A Two-Layer Spreading Code Scheme for Dual-Rate DS-CDMA Systems

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***Abstract*—This letter considers multiuser detection in variable-spreading-length multi-rate direct-sequence code-division multiple-access systems. A two-layer spreading (TLS) code scheme is proposed which facilitates the low-complexity adaptive implementation of linear minimum mean-square error multiuser receivers in a dual-rate system. It is demonstrated via large system analysis and simulation that imposing a TLS structure does not incur loss in terms of the output signal-to-interference ratio performance.**

***Index Terms*—Adaptive receiver, direct-sequence code-division multiple-access (DS-CDMA) systems, linear minimum mean-square error (MMSE) receiver, multirate systems, multiuser detection.**

I. Introduction

FUTURE code-division multiple-access (CDMA) systems are expected to support the simultaneous transmission of different information sources, including voice, video, or data packets. To accommodate multiple data rates in direct-sequence code-division multiple-access (DS-CDMA) systems, different multirate access schemes have been proposed. Among them, multicode (MC) and variable spreading length (VSL) are two of the most popular schemes [1], [2].

A major drawback of the MC system is the high peak-to-average power ratio, making it difficult to design the linear amplifier in the transmitter. Another problem is that the number of training symbols needed for a user is proportional to the ratio between this user's symbol rate and the basic rate of the system. On the other hand, the VSL system has more flexibility, and it has been shown recently in [3] that its performance matches that of the MC system when linear minimum mean-square error (MMSE) multiuser receivers are used.

One potential problem for the VSL systems is that for a user with symbol rates higher than the basic rate of the system, the cross correlations between different users' spreading sequences change from symbol to symbol, making it difficult to implement adaptive multiuser detection or adaptive power control. In this letter, we propose a simple VSL scheme that enables low-complexity adaptive multiuser detection without incurring any significant performance loss. While we will focus on dual-rate DS-CDMA systems, extension to more general cases is straightforward.

Paper approved by G. Cherubini, the Editor for CDMA Systems of the IEEE Communications Society. Manuscript received January 22, 2002; revised July 27, 2002 and November 9, 2002. This work was supported in part by the National Science Foundation under Grant CCR-99-79361 and in part by the New Jersey Center for Pervasive Information Technology. This paper was presented in part at the IEEE Vehicular Technology Conference, Vancouver, BC, Canada, September 2002.

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Digital Object Identifier 10.1109/TCOMM.2003.813266

A dual-rate system supports two different data rates: a basic rate and a higher rate. We will call the users transmitting at the basic rate the low-rate users and the users with higher data rate the high-rate users. In synchronous dual-rate systems, an optimal receiver should span the duration of one low-rate symbol in order to collect the sufficient statistic for data detection. We will call these low-rate receivers. While using low-rate receivers may yield the best performance, high complexity and large decision delay make it impractical in some applications. Also, in such a system, a high-rate user is treated as M low-rate users (assuming a rate ratio of M); hence, the number of training symbols, if used, must be increased M-fold. Due to these considerations, suboptimal receivers spanning only one or a few high-rate symbols are attractive alternatives. Here, we focus on the so-called high-rate receivers which span only a single high-rate symbol; extension to more general cases is straightforward.

In recent years, several types of multiuser receivers have been proposed for multirate CDMA systems, including the optimum receiver [4], the decorrelator [5], [6], the linear MMSE multiuser receiver [7], [8], successive interference cancellation (SIC) [9], parallel interference cancellation (PIC) [10], and the multistage receiver [11]. Among them, the linear MMSE multiuser receiver and (groupwise) SIC/PIC are more promising because of their good performance and relatively low complexity. SIC/PIC has the lowest complexity of any multiuser receivers (apart from the matched filter) and can be used in systems with long spreading codes. However, these techniques require the knowledge of all users' spreading sequences, and channel estimation is needed to estimate the delays and received amplitudes of all users. While the linear MMSE multiuser receiver also requires all this information, when implemented adaptively, only the training data or the spreading code and channel information for the desired user is needed.

As mentioned above, time-varying cross correlations between different users' spreading sequences make it difficult to implement adaptive algorithms. To deal with this problem, an adaptive MMSE receiver using cyclostationarity properties of the multirate DS-CDMA system has recently been proposed by Buzzi *et al.* [12]. Although this method performs well, it suffers from slow convergence speed and high complexity because the number of coefficients to be adapted is proportional to the rate ratio M. In [13], Ge proposed using repetition codes for the low-rate users to enable the adaptive implementation of the high-rate MMSE receiver. However, as shown in [3], the adoption of repetition codes for low-rate users incurs severe performance loss in terms of the output signal-to-interference ratio (SIR) of the low-rate users and the user capacity of the system.

