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Research Article

Spreading Code Assignment Strategies for MIMO-CDMA Systems Operating in Frequency-Selective Channels

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Code Division Multiple Access (CDMA) and multiple input multiple output- (MIMO-) CDMA systems suffer from multiple access interference (MAI) which limits the spectral efficiency of these systems. By making these systems more power efficient, we can increase the overall spectral efficiency. This can be achieved through the use of improved modulation and coding techniques. Conventional MIMO-CDMA systems use fixed spreading code assignments. By strategically selecting the spreading codes as a function of the data to be transmitted, we can achieve coding gain and introduce additional degrees of freedom in the decision variables at the output of the matched filters. In this paper, we examine the bit error rate performance of parity bit-selected spreading and permutation spreading under different wireless channel conditions. A suboptimal detection technique based on maximum likelihood detection is proposed for these systems operating in frequency selective channels. Simulation results demonstrate that these code assignment techniques provide an improvement in performance in terms of bit error rate (BER) while providing increased spectral efficiency compared to the conventional system. Moreover, the proposed strategies are more robust to channel estimation errors as well as spatial correlation.

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1. Introduction

The object of much research in wireless communications is to enable high and variable data rates to users to support the growing number of applications that involve the transfer of data [1]. Code Division Multiple Access (CDMA) systems employ spread spectrum (SS) technology and were developed for second and third generation (2G, 3G) wireless communications. For example, IS-95 and Wideband CDMA (WCDMA) systems are based on direct sequence SS techniques.

Multiple access interference (MAI) is present in CDMA systems due to the nonzero cross-correlation between the different users' spreading codes [2]. The MAI that each user's signal creates in all other users' signals results in increased bit error rate (BER). The overall system capacity is determined by the number of simultaneous transmitters that can be supported before the BER increases to an unacceptable level [3]. Much research presented in the literature has concentrated on making systems more power efficient as a means to increase the overall spectral efficiency of the CDMA system [4–7]. Other techniques, such as multiuser detection, have also been considered to increase the capacity of CDMA systems [2, 8–10].

Multiple input multiple output (MIMO) systems employ multiple antennas at the transmitter and receiver. This is done to increase the capacity of systems through the inherent spatial multiplexing [11] that can be obtained by using multiple transmit and receive antennas as well as receive diversity that comes from having multiple receive antennas. Coding can also be achieved by the transmit diversity that can be obtained by sending multiple copies of data over different transmit antennas [12, 13].

Recent research has shown that combining DS-CDMA systems with Multiple Input Multiple Output (MIMO) techniques can achieve high gains in capacity, reliability,

and data transmission speed [14–22]. This is achievable by exploiting the spatial diversity made possible by multiple antennas at the transmitter and the receiver, allowing more degrees of freedom when the transfer functions between different transmit and receive antenna pairs are sufficiently uncorrelated. The inherent beamforming capabilities of the receive antenna array also make MIMO-CDMA systems more robust to multiple access interference (MAI) than their single input single output (SISO) DS-CDMA counterparts. Currently, MIMO-CDMA is considered for many beyond 3G (B3G) applications [22].

Like CDMA systems, MIMO-CDMA systems encounter MAI as well as self interference (SI) due to the fact that autocorrelation and cross correlation properties of the employed spreading codes are not perfect [23]. MAI is the interference caused by other users who are simultaneously accessing the channel, while SI is the interference that the desired user's substreams cause to one another, due to spreading codes that are not orthogonal or by the loss of code orthogonality caused by frequency-selective fading. The effect that MAI and SI have on the BER performance of a system is determined by the kind of spreading codes employed (orthogonal or quasiorthogonal codes) and the frequency selective nature of the wireless channels [2]. As such, MAI and SI limit the performance and capacity of conventional MIMO-CDMA systems. To mitigate the interference, several multiuser detection (MUD) techniques have been proposed to improve the performance of the conventional rake receiver [16, 20, 24–27]. However, complexity represents one of the major issues impeding the widespread use of MUD receivers [27] and some alternative techniques need to be used to improve MIMO-CDMA systems.

In CDMA systems, spreading codes are assigned to different users to enable them to meet certain quality of service (QoS) requirements, such as data rate and bandwidth, [1]. Dynamic code assignment strategies are used to maximize system throughput by assigning codes to different users based on their cross-correlation properties [1, 28, 29]. These assignment strategies are centralized. In conventional MIMO-CDMA systems, unique codes are assigned per user [16–19] or per antenna [20]. Although the latter code assignment strategy requires the use of more spreading codes in the overall system, doing so improves the overall bit error rate (BER) performance. Indeed, the substreams can be differentiated by their codes as well as the spatial diversity. In this paper, we consider a code assignment strategy that allows the selected code(s) to impart some information to the receiver about the message that it carries. This selection is made by the transmitter, which selects a code from a set of codes that have been assigned to it. By allowing the selected spreading code to impart some redundant information about the message that is being carried, a coding gain is obtained. This coding gain can be traded off against increased system capacity. We compare our findings to the best existing conventional MIMO-CDMA system, which is one that assigns different codes to each antenna as well as to each user.

Spreading code assignment strategies in DS-CDMA systems and in particular for MIMO-CDMA systems play an important role in defining their overall performance [30, 31]. Unlike centralized spreading code assignment strategies, a user is assigned a set of mutually orthogonal spreading codes and the transmitter decides which code or codes to be used based on the data that is to be transmitted. In [30], for the first time, parity bit-selected spreading has been proposed where the code assignment in single input single output (SISO) DS-CDMA systems is determined by the transmitted bits. The code is drawn from a set of mutually orthogonal codes. In [31], parity bit-selected spreading has been extended to MIMO systems. In this same paper, a new technique named permutation spreading has also been proposed to improve the performance of the system while using the same number of spreading codes per user. Performance improvements can be briefly explained by the fact that in case of conventional MIMO-CDMA, if bits b_1, b_2, b_3, and b_4 are transmitted from different antennas, correctly determining b_1, b_2, and b_3 will not help to determine b_4. However, in case of parity bit-selected spreading or permutation spreading, correctly detection of 3 or even 2 of the bits will exactly determine the other bits. Therefore, bits that encounter poor channel conditions can be recovered by the other bits. Thus, a coding gain similar to Space Time Block Code (STBC) is obtained without the need to retransmit bits from different antennas.

All results presented in these two papers considered frequency nonselective channels. In [30, 31], simulation results demonstrated superior bit error rate (BER) performance when compared to the conventional system. The use of these spreading assignment techniques in frequency-selective channels is challenging since the dispersive nature of the channel deorthogonalizes the spreading codes that are assigned to a user.

In this paper, we propose a suboptimal detection strategy based on the maximum likelihood detector for parity bit-selected and permutation spreading strategies for MIMO-CDMA systems operating in frequency selective channels without any antenna selection strategy. The detection technique takes the loss of orthogonality of the different codes into account but treats all other users as noise. Therefore no attempt is made by the receiver to null out the interferers, as in beamforming systems. We also propose to study the detection stage of the different spreading strategies depending on the correlation properties of the spreading codes employed. Moreover, we will study the robustness of these detectors in presence of channel estimation errors and spatial correlation.

The use of MIMO is to provide increase channel capacity through spatial diversity and improved BER performance through receive diversity. No beamforming techniques are used. Although there is no transmit diversity obtained by retransmitting data from different transmit antennas, the permutation spreading strategy provides a BER that is similar to that obtained with transmit diversity. This is due to the relationship between the data that is transmitted from different antennas and the spreading code permutation used.

The rest of this paper is organized as follows. In Section 2, a general framework of MIMO-CDMA system operating in frequency selective channels is presented. Single user

detection of different spreading strategies is presented in Section 3. In Section 4, some simulation results are presented for single user and multiuser environments. Finally, some conclusions and future work are provided in Section 5.

