hand, it might not be very effective to convey shorter data packages such as short message and other shorter data bits since in LMS tracking detection, a training period with slower convergence is required in order to achieve satisfaction BER performance at the receivers.

6.2 Future Work

(1) The proposed LMS tracking scheme using for CDMA/MIMO systems with more

transit and receive antennas (above 4 receivers) in slowly varying Rayleigh fading channels need to be further examined especially in computational complexity, BER performance as well as dynamic tracking of Rayleigh fading channels;

(2) Another interesting proposition is to use the convergence of mean square error curve of the proposed LMS algorithm to determine the training sequence bounds instead of comparing the convergence point between the LMS sub vectors and corresponding Wiener sub vectors.

(3) An interesting proposition is to combine other optimal techniques, such as antenna selection technique, with the proposed LMS tracking detection algorithm. A research will be conducted in order to further reduce computational complexity and improve BER performance while still maintaining better dynamic tracking of fading channels;

(4) So far we are assuming perfect channel knowledge at the detector before reaching the training/pilot sequence bound required by proposed LMS tracking scheme. The next step of our work will be to investigate Recursive Least-square (RLS) technique to shorten the training sequence symbols. In this scheme, time varying step-size will be replied to the transmitter via a reliable feedback channel at the receiver. And the transmitter iteratively will use this feedback information to estimate the channel weights.

(5) Finally, in a wideband wireless communication system, there is the existence of multipath channel, as a result, ISI is subjected to the receive signals. Consequently, the next step of our work is to expand the proposed LMS tracking scheme to adapt the application, especially in correlated faster Rayleigh fading channels.

BIBLIOGRAPHY

[1] Niyato, D.; Hossain, E, "WIRELESS BROADBAND ACCESS: WIMAX AND BEYOND - Integration of WiMAX and WiFi: Optimal Pricing for Bandwidth Sharing," IEEE Commun., Vol.45, no.5, May 2007.

[2] Henry, P.S.; Hui Luo, "WiFi: what's next?" IEEE Commun., vol.40, no.12, Dec 2002.

[3] Aime, M.D.; Calandriello, G.; Lioy, A., "Dependability in Wireless Networks: Can We Rely on WiFi?" IEEE Security, vol. 5, no. 1 Jan. 2007.

[4] Kejie Lu; Yi Qian; Hsiao-Hwa Chen; Shengli Fu, "WiMAX networks: from access to service platform," Network, Vol.22, no.3, May-June 2008.

[5] Fan Wang; Ghosh, A.; Sankaran, C.; Fleming, P.; Hsieh, F.; Benes, S., "WiMAX systems: performance and evolution," IEEE Commun., Vol.46, no.10, Oct. 2008.

[6] Abichar, Z.; Yanlin Peng; Chang, J.M, "WiMax: The Emergence of Wireless Broadband," IT prof. Vol.8, no.4, July-Aug 2006.

[7] G. J. Foschini and M. J. Gans., "On limits of wireless communications in a fading environment when using multiple antennas," Wireless Personal Communications, vol. 6, pp. 311-335, March 1998.

[8] G. J. Foschini, "Layered space-time architecture for wireless communication in a fading environment when using multi-element antennas," Bell Labs Tech. J., pp. 41-59, Autumn 1996.

[9] E. Telatar, "Capacity of Multi-Antenna Gaussian Channels," technical memorandum, AT&T Bell Laboratories, June 1995.

[10] G. Raleigh and J. M. Cioffli, "Spatial-temporal coding for wireless communications," IEEE Transactions on Communications, vol. 46, no. 3, pp. 357-366, 1998.

[11] H. B¨olcskei, D. Gesbert, and A. J. Paulraj, "On the capacity of OFDM-based spatial multiplexing systems," IEEE Trans. Comm. Feb. 2002.

[12] I. E. Teletar, "Capacity of multi-antenna Gaussian channel," Europ. Trans. Telecommun., pp. 585-595, Nov 1999.

