SIC AND PIC MULTIUSER DETECTION FOR PREFIX-ASSISTED DS-CDMA SYSTEMS

Paulo Silva and Rui Dinis
CAPS-Instituto Superior Técnico, 1049-001 Lisboa, Portugal
Phone: + 351 21 8419358, Fax: + 351 21 8465303, e-mail: {psilva, rdinis}@ist.utl.pt

ABSTRACT

In this paper we present iterative frequency-domain multiuser detection (MUD) receivers for the uplink transmission of direct sequence code division multiple access systems (DS-CDMA) that combine iterative block decision feedback equalization (IB-DFE) principles with interference cancelation techniques. Both successive interference cancelation (SIC) and parallel interference cancelation (PIC) structures are considered. Our performance results show that the proposed receiver structures have excellent bit error rate (BER) performances, that can be close to the single-user matched filter bound (MFB), even for fully loaded systems and severely time-dispersive channels[1].

KEYWORDS

CDMA, multiuser detection, block transmission

1 Introduction

By combining direct sequence code division multiple access schemes (DS-CDMA) with CP-assisted (Cyclic Prefix) block transmission techniques, we can design frequency-domain receiver structures suitable for severely time-dispersive channels. The receiver design at the downlink is particularly simple: since all spreading codes are affected by the same multipath channel, the receiver can be based on a simple frequency-domain equalization (FDE), operating at the chip level, followed by the despreading procedure [1].

To avoid significant noise enhancement, the FDE are usually optimized under the minimum mean-squared error criterion (MMSE) [2]. Since an MMSE FDE does not perform an ideal channel inversion, when this type of equalizer is employed with DS-CDMA signals we are not able to fully orthogonalize the different spreading codes. This means that we can have significant residual interference levels when different powers are attributed to the different users. To avoid this problem, a promising nonlinear receiver structure was proposed in [3] which employs an iterative block decision feedback equalization (IB-DFE) [4, 5] especially designed for DS-CDMA signals. The IB-DFE can be regarded as a blockwise DFE where the feedforward and feedback parts are implemented in the frequency domain. Since the feedforward and feedback coefficients take into account the blockwise reliability, we have a turbo-like behavior, with small error propagation.

In this paper we consider the uplink transmission within a DS-CDMA system employing CP-assisted block transmission techniques. We present iterative frequency-domain MUD receivers combining IB-DFE principles with interference cancelation techniques. Both successive interference cancelation (SIC) and parallel interference cancelation (PIC) structures are considered.

This paper is organized as follow: the CP-assisted block transmission DS-CDMA schemes considered here are described in sec. 2. Sec. 3 describes linear, frequency-domain MUD for DS-CDMA and sec. 4 describes the iterative MUD receivers proposed in this paper. Sec. 5 presents a set of performance results and sec. 6 is concerned with the conclusions of the paper.

2 Block Transmission DS-CDMA

In this paper we consider the uplink transmission in DS-CDMA systems employing CP-assisted block transmission techniques. We have P users and it is assumed that the blocks transmitted by each frequency channel have the same dimensions and there is a suitable "time-advance" mechanism allowing perfect synchronization in time at the receiver (in practice, just a coarse synchronization is required since some time misalignments can be absorbed by the CP). For the sake of simplicity, it is assumed that all users have the same spreading factor K and the same data rate.

The size-M data block to be transmitted by the pth user is $\{a_{n,p}; n = 0, 1, \ldots, M-1\}$, with $a_{n,p}$ selected from a given constellation. The corresponding chip block to be transmitted is $\{s_{n,p}; n = 0, 1, \ldots, N-1\}$, where $N = MK$ and $s_{n,p} = a_{\lfloor n/K \rfloor,p} c_{n,p}$ ($\lfloor x \rfloor$ denotes "larger integer not higher than x"), with $c_{n,p}$ denoting the spreading symbols. Throughout this paper it is assumed that $c_{n,p} = \pm\sqrt{2}/2 \pm j/\sqrt{2}/2, n = mK, mK+1, \ldots, mK + K - 1$, is the product of an K-length Hadamard-Walsh sequence with a pseudo-random QPSK sequence (Quadrature Phase Shift Keying), common to all users of the BS; the spreading sequence is also assumed to be periodic, with period K (i.e., $c_{n+K,p} = c_{n,p}$).