2. MIMO-CDMA System Operating in Frequency-Selective Fading

Let us consider the K user $N_t \times N_r$ MIMO-CDMA uplink system model of [31], employing binary phase shift keying (BPSK) modulation with N_t transmit antennas for each user and N_r receive antennas at the base station. Figure 1 shows a MIMO-CDMA system operating in frequency-selective fading channels and Table 1 provides a list of symbols used throughout the paper. As shown in Figure 1, the data of each user converted into N_t parallel streams. Each stream is to be transmitted by one of N_t transmitting antennas. The substream to be transmitted on antenna i of user k on time interval n is spread by a spreading code vector $\mathbf{w}_{k,i}^{(n)}$. The spreading code vector is of dimension $N_c \times 1$:

$$\mathbf{w}_{k,i}^{(n)} = \left[w_{k,i}^{(n)}(1) \;\; w_{k,i}^{(n)}(2) \;\; \cdots \;\; w_{k,i}^{(n)}(N_c) \right]^T, \tag{1}$$

where N_c is the spreading factor and the subscript T represents the transpose operator. $N_c = T_s/T_c$ is an integer number where T_s is the symbol period and T_c is the chip period. The spreading code vector is selected from a set of N spreading vectors $\{\mathbf{c}_{k,1}, \mathbf{c}_{k,2}, \ldots, \mathbf{c}_{k,N}\} \in \mathbf{C}_k$.

The wireless media is considered to be a discrete-time baseband channel model with chip-spaced channel taps. We assume block fading chip-spaced channels perfectly known by the receiver. Thus, assuming that each transmit antenna to receive antenna link has L resolvable multipath components, the sampled channel response from the transmit antenna i to the receive antenna j of user k is given by the $L \times 1$ vector:

$$\mathbf{h}_{j,i,k} = \left[h_{j,i,k}^{(0)} \;\; h_{j,i,k}^{(1)} \;\; \cdots \;\; h_{j,i,k}^{(L-1)} \right]^T. \tag{2}$$

Assuming that the maximum channel delay is less than the one signaling interval, the received signal at antenna j is

$$\begin{aligned} \mathbf{r}_j^{(n)} = & \sum_{k=1}^{K} \sum_{i=1}^{N_t} \mathbf{S}_{k,i}^{(n)} \mathbf{h}_{j,i,k} b_{k,i}^{(n)} \\ & + \sum_{k=1}^{K} \sum_{i=1}^{N_t} \mathbf{S}p_{k,i}^{(n)} \mathbf{h}_{j,i,k} b_{k,i}^{(n-1)} \\ & + \sum_{k=1}^{K} \sum_{i=1}^{N_t} \mathbf{S}n_{k,i}^{(n)} \mathbf{h}_{j,i,k} b_{k,i}^{(n+1)} + \mathbf{n}_j^{(n)}. \end{aligned} \tag{3}$$

Due to the frequency selective nature of the channels, intersymbol interference (ISI) is present in the received signal. This is shown in (3), where the second term is the ISI caused by the data from the previous signaling interval

Table 1: List of symbols used throughout the paper.

Symbols	Definition
K	Number of users
N_t	Number of transmit antennas
N_r	Number of receive antennas
k	Index for user of interest
i	Index of transmitting antenna
n	Time interval
$\mathbf{w}_{k,i}^{(n)}$	$N_c \times 1$ spreading code vector for user k used for antenna i at time interval n
N_c	Spreading factor
$()^T$	Transpose operator
T_s	Symbol period
T_c	Chip period
N	Number of spreading vectors per user
$\mathbf{C}_k$	Set of N spreading vectors for user k
j	Index of receiving antenna
$\mathbf{h}_{j,i,k}$	$L \times 1$ chip-spaced sampled channel response between antenna i of user k and receiving antenna j
L	Number of Resolvable multipath components
$b_{k,i}^{(n)}$	Data transmitted by antenna i of user k at instant n
$\mathbf{S}_{k,i}^{(n)}, \mathbf{S}p_{k,i}^{(n)}, \mathbf{S}n_{k,i}^{(n)}$	$(N_c + L - 1) \times L$ Spreading matrices for antenna i of user k at instant n
$\mathbf{n}_j^{(n)}$	$(N_c + L - 1) \times 1$ complex Gaussian noise vector at receiving antenna j
σ_n^2	Gaussian noise variance
$\mathbf{r}_j^{(n)}$	$(N_c + L - 1) \times 1$ received vector at antenna j
$\mathbf{y}_{j,i,k}^{(n)}$	$L \times 1$ vector of correlators at receiving antenna j matched to spreading code vector for user k used for antenna i at time interval n
$\mathbf{R}_{k,i}^{(n)}$	$L \times L$ autocorrelation matrix
$\mathbf{n}_j^{'(n)}$	$L \times 1$ despread complex Gaussian noise + SI + MAI
$\mathrm{SI}_{j,i,k}^{(n)}$	$L \times 1$ self interference seen by the substream transmitted by antenna i of user k at receiving antenna j and instant n
$\mathrm{MAI}_{j,i,k}^{(n)}$	$L \times 1$ multiple access interference seen by the substream transmitted by antenna i of user k at receiving antenna j and instant n
$\hat{b}_{i,k}^{(n)}$	Estimated data transmitted by antenna i of user k at instant n
M	Set of all possible message vectors
M_m	Coset number m
$\mathbf{m}^{(m)}$	Word to be transmitted that belongs to coset M_m
$\mathbf{b}_k^{(n)}$	$N_t \times 1$ vector of transmitted bits at instant n
vec($\mathbf{A}$)	Matrix $\mathbf{A}$ is stacked into a vector columnwise

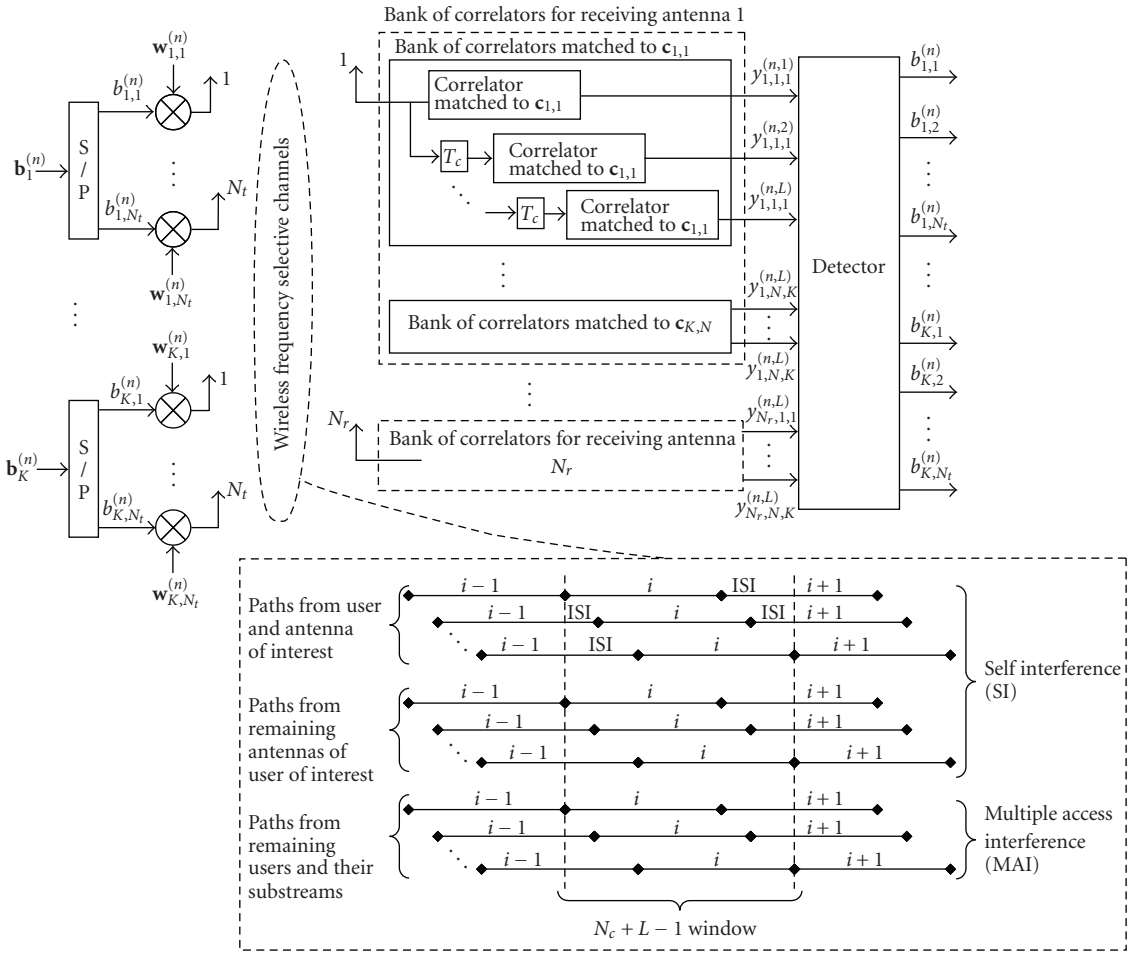

Figure 1: K user $N_t \times N_r$ MIMO-CDMA uplink system operating in frequency selective channels.