[13] G. J. Foschini, "Layerd space-time architecture for wireless communication in a fading environment when using multi-element antennas," Bell labs, Tech. J, vol. 1, no. 2, pp. 41-59, Jul 1996.

[14] D. Chizhik, F. R. Farrokhi, J. Ling, and A. Lozano, "Effect of antenna separation on the capacity of BLAST in correlated channels," IEEE Comm. Lett., vol. 4, no. 11, pp. 337–339, Nov. 2000.

[15] G. J. Foschini, G. D. Golden, R. A. Valenzuela, and P. W. Wolniansky, "Simplified processing for high spectral efficiency wireless communication employing multi-element arrays," IEEE J. Sel. Areas. Commun., vol. 17, no. 11, pp. 1841–1852, Nov. 1999.

[16] G. J. Foschini and M. J. Gans; "On limits of wireless communications in a fading environment when using multiple antennas," Wireless Personal Communications, vol. 6, no. 3, pp. 311 – 335, June 1998.

[17] C. D'Amours, J.-Y. Chouinard, "Parity Bit Selected and Permutation Spreading for CDMA/MIMO Systems in Frequency-Nonselective Rayleigh Fading Channels," IEEE Vehicular Technology Conference, pp 1475-1479, April 2007.

[18] F.J. MacWilliams and N.J.A. Sloane, *The Theory of Error-Correcting Codes*, North-Holland: New York, NY, 1977.

[19] Fang-Ming Han; Xian-Da Zhang, "MLSD for Hexagonal Multicarrier Transmission With Time–Frequency Localized Pulses", IEEE Trans. Vehicular Tech, vol.58, no.3, Mar. 2009.

[20] Zamiri-Jafarian, H.; Pasupathy, S., "Adaptive state allocation algorithm in MLSD receiver for multipath fading channels: structure and strategy," IEEE Trans. Vehicular Tech, vol.48, no.1, Jan. 1999.

[21] Heng Yang; Xian-Da Zhang, "A fast maximum likelihood sequence decoding method for multicarrier DS-CDMA using frequency spread coding," IEEE Trans. Wireless Comm. vol.3, no.3, May 2004.

[22] S. Haykin, *Adaptive Filter Theory*, Upper Saddle River, NJ: Prentice Hall, 2002

[23] Diniz, P.S.R.; Siqueira, M.G., "Fixed-point error analysis of the QR-recursive least square algorithm," IEEE Trans. Signal Processing, vol.42, no.5, Aug. 2008.

[24] Gomes, J.; Barroso, V.A.N., "Array-Based QR-RLS Multichannel Lattice Filtering," IEEE Trans. Signal Processing, vol. 56, no. 8, Aug. 2008.

[25] Harteneck, M.; McWhirter, J.G.; Proudler, I.K.; Stewart, R.W, "Algorithmically engineered fast multichannel adaptive filter based on QR-RLS," IEEE Trans. Signal Processing, vol. 146, no.1, Feb. 1999.

[26] Oates, J.H., "Application of degenerate perturbation theory to subspace tracking," IEEE Trans. Signal proc., vol. 48, no.1, Jan. 2000.

[27] Strobach, P, "Equirotational stack parameterization in subspace estimation and tracking," IEEE Trans. Signal proc. vol. 48, no.3, pp. 712-722, Mar. 2000.

[28] P. Loubaton, E. Moulines, and P. Regalia, "Subspace methods for blind identification and deconvolution (Chap. 3)," in Signal Processing Advances in Wireless and Mobile Communications. Giannakis, Hua, Stoica, Tong, Eds. Prentice Hall, 2001.

[29] Doukopoulos, X.G.; Moustakides, G.V, "Fast and Stable Subspace Tracking," IEEE Trans. Signal Processing, vol. 56, no.4, pp. 1452-1465, April 2008.

[30] Hosur, S.; Tewfik, A.H.; Boley, D., "ULV and generalized ULV subspace tracking adaptive algorithms," IEEE Trans. Signal Processing, vol. 46, no. 5, pp. 1282-1297, May 1998.

