TURBO MULTIUSER DETECTION FOR ASYNCHRONOUS CODED CDMA SYSTEMS IN THE PRESENCE OF INTERCELL INTERFERENCE

Shahram Talakoub and Behnam Shahrrava

Department of Electrical and Computer Engineering,
University of Windsor, Windsor, Ontario, Canada.
Emails: {talakou,shahrrav}@uwindsor.ca

ABSTRACT

A turbo multiuser receiver is proposed for the uplink of coded code-division multiple-access (CDMA) systems when intercell interference is present. The proposed receiver consists of a first stage of soft interference cancellation, and a group-blind linear minimum mean-square error filtering, followed by a second stage that performs the channel decoding. A receiver suitable for suppressing high intercell interference is obtained. By exchanging soft information between the first and second stages, the receiver performance is improved through iteration. Simulation results show the proposed group-blind receiver significantly outperforms the conventional turbo multiuser detector in the presence of intercell interference.

1. INTRODUCTION

In recent years, turbo multiuser detection techniques have received considerable attention, inspired by the discovery of turbo coding [1]. In [2], an iterative (turbo) receiver structure was proposed for decoding multiuser information data in a convolutionally coded asynchronous multipath code-division multiple-access (CDMA) system. Then, the concept of group-blind multiuser detection was developed in [3] and [4]. Turbo multiuser detection with unknown interferers was proposed in [5]. In this method in order to suppress the intercell and intracell interference, the multiuser detector performs a soft interference cancellation for each user, in which estimates of the multiuser interference from the other known users and an estimate for the interference caused by the unknown users are subtracted from the received signal. It is shown that this method has moderate gain in performance compared to the conventional turbo multiuser detection when there is low intercell interference in the system; however, as the intercell interference increases the performance of this method merges to that of the conventional turbo multiuser detector. In this paper we consider the group-blind multiuser detection scheme that combines the concept of group-blind detection and turbo multiuser detection for asynchronous CDMA systems. Specifically, it consists of two stages similar to those of [2] for recursive systematic convolutionally encoded CDMA systems. The first stage consists of soft interference cancellation and combined group-blind minimum mean-square error (MMSE) filtering, whereas the second stage consists of channel decoding. Simulation results show that this method preserves its advantage in performance over conventional turbo multiuser detection method even in case of high intercell interference. This is in contrast with the method proposed in [5] which loses its advantage over conventional turbo multiuser detection in a high intercell interference environment.

The remainder of this paper is organized as follows. In Section 2, we present our signal model and the system description. In Section 3, we derive a group-blind turbo multiuser detector for asynchronous CDMA by modifying the receiver given in [2] for all known users. In Section 4, we present simulation results to demonstrate the performance of the proposed receiver. Section 5 contains the conclusion.

2. SIGNAL MODEL

We consider a recursive systematic convolutionally (RSC) coded CDMA system with K users, employing normalized modulation waveforms $\{\mathbf{s}_1, \mathbf{s}_2, ..., \mathbf{s}_K\}$ and signaling through multipath channel with additive white Gaussian noise using binary phase shift keying (BPSK) modulation. Let M be the length of the channel codeword for each user at the output of channel encoder, which is denoted by $b_k(j)$. The channel encoder outputs are next interleaved by a random interleaver, and these interleaved symbols are next modulated by the user's spreading sequence, and transmitted through the channel. If we denote the interleaver function of user k by $\prod_k$, then the interleaver output can be written as $\{b_k(i)\}_{i=0}^{M-1}$, where $i = \prod_k(j)$ for $j = 0, 1, ..., M-1$. The spreading waveform of user k is assumed to be of the form

$$s_k(t) = \frac{1}{\sqrt{N}} \sum_{j'=0}^{N-1} s_k(j')\psi(t - j'Tc), \qquad (1)$$

where N denotes the processing gain of the CDMA system, $\mathbf{s}_k = [s_k(0), ..., s_k(N-1)]^T$ denotes the kth user's spreading code, T_c denotes the chip period, $s_k(j') \in \{(+1), (-1)\}$, and $\psi(t)$ is the normalized chip waveform (i.e. $\int_0^{T_c} \psi^2(t)dt = 1$). It is assumed that the receiver has knowledge of the signature waveforms of the first $\tilde{K}$ users ($\tilde{K} \le K$), whereas the signature waveforms of the remaining $K - \tilde{K}$ users are unknown to the receiver. The continuous time received signal can be written as

$$r(t) = \sum_{k=1}^{K} [x_k(t) \star f_k(t)] + n(t), \tag{2}$$

where $n(t)$ is complex white Gaussian noise process with zero mean and variance σ^2, and

$$x_k(t) \triangleq \sum_{i=0}^{M-1} b_k(i) s_k(t - iT), \tag{3}$$

$$f_k(t) \triangleq \sum_{l=1}^{L} g_{l,k} \delta(t - \tau_{l,k}), \tag{4}$$

where L is the number of pathes in multipath channel, $g_{l,k}$ denotes the corresponding complex path gain of the channel for user k, and $\tau_{l,k}$ is the delay of the lth path of the kth user's signal.