while the third term represents the ISI caused by the data on the next signaling interval. This is also shown in Figure 1. It is worth noting that the received vector per antenna has $(N_c + L - 1)$ elements which contain sufficient statistics for the detector. In (3) $b_{k,i}^{(n)}$ is the data transmitted by antenna i of user k at instant n, and $\mathbf{n}_j^{(n)}$ denotes the complex Gaussian $(N_c + L - 1)$ vector with variance σ_n^2. Finally, $\mathbf{S}_{k,i}^{(n)}$, $\mathbf{S}p_{k,i}^{(n)}$, and $\mathbf{S}n_{k,i}^{(n)}$ are $(N_c + L - 1) \times L$ spreading matrices used at instances n, $n-1$, and $n+1$ given by (4) to (6) respectively. These equations are easily derived from Figure 1. It is worth noting here that when the maximum channel delay is greater than the length of the spreading codes (which we assume is equal to one signaling interval in our paper), the model is easily extended by incorporating new matrices to take into account the additional ISI caused by symbols that are more than one signaling interval away from the desired signaling interval.

Moreover, the presented model is valid in synchronous and asynchronous MIMO-CDMA channels. Indeed, every SISO-CDMA channel has L different taps. The model is asynchronous if we impose that the first few paths of the interfering users have zero gain:

$$\mathbf{S}_{k,i}^{(n)} = \begin{bmatrix} w_{k,i}^{(n)}(1) & 0 & 0 & \cdots & 0 \\ w_{k,i}^{(n)}(2) & w_{k,i}^{(n)}(1) & 0 & & 0 \\ w_{k,i}^{(n)}(3) & w_{k,i}^{(n)}(2) & w_{k,i}^{(n)}(1) & & \vdots \\ w_{k,i}^{(n)}(4) & \vdots & \vdots & \ddots & 0 \\ \vdots & \vdots & \vdots & & w_{k,i}^{(n)}(1) \\ \vdots & \vdots & \vdots & & \vdots \\ w_{k,i}^{(n)}(N_c) & \vdots & & \cdots & w_{k,i}^{(n)}(N_c - L + 1) \\ 0 & w_{k,i}^{(n)}(N_c) & & \cdots & w_{k,i}^{(n)}(N_c - L + 2) \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & w_{k,i}^{(n)}(N_c) \end{bmatrix} \quad (4)$$

$$\mathbf{S}p_{k,i}^{(n)} = \begin{bmatrix} 0 & w_{k,i}^{(n-1)}(N_c) & w_{k,i}^{(n-1)}(N_c-1) & & w_{k,i}^{(n-1)}(N_c-L+2) \\ & 0 & w_{k,i}^{(n-1)}(N_c) & & \vdots \\ & & 0 & \ddots & w_{k,i}^{(n-1)}(N_c) \\ \vdots & \vdots & & 0 & 0 \\ & & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & 0 \end{bmatrix} \tag{5}$$

$$\mathbf{S}n_{k,i}^{(n)} = \begin{bmatrix} 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & & & \\ w_{k,i}^{(n+1)}(1) & 0 & & 0 \\ w_{k,i}^{(n+1)}(2) & w_{k,i}^{(n+1)}(1) & & \\ \vdots & \vdots & \ddots & 0 \\ w_{k,i}^{(n+1)}(L-1) & w_{k,i}^{(n+1)}(L-2) & & w_{k,i}^{(n+1)}(1) \quad 0 \end{bmatrix}. \tag{6}$$

3. Single User Detection and Spreading Strategies

Regardless of the spreading strategy employed, single user detection in this paper requires a bank of correlators matched to the spreading sequences employed by the transmitter. Since N different spreading codes are assigned per user (and since there is uncertainty at the receiver to which code or codes have been used), we need $N_r \times N \times L \times K$ correlators as illustrated in Figure 1.

3.1. Conventional MIMO-CDMA System. In conventional MIMO-CDMA, each user can use the same code for all transmitting antennas or one code per transmitting antenna. In our case, we use the latter technique. Hence, $\mathbf{w}_{k,i}^{(n)} = \mathbf{c}_{k,i}$. In our paper, we consider a system where the mobiles each use N_t transmit antennas, and therefore $N = N_t$. For each transmit antenna, we apply a correlator matched to the signature used by the transmitting antenna. Considering antenna i of user k as our substream of interest, we can rearrange (3) as

$$\begin{aligned} \mathbf{r}_j^{(n)} &= \mathbf{S}_{k,i}^{(n)}\mathbf{h}_{j,i,k}b_{k,i}^{(n)} + \sum_{\substack{i'=1 \\ i'\neq i}}^{N_t} \mathbf{S}_{k,i'}^{(n)}\mathbf{h}_{j,i',k}b_{k,i'}^{(n)} \\ &\quad + \sum_{i'=1}^{N_t} \mathbf{S}p_{k,i'}^{(n)}\mathbf{h}_{j,i',k}b_{k,i'}^{(n-1)} + \sum_{i'=1}^{N_t} \mathbf{S}n_{k,i'}^{(n)}\mathbf{h}_{j,i',k}b_{k,i'}^{(n+1)} \\ &\quad + \sum_{\substack{k'=1 \\ k'\neq k}}^{K}\sum_{i'=1}^{N_t} \mathbf{S}_{k',i'}^{(n)}\mathbf{h}_{j,i',k'}b_{k',i'}^{(n)} + \sum_{\substack{k'=1 \\ k'\neq k}}^{K}\sum_{i'=1}^{N_t} \mathbf{S}p_{k',i'}^{(n)}\mathbf{h}_{j,i',k'}b_{k',i'}^{(n-1)} \\ &\quad + \sum_{\substack{k'=1 \\ k'\neq k}}^{K}\sum_{i'=1}^{N_t} \mathbf{S}n_{k',i'}^{(n)}\mathbf{h}_{j,i',k'}b_{k',i'}^{(n+1)} + \mathbf{n}_j^{(n)}. \end{aligned} \tag{7}$$

We can now apply the bank of correlators matched to the code used by antenna i of user k at the receiving antenna j:

$$\mathbf{y}_{j,i,k}^{(n)} = \left(\mathbf{S}_{k,i}^{(n)}\right)^H \mathbf{r}_j^{(n)} = \left[y_{j,i,k}^{(n,1)}, \ldots, y_{j,i,k}^{(n,L)}\right]^T, \tag{8}$$

where the superscript H represents the conjugate transpose of a matrix. From (7) and (8), we can write

$$\mathbf{y}_{j,i,k}^{(n)} = \mathbf{R}_{k,i}^{(n)}\mathbf{h}_{j,i,k}b_{k,i}^{(n)} + \mathbf{n}_j^{\prime(n)}, \tag{9}$$

where

$$\mathbf{R}_{k,i}^{(n)} = \left(\mathbf{S}_{k,i}^{(n)}\right)^H \mathbf{S}_{k,i}^{(n)} \tag{10}$$

is the autocorrelation matrix and $\mathbf{n}_j^{\prime(n)}$ encompasses the despread complex Gaussian noise, the self interference (SI), and multiple access interference (MAI). It is given by

$$\mathbf{n}_j^{\prime(n)} = \mathrm{SI}_{j,i,k}^{(n)} + \mathrm{MAI}_{j,i,k}^{(n)} + \left(\mathbf{S}_{k,i}^{(n)}\right)^H \mathbf{n}_j^{(n)}, \tag{11}$$

