

An Investigation on Efficient Spreading Codes for Transmitter Based Techniques to Mitigate MAI and ISI in TDD/CDMA Downlink

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Abstract—We investigate efficient spreading codes for transmitter based techniques of code division multiple access (CDMA) systems. The channel is considered to be known at the transmitter which is usual in a time division duplex (TDD) system where the channel is assumed to be the same on uplink and downlink. For such a TDD/CDMA system, both bitwise and blockwise multiuser transmission schemes are taken up where complexity is transferred to the transmitter side so that the receiver has minimum complexity. Different spreading codes are considered at the transmitter to spread the signal efficiently over the entire spectrum. The bit error rate (BER) curves portray the efficiency of the codes in presence of multiple access interference (MAI) as well as inter symbol interference (ISI).

Keywords—Code division multiple access, time division duplex, transmitter technique, precoding, pre-rake, rake, spreading code.

I. INTRODUCTION

DIRECT sequence CDMA (DS-CDMA) is an efficient wireless communication channel accessing scheme, able to sustain many simultaneous high data-rate users [1]-[2]. In practical conditions, however, wireless DS-CDMA systems face a combination of channel effects that reduce the system effectiveness drastically unless these impairments are taken care of. The major problems encountered here are the MAI, due to simultaneous usage of the bandwidth by many users, and, ISI, due to multipath channels. MAI and ISI are always added to the background thermal noise modeled as additive white Gaussian noise (AWGN). Thus, the systems utility is limited by the amount of total interference instead of the background noise exclusively as in other cases. In other words, the signal to interference plus noise ratio (SINR) is the limiting factor for a mobile communications system instead of the signal to noise ratio (SNR). Therefore, in systems applying CDMA the two problems of equalization and signal separation have to be solved simultaneously to increase the SINR and achieve a good performance. Multiuser detection (MUD) has been studied extensively and a number of solutions have been proposed [3]-[5]. These techniques are all receiver based and they usually require channel estimation as well as knowledge of all the active users spreading codes and they have considerable computational cost. While this is feasible for the base station (for the uplink scheme), it contrasts with the desire

to keep portable units (for the downlink scheme), like mobile phones, simple and power efficient. An alternative to MUD is to use multiuser transmission scheme [6], i.e., precoding a common transmitted signal for the service of all users using the information of the channel impulse response such that the ISI and MAI effects are minimized before transmission in the downlink. The extra computational cost is transferred to the base station where power and computational resources are more readily available. This is possible in TDD systems where both uplink and downlink use the same frequency. Thus the transmitter is able to know the fast fading of the multipath channel based on the uplink received signal and use this knowledge for precoding on the downlink. This presumes that the TDD frame length is shorter than the coherence time of the channel. If the TDD system is intended only for slowly moving terminals then longer TDD frames could also be used. A possible scenario in which the above assumptions are satisfied would be a personal communication system with low mobility users such as pedestrians in an outdoor environment. Indoor and microcell environments are the most probable application areas for TDD communications [7]. A second scenario could be a wireless local area network (WLAN). In such a case the indoor radio frequency (RF) channel has a small delay spread and a computer workstation environment has essentially stationary channels. A slow variation of the channels could be addressed with a periodical update of the channel profile estimates in the base station.

In a multiuser transmission scheme, a DS-CDMA transmitter usually modulates the information signal by many *orthogonal* spreading codes and in the *i*th receiver the received signal is correlated with a replica of the same spreading code intended for *i*th user. Here, even if the system is constrained to be synchronous, the multipath nature of the channel essentially destroys the orthogonality between the received signals. Thus, low crosscorrelation between the desired and the interfering users is important to reduce the MAI. Moreover, adequate autocorrelation properties are required for reliable initial synchronization. Large sidelobes of the autocorrelation function can easily lead to erroneous code synchronization decisions. Good autocorrelation properties of the spreading code result in a better resolution of the multipath components of a spread spectrum signal. Crosscorrelation and autocorrelation properties are connected in such a way that both cannot be achieved simultaneously. For example, random codes in general exhibit good autocorrelation properties but worse cross correlation than the deterministic ones. Spreading codes are a

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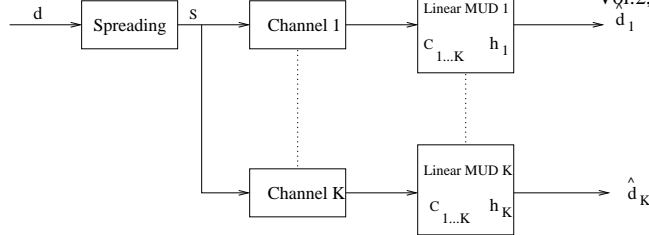


Fig. 1. Linearity of CDMA downlink.

