Interleaving-Based Multiple Access and Iterative Chip-by-Chip Multiuser Detection

W. K. Leung [†], Lihai Liu[†], and Li Ping[†]

Summary

This letter examines a very simple iterative chip-by-chip multiuser detection strategy for spread spectrum communication systems. An interleaving-based multiple-access transmission technique is employed to facilitate detection. The proposed scheme can achieve near single-user performance in situations with very large numbers of users while maintaining very low receiver complexity.

Key words:

CDMA, multiple access interference, multiuser detection, turbo detection.

1. Introduction

Recently, significant progress has been made in turbo-type multiuser detection for code-division multiple-access (CDMA) systems [1-4]. Many authors have discussed the roles of interleavers in multiple access systems [1][5-7]. In a conventional CDMA scheme, interleavers are placed before the spreaders and they are effective only when used in conjunction with channel coding [1][5][7]. Recently, a very interesting technique using chip-level interleavers is proposed in [8], which aims at mitigating intersymbol interference in multipath fading environments.

In this letter, we investigate the performance of the chip-interleaved CDMA (cI-CDMA) scheme at very high loading. We will show that the cI-CDMA scheme can support a very large number of users at very low decoding cost. Hence it offers an efficient alternative to the more complex methods based on maximum *a posteriori* probability (MAP) [1-3] or minimum mean squared error (MMSE) techniques [4].

Our study employs the principle that users are separated only by different interleavers (as opposed to different frequency carriers as in FDMA or different time slots as in TDMA or different signature sequences as in CDMA). All of the users employ a common spreading sequence. For convenience of discussion, we refer to this scheme as interleave-division multiple-access (IDMA). It is also a special form of CDMA if we view the interleaving index sequences as a code to distinguish users. It is interesting to see that the system works very well with very high loading based on this principle.

2. Transmitter Structure

Consider a spread spectrum communication system with K users. The transmitter and receiver structures are shown in Fig. 1. At the transmitter side, the nth bit $d_n^{(k)} \in \{+1, -1\}$, $n = 1, 2, \ldots, N$, in the input data stream $\boldsymbol{d}^{(k)}$ from user-k is spread using a length-S spreading sequence $\boldsymbol{s}^{(k)}$ in the form $d_n^{(k)} \to d_n^{(k)} \boldsymbol{s}^{(k)}$. We write the chip sequence obtained after spreading as $\{ c_j^{(k)}, j = 1, 2, \ldots, J\}$, where $J = N \times S$ is the frame length. A chip-level interleaver $\pi^{(k)}$ is then applied to produce the transmitted signals $\{ x_j^{(k)}, j = 1, 2, \ldots, J\}$. Removing the interleaver $\pi^{(k)}$ in Fig. 1 leads to a conventional CDMA scheme, in which the different signature sequences $\{\boldsymbol{s}^{(k)}, k = 1, 2, \ldots, K\}$ are employed for user separation. Alternatively, we can use a common spreading sequence for all users, i.e., setting $\boldsymbol{s}^{(1)} = \boldsymbol{s}^{(2)} = \ldots = \boldsymbol{s}^{(k)} = \ldots = \boldsymbol{s}^{(K)} = \boldsymbol{s}$, and employ user-specific interleavers $\{\pi^{(k)}, k = 1, 2, \ldots, K\}$ for user separation. This results in the so-called IDMA scheme, which inherits many advantages from CDMA such as diversity against fading and mitigation of other-cell user interference.