In this letter, we propose a two-layer spreading (TLS) code scheme for the dual-rate VSL systems. (This concept can be easily extended to general multirate VSL systems, where multilayer spreading will be used.) Although this scheme is a simple modification of the repetition code scheme, simulation results show that it has much better performance. To establish the advantage of the TLS scheme theoretically, we study its large system performance using random spreading sequence analysis, i.e., we let the number of users K and the spreading gain N grow without bound while fixing their ratio K/N. This approach facilitates the analysis of CDMA systems and has been adopted in a number of recent studies [14]–[21]. We show that the proposed scheme enables the implementation of low-complexity adaptive linear multiuser receivers without incurring any significant performance loss relative to systems employing general spreading codes.

The rest of this letter is organized as follows. The signal model is described in Section II. In Section III, we present the TLS. Analytical and numerical results concerning the performance of this new scheme are given in Sections IV and V, respectively. Finally, we present some concluding remarks in Section VI.

II. Signal Model

For a dual-rate synchronous DS-CDMA system, the received signal in a given low-rate symbol interval can be written (after chip-matched filtering and chip-rate sampling) as

$$r(n) = \sum_{j=1}^{K_0} A_{j,0} b_{j,0} s_{j,0}(n) + \sum_{i=1}^{K_1} \sum_{m=1}^{M} \times A_{i,1}^m b_{i,1}^m s_{i,1}^m(n) + w(n), \qquad n = 1, \ldots, N \quad (1)$$

where we adopt the notations used by Chen and Mitra [7], as follows. The second subscript of a variable indicates whether the parameter is for a low-rate user (0) or for a high-rate user (1). The numbers of low-rate and high-rate users are K_0 and K_1, respectively. The spreading gain of the low-rate users is N, and M is the rate ratio between the high-rate users and the low-rate users. $A_{j,0}$ and $b_{j,0}$ represent the received amplitude and the received bit, respectively, for the jth low-rate user. Similarly, $A_{i,1}^m$ and $b_{i,1}^m$ are the amplitude and the received bit, respectively, of the mth virtual user belonging to the ith high-rate user. The signature sequences are denoted by $s_{j,0}(n)$ and $s_{i,1}^m(n)$ for low-rate and high-rate users, respectively. And, finally, $w(n)$ is white Gaussian noise with variance σ^2.

The above signal model can also be written in vector form

$$\boldsymbol{r} = \sum_{j=1}^{K_0} A_{j,0} b_{j,0} \boldsymbol{s}_{j,0} + \sum_{i=1}^{K_1} \sum_{m=1}^{M} A_{i,1}^m b_{i,1}^m \boldsymbol{s}_{i,1}^m + \boldsymbol{w} \quad (2)$$

where

$$\boldsymbol{r} = [r(1), r(2), \ldots, r(N)]^T$$
$$\boldsymbol{w} = [w(1), w(2), \ldots, w(N)]^T$$
$$\boldsymbol{s}_{j,0} = [s_{j,0}(1), s_{j,0}(2), \ldots, s_{j,0}(N)]^T = \frac{1}{\sqrt{N}} [V_{j,0}(1), V_{j,0}(2), \ldots, V_{j,0}(N)]^T$$
$$\boldsymbol{s}_{i,1}^m = \left[s_{i,1}^m(1), s_{i,1}^m(2), \ldots, s_{i,1}^m(N)\right]^T = \frac{1}{\sqrt{N_1}} \left[\mathbf{0}_{(m-1)N_1}, V_{i,1}^m(1), \ldots, V_{i,1}^m(N_1), \mathbf{0}_{(M-m)N_1}\right]^T$$

and $V_{j,0}(n)$, $V_{i,1}^m(n) \in \{-1, +1\}$. Here $N_1 = N/M$ is the spreading gain of the high-rate users.