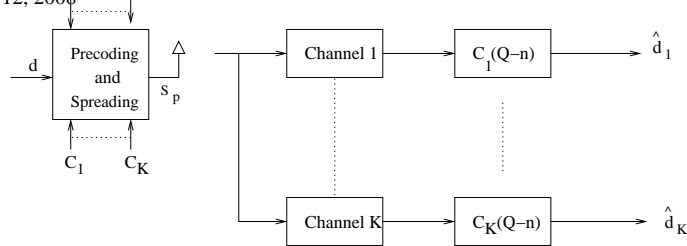


Fig. 2. Linear precoding with a linear transformation.

kind of pseudo random codes and can be divided into pseudo-noise (PN) codes and orthogonal codes. PN sequences are generated with a linear feedback shift register. The outputs of the shift register cells are connected through a linear function formed by exclusive-or (XOR) logic gates into the input of the shift register. Some of the PN sequences are (i) maximal length m -sequence, (ii) Gold, (iii) Kasami etc. Examples of Orthogonal codes include (i) Walsh-Hadamard (ii) modified Walsh-Hadamard, (iii) orthogonal Gold etc. A comparative study of many PN and orthogonal sequences can be found in [8].

In this paper we concentrate on exploring some of the spreading sequences described above which can be advantageous in multiuser transmission for TDD/CDMA systems. For investigating the efficiency of any spreading code, we use the asynchronous CDMA system code measurements. In particular, we want to look for certain spreading codes with good cross-correlation properties so that they can be applied readily to those channels with multipath problems. This would not only take care of MAI and ISI at the transmitter side, but also would void the requirement of equalization process at the receiver side. To check for the effectiveness of the spreading codes, we consider both blockwise (e.g., joint transmission) and bitwise (e.g., pre-rake and rake diversity) techniques. Certain correlation measurements, based on [8], are applied to find out the suitability of these sequences for the said techniques and depending on these, we find the BER performance of the transmitted sequences with different number of users in a system.

The paper is organized as follows: we briefly discuss the mathematical and conceptual backgrounds of transmitter based techniques in Section 2, treating both blockwise and bitwise techniques sequentially. Complexity issues of these techniques are taken up in Section 3. Section 4 deals with the different spreading codes and their correlation measurements. Based on these, results are given in Section 5 and finally, we conclude by summarizing the important concepts discussed herein in Section 6.

II. TRANSMITTER BASED TECHNIQUES IN CDMA

The problems of implementing multiuser techniques in mobile receivers and the need for their removal is underlined in the last section. The linearity of the conventional CDMA downlink system, presented simplified in Fig. 1, brings the concept of somehow reversing the MUD technique. Here, the aim is to transfer the complexity and the computational load to

the transmitter (BS) where weight and size is not of concern and resources, like power and space for hardware are readily available while maintaining at least the same performance that the receiver based MUD techniques provide. The mobile receiver (MS) will be restricted to the knowledge of its own signature waveform. Therefore, the k th subscriber's receiver shall consist of a simple correlator or a filter matched to the spreading sequence c_k , ideal for single user in an AWGN channel and no channel estimation, adaptive equalizer or feedback from the BS is required. In addition to that the overall capacity of the downlink in system is increased as no training sequences are needed to be transmitted.

An answer to the concept posed here is to apply a linear transformation matrix T on the transmitted vector d (the data spreading is included in the T matrix) in order to eliminate ISI and MAI, the major impairments of a CDMA system, before transmission. Under this scheme, the actual transmitted signal is distorted before transmission in such a way that after passing through the radio channel, the MS yields the desired data. Each MS should have the knowledge of the downlink channel impulse response and the spreading codes of every user to apply a joint MUD. If we take into account all mobile receivers, then the total information required is all K downlink channels and signature waveforms. The transformation matrix T should be a function of the same knowledge in linear precoding. In other words, to achieve good performance the transmitted signals in the downlink must be jointly optimized based on the spreading code and the downlink channel impulse response of every user. The BS obviously knows the spreading codes of all the active users in a cell and all it needs are the downlink channel impulse responses. The uplink channels can be estimated by the BS but this knowledge cannot be used for the downlink unless the principle of reciprocity is valid. In TDD this is valid which is the cause of using TDD in precoding. As shown in Fig. 2, the precoded transmitted signal can be described in general with a linear transformation matrix T applied on the data. In the following subsections we classify the realization of this linear algorithm either as blockwise or bitwise technique. Although both of them can be described by an appropriate matrix T , there are important differences which we discuss in the following subsections.

A. Blockwise Techniques

In blockwise algorithms, the data is precoded and transmitted in blocks of N data bits for each of the K users. This means that transformation matrix T is applied to a block of

NK data bits. Furthermore, it is desirable for the resulting signal \mathbf{s}_p to retain the same length NQ as produced by the conventional CDMA system where Q denotes the length of the specific spreading codes. Thus, dimensions of the T matrix shall be $NK \times NQ$. Note that T can be chosen according to different optimization criteria and the complexity for determining it varies from algorithm to algorithm. Ignoring this complexity, the multiplications required per bit per user for transmission of any blockwise technique, resulting from $\mathbf{s}_p = T\mathbf{d}$, is given as

$$\theta_{block} = \frac{(KN)(NQ)(KN)}{KN} = N^2QK \quad (1)$$

which shows that the multiplications required for one symbol transmission are proportional to the square of a block length N^2 which can be excessively high for any real TDD/CDMA scheme. A not so apparent problem with the blockwise algorithms is the fact that in a multipath environment the end bits of each block are not correctly precoded and this deteriorates the overall performance. Each block is treated independently and the ISI, between the symbols of the block itself, is canceled. However, under the scenario of continual block transmission each block is extended in duration due to multipath and therefore it overlaps with the next one. The degree of damage (the number of symbols affected) depends on the channels delay spread L . One solution to mitigate this problem is to increase the block length, but this results in an increased complexity. A second solution is to neglect the number of affected symbols resulting in loss of capacity.

