CHIP-INTERLEAVED BLOCK-SPREAD CDMA FOR THE DOWNLINK WITH INTER-CELL INTERFERENCE AND SOFT HAND-OFF*

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ABSTRACT

Recently, a so-termed Chip-Interleaved Block-Spread (CIBS) CDMA system has been introduced for cellular applications in the presence of frequency selective multipath channels. In both uplink and downlink operations, CIBS-CDMA achieves Multi-User-Interference (MUI) free reception within each cell. This paper focuses on the cellular downlink configuration, and analyzes the performance in the presence of inter-cell interference and soft handoff. Performance results favor the proposed CIBS-CDMA over the conventional DS-CDMA with chip equalizers.

1. INTRODUCTION

Relying on orthogonal spreading codes, Code Division Multiple Access (CDMA) enables simultaneous transmissions from multiple users over the same time-bandwidth slot. However, as the chip rate increases in high rate wireless applications, the underlying multipath channels become time-dispersive (or frequency selective). Frequency-selective channels cause inter chip interference (ICI) which destroys code orthogonality at the receiver. The latter gives rise to multiuser interference (MUI), and severely limits the performance of single user RAKE receivers in a multi-user setting. To suppress MUI, various linear or nonlinear multiuser detectors have been proposed [7]. However, these schemes are more suitable for uplink transmissions, where the Base Station (BS) has knowledge of the multipath channels and spreading codes of all users, and is thus able to demodulate all users' information either jointly, or, separately.

In this paper, we focus on downlink CDMA that presents some distinct challenges and characteristics relative to its uplink counterpart. First, downlink transmissions come with symbol-aperiodic spreading, where each user's information symbols are spread by a short user-specific code, and then scrambled by a long BS-specific code. Second, the chip sequences of all users are multiplexed in a synchronous fashion before transmission. The signals of all users thus experience a single propagation channel to reach each particular mobile station (MS). Finally, each MS only needs to demodulate its own data, and generally does not know the spreading codes of other users.

Accounting for these unique downlink features, a class of linear receivers with chip equalization has been developed to suppress MUI in downlink DS-CDMA [1–5]. These receivers share the simple but neat idea of first linearly equalizing the frequency-selective channel to restore completely, or partially, the multi-user signal transmitted from the BS at the chip rate, and then correlating the resulting chip sequence with the spreading code to decode the information of the desired user. DS-CDMA receivers equipped with Zero Forcing (ZF) or Minimum Mean Square Error (MMSE) chip equalizers have been shown to offer significant performance gains over the conventional RAKE receiver [1, 3, 4].

Recently, transceiver designs have been proposed, that remove MUI deterministically regardless of the underlying multipath channels, and are applicable to both uplink and downlink operations; see the references in [9]. The comparisons among MUI-free transceivers favor the CIBS-CDMA [9], and thus we focus on CIBS-CDMA in this paper. Mutual orthogonality among different users' codes is preserved by the CIBS design even after frequency-selective propagation, which enables deterministic MUI-free reception that is implemented with low-complexity code-matched filtering [9]. However, only one cell is considered in [9].

In this paper, we investigate the performance of downlink CIBS-CDMA in the presence of inter-cell interference, and under soft-handoff operations. The comparisons against the conventional DS-CDMA equipped with chip equalization favor the proposed CIBS-CDMA, and reveals its potential for future wireless systems [10].

Notation: Bold upper letters denote matrices, bold lower letters denote column vectors; $(\cdot)^T$ and $(\cdot)^H$ denote transpose and Hermitian transpose, respectively; $\otimes$ denotes the Kronecker product, and $\delta[\cdot]$ denotes the Kronecker delta; $E\{\cdot\}$ stands for ensemble expectation; $\mathbf{I}_K$ denotes the $K \times K$ identity matrix, and $\mathbf{0}_{M\times N}$ denotes the $M \times N$ all zero matrix; $[\cdot]_p$ stands for the $(p+1)$th entry of a vector, and $[\cdot]_{p,q}$ stands for the $(p+1, q+1)$th element of the matrix.

2. SYSTEM MODEL

In this section, we present the downlink transceiver model for CIBS-CDMA in the presence of inter-cell interference, considering only one interfering Base Station (BS). Generalization to more BSs is straightforward. Let us denote the host BS as A and the interfering BS as B; $(\cdot)^a$ and $(\cdot)^b$ (or $(\cdot)_a$ and $(\cdot)_b$ when more convenient) will pertain to variables associated with BSs A and B, respectively. We assume that during each block interval, the channels remain invariant, and the number of active users U^a, U^b are constant.