The signal received at the BS is sampled at the chip

[1]This work was partially supported by the FCT project POSI/CPS/46701/2002 - MC-CDMA and the B-BONE project IST-2003-507607.

rate (the generalization for multiple samples per chip is straightforward) and the CP is removed, leading to the time-domain block $\{y_n; n = 0, 1, \ldots, N-1\}$. It can be shown that, when the CP is longer than the overall channel impulse response for all users, the corresponding frequency-domain block is $\{Y_k; k = 0, 1, \ldots, N-1\}$, where $Y_k = \sum_{p=1}^{P} S_{k,p} H_{k,p}^{Ch} + N_k$, with $H_{k,p}^{Ch}$ denoting the channel frequency response for the pth user and the kth frequency and N_k the channel noise for that frequency. The frequency-domain block $\{S_{k,p}; k = 0, 1, \ldots, N-1\}$ is the DFT of the chip block transmitted by the pth user, $\{s_{n,p}; n = 0, 1, \ldots, N-1\}$. Since $s_{n,p} = a_{\lfloor n/K \rfloor, p} c_{n,p}$, it can easily be shown that $S_{k,p} = A'_{k,p} C'_{k,p}$, where $\{A'_{k,p}; k = 0, 1, \ldots, N-1\}$ = DFT $\{a'_{n,p}; n = 0, 1, \ldots, N-1\}$, with $a'_{n,p} = a_{n',p}$ for $n = n'K$ and 0 otherwise, and $\{C'_{k,p}; k = 0, 1, \ldots, N-1\}$ = DFT $\{c'_{n,p}; n = 0, 1, \ldots, N-1\}$, with $c'_{n,p} = c_{n,p}$ for $0 \leq n < K$ and 0 otherwise.

Clearly, $A'_{k,p} = \frac{1}{K} A_{k \ mod \ M, p}, k = 0, 1, \ldots, N-1$, with $\{A_{k,p}; k = 0, 1, \ldots, M-1\}$ = DFT $\{a_{n,p}; n = 0, 1, \ldots, M-1\}$ (i.e., apart a constant, the block $\{A'_{k,p}; k = 0, 1, \ldots, N-1\}$ is the size-N periodic extension of the DFT of the data block associated to the pth user $\{A_{k,p}; k = 0, 1, \ldots, M-1\}$). Therefore,

$$Y_k = \sum_{p=1}^{P} A_{k,p} H_{k,p} + N_k, \quad (1)$$

with $H_{k,p} = \frac{1}{K} H_{k,p}^{Ch} C'_{k,p}$ denoting the equivalent channel frequency response for the pth user and the kth frequency.

3 Linear MUD for CP-Assisted DS-CDMA

The K replicas associated to a given frequency domain sample $A_{k,p}$ can be employed to separate $P \leq K$ users. Therefore, the detection of the pth user could be made based on $\{\hat{a}_{n,p}; n = 0, 1, \ldots, M-1\}$ = DFT $\{\hat{A}_{k,p}; k = 0, 1, \ldots, M-1\}$, where $\tilde{A}_{k,p} = \sum_{l=0}^{K-1} F_{k+lM,p} Y_{k+lM}$. For each k ($k = 0, 1, \ldots, M-1$), the K coefficients $F_{k+lM,p}$, $l = 0, 1, \ldots, K-1$, are obtained by solving the following system of K equations:

$$H^*_{k+lM,p} \sum_{l'=0}^{K-1} F_{k+l'M,p} H_{k+l'M,p} + \\ + \sum_{p' \neq p} H^*_{k+lM,p'} \sum_{l'=1}^{K-1} F_{k+l'M,p} H_{k+l'M,p'} + \\ + \alpha_p F_{k+lM,p} = H^*_{k+lM,p}, \quad l = 0, 1, \ldots, K-1, \quad (2)$$

with $\alpha_p = E[|N_k|^2]/E[|A_{k,p}|^2]$.