1) *Joint transmission:* In joint transmission (JT) [9]-[10] the algorithm employs a common signal \mathbf{s}_p of length NQ which gives the desired data at the output of all individual MS. The received signal \mathbf{e}_k at the k th user is given as

$$\mathbf{e}_k = \mathbf{H}_k \mathbf{s} + \mathbf{v}, \quad (2)$$

where channel matrix $\mathbf{H}_k = [h_k^{i,j}]$, $i = 1, \dots, NQ + L - 1$, $j = 1, \dots, NQ$, and

$$[h_k]^{i,j} = \begin{cases} h_k^{i-j} & 0 \leq i - j \leq L - 1 \\ 0 & \text{otherwise.} \end{cases} \quad (3)$$

In (2), \mathbf{v} is a noise vector of length $(NQ+L-1)$. The noiseless version of \mathbf{e}_k can be written as $\mathbf{e}_k = \mathbf{H}_k \mathbf{s}$. After arranging all K matrices \mathbf{H}_k into a new $K(NQ + W - 1) \times NQ$ matrix \mathbf{H} where

$$\mathbf{H} = [\mathbf{H}_1^T, \dots, \mathbf{H}_k^T, \dots, \mathbf{H}_K^T]^T \quad (4)$$

and all \mathbf{e}_k , $k = 1, \dots, K$, vectors to a total received vector $\mathbf{e} = [\mathbf{e}_1^T, \dots, \mathbf{e}_k^T, \dots, \mathbf{e}_K^T]^T$, it can be concisely written as

$$\mathbf{e} = \mathbf{H} \mathbf{s}_p. \quad (5)$$

The total received signal \mathbf{e} in the above equation cannot be observed by a single MS. An MS can only observe \mathbf{e}_k as given in (2). The output vectors $\hat{\mathbf{d}}_k$, $k = 1, \dots, K$, at the decision variable of the K users are combined to form the vector $\hat{\mathbf{d}} = [\hat{\mathbf{d}}_1^T, \dots, \hat{\mathbf{d}}_k^T, \dots, \hat{\mathbf{d}}_K^T]^T$ where any $\hat{\mathbf{d}}_k = [\hat{d}_1^T, \dots, \hat{d}_k^T]^T$.

The k th receiver filter matched to the users spreading code can be written as

$$\hat{\mathbf{d}} = \mathbf{B}^T \mathbf{H} \mathbf{s}_p \quad (6)$$

where the $K(NQ+W-1) \times KN$ diagonal matrix \mathbf{B} is defined as

$$\mathbf{B} = \text{blockdiag}(\mathbf{B}_1, \dots, \mathbf{B}_k, \dots, \mathbf{B}_K), \quad (7)$$

with any $(NQ + L - 1) \times N$ matrix \mathbf{B}_k defined as

$$\mathbf{B}_k = [\mathbf{C}_k^T \quad \mathbf{O}]^T,$$

and \mathbf{O} being a $N \times (L - 1)$ zero matrix. The $NQ \times N$ matrix $\mathbf{C}_k = [\mathbf{C}_k]^{i,j}$, $i = 1, \dots, NQ$, $j = 1, \dots, N$ where

$$[\mathbf{C}_k]^{i,j} = \begin{cases} c_k^{i-Q(j-1)-1} & \text{for } i \leq Q(j-1) \leq Q \\ 0 & \text{otherwise} \end{cases} \quad (8)$$

and c_k s are the transmitted CDMA codes. The objective of any precoding algorithm is that the output of the mobile receiver yields the transmitted data, i.e., $\hat{\mathbf{d}} = \mathbf{d}$. Substituting this into (6) the problem of JT takes the form of

$$\mathbf{B}^T \mathbf{H} \mathbf{s}_p = \mathbf{d}. \quad (9)$$

Matrices \mathbf{B} , \mathbf{H} and the vector \mathbf{d} in (9) are known at the BS and \mathbf{s}_p is an unknown vector with length NQ . The condition $KN < NQ$ is a basic assumption for TDD/CDMA, and hence (9) constitutes an optimization problem, where the number of restrictions contained in the vector \mathbf{d} of length KN is smaller than the number NQ of degrees of freedom, expressed by the vector \mathbf{s}_p . Therefore, the validity of (9) implies that it has infinitely many solutions for \mathbf{s}_p . A constraint criterion is necessary to be imposed to the system. It is desirable for the transmitted vector \mathbf{s}_p to be of minimum energy and it can be achieved by standard Lagrange techniques. The solution after solving through Lagrange techniques is

$$\mathbf{s}_p = \mathbf{H}^T \mathbf{B} (\mathbf{B}^T \mathbf{H} \mathbf{H}^T \mathbf{B})^{-1} \mathbf{d} \quad (10)$$

where the joint precoding matrix T for JT can be written as

$$\mathbf{T}_{JT} = \mathbf{H}^T \mathbf{B} (\mathbf{B}^T \mathbf{H} \mathbf{H}^T \mathbf{B})^{-1}. \quad (11)$$