At BS A, each user transmits K information symbols per block, which are collected as $\mathbf{s}_u^a := [s_u^a[0], \ldots, s_u^a[K-1]]^T$, where $u \in [1, U^a]$. The information block $\mathbf{s}_u^a$ is first spread to form an $N \times 1$ chip block $\mathbf{x}_u^a = \mathbf{C}_u^a \mathbf{s}_u^a$, where $\mathbf{C}_u^a$ denotes the $N \times K$ spreading matrix of user u at BS A. For synchronous trans-

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missions in the downlink, BS A sums all users' chip sequences to obtain $\mathbf{x}^a = \sum_{u=1}^{U^a} A_u^a \mathbf{x}_u^a = \sum_{u=1}^{U^a} A_u^a \mathbf{C}_u^a \mathbf{s}_u^a$, where the weight A_u^a is introduced to control transmit-power. The multi-user chip sequence is then passed through the pulse-shaping filter, modulated to a high carrier frequency, and transmitted. Quantities $\mathbf{x}^b, A_u^b, \mathbf{C}_u^b, \mathbf{s}_u^b$ are similarly defined for the interfering BS B.

At the receiver, we allow for multichannel reception which becomes available either by oversampling the received signal or by employing multiple antennas. Let M_s be the oversampling factor at each receive antenna and M_r the number of receive antennas, giving rise to a system with $M = M_r M_s$ effective channels. It is noted that, multiple-antenna reception results in independent channels, while oversampling often yields dependent channels. For now, we will not differentiate them and their difference in performance will show up in the simulation part. Denote with $\mathbf{h}_m^a := [h_m^a[0], \ldots, h_m^a[L]]^T$ the discrete-time baseband equivalent channel between BS A's transmitter and the mth ($m \in \{1, 2, \ldots, M\}$) receiver, which includes the physical channel as well as transmit- and receive-filters; L is an upper-bound on the channel order, and $\mathbf{h}_m^b$ is defined similarly for BS B.

The received sequence at the mth output can thus be written as $y_m[n] = \sum_{l=0}^{L} h_m^a[l] x^a[n-l] + \sum_{l=0}^{L} h_m^b[l] x^b[n-l] + w_m[n]$, where $w_m[n]$ is the additive white Gaussian noise (AWGN) with variance σ_w^2. Collect every N received chip samples in a block, $\mathbf{y}_m := [y_m[0], \ldots, y_m[N-1]]^T$. A guard interval between successive blocks has been introduced to remove inter block interference (IBI) [9, 10]; guard insertion is described by the zero padding matrix later on. We thus obtain the IBI-free block model for the mth channel as

$$\mathbf{y}_m = \mathbf{H}_m^a \mathbf{x}^a + \mathbf{H}_m^b \mathbf{x}^b + \mathbf{w}_m, \tag{1}$$

where $\mathbf{w}_m$ is defined similar to $\mathbf{y}_m$, $\mathbf{H}_m^a$ is the lower triangular $N \times N$ Toeplitz matrix with $[\mathbf{H}_m^a]_{p,q} = h_m^a[p-q]$, and $\mathbf{H}_m^b$ is designed accordingly. When the mobile user is located far away from the edge of cell, $\mathbf{H}_m^b \mathbf{x}^b$ is negligible. When the mobile user is close to the edge of cell, the relative propagation delay from the two base stations is small, and can be incorporated as zero taps in the discrete-time equivalent channels $\mathbf{H}_m^a$ and $\mathbf{H}_m^b$.