4 Iterative MUD Receiver with Interference Cancelation

We consider iterative, frequency-domain MUD receivers that combines IB-DFE principles with interference cancelation. Each iteration consists of P detection stages, one for each user (it is assumed that the users are ordered in power). When detecting a given user, the interference from previously detected users is canceled, as well as the residual ISI associated to that user. These interference and residual ISI cancelations take into account the reliability of each of the previously detected users.

For a given iteration, the detection of the pth user employs the structure depicted in fig. 1, where we have a feedforward filter, followed by a decimation procedure and P feedback filters (one for each user). The feedforward filter is designed to minimize both the ISI and the multiuser interference that cannot be canceled by the feedback filters, due to decision errors in the previous detection steps. After an IDFT operation, the corresponding time-domain outputs are passed through a hard-decision device so as to provide an estimate the data block transmitted by the pth user. For the case where we do not have any information about the users' data blocks, the receiver reduces to the linear frequency-domain MUD described in sec. 3.

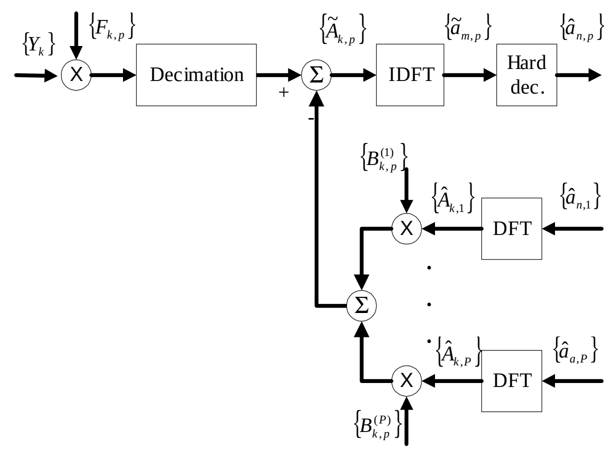

Figure 1. Detection of the pth user.

We can consider either a SIC or a PIC MUD receiver. For the SIC receiver, we cancel the interference from all users using the most updated version of it, as well as the residual ISI for the user that is being detected. For the PIC receiver, we cancel the interference from all users, as well as the residual ISI for the user that is being detected, employing the users' estimate from the previous iteration. The main advantage of the PIC structure is the possibility of a parallel implementation, with the simultaneous detection of all users, at each iteration.

For each iteration, the frequency-domain samples associated with the pth user at the detector output are given by

$$\tilde{A}_{k,p} = \sum_{l=0}^{K-1} F_{k+lM,p} Y_{k+lM} - B_{k,p}^{(p)} \hat{A}_{k,p} - \sum_{p' \neq p} B_{k,p}^{(p')} \hat{A}_{k,p'}$$

where $F_{k,p}$ ($k = 0, 1, \ldots, N-1$) denotes the feedforward coefficients and $B_{k,p}^{(p')}$ ($k = 0, 1, \ldots, M-1$;

$p = 1, 2, \ldots, P$) denotes the feedback coefficients. The coefficients $\{B_{k,p}^{(p)}; k = 0, 1, \ldots, M-1\}$ are used for residual ISI cancelation and the coefficients $\{B_{k,p}^{(p')}; k = 0, 1, \ldots, M-1\}$ ($p' \neq p$) are used for interference cancelation. The block $\{\hat{A}_{k,p'}; k = 0, 1, \ldots, M-1\}$ is the DFT of the block $\{\hat{a}_{n,p'}; n = 0, 1, \ldots, M-1\}$, where the time-domain samples $\hat{a}_{n,p'}, n = 0, 1, \ldots, M-1$, are the latest estimates for the p'th user transmitted symbols, i.e., the hard-decisions associated with the block of time-domain samples $\{\tilde{a}_{n,p'}; n = 0, 1, \ldots, M-1\} =$ IDFT $\{\tilde{A}_{k,p'}; k = 0, 1, \ldots, M-1\}$. For the ith iteration of a SIC receiver, $\hat{a}_{n,p'}$ is associated with the ith iteration for $p' < p$ and with the $(i-1)$th iteration for $p' \geq p$ (in the first iteration, we do not have any information for $p' \geq p$ and $\hat{a}_{n,p'} = 0$); for the PIC receiver, $\hat{a}_{n,p'}$ is always associated with the previous iteration (for the first iteration $\hat{a}_{n,p'} = 0$).