Equation (11) shows that joint transmission can be considered as a set of independent pre-rake ($\mathbf{H}^T \mathbf{B}$) applied on the modified information signal given by the linear transformation of the data vector \mathbf{d} [11].

B. Bitwise Techniques

In the bitwise techniques, the precoding realization does not include blocks of data to be processed. The data of user k after being spread is pre-filtered by an FIR filter of length P with a discrete time impulse response $p_k(n)$ as shown in Fig. 3. The resulting modified signals are summed to form the final transmitted signal \mathbf{s}_p . The filter is applied on the transmitted waveform rather than the data symbols as in the blockwise techniques. Thus the multipath resolution afforded by the CDMA spreading is exploited. Moreover, since the filters are applied at the chip level and the derivation of the algorithms are restricted to consider only a few symbols (even one), the higher computation required for data-block solutions is eliminated. Pre-filters also have the advantage of not modifying the original CDMA structure directly as it is a simple addition of an array of FIR filters to the existing BS transmission system. Furthermore, the bitwise nature of the

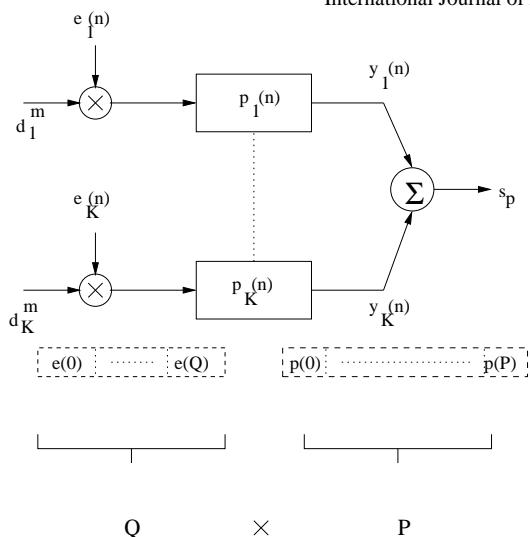


Fig. 3. Bitwise precoding scheme.

algorithms removes the undesirable effect of the end bockbits as described in the previous section. The taps of the pre-filters are determined by the adopted technique. Ignoring the complexity of the algorithm used to determine the taps, the multiplications required now per transmitted symbol per user bitwise is given by

$$\theta_{bit} = PQ. \quad (12)$$

Comparing (1) and (12), we observe that the complexity ratio of blockwise and bitwise techniques comes as

$$\frac{\theta_{block}}{\theta_{bit}} = \frac{N^2 K/2}{P}. \quad (13)$$

In a CDMA system with linear MUD the number of users that can be accommodated do not outnumber the spreading gain $K \leq Q$. If we set as a reasonable pre-filter length P as twice the spreading gain Q and K as $Q/2$, then

$$\frac{\theta_{block}}{\theta_{bit}} = \frac{N^2 Q/2}{2Q} = \frac{N^2}{4}. \quad (14)$$

Clearly, for $N \geq 2$ (in a realistic system, $N \gg 2$) the multiplications required with a blockwise implementation of precoding outnumber the corresponding bitwise implementation by a large number. For less complexity, the bitwise techniques like pre-rake thus has gained importance.

1) *Pre-rake diversity*: This technique was initially described in [12] for DS spread spectrum systems and then extended in [13] for TDD/CDMA mobile communications. The algorithm for pre-rake origins from the diversity theory in frequency selective channels. In a mobile environment the combination of the received signals from diverse independent paths or mediums can improve the system performance. Hence in the radio mobile communications it is desirable to receive a signal from diverse independent paths and then combine their powers. This is what a rake receiver does.

The pre-rake technique is straightforward and takes direct advantage of the fact that in TDD the channel impulse response can be assumed the same for the uplink and the downlink. The idea is to transmit a number of signals that

merge to a signal with the characteristics of a rake diversity signal when received after the multipath channel. Each one of these transmissions should be then delayed according to the estimated relative path delay and amplified according to the estimated path complex coefficient. In other words, in the downlink the BS multiplies the signal to be sent to user k by the time inverted complex conjugate of the uplink channel impulse response of the same user. When the signal is transmitted it is convolved with the channel impulse response of user k . This produces a strong peak at the output of the channel which is equivalent to the rake receivers output. Therefore, the receiver of the MS does not need to estimate the channel impulse response and only uses a matched filter tuned to this peak. The scenario is explained with the analogy of rake and pre-rake concept for a single user scheme in the following. We begin with the SNR analysis at the output of a rake receiver with the input signal $x(n) = w_k d_k^n c_k^n$ with a transmission power w_k^2 . The signal y_2 after passing from the multipath channel and being perturbed by AWGN is