Users in CIBS-CDMA are assigned orthonormal signature codes $\mathbf{c}_u^a, \mathbf{c}_u^b$ of length P. Distinct from conventional *symbol* spreading, CIBS-CDMA relies on *block* spreading. Specifically, each block $\mathbf{s}_u^a$ is *block* spread by a tall matrix $\mathbf{C}_u^a$ designed as [9]:

$$\mathbf{C}_u^a = \mathbf{D}_u^a \mathbf{T}_K, \quad \text{with } \mathbf{D}_u^a = (\mathbf{\Delta}^a \mathbf{c}_u^a) \otimes \mathbf{I}_{K+L}, \tag{2}$$

where $\mathbf{T}_K := [\mathbf{I}_K, \mathbf{0}_{K \times L}]^T$ describes the guard inserting operation, and $\mathbf{\Delta}^a$ is a $P \times P$ diagonal matrix holding on its diagonal the scrambling code with each chip having unit amplitude. Notice that here the scrambling code is applied in a block by block fashion, rather than symbol by symbol fashion as in DS-CDMA [4]. The block spreading enabled by $\mathbf{C}_u^a$ can be easily implemented by conventional symbol-spreading followed by a redundant chip interleaver as detailed in [9, Fig.4]. Here we see that the system parameters are related as $N = (K+L)P$.

Using (2), we obtain from [9] that $\mathbf{C}_u^a$ lies in the column space of $\mathbf{D}_u^a$ after propagation through a frequency-selective channel: $\mathbf{H}_m^a \mathbf{C}_u^a = \mathbf{D}_u^a \boldsymbol{\mathcal{H}}_m^a$, where $\boldsymbol{\mathcal{H}}_m^a$ is the $(K+L) \times K$ Toeplitz matrix with $[\boldsymbol{\mathcal{H}}_m^a]_{p,q} = h_m^a[p-q]$. Hence, we can rewrite (1) as

$$\mathbf{y}_m = \sum_{u=1}^{U^a} (A_u^a \mathbf{D}_u^a \boldsymbol{\mathcal{H}}_m^a \mathbf{s}_u^a) + \sum_{v=1}^{U^b} \left(A_v^b \mathbf{D}_v^b \boldsymbol{\mathcal{H}}_m^b \mathbf{s}_v^b \right) + \mathbf{w}_m. \tag{3}$$

The second term in the right hand side of (3) is the inter-cell interference and can be neglected when the mobile user is located far away from the edge of its cell. Define the code correlation coefficient $\rho_{\mu,v}^{a,b} = (\mathbf{\Delta}^a \mathbf{c}_\mu^a)^H (\mathbf{\Delta}^b \mathbf{c}_v^b)$, and $\mathbf{s}_I^b := \sum_{v=1}^{U^b} A_v^b \rho_{\mu,v}^{a,b} \mathbf{s}_v^b$. Exploiting the fact that $\mathbf{D}_u^a$ possesses mutual orthogonality among users: $(\mathbf{D}_u^a)^H \mathbf{D}_{u'}^a = \delta(u-u') \mathbf{I}_{K+L}$ [9], the desired user μ despreads each block $\mathbf{y}_m$ using $(\mathbf{D}_\mu^a)^H$ to obtain:

$$\mathbf{r}_{\mu,m}^a := (\mathbf{D}_\mu^a)^H \mathbf{y}_m = A_\mu^a \boldsymbol{\mathcal{H}}_m^a \mathbf{s}_\mu^a + \boldsymbol{\mathcal{H}}_m^b \mathbf{s}_I^b + (\mathbf{D}_\mu^a)^H \mathbf{w}_m. \tag{4}$$

Define $\boldsymbol{\eta}_{\mu,m} := \boldsymbol{\mathcal{H}}_m^b \mathbf{s}_I^b + (\mathbf{D}_\mu^a)^H \mathbf{w}_m$ as the residual interference plus noise. Let us now collect $\{\mathbf{r}_{\mu,m}^a\}_{m=1}^M$ into one super vector $\mathbf{r}_\mu^a := [(\mathbf{r}_{\mu,1}^a)^T \ldots (\mathbf{r}_{\mu,M}^a)^T]^T$, and define $\boldsymbol{\eta}_\mu$ similarly. Define $\boldsymbol{\mathcal{H}}^a := [(\boldsymbol{\mathcal{H}}_1^a)^T \ldots (\boldsymbol{\mathcal{H}}_M^a)^T]^T$. We thus have

$$\mathbf{r}_\mu^a = A_\mu^a \boldsymbol{\mathcal{H}}^a \mathbf{s}_\mu^a + \boldsymbol{\eta}_\mu. \tag{5}$$