where the SI is seen by the substream transmitted by antenna i of user k at the receiving antenna j:

$$\begin{aligned} \mathrm{SI}_{j,i,k}^{(n)} &= \sum_{\substack{i'=1 \\ i'\neq i}}^{N_t} \left(\mathbf{S}_{k,i}^{(n)}\right)^H \mathbf{S}_{k,i'}^{(n)}\mathbf{h}_{j,i',k}b_{k,i'}^{(n)} \\ &\quad + \sum_{i'=1}^{N_t} \left(\mathbf{S}_{k,i}^{(n)}\right)^H \mathbf{S}p_{k,i'}^{(n)}\mathbf{h}_{j,i',k}b_{k,i'}^{(n-1)} \\ &\quad + \sum_{i'=1}^{N_t} \left(\mathbf{S}_{k,i}^{(n)}\right)^H \mathbf{S}n_{k,i'}^{(n)}\mathbf{h}_{j,i',k}b_{k,i'}^{(n+1)}, \end{aligned} \tag{12}$$

and the corresponding MAI:

$$\begin{aligned} \mathrm{MAI}_{j,i,k}^{(n)} &= \sum_{\substack{k'=1 \\ k'\neq k}}^{K}\sum_{i'=1}^{N_t} \left(\mathbf{S}_{k,i}^{(n)}\right)^H \mathbf{S}_{k',i'}^{(n)}\mathbf{h}_{j,i',k'}b_{k',i'}^{(n)} \\ &\quad + \sum_{\substack{k'=1 \\ k'\neq k}}^{K}\sum_{i'=1}^{N_t} \left(\mathbf{S}_{k,i}^{(n)}\right)^H \mathbf{S}p_{k',i'}^{(n)}\mathbf{h}_{j,i',k'}b_{k',i'}^{(n-1)} \\ &\quad + \sum_{\substack{k'=1 \\ k'\neq k}}^{K}\sum_{i'=1}^{N_t} \left(\mathbf{S}_{k,i}^{(n)}\right)^H \mathbf{S}n_{k',i'}^{(n)}\mathbf{h}_{j,i',k'}b_{k',i'}^{(n+1)}. \end{aligned} \tag{13}$$

In single user detection of conventional MIMO-CDMA system, the detection block uses only the correlators corresponding to the substream of interest while considering the SI and MAI as white noise. In this case, the detector is able to estimate the substream of interest by applying maximal ratio combining (MRC) to (9) for all receiving antennas. Therefore, $b_{i,k}^{(n)}$ can be estimated by the following equation:

$$\widehat{b}_{i,k}^{(n)} = \operatorname{sgn}\left(\sum_{j=1}^{N_r}\left(\mathbf{h}_{j,i}\right)^H \mathbf{y}_{j,i,k}^{(n)}\right). \tag{14}$$

3.2. Parity Bit-Selected Spreading System. In parity bit-selected spreading, the data on different antennas is spread by a single spreading waveform that is selected based on the parity bits that are generated when a message is encoded using a systematic linear block code [31]. For each user with N_t transmit antennas, the set M of all possible message vectors has 2^{N_t} different elements. The different messages that produce the all zero parity vector form subset of M that is closed under modulo-2 addition. We denote this subset as M_1. If we select an element $e \in M$ such that $e \notin M_1$ and add modulo-2 to all elements in M_1, the resulting set is called a coset of M_1. Messages from distinct cosets of M_1 produce unique parity bit vectors when being input to the parity bit calculator. In parity bit-selected spreading, each of the cosets is assigned one of the N spreading codes. For example, if user k has 4 transmitting antennas, the set M has 16 elements. If each user is assigned $N = 8$ spreading codes, then we can partition M into 8 cosets as follows: $M_1 = \{0000, 1111\}$, $M_2 = \{0001, 1110\}$, ..., and $M_8 = \{0111, 1000\}$. Each of these cosets is assigned one of the N spreading waveforms; therefore if the word to be transmitted is $\mathbf{m}^{(m)} \in M_m$, then all transmitting antennas will use the spreading code assigned to coset M_m. The same spreading code is used on each transmit antenna. Hence $\mathbf{w}_{k,1}^{(n)} = \cdots = \mathbf{w}_{k,N_t}^{(n)} = \mathbf{c}_{k,m}$. In this case, (3) can be written as

$$\begin{aligned}\mathbf{r}_j^{(n)} = {} & \sum_{k=1}^{K}\mathbf{S}_k^{(n)}\sum_{i=1}^{N_t}\mathbf{h}_{j,i,k}b_{k,i}^{(n)} + \sum_{k=1}^{K}\mathbf{S}p_k^{(n)}\sum_{i=1}^{N_t}\mathbf{h}_{j,i,k}b_{k,i}^{(n-1)} \\ & + \sum_{k=1}^{K}\mathbf{S}n_k^{(n)}\sum_{i=1}^{N_t}\mathbf{h}_{j,i,k}b_{k,i}^{(n+1)} + \mathbf{n}_j^{(n)}.\end{aligned} \tag{15}$$

Indeed, for each user, the code matrices are the same for all transmitting antennas. Hence, they no longer depend on the index i.

In this paper, we consider a MIMO-CDMA system employing $N_t = 2$, 3, or 4 transmit antennas. In each case, we choose $N = 2^{N_t-1}$; therefore all cosets are made up of 2 message vectors. This is not necessarily the optimum choice for N. In the two transmit antenna case, $N = 2$ and $M_1 = \{00, 11\}$, and $M_2 = \{01, 10\}$. If the message $\mathbf{m}^{(m)}$ comes from M_1, $\mathbf{c}_{k,1}$ is used to spread the output of both antennas, otherwise $\mathbf{c}_{k,2}$ is used.

From the detector's perspective, since we do not have prior knowledge of which codes have been used by each user, we need to apply a bank of correlators for each possible code (Figure 1). For each $\mathbf{w}_{k,1}^{(n)} = \cdots = \mathbf{w}_{k,N_t}^{(n)} = \mathbf{c}_{k,m}$, we construct $\mathbf{S}_{k,i}^{(n,m)}$ using (4). Since all transmit antennas from the same user use the same code at instant n, all $\mathbf{S}_{k,i}^{(n,m)}$ are the same. In this case, we can use

$$\mathbf{S}_{k,1}^{(n,m)} = \cdots = \mathbf{S}_{k,N_t}^{(n,m)} = \mathbf{S}_k^{(n,m)}. \tag{16}$$

We will then be able to compute the corresponding correlator outputs:

$$\mathbf{y}_{j,k}^{(n,m)} = \left(\mathbf{S}_k^{(n,m)}\right)^H \mathbf{r}_j^{(n)}. \tag{17}$$

The detection strategy in case of parity bit-selected spreading is different from the conventional MIMO system. Indeed, for each user k, we must detect the $N_t \times 1$ vector

$$\mathbf{b}_k^{(n)} = \left[b_{k,1}^{(n)}, b_{k,2}^{(n)}, \ldots, b_{k,N_t}^{(n)}\right]^T \tag{18}$$

of bits transmitted by all its antennas at instant n since the choice of spreading code depends upon the value of this vector.

Using the same development in previous section, we can rewrite (17) using (16) as follows:

$$\mathbf{y}_{j,k}^{(n,m)} = \left(\mathbf{S}_k^{(n,m)}\right)^H \mathbf{S}_k^{(n)}\sum_{i=1}^{N_t}\mathbf{h}_{j,i,k}b_{k,i}^{(n)} + \mathbf{n}_j^{\prime\prime(n)}, \tag{19}$$

where $\mathbf{n}_j^{\prime\prime(n)}$ represents the despread noise, the MAI, and part of SI. Indeed, $\mathbf{y}_{j,k}^{(n,m)}$gathers part of the SI since we need the information from all transmitting antennas of the user of interest.