$$y_2 = \sum_{l=0}^{L-1} h(l)x(n - lT_c) + v(n). \quad (15)$$

The filter right after y_2 is matched to the spreading code. The rake combination follows this matched filtering and we have

$$y_3 = \sum_{l=0}^{L-1} \sum_{m=0}^{L-1} h(l)h^*(L-1-m)x(n - (l+m)T_c) + \sum_{l=0}^{L-1} h^*(L-1-nT_c)v(n - lT_c) \quad (16)$$

at the output of the rake combiner. The desired output of the rake system is $\sum_{l=0}^{L-1} h(l)x(n - lT_c)$ and occurs at time $n = (L-1)T_c$, ($l+m = L-1$), which has a signal strength of

$$\left(\sum_{l=0}^{L-1} h(l)h^*(l) \right)^2 w_k^2. \quad (17)$$

Noise adds up incoherently with power σ^2 . From (17), the SNR at the output of the rake receiver is

$$SNR_{rake} = \frac{w_k^2}{\sigma^2} \left(\sum_{l=0}^{L-1} h(l)h^*(l) \right)^2. \quad (18)$$

In contrast, in a pre-rake, to make sure that the power of the signal at the output of the pre-rake transmitter is equal to w_k^2 , a power scaling factor is chosen to compensate for the gains produced by $h^*(l)$ and can be taken as [12]

$$F = \frac{1}{\sqrt{\sum_{l=0}^{L-1} h(l)h^*(l)}}. \quad (19)$$

If we think about a pre-rake combining which is similar to a multipath estimation, the output signal is

$$y_4 = F \left(\sum_{l=0}^{L-1} h(l - nT_c)^* x(n - lT_c) \right). \quad (20)$$

After transmission, convolution with the multipath channel and addition of AWGN yields the output signal

$$y_6 = F\left(\sum_{l=0}^{L-1} \sum_{m=0}^{L-1} h^*(l)h(L-1-m)x(n-(l+m)T_c)\right) + v(n). \quad (21)$$

The desired signal occurs again at time $n = (L-1)T_c$ and has a power equal to

$$\left(\sum_{l=0}^{L-1} h(l)h^*(l)\right)^2 w_k^2 F^2. \quad (22)$$

The noise at the output of the matched filter has a power equal to σ^2 . We replace F with the expression given above and thus the SNR can be written as

$$\text{SNR}_{\text{pre-rake}} = \left(\sum_{l=0}^{L-1} h(l)h^*(l)\right)^2 \frac{w_k^2}{\sigma^2} F^2 = \left(\sum_{l=0}^{L-1} h(l)h^*(l)\right) \frac{w_k^2}{\sigma^2}. \quad (23)$$

Equations (18) and (23) show that the SNR for the pre-rake system is equal to that of the rake system for a single user except the power scaling factor. This analysis states that under the assumption that the channel parameters are estimated ideally on the transmitter, the two systems have similar performance.

In [13] the concept of pre-rake was extended to a multiuser TDD/CDMA system. The signal for user k after spreading is filtered by the time inverse complex conjugate impulse response of the k th user channel and this process is repeated for every user before transmission. The produced signals are appropriately scaled to maintain the power at the desired levels and then superimposed at the antenna element. The block diagram of the pre-rake technique applied in a TDD/CDMA is identical with the general description of a bitwise precoding technique as illustrated in Fig. 3. Therefore, pre-rake has the advantages of a bitwise approach in terms of simplicity in implementation. Furthermore, the calculation of the pre-filter's tap coefficients don't require any complicated algorithm. Each pre-filter's impulse response is the time inverse conjugated of the corresponding uplink channel.

The principle applied is that in the downlink the desired user's signal is maximal ratio combined by the channel itself while other user signals are not. Under the multiuser scenario, however, the pre-rake is proved to be an insufficient technique unable to compensate for the multipath interference and MAI as shown in [13],[14].

III. COMPLEXITY ISSUES

The precoding techniques described in the earlier section require excessive computational cost compared to the usual conventional spreading. The complexity is similar or exceeds the one demonstrated by the receiver based multiuser techniques as described in [4]. However, it is shifted to the BS, where the resources are more readily available and thus it is less critical. Table I summarizes the computational cost for JT and pre-rake schemes. The criteria used are the dimension of the matrix that needs to be inverted and the number of multiplications per transmitted symbol. The number of

Precoding algorithm	Dimension of matrix to be inverted	Number of mult. per symbol
JT	$KN \times KN$	$N^2 QK$
Pre-rake	none	LQ

multiplications are calculated after the final transformation matrix T for the blockwise techniques, as discussed in above section. As expected the blockwise technique JT is more demanding in terms of complexity compared to the bitwise pre-rake.