[31] Zuqiang Fu; Dowling, E.M., "Conjugate gradient projection subspace tracking," IEEE Trans. Signal Processing, vol. 45, no. 6, pp. 1664-1668, June 1997.

[32] Zhang, Y.; Bi, G.; Ng, B.P, "Subspace-based multiuser detection for DS-CDMA systems with correlated noise," IEEE Proc. Comm. vol. 148, no. 5, Oct. 2001.

[33] Xiaodong Wang; Host-Madsen A., "Group-blind multiuser detection for uplink CDMA," IEEE journal, vol.17, no.11, Nov. 1999.

[34] Shahbazpanahi, S.; Gershman, A.B, "Robust blind multiuser detection for synchronous CDMA systems using worst-case performance optimization," IEEE Trans. Wireless communications, vol.3, no.6, Nov. 2004.

[35] Liping Sun; Guoan Bi; Liren Zhang, "Orthonormal Subspace Tracking Algorithm for Space–Time Multiuser Detection in Multipath CDMA Channels," IEEE Trans. Vehicular technology, vol. 56, no.6, Nov. 2007.

[36] Huanyu Dai, H. Vincent Poor, "Iterative Space–Time Processing for Multiuser Detection in Multipath CDMA Channels," IEEE trans. Comm. June 2002.

[37] Reynolds, D.; Xiaodong Wang, "Turbo multiuser detection with unknown interferers," IEEE Trans. Comm. vol.50, no.4, April 2002.

[38] Guosen Yue; Xiaodong Wang, "Coding-spreading tradeoff in LDPC-coded CDMA with turbo multiuser detection," IEEE Trans. Wireless Comm. vol.3, no.5, Sept 2004.

[39] Qinghua Li; Xiaodong Wang; Georghiades, C.N., "Turbo multiuser detection for turbo-coded CDMA in multipath fading channels," IEEE Trans. Vehicular Tech. vol.51, no.5, Sept. 2002.

[40] Junqiang Li; Letaief, K.B.; Zhigang Cao, "Space-time turbo multiuser detection for coded MC-CDMA," IEEE Trans. Wireless Comm. vol.4, no.2, Mar. 2005.

[41] S. Verdu, "Multi-user detection," in Advances in statistical signal processing (V. Poor, ed.), pp. 369-409, JAI Press, 1993.

[42] Dumard, C.; Zemen, T, "Low-Complexity MIMO Multiuser Receiver: A Joint Antenna Detection Scheme for Time-Varying Channels," IEEE Trans. Signal Processing, vol. 56, part 1, July 2008.

[43] Yong Li; Jaekyun Moon, "Reduced-Complexity Soft MIMO Detection Based on Causal and Noncausal Decision Feedback," IEEE Trans. Signal proc. vol.56, no.3, Mar. 2008.

[44] John G. Proakis, *Digital Communications (3rd edition ed.)*. Singapore: McGraw-Hill Book Co. pp. 767–768. ISBN-07-113814-5, 1995

[45] Bernard Sklar, "Rayleigh Fading Channels in Mobile Digital Communication Systems Part I: Characterization". IEEE Communications Magazine 35 (7), pp.90–100, July 1997

[46] Visintin, M., "Karhunen-Loeve expansion of a fast Rayleigh fading process," Electronics letters, vol. 32, no.18, Aug. 1996.

[47] G. N. Watson, *A Treatise on the Theory of Bessel Functions, Second Edition*, Cambridge University Press, 1995.

[48] Abou-Faycal, I.; Medard, M.; Madhow, U., "Binary adaptive coded pilot symbol assisted modulation over Rayleigh fading channels without feedback," IEEE Trans. Comm. vol.53, no.5, June 2005.

[49] Min Dong; Lang Tong, "Optimal design and placement of pilot symbols for channel estimation," IEEE Trans. Signal proc. vol.50, no.12, Dec. 2002.

[50] Evans, J.S., "Optimal resource allocation for pilot symbol aided multiuser receivers in Rayleigh faded CDMA channels," IEEE Trans. Comm. vol.50, no.8, Aug. 2002.