III. Two-Layer Spreading Code Scheme

A high-rate receiver spans only the length of a single high-rate symbol. If we divide the received vector $\boldsymbol{r}$ into M equal-length segments, the mth segment can be written as

$$\boldsymbol{r}^m = \sum_{j=1}^{K_0} A_{j,0} b_{j,0} \boldsymbol{s}_{j,0}^m + \sum_{i=1}^{K_1} A_{i,1}^m b_{i,1}^m \boldsymbol{s}_{i,1} + \boldsymbol{w}^m, \quad m = 1, \ldots, M \quad (3)$$

where $\boldsymbol{s}_{j,0}^m$ is the mth segment of the jth low-rate user's spreading code. We assume that repeated codes are adopted by the high-rate users and with slight abuse of notation, denote the ith high-rate user's spreading sequence as $\boldsymbol{s}_{i,1}$.

In general, $\boldsymbol{s}_{j,0}^m \neq \boldsymbol{s}_{j,0}^n$ for $m \neq n$, making the linear MMSE multiuser receiver vary from symbol to symbol. One way to deal with this problem is to use repetition codes for the low-rate users, i.e., let $\boldsymbol{s}_{j,0}^1 = \cdots = \boldsymbol{s}_{j,0}^M$. As mentioned previously, this will incur severe performance loss. Here we propose using two-layer spreading codes for the low-rate users as follows. First, a random sequence $\boldsymbol{c}_{j,0} = [c_{j,0}^{(1)}, \ldots, c_{j,0}^{(M)}]$ of length M is generated independently for each low-rate user. Here, we assume $c_{j,0}^{(m)} \in \{1, -1\}$, but it can be chosen according to any zero-mean symmetric distribution with unit variance. Then these random sequences are used to mask the repetition codes of the low-rate users, resulting in the following code for the jth low-rate user:

$$\boldsymbol{s}_{j,0} = \left[c_{j,0}^{(1)} \boldsymbol{s}_{j,0}^1, \ldots, c_{j,0}^{(M)} \boldsymbol{s}_{j,0}^1\right]. \quad (4)$$

A receiver for a low-rate user can remove the corresponding mask with negligible complexity. In the following, we demonstrate through analytical and numerical results that the proposed scheme facilitates the adaptive implementation of multiuser receivers while avoiding the performance loss suffered by the repetition code scheme.

IV. Random Spreading Sequence Analysis

A. High-Rate MMSE Receivers

A motivation for proposing this new scheme is to ease the adaptive implementation of high-rate MMSE receivers. However, let us first examine the performance of a nonadaptive version of high-rate receivers under this scheme. We will assume that the spreading sequence of each user is randomly and independently chosen and investigate the performance of this system under the large system limit, where $\alpha_0 \triangleq K_0/N$ and $\alpha_1 \triangleq K_1/N$ are fixed as the spreading gain N goes to infinity. Such an approach has been used in recent studies to analyze the performance of linear multiuser receivers in single-rate DS-CDMA systems [14], [15]. In [3] and [21], this approach has been extended to investigate the capacity of multirate DS-CDMA systems.

For comparison, we will also look at the performance of VSL systems in which low-rate users use general random codes (GRCs) and random repetition codes (RRCs). Since for systems using high-rate receivers, the performance of the high-rate users is the same for these three schemes, we will look only at the SIR of the low-rate users. Here, the soft decision for a low-rate user is obtained by combining the outputs from all the subintervals using weights proportional to their SIR (i.e., maximal ratio combining). In [3], it is shown that for systems using general random codes, the output SIR of the first low-rate user should satisfy (5), shown at the bottom of the page, where P_1 is the power of the desired user, F_0 and F_1 are the empirical distributions of low-rate and high-rate user's power, respectively, and $I(P, P_1, \beta) \triangleq PP_1/(P_1 + P\beta)$ can be interpreted as the effective interference of a user. It has also been shown that when using random repetition codes, the output SIR of the low-rate users can be upper bounded by the solution to (6), also shown at the bottom of the page.

Now let us examine the performance of the low-rate users when TLS codes are used. Assuming the received power of each high-rate user is constant over the duration of the low-rate symbol, the received vector in the mth subinterval can be written as

$$\boldsymbol{r}^m = \sum_{j=1}^{K_0} A_{j,0} b_{j,0} c_{j,0}^{(m)} \boldsymbol{s}_{j,0}^1 + \sum_{i=1}^{K_1} A_{i,1} b_{i,1}^m \boldsymbol{s}_{i,1} + \boldsymbol{w}^m, \quad m = 1, \ldots, M. \tag{7}$$