Due to decision errors, we have $\hat{a}_{n,p} \neq a_{n,p}$ for some symbols. Consequently, $\hat{A}_{k,p} \neq A_{k,p}$. For the computation of the receiver coefficients, it is assumed that $\hat{S}_{k,p} = \rho_p S_{k,p} + \Delta_{k,p}$, where $E[\Delta_{k,p}] \approx 0$, $E[\Delta_{k,p} A_{k',p}] \approx 0$, regardless of k and k', and the correlation coefficient ρ_p is given by $\rho_p = E[\hat{a}_{n,p} a_{n,p}^*]/E[|a_{n,p}|^2] = E[\hat{A}_{k,p} A_{k,p}^*]/E[|A_{k,p}|^2]$. Clearly, $E[|\Delta_{k,p}|^2] = (1 - \rho_p^2) E[|A_{k,p}|^2]$.

Clearly,

$$\tilde{A}_{k,p} =$$

$$= \gamma_p A_{k,p} + \left(\sum_{l=0}^{K-1} F_{k+lM,p} H_{k+lM,p} - \gamma_p - \rho_p B_{k,p}^{(p)} \right) A_{k,p} +$$

$$+ \sum_{p' \neq p} \left(\sum_{l=0}^{K-1} F_{k+lM,p} H_{k+lM,p'} - \rho_{p'} B_{k,p}^{(p')} \right) A_{k,p'} -$$

$$- \sum_{p'=1}^{P} B_{k,p}^{(p')} \Delta_{k,p'} + \sum_{l=0}^{K-1} F_{k+lM,p} N_{k+lM}$$

with $\gamma_p = \frac{1}{M} \sum_{k=0}^{M-1} \sum_{l=0}^{K-1} F_{k+lM,p} H_{k+lM,p}$. This means that $\tilde{A}_{k,p}$ has a "signal" component, $\gamma_p A_{k,p}$, and four "noise" components: the residual ISI, the MAI (Multiple Access Interference), the "noise" due to decision errors and the channel noise.

The forward and backward coefficients, $\{F_{k,p}; k = 0, 1, \ldots, N-1\}$ and $\{B_{k,p}^{(p')}; k = 0, 1, \ldots, M-1\}$, $p' = 1, 2, \ldots, P$, respectively, are chosen so as to maximize the "signal-to-noise plus interference ratio" (SNIR) for the pth user. It can be shown that the optimum feedforward coefficients are given by set of K equations

$$(1 - \rho_p^2) H_{k+lM,p}^* \sum_{l'=0}^{K-1} F_{k+l'M,p} H_{k+l'M,p} +$$

$$+ \sum_{p' \neq p} (1 - \rho_{p'}^2) H_{k+lM,p'}^* \sum_{l'=0}^{K-1} F_{k+l'M,p} H_{k+l'M,p'} +$$

$$+ \alpha_p F_{k+lM,p} =$$

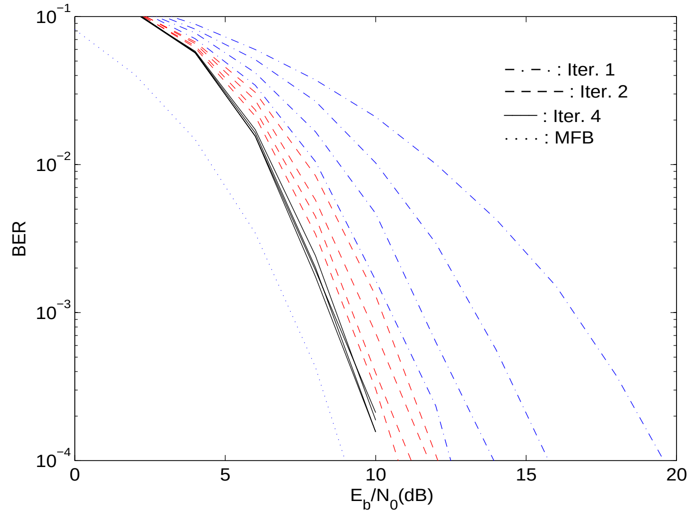

Figure 2. BER for each user, when $K = P = 4$ and a SIC receiver is employed with 1, 2 or 4 iterations (for a given iteration, the users that are detected later have better BER).