Equation (19) can be rewritten as

$$\mathbf{y}_{j,k}^{(n,m)} = \mathbf{R}_k^{(n,m)}\sum_{i=1}^{N_t}\mathbf{h}_{j,i}b_{k,i}^{(n)} + \mathbf{n}_j^{\prime\prime(n)}, \tag{20}$$

where

$$\mathbf{R}_k^{(n,m)} = \left(\mathbf{S}_k^{(n,m)}\right)^H \mathbf{S}_k^{(n)} \tag{21}$$

is the correlation matrix between the codes used by user k. It is worth noting here that when $\mathbf{S}_k^{(n,m)} = \mathbf{S}_k^{(n)}$, the correlation matrix has important diagonal elements. However, it will not be diagonal because of cross-correlation due to the multipath effect. This is true even with perfectly orthogonal codes. When $\mathbf{S}_k^{(n,m)} \neq \mathbf{S}_k^{(n)}$, the diagonal elements are zeros (case of orthogonal codes) while off-diagonal elements are nonzero.

Contrary to the case of frequency nonselective channels [2], to apply maximum likelihood detection in the case of frequency selective channels, SI and MAI have to be taken into account due to the loss of orthogonality. In our case, to keep the complexity at a low level while maintaining very good BER performance when compared to the conventional MIMO-CDMA system (see Section 4), a suboptimal detector is proposed. Indeed, we only consider the information from the user of interest in order to define our decision

metric. Therefore, the estimated data is determined using the following decision rule:

$$\widehat{\mathbf{b}}_k^{(n)} = \min_{\mathbf{b}^{(m)} \in B} \left(\sum_{j=1}^{N_r} \left\| \mathbf{y}_{j,k}^{(n,m)} - \mathbf{R}_k^{(n,m)} \sum_{i=1}^{N_t} \mathbf{h}_{j,i,j} b_i^{(m)} \right\|^2 + \left\| \overline{\mathbf{y}}_k^{(n)} \right\|^2 \right), \tag{22}$$

where $\overline{\mathbf{y}}_k^{(n)}$ is a vector containing a concatenation of all $\mathbf{y}_k^{(n,m')}$ with $m' = 1 \cdots N$ and $m' \neq m$ and $\mathbf{y}_k^{(n,m')}$ is an $N_r L \times 1$ vector:

$$\mathbf{y}_k^{(n,m')} = \left[\mathbf{y}_{1,k}^{(n,m')}, \mathbf{y}_{2k}^{(n,m')}, \ldots, \mathbf{y}_{N_r,k}^{(n,m')} \right]^T. \tag{23}$$

And B represents the set of 2^{N_t} possible values of $\mathbf{b}^{(m)}$, where $\mathbf{b}^{(m)} = [b_1^{(m)} \quad \cdots \quad b_i^{(m)} \quad \cdots \quad b_{N_t}^{(m)}]^T$.

3.3. Permutation Spreading System. In contrast to the parity bit-selected spreading technique, the permutation spreading technique allocates different spreading codes to each transmit antenna. When permutation spreading is used, depending on which coset the message comes from, a unique permutation of the spreading codes assigned to the user is employed. Each permutation employs N_t of the N spreading waveforms and we attempt to minimize the number of spreading codes that each permutation has in common. Furthermore, if a spreading waveform is used by antenna i of user k in one permutation, it cannot be used by antenna i in any other permutation for this same user. The design of the different spreading permutations is based on t-designs [32] which are used in permutation modulation schemes [33, 34]. Table 2 lists the spreading permutations when user k has 2, 3, and 4 transmitting antennas.

From the detector's perspective, as for the case of parity bit-selected spreading, we do not have prior knowledge of which codes have been used by each user. However, we know that we have to pick N_t different codes from the set $\mathbf{C}_k$ of N different codes for user k. Hence, we need to apply a bank of correlators for each possible code assignment:

$$\mathbf{y}_{j,k}^{(n,m)} = \sum_{i=1}^{N_t} \left(\mathbf{S}_{k,i}^{(n,m)} \right)^H \mathbf{S}_{k,i}^{(n)} \mathbf{h}_{j,i} b_{k,i}^{(n)} + \mathbf{n}_j^{\prime\prime(n)}, \tag{24}$$

where $\mathbf{n}_j^{\prime\prime(n)}$ is the same as the one defined earlier. In Table 2, we notice that depending on the message vector, we can build $\mathbf{S}_{k,i}^{(n,m)}$ using the corresponding spreading code for each antenna.

Equation (24) can be rewritten as

$$\mathbf{y}_{j,k}^{(n,m)} = \sum_{i=1}^{N_t} \mathbf{R}_{k,i}^{(n,m)} \mathbf{h}_{j,i,k} b_{k,i}^{(n)} + \mathbf{n}_j^{\prime\prime(n)}, \tag{25}$$

where

$$\mathbf{R}_{k,i}^{(n,m)} = \left(\mathbf{S}_{k,i}^{(n,m)} \right)^H \mathbf{S}_{k,i}^{(n)} \tag{26}$$

Table 2: Spreading permutations for MIMO-CDMA system using permutation spreading technique.

N_t	Coset	Message vectors	$\mathbf{w}_{k,1}^{(n)}$	$\mathbf{w}_{k,2}^{(n)}$	$\mathbf{w}_{k,3}^{(n)}$	$\mathbf{w}_{k,4}^{(n)}$
2 antennas	M_1	00	$\mathbf{c}_{k,1}$	$\mathbf{c}_{k,2}$	—	—
		11				
	M_2	01	$\mathbf{c}_{k,2}$	$\mathbf{c}_{k,1}$	—	—
		10				
3 antennas	M_1	000	$\mathbf{c}_{k,1}$	$\mathbf{c}_{k,2}$	$\mathbf{c}_{k,3}$	—
		111				
	M_2	001	$\mathbf{c}_{k,2}$	$\mathbf{c}_{k,3}$	$\mathbf{c}_{k,4}$	—
		110				
	M_3	010	$\mathbf{c}_{k,3}$	$\mathbf{c}_{k,4}$	$\mathbf{c}_{k,1}$	—
		101				
	M_4	100	$\mathbf{c}_{k,4}$	$\mathbf{c}_{k,1}$	$\mathbf{c}_{k,2}$	—
		011				
4 antennas	M_1	0000	$\mathbf{c}_{k,1}$	$\mathbf{c}_{k,3}$	$\mathbf{c}_{k,5}$	$\mathbf{c}_{k,7}$
		1111				
	M_2	0001	$\mathbf{c}_{k,8}$	$\mathbf{c}_{k,1}$	$\mathbf{c}_{k,4}$	$\mathbf{c}_{k,5}$
		1110				
	M_3	0010	$\mathbf{c}_{k,2}$	$\mathbf{c}_{k,4}$	$\mathbf{c}_{k,3}$	$\mathbf{c}_{k,8}$
		1101				
	M_4	0011	$\mathbf{c}_{k,5}$	$\mathbf{c}_{k,2}$	$\mathbf{c}_{k,6}$	$\mathbf{c}_{k,3}$
		1100				
	M_5	0100	$\mathbf{c}_{k,6}$	$\mathbf{c}_{k,7}$	$\mathbf{c}_{k,1}$	$\mathbf{c}_{k,4}$
		1011				
	M_6	0101	$\mathbf{c}_{k,3}$	$\mathbf{c}_{k,6}$	$\mathbf{c}_{k,8}$	$\mathbf{c}_{k,1}$
		1010				
	M_7	0110	$\mathbf{c}_{k,7}$	$\mathbf{c}_{k,8}$	$\mathbf{c}_{k,2}$	$\mathbf{c}_{k,6}$
		1001				
	M_8	0111	$\mathbf{c}_{k,4}$	$\mathbf{c}_{k,5}$	$\mathbf{c}_{k,7}$	$\mathbf{c}_{k,2}$
		1000				

is the correlation matrix of the code employed to spread the message sent by antenna i of user k and one of the N possible codes available for user k. In case of orthogonal normalized spreading codes, the correlation matrix is an identity matrix when $\mathbf{S}_{k,i}^{(n,m)} = \mathbf{S}_{k,i}^{(n)}$. Otherwise, the correlation matrix is a nonzero matrix with zeros in its diagonal.