IV. CORRELATION MEASURES OF DIFFERENT SPREADING SEQUENCES

In order to compare different sets of spreading sequences, we need a quantitative measure for the judgment. Therefore, we take help of some useful criteria as given in [8], that can be used for such a purpose. These are based on correlation functions of the set of sequences since both the MAI and synchronization amiability depend on the crosscorrelation between the sequences and the autocorrelation functions of the sequences, respectively. There are, however, several specific correlation functions that can be used to characterize a given set of the spreading sequences.

In [1], one of the first detailed investigations of the asynchronous DS-CDMA system performance was given. The work obtained a bound on the SNR at the output of the correlation receiver for a CDMA system with hard-limiter in the channel. The need for considering the aperiodic crosscorrelation properties of the spreading sequences is also clearly demonstrated. Since that time, many additional results have been obtained which helped to clarify the role of aperiodic correlation in asynchronous DS-CDMA systems.

For general polyphase sequences $\{\mu_n^{(i)}\}$ and $\{\mu_n^{(l)}\}$ of length N , the discrete aperiodic correlation function is defined as

$$\rho_{i,k}(\tau) = \begin{cases} \frac{1}{N} \sum_{n=0}^{N-1-\tau} \mu_n^{(i)} [\mu_{n+\tau}^{(l)}]^* & \text{for } 0 \leq \tau \leq N-1 \\ \frac{1}{N} \sum_{n=0}^{N-1+\tau} \mu_{n-\tau}^{(i)} [\mu_n^{(l)}]^* & \text{for } N-1 \leq \tau < 0 \\ 0 & |\tau| \geq N \end{cases} \quad (24)$$

when $\{\mu_n^{(i)}\} = \{\mu_n^{(l)}\}$ then (24) defines the discrete aperiodic autocorrelation function.

Another important parameter used to assess the synchronization amiability of the spreading sequence $\{\mu_n^{(i)}\}$ is a merit factor, or a figure of merit, which specifies the ratio of the energy of autocorrelation function main-lobes to the energy of the autocorrelation function side-lobes in the form

$$\Psi = \frac{\rho_i(0)}{2 \sum_{\tau=1}^{N-1} |\rho_i(\tau)|^2}. \quad (25)$$

In DS-CDMA systems, we want to have the maximum values of aperiodic cross correlation functions and the maximum values of out-of-phase aperiodic autocorrelation functions as small as possible, while the merit factor as large as possible for all of the sequences used.

The BER in a multiple access environment depends on the modulation technique used, demodulation algorithm, and the

signal to noise power ratio (SNR) available at the receiver. Pursley [2] showed that in case of a BPSK asynchronous DS CDMA system, it is possible to express the average SNR at the receiver output of a correlator receiver of the i th user as a function of the average interference parameter (AIP) for the other K users of the system, and the power of AWGN present in the channel.

A. Mean Square Correlation Measures

In order to evaluate the performance of a whole set of M spreading sequences, the mean-square aperiodic crosscorrelation (MSACC) for all sequences in the set, denoted by R_{CC} , was introduced by [17] as a measure of the set crosscorrelation performance, where

$$R_{CC} = \frac{1}{M(M-1)} \sum_{i=1}^M \sum_{k=1, k \neq i}^{N-1} \sum_{\tau=1-N}^{N-1} |\rho_{i,k}(\tau)|^2. \quad (26)$$

A similar measure known as mean-square aperiodic autocorrelation (MSAAC), denoted by R_{AC} , was introduced for comparing the autocorrelation performance and is given by

$$R_{AC} = \frac{1}{M} \sum_{i=1}^M \sum_{\tau=1-N, \tau \neq 0}^{N-1} |\rho_{i,k}(\tau)|^2. \quad (27)$$

For DS-CDMA applications we want both parameters R_{CC} and R_{AC} to be as low as possible [16], [17]. Because these parameters characterize the whole sets of spreading sequences, it is convenient to use them as the optimization criteria in design of new sequence sets. We need to find out maximum value of aperiodic crosscorrelation functions since this parameter is very important when the worst-case scenario is considered.

B. Optimized Codes for Pre-Rake and JT

The autocorrelation and crosscorrelation measures which are discussed above are calculated for the following sequences: (a) maximal length, (b) Gold, (c) Walsh-Hadamard, and, (iv) modified Walsh-Hadamard [18]. The different correlation parameters for the above sequences can be found in [8]. For our purpose, the parameters are calculated for a sequence of length 31, for m and Gold sequences, and, of length 32, for Walsh-Hadamard and modified Walsh-Hadamard sequences.

JT is a transmitter based precoding which uses all users codes and channel impulse response for precoding. It is similar to joint detection which is used at mobile unit. The advantage of using JT transmission over pre-rake diversity combiner technique is that it reduces the MAI which cannot be done by pre-rake or rake receiver. So the optimized code for JT is the one which has very low mean-square out of phase autocorrelation (which is a must) along with a low crosscorrelation value. For rake receiver and pre-rake receiver, however, which is generally considered single user receiver the code should have good autocorrelation and crosscorrelation properties.