$$= \gamma_p (1 - \rho_p^2) H_{k+lM,p}^*, \quad l = 0, 1, \ldots, K-1. \quad (3)$$

The optimum values of $B_{k,p}^{(p')}$, $p' = 1, 2, \ldots, P$, are

$$B_{k,p}^{(p')} = \rho_{p'} \left(\sum_{l'=0}^{K-1} F_{k+l'M,p} H_{k+l'M,p'} - \gamma_p \delta_{p,p'} \right). \quad (4)$$

($\delta_{p,p'} = 1$ if $p = p'$ and 0 otherwise).

5 Performance Results

In this section, we present a set of performance results concerning the proposed SIC and PIC MUD receivers. We consider the uplink transmission within a CP-assisted DS-CDMA system where each user transmits a block of $M = 64$ data symbols, selected from a QPSK constellation under a Gray mapping rule. Two different spreading factors are considered: $K = 4$ and $K = 8$, leading to transmitted blocks with length $L = KM = 256$ or 512 chips, respectively, plus the CP. We consider strongly time-dispersive channels for each user and uncoded BER performances under perfect synchronization and channel estimation conditions. We have $P = K$ users (i.e., a fully loaded scenario), and the signals associated to all users have the same average power at the receiver (i.e., the BS), which corresponds to a scenario where an "ideal average power control" is implemented.

Figs. 2 and 3 show the impact of the number of iterations on the BER for each user when a SIC receiver is employed. For the sake of comparisons, we also include the corresponding MFB performance (Matched Filter Bound). From these figure, we can observe that the iterative SIC receiver allows a significant improvement on the BER performance. For a given iteration, the users that are detected

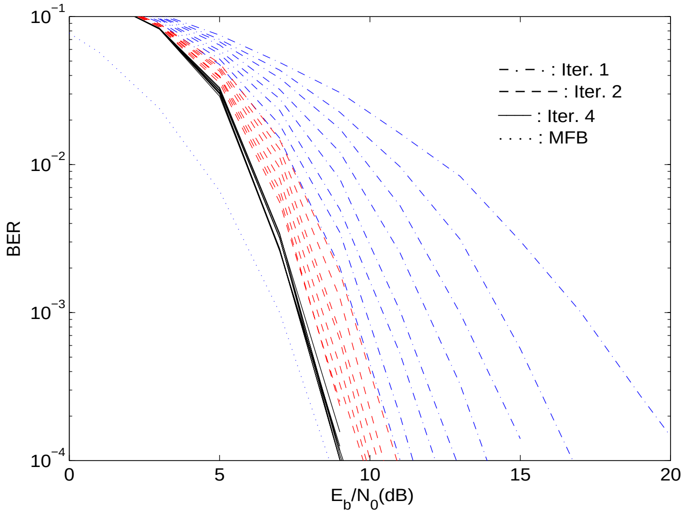

Figure 3. As in Fig. 2, but for $K = P = 8$.