We see that after despreading, MUI from intra-cell users is removed deterministically. Single user channel equalization can now be performed on (5). The small size of symbol blocks makes block equalization possible. The CIBS-CDMA receiver relies on a block equalizer $\mathbf{G}_\mu$, with dimensionality $K \times M(K+L)$, to estimate the symbol block as: $\hat{\mathbf{s}}_\mu^a = \mathbf{G}_\mu \mathbf{r}_\mu^a$. Assuming that $s_\mu[k]$ is white with variance σ_s^2, and letting $\mathbf{R}_\eta := E\{\boldsymbol{\eta}_\mu \boldsymbol{\eta}_\mu^H\}$, the linear MMSE block symbol equalizer can be expressed as [10]:

$$\mathbf{G}_\mu = \left[(A_\mu^a \boldsymbol{\mathcal{H}}^a)^H \mathbf{R}_\eta^{-1} (A_\mu^a \boldsymbol{\mathcal{H}}^a) + \frac{1}{\sigma_s^2} \mathbf{I}_K \right]^{-1} (A_\mu^a \boldsymbol{\mathcal{H}}^a)^H \mathbf{R}_\eta^{-1}. \tag{6}$$

Equalization choices for (5) are quite flexible. We have only listed linear MMSE equalizers in (6). Linear ZF equalizers, nonlinear equalizers, e.g., the block Decision Feedback Equalizer (DFE) are also applicable [10]. In addition, serial equalizers can be also employed. The difference with DS-CDMA systems using chip equalizers is that the serial equalizers herein operate on the symbol level, rather than the chip level [10].

Assume that the scrambled spreading codes from different cells are uncorrelated, $E\{(\mathbf{D}_\mu^a)^H \mathbf{D}_v^b\} = E\{\rho_{\mu,v}^{a,b}\} \mathbf{I}_{K+L} = \mathbf{0}$. The coefficient $\rho_{\mu,v}^{a,b}$ is zero mean with variance $1/P$. We then obtain $\mathbf{R}_\eta = \sigma_{I,b}^2 \boldsymbol{\mathcal{H}}^b (\boldsymbol{\mathcal{H}}^b)^H + \sigma_w^2 \mathbf{I}_{M(K+L)}$ where $\sigma_{I,b}^2 := \sum_{v=1}^{U^b} (A_v^b)^2 \sigma_s^2 / P$. Computation of $\mathbf{R}_\eta^{-1}$ can be simplified using matrix inversion lemma as:

$$\mathbf{R}_\eta^{-1} = \frac{1}{\sigma_w^2} \left\{ \mathbf{I}_{M(K+L)} - \boldsymbol{\mathcal{H}}^b [(\boldsymbol{\mathcal{H}}^b)^H \boldsymbol{\mathcal{H}}^b + \frac{\sigma_w^2}{\sigma_{I,b}^2} \mathbf{I}_K]^{-1} (\boldsymbol{\mathcal{H}}^b)^H \right\}. \tag{7}$$

When the inter-cell interference is negligible, the equalizers can be further simplified by using $\mathbf{R}_\eta = \sigma_w^2 \mathbf{I}_{M(K+L)}$.

We now proceed to analyze the performance of the MMSE equalizer. The estimate for $\mathbf{s}_\mu^a$ is obtained as:

$$\hat{\mathbf{s}}_\mu^a = \mathbf{G}_\mu \mathbf{r}_\mu^a = A_\mu^a \mathbf{G}_\mu \boldsymbol{\mathcal{H}}^a \mathbf{s}_\mu^a + \mathbf{G}_\mu \boldsymbol{\eta}_\mu. \tag{8}$$

The residual interference plus noise can be well approximated as additive Gaussian noise for MMSE equalizers [6, 8]. With symbol by symbol detection on $\hat{\mathbf{s}}_\mu^a$, eq. (8) is equivalent to

$$\hat{s}_{\mu,k}^a = \alpha_{\mu,k} s_{\mu,k}^a + n_{\mu,k}, \quad \forall k = 0, \ldots, K-1, \tag{9}$$

where $\hat{s}_{\mu,k}^a$ is the kth entry of $\hat{\mathbf{s}}_\mu^a$; the coefficient $\alpha_{\mu,k}$ can be expressed as $\alpha_{\mu,k} = [A_\mu^a \mathbf{G}_\mu \boldsymbol{\mathcal{H}}^a]_{k,k}$; and $n_{\mu,k}$ denotes the residual interference-plus-noise with variance $\sigma_s^2(\alpha_{\mu,k} - \alpha_{\mu,k}^2)$ [8]. Therefore, the signal to interference-plus-noise ratio (SINR) for the kth symbol is $\mathrm{SINR}_{\mu,k} = \alpha_{\mu,k}/(1-\alpha_{\mu,k})$. The average BER of the μth user, with BPSK signaling, is thus

$$P_{e,\mu} = E\left\{\frac{1}{K}\sum_{k=0}^{K-1} \mathcal{Q}\left(\sqrt{2\,\mathrm{SINR}_{\mu,k}}\right)\right\}, \tag{10}$$

where the expectation is taken over random channel realizations.