For the same reasons as the parity bit-selected spreading system, a suboptimal detector is proposed. The estimated data is determined using the following decision rule:

$$\widehat{\mathbf{b}}_k^{(n)} = \min_{\mathbf{b}^{(m)} \in B} \left(\sum_{j=1}^{N_r} \left\| \mathbf{y}_{k,j}^{(n,m)} - \sum_{i=1}^{N_t} \mathbf{R}_{k,i}^{(n,m)} \mathbf{h}_{j,i,k} b_{k,i}^{(n)} \right\|^2 + \left\| \overline{\mathbf{y}}_k^{(n)} \right\|^2 \right), \tag{27}$$

where $\overline{\mathbf{y}}_k^{(n)}$ is a vector containing a concatenation of all $\mathbf{y}_{k,j}^{(n,m')}$ with $m' = 1 \cdots N$, $m' \neq m$, and $j = 1 \cdots N_r$. B is the set of 2^{N_t} possible values of $\mathbf{b}^{(m)}$, where $\mathbf{b}^{(m)} = [b_1^{(m)} \quad \cdots \quad b_i^{(m)} \quad \cdots \quad b_{N_t}^{(m)}]^T$.

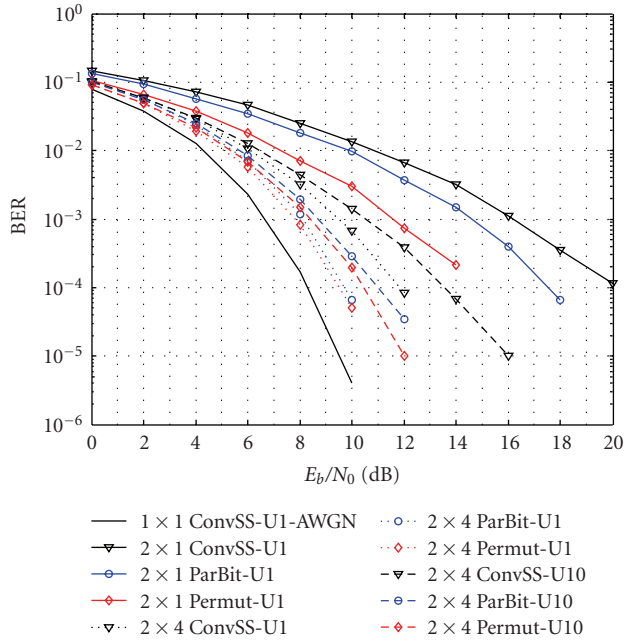

Figure 2: Performance comparison of three different MIMO-CDMA systems in frequency nonselective channels using Hadamard codes of length 32 where each user has 2 transmit antennas.

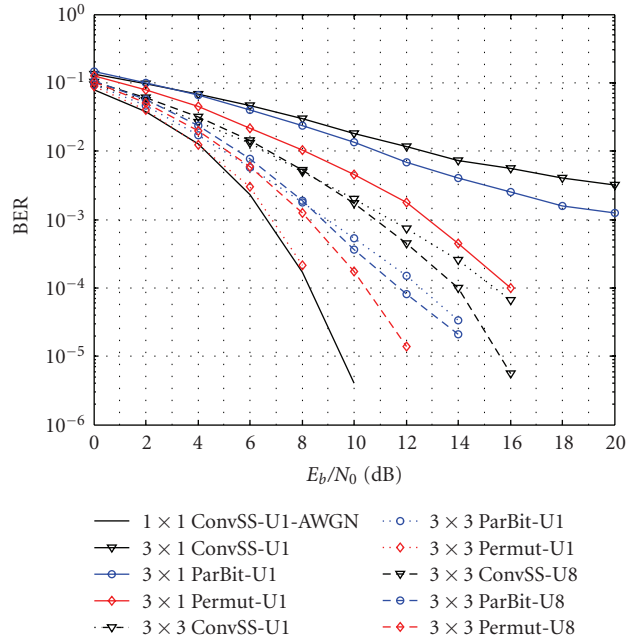

Figure 3: Performance comparison of three different MIMO-CDMA systems in frequency nonselective channels using Hadamard codes of length 32 where each user has 3 transmit antennas.

4. Simulation Results

In this section, we present the simulation results of spreading code assignment strategies presented in this paper. Among the parameters that can influence the performance of these schemes, we have

(i) number of transmitting antennas,

(ii) number of receiving antennas,

(iii) frequency selectivity of the channels,

(iv) spreading code cross-correlation properties,

(v) nonperfect channel estimation

(vi) space correlation.

We will study the effect of all these parameters in the following four subsections. Performance of each system is presented in terms of raw bit error rate (BER) before decoding for different E_b/N_0 using synthetic data. Quasistatic channels are used throughout the simulations. We consider both the frequency nonselective and frequency selective fading case. For the frequency selective case, we consider a channel with 6 resolvable paths. We assume that the channel gains on each resolvable path are independent of those on the other paths and that all have equal variance.

In all simulation results, the following notations have been adopted:

(i) $A \times B$: MIMO system with A transmit and B receive antennas (e.g., 2×4: 2 transmit and 4 receive antennas),

(ii) *UA*: A users are active in a cell (e.g., U1: 1 active user and U10: 10 active users),

(iii) ConvSS: conventional code assignment,

(iv) ParBit: parity bit selected spreading strategy,

(v) Permut: permutation spreading code strategy,

(vi) AWGN: additive white Gaussian noise channel.

4.1. Number of Transmit and Receive Antennas. To study the effect of the number of transmit and receive antennas, we have used Hadamard codes of length 32 and consider only one path between each transmit and receive antenna pair. There are only 32 Hadamard codes of length 32 and each user is assigned N of these codes. As each user is assigned a different set of these codes, the maximum number of users is $32/N$. Moreover, channel estimation is considered perfect and channel taps are spatially uncorrelated. In these conditions, it is possible for us to analyze the added value of both proposed schemes when compared to the conventional scheme in absence of SI and MAI. Figures 2, 3, and 4 present simulation results with 2, 3, and 4 transmit antennas, respectively. For each case, we have varied the number of receive antennas and the number of users that simultaneously share the same cell. The performance of all systems is compared to that of a single user system operating in AWGN channel. In all cases, our proposed schemes perform better than the conventional MIMO-CDMA scheme. Moreover, when subjected to the same conditions the permutation spreading scheme outperforms parity bit-selected spreading technique as well as the conventional MIMO-CDMA.

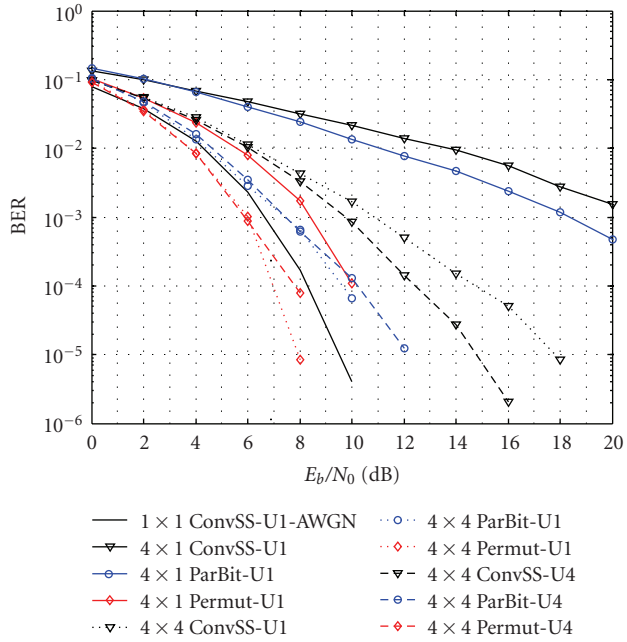

FIGURE 4: Performance comparison of three different MIMO-CDMA systems in frequency nonselective channels using Hadamard codes of length 32 where each user has 4 transmit antennas.