Suppose the desired user is the first low-rate user. The linear MMSE receiver for this subinterval can be written as $\boldsymbol{v}_{1,0}^m = c_{1,0}^{(m)} \boldsymbol{v}_{1,0}$, where

$$\boldsymbol{v}_{1,0} = \frac{(A_{1,0})^2 \Sigma^{-1} \boldsymbol{s}_{1,0}^1}{1 + (A_{1,0})^2 \left(\boldsymbol{s}_{1,0}^1\right)^T \Sigma^{-1} \boldsymbol{s}_{1,0}^1} \tag{8}$$

and where Σ is the covariance matrix of the cochannel interference and additive noise, which can be written as

$$\Sigma = \sum_{j=2}^{K_0} (A_{j,0})^2 \boldsymbol{s}_{j,0}^1 \left(\boldsymbol{s}_{j,0}^1\right)^T + \sum_{i=1}^{K_1} (A_{i,1})^2 \boldsymbol{s}_{i,1} (\boldsymbol{s}_{i,1})^T + \sigma^2 \mathbf{I}. \tag{9}$$

On maximal ratio combining of the linear MMSE receiver outputs for M subintervals, we obtain

$$\begin{aligned} y = {} & M A_{1,0} b_{1,0} (\boldsymbol{v}_{1,0})^T \boldsymbol{s}_{1,0}^1 \\ & + \sum_{m=1}^{M} \times \Bigg(\sum_{j=2}^{K_0} A_{j,0} b_{j,0} c_{1,0}^{(m)} c_{j,0}^{(m)} (\boldsymbol{v}_{1,0})^T \boldsymbol{s}_{j,0}^1 \\ & + \sum_{i=1}^{K_1} A_{i,1} b_{i,1}^m c_{1,0}^{(m)} \times (\boldsymbol{v}_{1,0})^T \boldsymbol{s}_{i,1} + c_{1,0}^{(m)} (\boldsymbol{v}_{1,0})^T \boldsymbol{w}^m \Bigg). \end{aligned} \tag{10}$$

The reason for the poor performance of random repetition codes can be seen clearly from the above equation. When random repetition codes are used, i.e., $c_{j_0}^{(m)} = 1, \forall j, m$, the second term on the right-hand side of the equation, i.e., $A_{j,0} b_{j,0} c_{1,0}^{(m)} c_{j,0}^{(m)} (\boldsymbol{v}_{1,0})^T \boldsymbol{s}_{j,0}^1$, will add coherently across M subintervals, causing the performance loss. By using the random masking sequences, we destroy this coherence and avoid the performance loss. If the masking sequences $\{\boldsymbol{c}_{j,0}\}_{j=1,\ldots,K_0}$ are randomly and independently selected for each low-rate symbol, then it can be seen easily that the output SIR is

$$\beta_{\text{tls}} = M (A_{1,0})^2 \left(\boldsymbol{s}_{1,0}^1\right)^T \Sigma^{-1} \boldsymbol{s}_{1,0}^1 \tag{11}$$

which can be shown to satisfy (12) for large systems, as shown at the bottom of the page. Simulation results show that (12) is accurate even when the same masking sequences are repeated. Comparing (5), (6), and (12), it is straightforward to see that

$$\beta_{\text{tls}} = \beta_{\text{grc}} > \beta_{\text{rrc}}. \tag{13}$$

$$\beta_{\text{grc}} = \frac{P_1}{\sigma^2 + \alpha_0 \int I\left(P, P_1, \frac{\beta_{\text{grc}}}{M}\right) dF_0(P) + M\alpha_1 \int I(P, P_1, \beta_{\text{grc}}) dF_1(P)} \tag{5}$$

$$\beta_{\text{rrc}} = \frac{P_1}{\sigma^2 + M\alpha_0 \int I(P, P_1, \beta_{\text{rrc}}) dF_0(P) + M\alpha_1 \int I(P, P_1, \beta_{\text{rrc}}) dF_1(P)} \tag{6}$$

$$\beta_{tls} = \frac{P_1}{\sigma^2 + \alpha_0 \int I\left(P, P_1, \frac{\beta_{tls}}{M}\right) dF_0(P) + M\alpha_1 \int I(P, P_1, \beta_{tls}) dF_1(P)}. \tag{12}$$

B. Low-Rate MMSE Receivers

While we have shown that the adoption of TLS codes does not incur any performance loss with respect to the general random codes when high-rate linear MMSE receivers are used, it is also of interest to know whether this is also the case in systems with low-rate receivers. In this section, we will examine the performance of low-rate linear MMSE receivers when the TLS codes are used.