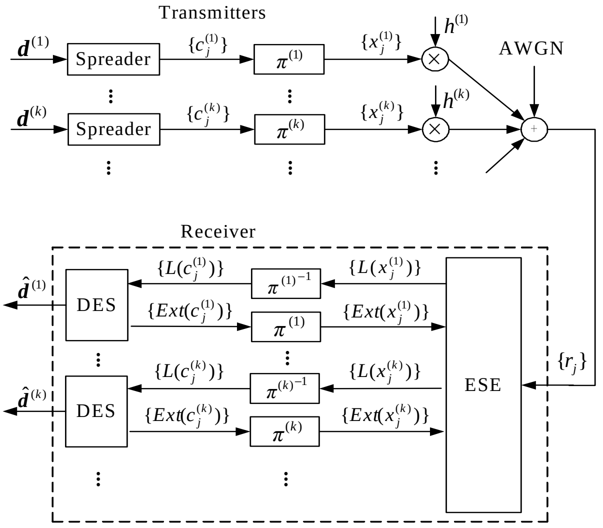

Fig. 1 IDMA transmitter and receiver structures, where $\pi^{(k)}$ is an interleaver for user-k.

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3. Iterative Chip-by-Chip Receiver

For simplicity, we only consider synchronous BPSK systems over a time-invariant single-path channel. The received signal at time instant *j* can be written as

$$r_j = \sum_{k=1}^{K} h^{(k)} x_j^{(k)} + n_j\,,\ j = 1, 2, \ldots, J \qquad (1)$$

where $x_j^{(k)} \in \{+1,-1\}$ denotes the transmitted chip from user-*k* at time instant *j*, $h^{(k)}$ the channel coefficient for user-*k*, and n_j zero-mean additive white Gaussian noise (AWGN) with variance $\sigma^2 = N_0/2$. We will assume perfect knowledge of the channel coefficients at the receiver. To simplify discussion, we also assume that the channel coefficients $\{h^{(k)}\}$ are real, but the principle can be extended to situations with complex channel coefficients.

The iterative chip-by-chip receiver in Fig. 1 consists of an elementary signal estimator (ESE) and a bank of *K* single-user *a posteriori* probability decoders for the de-spreading operation (DES) working in a turbo-type manner, as shown in Fig. 1. The ESE performs a coarse chip-by-chip estimation. We concentrate on $x_j^{(k)}$ and re-write (1) as

$$r_j = h^{(k)} x_j^{(k)} + \zeta_j^{(k)} \qquad (2)$$

where $\zeta_j^{(k)} \equiv r_j - h^{(k)} x_j^{(k)}$ represents a distortion term with respect to $x_j^{(k)}$. We treat each $x_j^{(k)}$ as a random variable with mean $\mathrm{E}(x_j^{(k)})$ and variance $\mathrm{Var}(x_j^{(k)})$ (initialized to 0 and 1 respectively). Then from (1), we have

$$\mathrm{E}(r_j) = \sum_{k=1}^{K} h^{(k)} \mathrm{E}(x_j^{(k)}) \qquad (3a)$$

$$\mathrm{Var}(r_j) = \sum_{k=1}^{K} \left|h^{(k)}\right|^2 \mathrm{Var}(x_j^{(k)}) + \sigma^2\,. \qquad (3b)$$

Using the central limit theorem, $\zeta_j^{(k)}$ in (2) can be approximated by a Gaussian random variable with

$$\mathrm{E}(\zeta_j^{(k)}) = \mathrm{E}(r_j) - h^{(k)} \mathrm{E}(x_j^{(k)}) \qquad (4a)$$

$$\mathrm{Var}(\zeta_j^{(k)}) = \mathrm{Var}(r_j) - \left|h^{(k)}\right|^2 \mathrm{Var}(x_j^{(k)})\,. \qquad (4b)$$

The ESE outputs are the logarithm likelihood ratios (LLRs) about $\{\, x_j^{(k)} \,\}$ computed based on (3) (using (4)) as

$$\begin{aligned} L(x_j^{(k)}) &\equiv \log\left(\frac{Pr(x_j^{(k)} = +1 \mid r_j)}{Pr(x_j^{(k)} = -1 \mid r_j)}\right) \\ &= \log \frac{\exp(-\dfrac{(r_j - \mathrm{E}(\zeta_j^{(k)}) - h^{(k)})^2}{2\mathrm{Var}(\zeta_j^{(k)})})}{\exp(-\dfrac{(r_j - \mathrm{E}(\zeta_j^{(k)}) + h^{(k)})^2}{2\mathrm{Var}(\zeta_j^{(k)})})} \\ &= \frac{2h^{(k)}(r_j - \mathrm{E}(\zeta_j^{(k)}))}{\mathrm{Var}(\zeta_j^{(k)})}\,,\ \forall k, j\,. \end{aligned} \qquad (5)$$