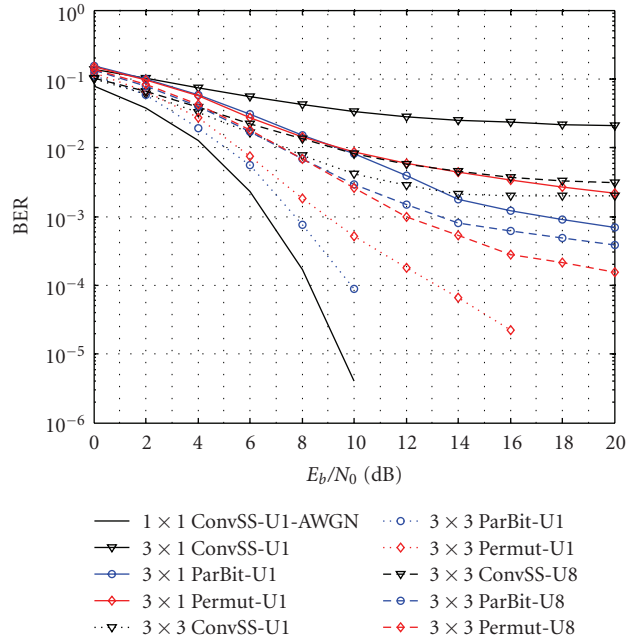

FIGURE 5: Performance comparison of three different MIMO-CDMA systems in frequency selective channels with 6 resolvable paths using Hadamard codes of length 32 where each user has 3 transmit antennas.

Since the single user AWGN case has the same curve for all three figures, we can observe the increase of robustness of the proposed scheme when increasing the number of transmitting antennas. This is quite expected since the number of spreading codes per user increases. Hence, systems with more transmit antennas at the receiver for the proposed schemes have more degrees of freedom (more code diversity) leading to improved BER performance compared to the conventional system.

4.2. Spreading Codes and Frequency Selectivity. Hadamard codes are well suited to establish the performance of CDMA systems in frequency nonselective channels and multiuser environments. However, in frequency selective channels, the orthogonality between the different codes in a user's set is lost and cross-correlation properties of the codes employed become very important. Two families of codes are compared in this subsection: Hadamard and Gold codes. Here we are interested in the frequency selective case. We assume that all fading gains are to be uncorrelated and that the receiver estimates all channel gains perfectly.

Figure 5 shows the BER performance when Hadamard (length 32) is used in a three transmit antenna system. Figure 6 shows the BER performance when Hadamard codes are replaced by Gold codes (length 31). The performance in both figures is given for one and three antenna receivers. Comparing the results of Figures 5 and 6, we see that, under the same conditions, Gold codes are better suited in the case of frequency selective channels due to their better cross-correlation properties [15, 35]. These results are further confirmed by Figures 7 and 8 when 4 transmit antennas are

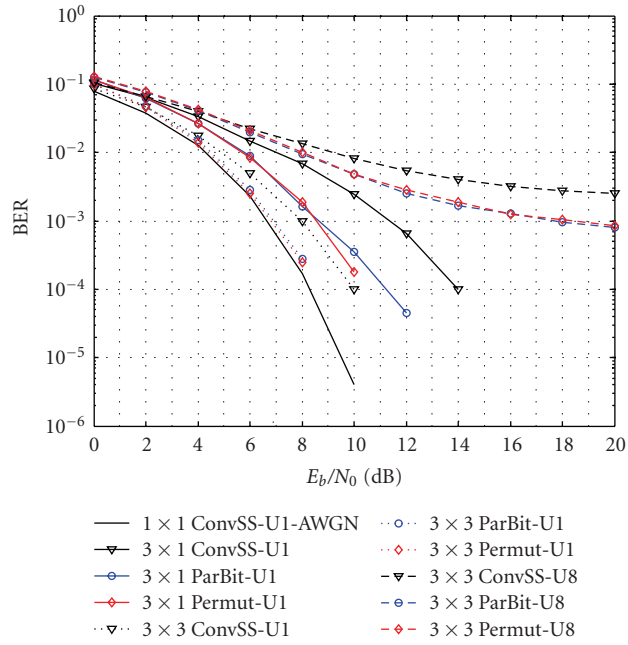

FIGURE 6: Performance comparison of three different MIMO-CDMA systems in frequency selective channels with 6 resolvable paths using Gold codes of length 31 where each user has 3 transmit antennas.

used. In all simulated conditions, proposed schemes are more robust to SI and MAI compared to conventional MIMO-CDMA systems. As mentioned in the previous subsection, this is mainly due to the code diversity. This means that more codes are needed which might represent a constraint in practice.

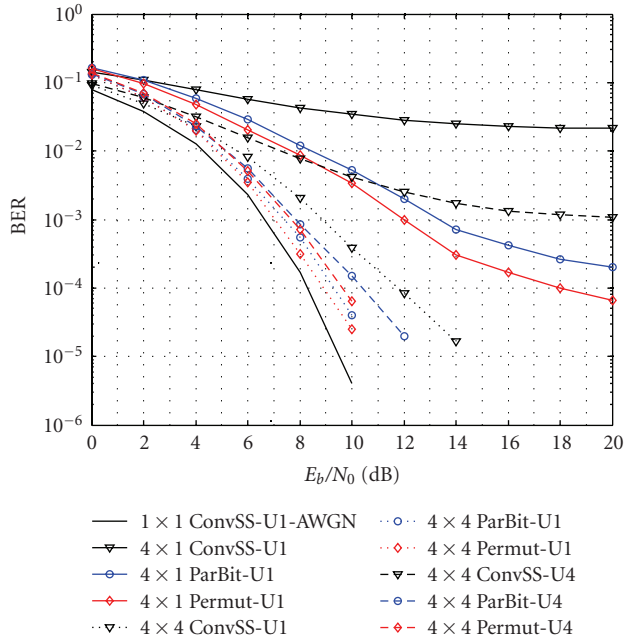

FIGURE 7: Performance comparison of three different MIMO-CDMA systems in frequency selective channels with 6 resolvable paths using Hadamard codes of length 32 where each user has 4 transmit antennas.

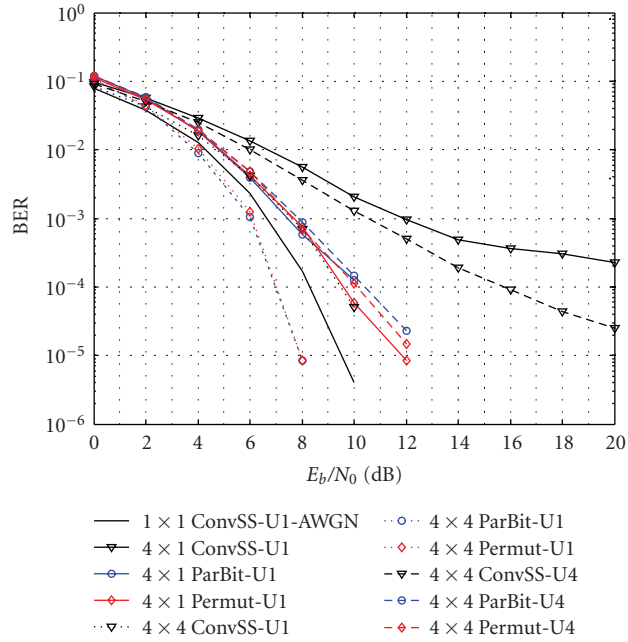

FIGURE 8: Performance comparison of three different MIMO-CDMA systems in frequency selective channels with 6 resolvable paths using Gold codes of length 31 where each user has 4 transmit antennas.

To overcome this drawback, we propose an alternative way to assign codes by assigning each user the same set of Hadamard codes as well as a unique scrambling code. This is similar to the way codes assigned in third generation wideband CDMA systems [36]. Indeed, the latter uses OVSF (Orthogonal Variable Spreading Factor) codes to spread users' data and one scrambling code per user to distinguish them. Figure 9 shows the BER performance of the different MIMO-CDMA systems that assign all users the same set of Hadamard sequence along with a unique scrambling code operating in a 4 × 4 MIMO frequency selective channel. We assume a spreading factor of 32. Here we notice that the number of users is not limited to 4 even though the spreading factor is 32. Therefore, the number of available codes does not become a limiting factor, which is the same as for conventional WCDMA systems.

In perfect channel conditions (perfectly estimated and uncorrelated), there is little or no advantage to using the permutation spreading strategy over the parity bit-selected spreading strategy. However, this will not be the case under non ideal conditions, which will be shown in the upcoming sections.