To facilitate the analysis, we will assume a simplified setting where the number of high-rate users is 0. The spreading code for the jth low-rate user is $\boldsymbol{s}_{j,0} = \boldsymbol{c}_{j,0} \otimes \boldsymbol{s}^1_{j,0}$, where $\otimes$ denotes the Kronecker product. The entries of the masking sequences are independently selected from the set $\{+1, -1\}$ and the elements of $\boldsymbol{s}^1_{j,0}$ are independent, identically distributed (i.i.d.) circular complex Gaussian random variables with zero mean and variance $1/N$. We will also assume perfect power control, i.e., the received powers for all users are the same. We then have the following result for the output SIR of the low-rate linear MMSE receivers.

Proposition 1: The output SIR of the low-rate linear MMSE receiver for any given user in systems using TLS codes is the same as that of systems using general random codes.

Proof: Due to the structure of the TLS codes, the proof of this proposition needs to use results from free probability theory [16], [22]. Since a detailed treatment will be quite lengthy and will not be unsimilar to the proof of [16, Th. 3], we will only sketch the outline of the proof. For more details, we refer the readers to the above references.

We can construct a noncommutative probability space $(\mathcal{A}, \phi)$, where $\mathcal{A} = M_N$ is the algebra of complex $N \times N$ random matrices and $\phi_N(X) = (1/N) \cdot E\{TrX\}$, for $X \in M_N$. The distribution of X is specified by the moments $\phi_N(X^k)$, $k \geq 1$. It can be shown that this distribution is equivalent to the expected eigenvalue distribution of X.

First, we will show that when N is large, the expected eigenvalue distributions of $\mathbf{S}_0\mathbf{S}_0^H$ (the columns of $\mathbf{S}_0$ are the spreading codes of the low-rate users) are the same for systems using TLS codes and general random codes. When general random codes are used, we have

$$\phi\left(\left(\mathbf{S}_0\mathbf{S}_0^H\right)^r\right) = \phi\left(\left(\mathbf{S}_0^H\mathbf{S}_0\right)^r\right) = \phi\left(\left(\sum_{m=1}^{M} \mathbf{S}_{m,0}^H \mathbf{S}_{m,0}\right)^r\right) \tag{14}$$

where $\mathbf{S}_{m,0}$ contains the segments of all low-rate users' spreading codes in the mth subinterval. According to results from free probability theory, the family of matrices $\{\mathbf{S}_{m,0}^H\mathbf{S}_{m,0}\}_{\{1 \leq m \leq M\}}$ is asymptotically (in N) free, and when $N \to \infty$, the distribution of $\mathbf{S}_0\mathbf{S}_0^H$ is completely determined by $\phi((\mathbf{S}_{m,0}^H\mathbf{S}_{m,0})^r)$, $r \geq 1$, $m = 1, \ldots, M$. Now let us look at systems using TLS codes. Similarly, we have

$$\begin{aligned}\phi\left(\left(\mathbf{S}_0\mathbf{S}_0^H\right)^r\right) &= \phi\left(\left(\mathbf{S}_0^H\mathbf{S}_0\right)^r\right) \\ &= \phi\left(\left(\sum_m \mathbf{C}_m^H\mathbf{S}_{1,0}^H\mathbf{S}_{1,0}\mathbf{C}_m\right)^r\right)\end{aligned} \tag{15}$$

where $\mathbf{S}_{1,0} = [\boldsymbol{s}^1_{1,0}, \ldots, \boldsymbol{s}^1_{K_0,0}]$ and $\mathbf{C}_m = \mathrm{diag}\{c_{1,0}^{(m)}, \ldots, c_{K_0,0}^{(m)}\}$. Again, using free probability theory and the fact that $\mathbf{C}_m^H\mathbf{C}_m = \mathbf{C}_m\mathbf{C}_m^H = I$, we can show that for large N, the distribution of $\mathbf{S}_0\mathbf{S}_0^H$ is determined by

$$\begin{aligned}\phi\left(\left(\mathbf{C}_m^H\mathbf{S}_{1,0}^H\mathbf{S}_{1,0}\mathbf{C}_m\right)^r\right) &= \phi\left(\mathbf{C}_m^H\left(\mathbf{S}_{1,0}^H\mathbf{S}_{1,0}\right)^r\mathbf{C}_m\right) \\ &= \phi\left(\left(\mathbf{S}_{1,0}^H\mathbf{S}_{1,0}\right)^r\right).\end{aligned} \tag{16}$$

Since the matrices $\{\mathbf{S}_{m,0}^H\mathbf{S}_{m,0}\}_{\{1 \leq m \leq M\}}$ are i.i.d. copies of $\mathbf{S}_{1,0}^H\mathbf{S}_{1,0}$, we conclude that the large-N limit distributions of $\mathbf{S}_0\mathbf{S}_0^H$ are the same for systems using TLS codes and general random codes.