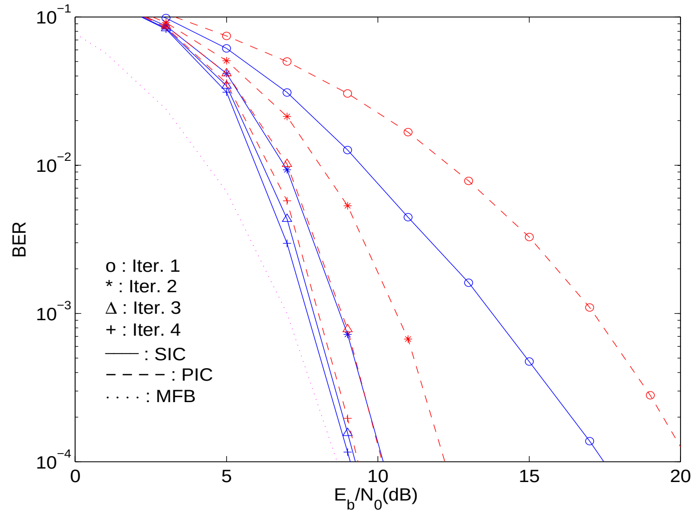

Figure 5. Average BER for PIC and SIC receivers, when $K = P = 8$.

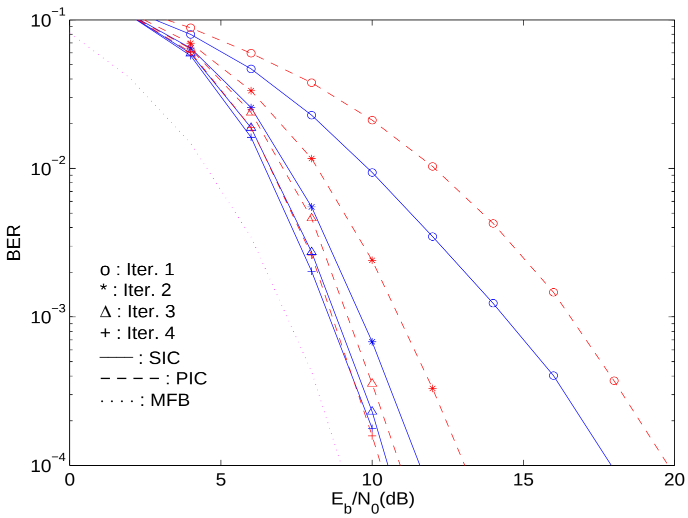

Figure 4. Average BER for PIC and SIC receivers, when $K = P = 4$.

first face stronger interference levels and have worse BER (this is especially important at the first iteration). After four iterations the performances are already similar for all users, and very close to the MFB, especially for $K = 8$.

In figs. 4 and 5 we present the average BER (averaged over all users) for PIC a SIC receivers. From these figure, we can observe that the PIC receiver has worse performance, especially for the first iteration. This is a consequence of the fact that the PIC receiver uses the block estimates from the previous iteration for all users and the SIC receiver uses the most updated version of it. After four iterations the performance of PIC and SIC receivers are similar and, once again, very close to the MFB.

6 Conclusions

In this paper we proposed iterative frequency-domain MUD receivers for CP-assisted DS-CDMA systems. Both SIC and PIC receivers were considered. Our performance results show that the proposed receivers are appropriate for DS-CDMA wireless systems, with performances very close to the single-user MFB after just a few iterations, even for fully loaded systems and severe time-dispersive channels.

References

[1] K. Baum, T. Thomas, F. Vook, V. Nangia, "Cyclic-Prefix CDMA: An Improved Transmission Method for Broadband DS-CDMA Cellular Systems", *IEEE WCNC*, pp. 183–188, 2002.

[2] A.Gusmão, R.Dinis and N.Esteves, "On Frequency-domain Equalization and Diversity Combining for Broadband Wireless Communications", *IEEE Trans. on Comm.*, Vol. 51, No. 7, pp. 1029–1033, July 2003.

[3] P. Silva and R. Dinis, "An Iterative Frequency-Domain Decision Feedback Receiver for CDMA Systems", *IEEE ISWCS'04*, Sep. 2004.

[4] N. Benvenuto and S. Tomasin, "Block Iterative DFE for Single Carrier Modulation", *IEE Elec. Let.*, Vol. 39, No. 19, pp. 1144–1145, Sep. 2002.

[5] R. Dinis, A. Gusmão, and N. Esteves, "On Broadband Block Transmission over Strongly Frequency-Selective Fading Channels", *Proc. Wireless 2003*, Calgary, Canada, July 2003.