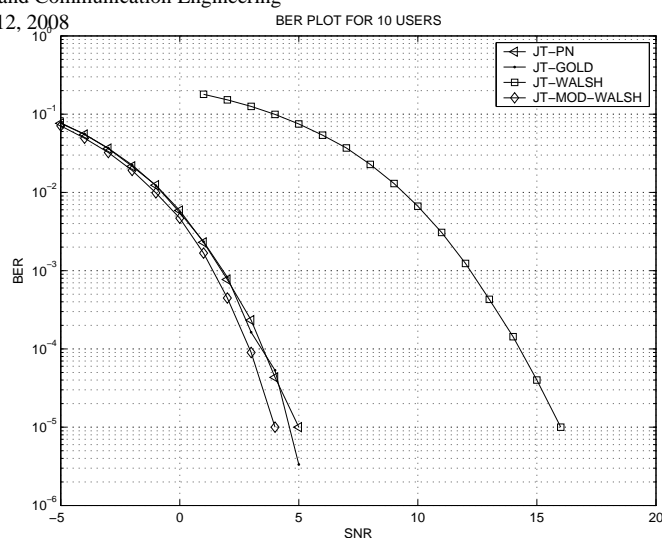


Fig. 4. BER plots of JT for 10 users using different sequences.

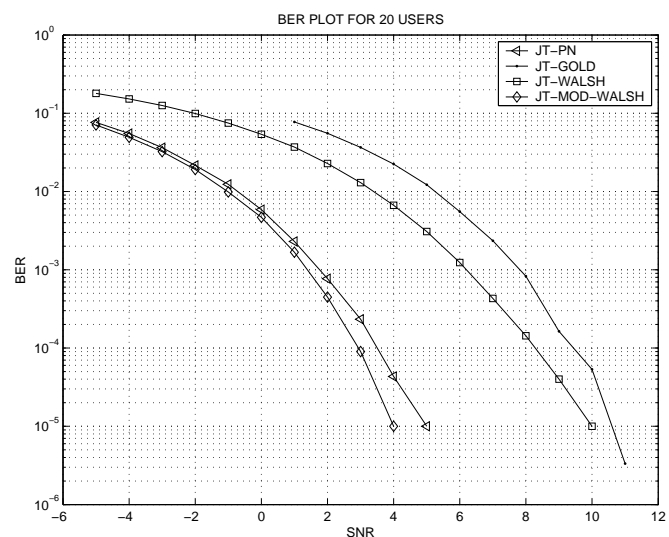


Fig. 5. BER plots of JT for 20 users using different sequences.

V. RESULTS AND DISCUSSIONS

The performance of the JT, pre-rake and rake receivers is analyzed with different codes which are discussed in the above section, for 10 and 20 users. Simulation is done with the following assumptions: (a) modulation scheme is simply binary phase shift keying (BPSK), (b) system is simulated for HIPERLAN channel models (we used channel model 5 for simulation purpose), and (c) channel estimated in uplink is exactly equal to channel in downlink, i.e., it is a TDD system.

BER plots for joint transmission for 10 users and 20 users are shown in Figs. 4 and 5, respectively. It is clear from the plots that JT has good performance for Gold, modified Walsh and m -sequence for 10 users and they are approximately same because these codes have good autocorrelation properties whereas Walsh doesn't have that. But when the number of users are increased the performance of m -sequence is not as good as Gold and modified Walsh because it has high mean

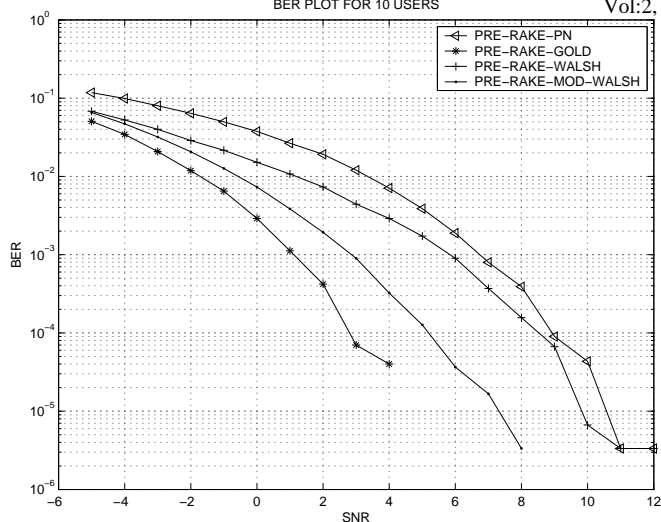


Fig. 6. BER plots of pre-rake for 10 users using different sequences.