3. SOFT HANDOFF

In the soft-handoff mode, the same information block for the desired user is transmitted simultaneously from all candidate base stations. Usually, only two base stations are involved. Let us denote again these two base stations as A and B. One can first obtain individual symbol estimates $\hat{\mathbf{s}}_\mu^a$ and $\hat{\mathbf{s}}_\mu^b$, and then combine them optimally. This two-step approach is detailed in [10]. Instead, we will pursue here a joint, one-step approach. Specifically, for base station B, we have

$$\mathbf{r}_{\mu,m}^b := (\mathbf{D}_\mu^b)^H \mathbf{y}_m = A_\mu^b \mathcal{H}_m^b \mathbf{s}_\mu + \mathcal{H}_m^a \mathbf{s}_I^a + (\mathbf{D}_\mu^b)^H \mathbf{w}_m, \tag{11}$$

where $\mathbf{s}_I^a$ is defined similarly as $\mathbf{s}_I^b$. In particular, suppose we have two receivers ($M = 2$), and we stack $(\mathbf{r}_{\mu,m}^a, \mathbf{r}_{\mu,m}^b)$ from different channels to obtain:

$$\mathbf{r}_\mu := \begin{bmatrix} \mathbf{r}_{\mu,1}^a \\ \mathbf{r}_{\mu,2}^a \\ \mathbf{r}_{\mu,1}^b \\ \mathbf{r}_{\mu,2}^b \end{bmatrix} = \begin{bmatrix} A_\mu^a \mathcal{H}_1^a & \mathcal{H}_1^b & \mathbf{0} \\ A_\mu^a \mathcal{H}_2^a & \mathcal{H}_2^b & \mathbf{0} \\ A_\mu^b \mathcal{H}_1^b & \mathbf{0} & \mathcal{H}_1^a \\ A_\mu^b \mathcal{H}_2^b & \mathbf{0} & \mathcal{H}_2^a \end{bmatrix} \begin{bmatrix} \mathbf{s}_\mu \\ \mathbf{s}_I^b \\ \mathbf{s}_I^a \end{bmatrix} + \begin{bmatrix} (\mathbf{D}_\mu^a)^H \mathbf{w}_1 \\ (\mathbf{D}_\mu^a)^H \mathbf{w}_2 \\ (\mathbf{D}_\mu^b)^H \mathbf{w}_1 \\ (\mathbf{D}_\mu^b)^H \mathbf{w}_2 \end{bmatrix}. \tag{12}$$

If the noise vectors $\mathbf{w}_1, \mathbf{w}_2$ are independent and white Gaussian, the processed additive noise is still white Gaussian provided that the scrambling codes from different cells are uncorrelated. Thus, we can rewrite (12) as:

$$\mathbf{r}_\mu = \begin{bmatrix} A_\mu^a \mathcal{H}^a \\ A_\mu^b \mathcal{H}^b \end{bmatrix} \mathbf{s}_\mu + \begin{bmatrix} \mathcal{H}^b \mathbf{s}_I^b \\ \mathcal{H}^a \mathbf{s}_I^a \end{bmatrix} + \text{AWGN}. \tag{13}$$

Based on the similarity of (13) with (5), we can now apply the block MMSE equalizer in (6). The correlation between $\mathbf{s}_I^a$ and $\mathbf{s}_I^b$ is on the order of $\mathcal{O}(1/P)$, and thus negligible. The correlation matrix accounting for the interference-plus-noise now becomes $\mathbf{R}_\eta = \mathrm{diag}(\mathbf{R}_\eta^a, \mathbf{R}_\eta^b)$, where $\mathbf{R}_\eta^a$ and $\mathbf{R}_\eta^b$ correspond to the correlation matrices in the two-step approach. Also, the analysis of Section 2 can be applied as well.