It can be shown that the expected output SIR of the linear MMSE multiuser receivers is related to the eigenvalue distribution of $\mathbf{S}_0\mathbf{S}_0^H$ as follows:

$$\frac{1}{N}E\left\{\frac{1}{1+\mathrm{SIR}^N}\right\} = \frac{K}{N} - 1 + \frac{\sigma^2}{N}\int_0^\infty \frac{1}{\lambda+\sigma^2}dF_{S_0S_0^H}(\lambda) \tag{17}$$

where SIR^N is the output SIR when the spreading gain is N and $F_{S_0S_0^H}$ denotes the eigenvalue distribution of the matrix $\mathbf{S}_0\mathbf{S}_0^H$. From the above results, we can see easily that the expected output SIR $E\{\beta_{\mathrm{tls}}^N\}$ of systems using TLS codes converges to the output SIR of systems using general random codes β_{grc} as N goes to infinity. Using the same arguments as those in [16], it can also be shown that the variance of β_{tls}^N goes to zero as $N \to \infty$. Hence, we have that β_{tls}^N converges in probability to β_{grc}. ■

While we have assumed that the number of high-rate users is zero in proving *Proposition 1*, simulation results indicate that the same results hold for the case when there are high-rate users in the system. Among the other assumptions we have made, the perfect power control assumption is not essential since the proof in [16] can be extended straightforwardly to the case when there is a finite number of power levels in the system. The Gaussian spreading sequences assumption is necessary for the free probability results to be applicable; however, simulation results seem to suggest that this result holds for other random sequences such as binary random spreading sequences, as well.

V. Simulation Results

A. Nonadaptive Linear MMSE Receivers

We first compare the performance of both high-rate and low-rate nonadaptive linear MMSE multiuser receivers under the three different schemes we have discussed in this letter: general codes, repetition codes, and TLS codes. Since when high-rate receivers are used, the performance of high-rate users is the same under all three schemes, we only examine the performance of low-rate users in this scenario. For the case when low-rate receivers are used, the performance of both classes of users is simulated. As will be seen in the following simulation results, adopting repetition codes brings performance loss for low-rate users, while imposing the TLS code structure does not incur any performance loss.