4.3. Channel Estimation Errors. Here we present the BER performance of the 3 techniques with channel uncertainties. Channel estimation errors are introduced within the channel gains as random values with fixed variances. Figure 10 shows the BER performance of the 4 × 4 MIMO systems with uncorrelated channels when channel estimation errors are present at the receiver. The estimation error is measured in normalized mean square error (NMSE). We consider estimation errors with NMSE of 0 (perfect estimation), 10, and 30 percent. From Figure 10, we note that the permutation spreading strategy is more robust to channel estimation errors when compared to parity bit-selected spreading. Indeed, both techniques present almost the same result when the receiver has perfect channel estimates. However, the parity bit-selected spreading strategy registers a performance loss up to 0.7 dB at a BER of 10^{-3} when the channel estimates have a normalized mean square error (NMSE) of 30%. When compared to the conventional system, both proposed strategies are more robust to channel estimation errors as the conventional system suffers a higher power loss at a BER of 10^{-3} when channel estimation errors are present.

4.4. MIMO Channel Correlations due to Antenna Spacing. In this subsection, spatial correlation, due to inadequate antenna spacing, effects are analyzed. Each $N_t \times N_r$ MIMO correlated channel tap is generated as follows [37]:

$$\text{vec}\left(\mathbf{H}^{(l)}\right) = \mathbf{R}^{1/2}\,\text{vec}\left(\mathbf{H}_w^{(l)}\right), \tag{28}$$

where $\mathbf{H}_w^{(l)}$ is the spatially white $N_t \times N_r$ MIMO channel for tap l, $\mathbf{R}$ is the $N_tN_r \times N_tN_r$ covariance matrix, and vec($\mathbf{A}$) stacks the matrix $\mathbf{A}$ into a vector columnwise. In our case, $\mathbf{R}$ has diagonal elements equal 1 and all off-diagonal elements are the same and equal to some value α. If $\alpha = 0$, $\mathbf{R}$ becomes an identity matrix and the MIMO channels are uncorrelated. As α increases, the channels become more correlated. In our simulations, we consider a 4 × 4 MIMO system operating in the frequency selective channel with 6 resolvable paths, with

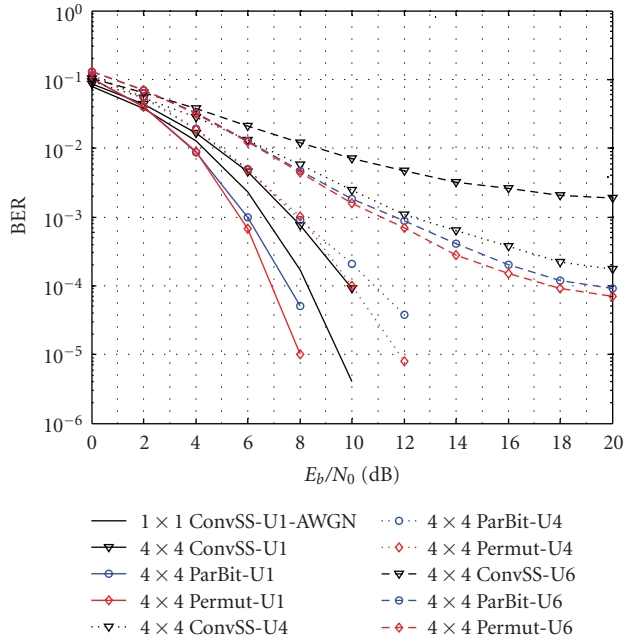

Figure 9: Performance comparison of three different MIMO-CDMA systems in frequency selective channels with 6 resolvable paths using a mix of Hadamard codes of length 32 for spreading and scrambling codes to distinguish between users.

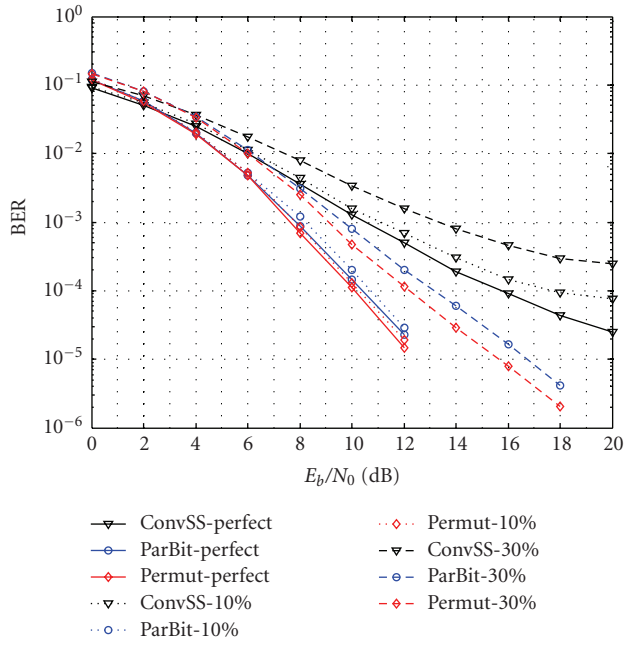

Figure 10: Effect of channel estimation errors on BER performance of 4 × 4 MIMO systems with 4 users in frequency selective channels (6 taps) and Gold codes of length 31.

4 active users, Gold spreading sequences of length 31, and three values for α: 0, 0.4, and 0.6. Under these conditions, the BER performance of the different spreading allocation techniques is given in Figure 11.

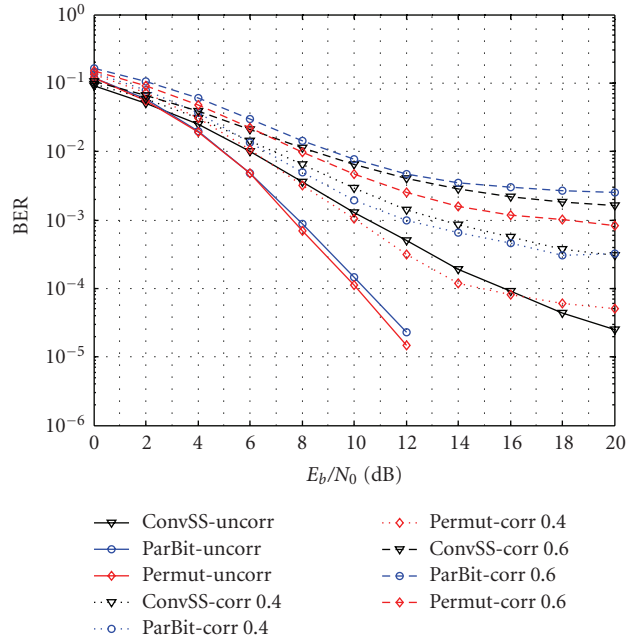

Figure 11: Effect of spatial correlation on BER performance o 4 × 4 MIMO systems with 4 users in frequency selective channels (6 taps) and Gold codes of length 31.

As the channel correlation increases, the parity bit-selected spreading technique suffers the most. Indeed, its performance relies on the degree of separation than can be achieved among users and antennas. As seen in Figure 11, when the correlation increases, the parity bit-selected spreading strategy loses some degrees of freedom. Even though the permutation spreading is also affected, the power loss due to correlation effects at a BER of 10^{-3} is less than that of both the parity bit-selected spreading technique and the conventional system. Indeed, at this target BER, permutation spreading strategy shows 2 dB improvement over the parity bit-selected strategy and a 3.5 dB improvement compared to the conventional technique when the spatial correlation coefficient is 0.4. Moreover, the permutation spreading strategy is the only technique that was capable of achieving a BER of 10^{-3} when the spatial correlation coefficient is as high as 0.6.

5. Conclusion

Different spreading strategies have been presented in this paper in frequency selective MIMO-CDMA systems. Simulation results allow us to establish the performance of proposed techniques in different scenarios and different construction parameters. The proposed parity bit-selected spreading and permutation spreading strategies are more robust to SI and MAI than the conventional system due to the extra code diversity. The latter increases with the number of transmitting antennas employed. Although the two proposed strategies have similar performance in frequency-selective fading when the receiver estimates the channel perfectly, the permutation spreading technique is less affected by the presence of channel estimation errors or spatial correlation.

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