The inverse of $\mathbf{R}_\eta$ can be performed in a block diagonal fashion: $\mathbf{R}_\eta^{-1} = \mathrm{diag}((\mathbf{R}_\eta^a)^{-1}, (\mathbf{R}_\eta^b)^{-1})$, with each block matrix inversion expressed as in (7). Thus, only matrix inversion of size K is involved, and no complexity increase occurs relative to the aforementioned two-step approach.

The joint one-step approach outperforms the suboptimum two-step approach. Notice that in the one-step approach, (13) is an over-determined system with $2M(K+L)$ (which equals $4(K+L)$ when $M = 2$) equations and only $3K$ unknowns in the absence of noise. In contrast, for the two-step approach, individual block equalization is based on $M(K+L)$ equations containing $2K$ unknowns.

4. SIMULATED PERFORMANCE

In this section, we compare the performance of downlink CIBS-CDMA against that of DS-CDMA using chip equalizers [1–5].

We consider transmissions at a chip rate of $1/T_c = 1.2288$ MHz, as in standard IS-95. We assume that the maximum channel delay spread is $\tau_{\max} = 10\mu s$, which is an upper bound for most channels encountered in urban cellular systems. As in [4], we assume that each channel has 4 equal power Rayleigh fading paths, each having variance 1/4. The first and the fourth paths have fixed delays $0\mu s$ and $10\mu s$, respectively. The other two paths are positioned randomly on the chip grids in the interval $(0, 10)\mu$s. For the transmit- and receive-filters, we consider a root raised cosine filter with roll-off factor $\alpha = 0.22$, and impulse response truncated to 5 chips on each side (11 chips in total). Hence, as an upper bound on the channel order we take $\lceil \tau_{\max}/T_c \rceil + 11 + 11 - 1 = 34 \leq L$. In the ensuing simulations, we fix $L = 39$ for convenience. All channels are generated at 4 times the chip rate and then downsampled to the chip rate. For the channels induced by oversampling, different offsets are taken before downsampling.

For the DS-CDMA systems with chip equalizers, we set the frame interval $T_f = 10$ms, so that each frame contains $N_f = T_f/T_c = 12,288$ chips. A Walsh-Hadamard code of gain $P_{ds} = 40$ is used as the spreading code, and a guard interval of length $N_g = 48$ is inserted at the end of each frame. In each frame, $K_f = 306$ symbols are transmitted per user, so that $N_f = K_f P_{ds} + N_g$. We consider serial MMSE chip equalizers with order $L_g = L = 39$. We fix the delay $D = \lfloor (L_g + L + 1)/2 \rfloor$ since the performance of the MMSE chip equalizer is insensitive to the choice of D, as reported in [4].

For CIBS-CDMA, we set $K = 153$ and use a length $P = 32$ Walsh-Hadamard code for spreading. Thus, each frame contains two CIBS blocks: $N_f = 2(K+L)P$, and $K_f = 2K$. Complex QPSK sequences with unit amplitude are used as scrambling codes for both systems. In the following simulations, we consider two typical cases for DS-CDMA: $U^a = 15$ for a medium system load, and $U^a = 30$ for a high system load. While in CIBS-CDMA, each user's performance is not affected by the system load, and thus U^a can take an arbitrary value in $[1, 32]$. We fix $A_u = 1$, $\forall u \in [1, U^a]$. We adopt BPSK signaling, and define the signal to noise ratio as $\mathrm{SNR} := \sigma_s^2/\sigma_w^2$. Simulation results are averaged over 500 channels.

Test Case 1 (without inter-cell interference): We assume that the desired user is located close to its base station, and the inter-cell interference is negligible. Figure 1 compares the performance of CIBS-CDMA against DS-CDMA with 30 users. With a single receive antenna ($M_r = 1$), CIBS-CDMA outperforms DS-CDMA, which exhibits an error-floor at high SNR. With two receive antennas, CIBS-CDMA also has better performance than DS-CDMA at high SNR. Because our simulated channels are sparse, oversampling yields strongly correlated channels and is responsible for the persistent error floor in DS-CDMA. The performance with oversampling ($M_r = 1, M_s = 2$) is noticeably worse than that with two receive antennas ($M_r = 2, M_s = 1$).