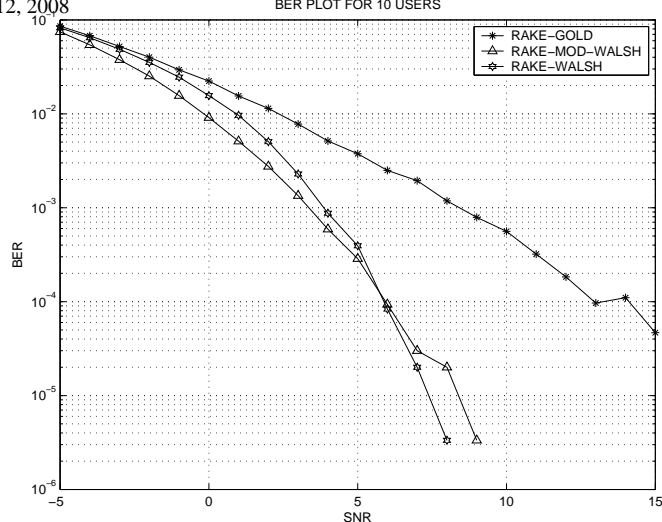


Fig. 8. BER plots of rake for 10 users using different sequences.

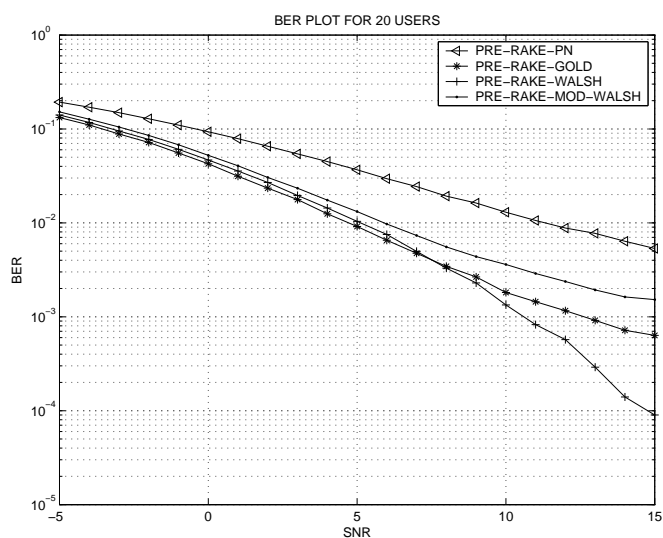


Fig. 7. BER plots of pre-rake for 20 users using different sequences.

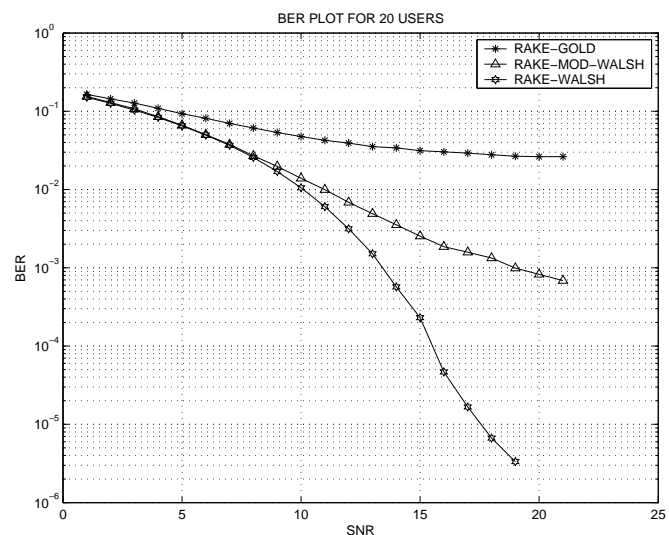


Fig. 9. BER plots of rake for 20 users using different sequences.

square crosscorrelation value and maximum peaks of aperiodic crosscorrelation than Gold and modified Walsh sequences.

Similarly BER plots for pre-rake are shown in Figs. 6 and 7. For rake receiver, these are shown in Fig. 8 and Fig. 9 for 10 and 20 users as earlier. JT scheme uses all codes and channel impulse response of all users for precoding which reduces the multiple access interference. It is found that in case of pre-rake, for less number of users, Gold sequence performs better than the all other codes but for 20 users and above the performance of Walsh sequence is better than the others since Walsh codes have less mean-square crosscorrelation value. Whereas for rake receiver the performance of modified Walsh and Walsh are good for 10 and 20 users, respectively, because Walsh codes have low mean-square correlation value than the modified Walsh sequence.

VI. CONCLUSIONS

In CDMA systems, an alternative to multiuser detection is to use multiuser transmission scheme where the extra computational cost is transferred to the base station where power and computational resources are more readily available. Here the channel estimation at the transmitter is possible if we assume TDD where both uplink and downlink use the same frequency. We have taken up both the blockwise and bitwise techniques for such multiuser transmission schemes. In particular, the performance of joint transmission, pre-rake and rake diversity combiners for a TDD/CDMA system is investigated with the help of different spreading codes. The main virtue of JT is that it reduces the MAI effectively than pre-rake or rake, but it is more complex than the latter two algorithms. Although we assumed that the systems are synchronous, we have used the measures of spreading codes which are used for asynchronous system. It is observed that optimized codes for the JT scheme are Gold and modified Walsh-Hadamard codes. On the other

hand, for pre-rake and rake combining, the optimized codes come out to be Walsh-Hadamard codes.

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