For user-*k*, the corresponding ESE outputs $\{\, L(x_j^{(k)})\,,\ j = 1, 2, \ldots, J\}$ are de-interleaved to form $\{\, L(c_j^{(k)})\,,\ j = 1, 2, \ldots, J\}$ and delivered to the DES for user-*k*. The DES performs a soft-in/soft-out chip-by-chip de-spreading operation as detailed below.

For simplicity, we focus on the chips related to $d_1^{(k)}$, the first bit of user-*k*. The treatment for other chips is similar. Recall that $d_1^{(k)}$ is spread into the chip sequence $d_1^{(k)} \boldsymbol{s}^{(k)} = \{\, c_j^{(k)}\,,\ j = 1, 2, \ldots, S\}$, where $\boldsymbol{s}^{(k)} = \{\, s_j^{(k)} \,\}$ is the binary signature sequence (over {+1, –1}) for user-*k*. We assume that $\{L(c_j^{(k)})\}$ are uncorrelated (which is approximately true due to interleaving [9]). Let the interleaving for user-*k* be expressed as $\pi^{(k)}(j) = j'$, i.e., $c_j^{(k)} = x_{j'}^{(k)}$ (see Fig. 1). Then based on (5), the *a posteriori* LLR for $d_1^{(k)}$ can be computed using $\{\, L(c_j^{(k)}) \,\}$ as

$$\begin{aligned} L(d_1^{(k)}) &\equiv \log\left(\frac{Pr(d_1^{(k)} = +1 \mid \boldsymbol{r})}{Pr(d_1^{(k)} = -1 \mid \boldsymbol{r})}\right) \\ &= \log\left(\frac{\prod_{j=1}^{S} Pr(c_j^{(k)} = s_j^{(k)} \mid r_{j'})}{\prod_{j=1}^{S} Pr(c_j^{(k)} = -s_j^{(k)} \mid r_{j'})}\right) \\ &= \sum_{j=1}^{S} \log \frac{Pr(c_j^{(k)} = s_j^{(k)} \mid r_{j'})}{Pr(c_j^{(k)} = -s_j^{(k)} \mid r_{j'})} \\ &= \sum_{j=1}^{S} s_i^{(k)} L(c_j^{(k)})\,. \end{aligned} \qquad (6)$$

The extrinsic LLR for a chip $c_j^{(k)}$ within $d_1^{(k)} \boldsymbol{s}^{(k)}$ is defined by

$$Ext(c_j^{(k)}) \equiv \log\left(\frac{Pr(c_j^{(k)} = +1 \mid \boldsymbol{r})}{Pr(c_j^{(k)} = -1 \mid \boldsymbol{r})}\right) - L(c_j^{(k)})\,.$$

We notice that $c_j^{(k)} = +1$ if $s_j^{(k)} = d_1^{(k)}$ and $c_j^{(k)} = -1$ otherwise. Therefore we have [8]

$$Ext(c_j^{(k)}) = s_j^{(k)} L(d_1^{(k)}) - L(c_j^{(k)})\,. \qquad (7)$$

The extrinsic LLRs $\{Ext(c_j^{(k)})\}$ form the outputs of the DES and are fed back to the ESE after interleaving (see Fig. 1). In the next iteration, $\{Ext(x_j^{(k)})\}$ are used to update $\{\, \mathrm{E}(x_j^{(k)}) \,\}$ and $\{\, \mathrm{Var}(x_j^{(m)}) \,\}$ as [4]

$$\mathrm{E}(x_j^{(k)}) = \frac{\exp(Ext(x_j^{(k)})) - 1}{\exp(Ext(x_j^{(k)})) + 1} = \tanh(\frac{Ext(x_j^{(k)})}{2}) \qquad (8a)$$

$$\mathrm{Var}(x_j^{(k)}) = 1 - \mathrm{E}(x_j^{(k)})^2\,. \qquad (8b)$$

This iterative process is repeated a preset number of times. In the final iteration the DES produces hard decisions $\hat{\boldsymbol{d}}^{(k)}$ on information bits $\boldsymbol{d}^{(k)}$ based on (6).