Test Case 2 (with inter-cell interference): The desired user is now located on the edge of its cell. We assume operation mid-way of the two base stations, and that the channels corresponding to the interfering base station have the same average power as those of the desired base station. We adopt two receive antennas, and we assume that the interfering cell has $U^b = 30$ active users. Figure 2 shows that CIBS-CDMA has much better performance than DS-

CDMA, when a strong inter-cell interference is present.

Test Case 3 (soft handoff): We assume that the desired user is located on the edge of two cells, and soft handoff is invoked. Since the number of active users in one cell determines the interference power to the other cell, the performance of both systems under soft handoff depends on the number of active users in both cells. We set $U^a = U^b$, and compare the performance of CIBS-CDMA and DS-CDMA with two receive antennas in Figure 3. We infer that CIBS-CDMA has clear advantage over DS-CDMA in soft handoff.

5. CONCLUSIONS

In this paper, we investigated CIBS-CDMA specifically in downlink operation with inter-cell interference and soft handoff. The performance is analyzed and compared with that of conventional DS-CDMA using chip equalizers. Performance results favor the proposed CIBS-CDMA.

We have assumed perfect channel knowledge at the receiver. Practical issues including synchronization, channel estimation and their effects on performance, constitute future work for CIBS-CDMA systems.

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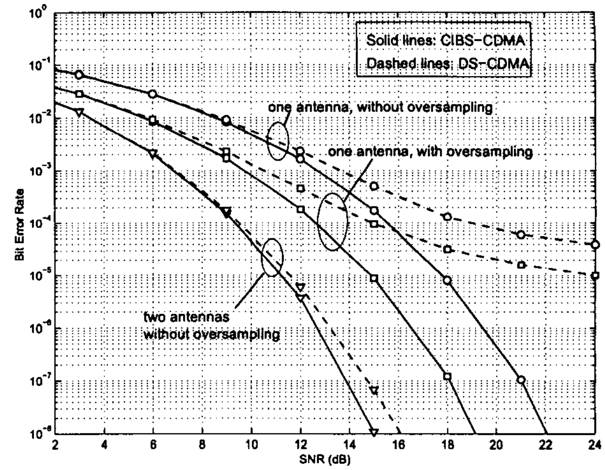

Fig. 1. Without inter-cell interference, 1-32 users in CIBS-CDMA, 30 users in DS-CDMA

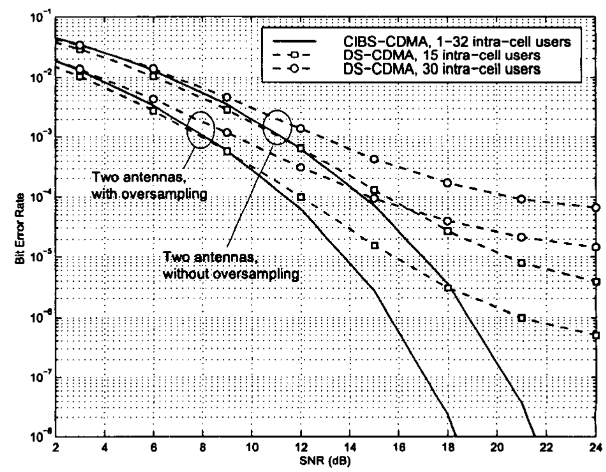

Fig. 2. With intercell interference, 30 inter-cell users

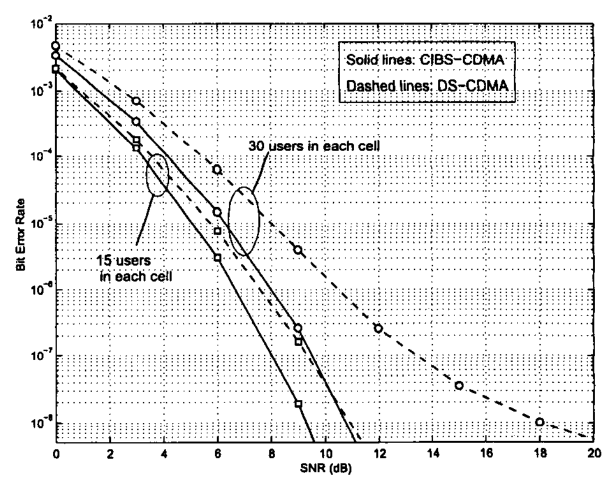

Fig. 3. Soft handoff, two antennas with oversampling