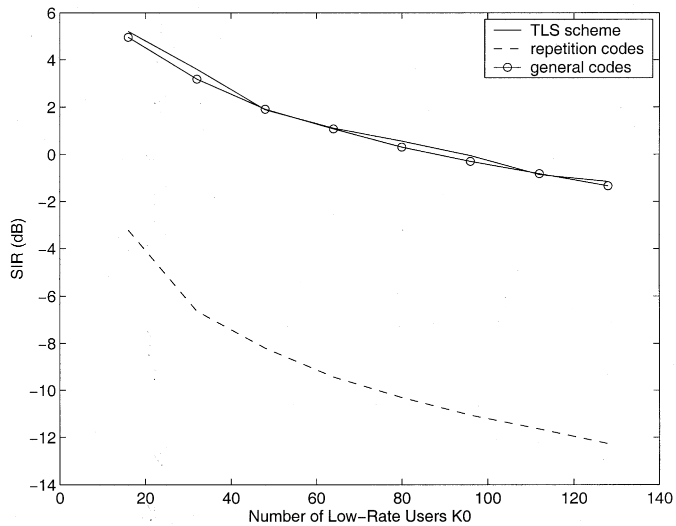
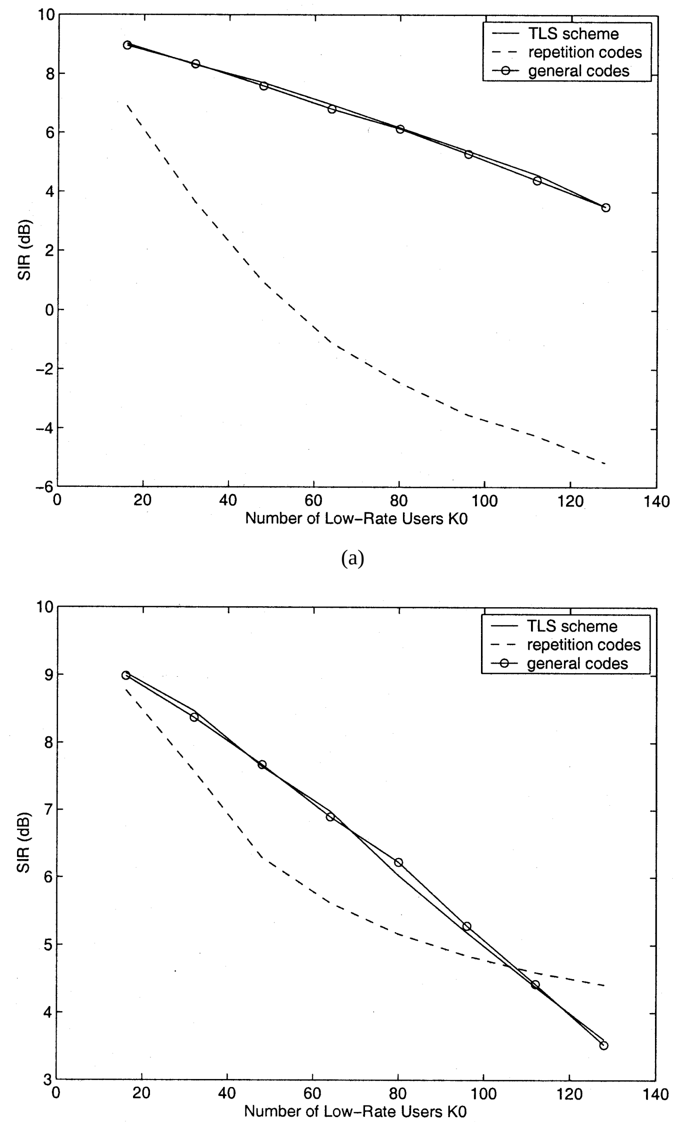


Fig. 1. Performance of low-rate users using nonadaptive high-rate receivers.

We simulate a system with basic spreading gain 128. The rate ratio is $M = 16$ and the signal-to-noise ratios (SNRs) for all users are 10 dB. We fix the number of high-rate users at four and look at the dependence of SIR on the number of low-rate users.

Fig. 1 shows the performance of low-rate users when the high-rate linear MMSE receivers are used. While there is no performance difference between the new scheme and a system using GRCs, a system using RRCs incurs a performance loss of more than 8 dB.

We also compare the performance of these three schemes when nonadaptive low-rate linear MMSE receivers are used. The simulation settings are the same as those we used to obtain Fig. 1, except that now we set $M = 4$. The output SIRs for the low-rate users and the high-rate users are shown in Fig. 2. We can see that in a dual-rate system, the adoption of the TLS codes does not incur any performance loss for either the low-rate users or the high-rate users. Worth noting is that high-rate users achieve the best performance under RRC when the number of low-rate users is large. This can be ascribed to the fact that when using RRCs, low-rate users' spreading codes can, at most, occupy N/M dimensions.



(b)

Fig. 2. Output SIR performance of nonadaptive low-rate receivers. (a) Performance of low-rate users. (b) Performance of high-rate users.

B. Adaptive Linear MMSE Receivers

Having verified that the adoption of the TLS codes does not incur performance loss for the nonadaptive linear MMSE receiver, we will now examine the behavior of an adaptive linear MMSE receiver under this scheme. Since the main purpose of introducing the TLS codes is to facilitate the adaptive implementation of high-rate linear MMSE multiuser receivers for high-rate users, we will focus on the adaptive version of such receivers in the following simulations. In particular, we will compare the performance of the recursive least-squares (RLS) receivers [23] under different schemes. We will see from the simulation results that in systems using general codes, the RLS receivers fail to converge to the true linear MMSE multiuser receivers due to the variation from symbol to symbol of the spreading codes. On the contrary, in systems adopting the TLS codes, the RLS receivers converge to the linear MMSE multiuser receivers quickly and are able to track the changes in the channel. Note that while we only study the performance of the RLS receivers here, it is easy to see that the adoption of the TLS codes would lead to the improvement of the performance of other adaptive linear MMSE algorithms (e.g., the stochastic gradient descent algorithm).