The detection algorithm in (3)-(8) does not rely on coding unlike other methods [2-4], but introducing coding can further enhance performance (details omitted here). The principle can be generalized to situations with multipath fading [10].

For complexity, notice that (3) involves summations over all of the users, but the results (and so the cost) are shared by all of the users. The related cost is only two additions and two multiplications per chip per user per iteration. Several more simple operations per chip per user per iteration are required in (4)-(8).

Overall, the normalized complexity per information bit per user per iteration increases linearly with the spreading length but is independent of the number of users K. In comparison, the MAP-based methods [1-3] have a complexity $O(2^K)$ and the matrix MMSE method [4] has a complexity $O(K^2)$, where K is the number of users. The cost advantage of the algorithm described above is clear.

4. Simulation Results

For simplicity, we only consider uncoded systems in AWGN channels in this letter. All channel coefficients are set to $h^{(k)} = 1$, $k = 1, 2, \ldots, K$. Fig. 2 shows the performance of the chip-by-chip detector for CDMA (with randomly generated length-64 signature sequences) and IDMA (with randomly generated interleavers and a common length-64 spreading sequence for all users) in AWGN channels. The only constraint used in selecting the spreading sequence for IDMA is that it should contain a balanced number of +1 and –1 (so as to ensure randomness). We simply use {+1, −1, +1, −1, …} for all users. The length of the information block is $N = 256$ bits per user.

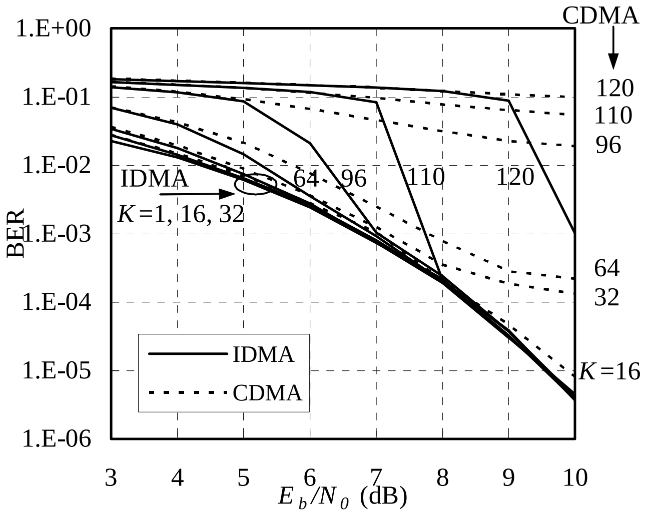

Fig. 2. Performance of chip-by-chip detectors for CDMA and IDMA systems over AWGN channels. The spreading length is equal to 64. The user number K is marked in the figure. The iteration number equals 10 for both CDMA and IDMA.

It is observed from Fig. 2 that for the conventional CDMA scheme, the simple chip-by-chip detection following (3)-(8) does not perform well for $K > 32$. However, we can see that the IDMA scheme can achieve near single-user performance even for $K = 96$ (measured at BER = 10^{-3}). This represents a very high loading as the spreading length is only 64, (compared with, say, the loadings considered in [2-4]).

The MAP [1-3] or matrix MMSE [4] principles may be applied to improve the conventional CDMA scheme. We observed that by employing these more sophisticated techniques, the conventional CDMA scheme can achieve similar performance as that shown in Fig. 2 for IDMA. However, the related cost is significantly higher than the simple chip-by-chip method used here, as analyzed at the end of Section 3.

5. Conclusions

The use of chip-level interleavers in IDMA greatly facilitates the simple chip-by-chip detection strategy. We are currently working on a theoretical analysis of this observation.

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