In Fig. 3, we compare the tracking performance of the blind linear MMSE multiuser receivers under the TLS code scheme and general random code scheme. We simulate a system with ten low-rate users and two high-rate users. The SNR of all users are 10 dB and the data rate ratio is four. At time 500, four low-rate users with SNR 20 dB are added to the system. The simulation results are obtained by averaging over 100 simulation runs. The spreading codes at all levels are randomly chosen in each run. We can see that in systems using GRCs the blind RLS algorithm fails, while under the TLS scheme, the blind receiver is able to track the change in the system.

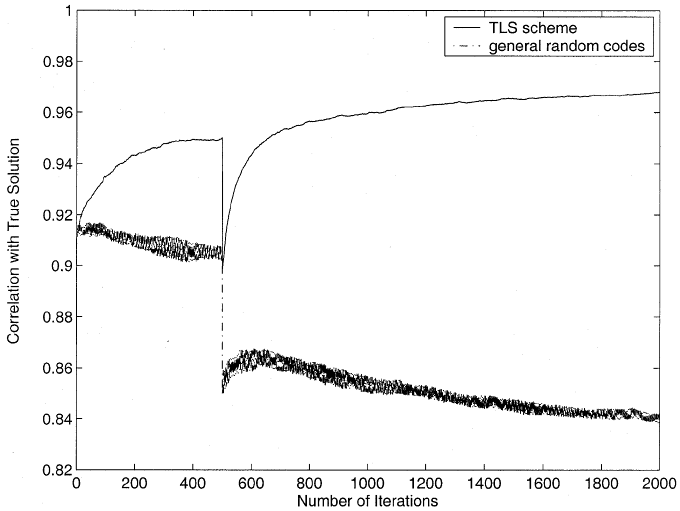


Fig. 3. Tracking performance of the blind RLS receiver.

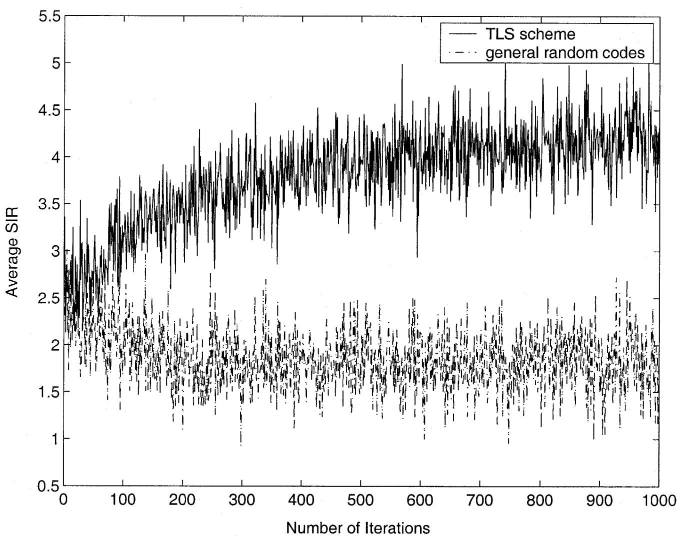


Fig. 4. Performance of the blind RLS receiver in asynchronous systems.

While we have focused on synchronous systems thus far, the TLS code scheme can be applied to asynchronous systems as well. In the following simulation, we examine its performance in asynchronous systems, assuming one-shot receivers are used. Because of the asynchronous transmissions, the true linear MMSE receiver changes from (high-rate) symbol to symbol in our scheme. However, the structure in our codes ensures that the adaptive receiver will converge to a suboptimal linear MMSE receiver which treats each low-rate user as two virtual users. In Fig. 4, we compare the average output SIR of the blind RLS receiver using new codes and GRCs. In this simulation, the received SNRs are set at 16 dB for low-rate users and 10 dB for high-rate users. Their delays are assumed to be uniformly distributed. The results are obtained by averaging over 400 simulation runs. The spreading codes and the users' delays are randomly chosen in each run. From the simulation results, we can see that using TLS codes improves the steady-state performance of RLS receivers by more than 2 dB.

VI. Conclusion

In this letter, we have proposed a multilayer spreading code scheme for multirate DS-CDMA systems. This scheme facilitates the adaptive implementation of low-complexity linear multiuser receivers. In particular, we study a TLS code scheme for dual-rate DS-CDMA systems, the extension to more general systems being straightforward. As shown by analytical and numerical results, the performance of our scheme is superior to the previously known schemes. While we have only investigated RLS receivers in our simulations, it is easy to see that our scheme will improve the performance of other adaptive receivers or adaptive power control algorithms.

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