3. GROUP-BLIND TURBO MULTIUSER DETECTOR FOR ASYNCHRONOUS CDMA SYSTEMS

In this section, we generalize the turbo multiuser detector (TMUD) proposed in [2] for group-blind CDMA systems. We modify the MMSE-based receiver in a way that it will be able to suppress the multiple access interference (MAI) from unknown users, in expense of adding computational complexity. In the first stage of the receiver we assume that the *a priori* information about the coded symbols $b_k(i)$ for $k = 1, ..., \tilde{K}$ and $i = 0, ..., M-1$ is available to the receiver. The proposed group-blind multiuser detector consists of soft interference cancellation for known users and a combined MMSE filtering, which tries to minimize the intracell and intercell interference using MMSE criterion. The unknown users' signals are suppressed by identifying the subspace spanned by these users followed by a linear transformation in this subspace based on MMSE criterion. At the receiver, the received signal $r(t)$ is filtered by a chip matched filter and sampled at a multiple p of the chip rate, which the resulting discrete-time signal is denoted by $r_q[i]$ for $q = 0, \ldots, P-1$. This is similar to what is proposed in [4]. Let us define $P \triangleq Np$ as the number of samples per symbol period, and $\iota \triangleq \max_{1 \le k \le K} \{\lceil \frac{\tau_{l,k} + T_c}{T} \rceil\}$ be the maximum delay spread in terms of symbol interval. Denote

$$\underline{r}[i] \triangleq \left[r_0[i], \cdots, r_{P-1}[i]\right]^T,$$
$$\underline{b}[i] \triangleq \left[b_1[i], \cdots, b_K[i]\right]^T,$$
$$\underline{n}[i] \triangleq \left[n_0[i], \cdots, n_{P-1}[i]\right]^T.$$

Define

$$h_k[n] \triangleq \frac{1}{\sqrt{N}} \sum_{j'=0}^{N-1} s_k(j') \sum_{l=1}^{L} g_{l,k} \times \int_0^{T_c/p} \psi(t)\psi(t - \tau_{l,k} + n\frac{T_c}{p} - j'T_c)dt. \tag{5}$$

Then matrix $\underline{H}(j)$ can be defined as follow:

$$\underline{H}[j] \triangleq \begin{bmatrix} h_1[jP] & \ldots & h_K[jP] \\ \vdots & \vdots & \vdots \\ h_1[jP+P-1] & \ldots & h_K[jP+P-1] \end{bmatrix},$$

for $j = 0, ..., \iota$. The discrete received signal can be written in terms of vector convolution as

$$\underline{r}[i] = \underline{H}[i] \star \underline{b}[i] + \sigma \underline{n}[i]. \tag{6}$$

By stacking m successive sample vectors, the following vectors can be defined,

$$\mathbf{r}[i] \triangleq \begin{bmatrix} \underline{r}[i] \\ \vdots \\ \underline{r}[i+m-1] \end{bmatrix}_{Pm \times 1}, \mathbf{n}[i] \triangleq \begin{bmatrix} \underline{n}[i] \\ \vdots \\ \underline{n}[i+m-1] \end{bmatrix}_{Pm \times 1},$$

$$\mathbf{b}[i] \triangleq \begin{bmatrix} \underline{b}[i-\iota] \\ \vdots \\ \underline{b}[i+m-1] \end{bmatrix}_{K(m+\iota) \times 1}.$$

Finally matrix $\mathbf{H}$ is defined as follow,

$$\mathbf{H} \triangleq \begin{bmatrix} \underline{H}[\iota] & \ldots & \underline{H}[0] & \ldots & \mathbf{0} \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ \mathbf{0} & \ldots & \underline{H}[\iota] & \ldots & \underline{H}[0] \end{bmatrix}_{Pm \times K(m+\iota)}$$

where the smoothing factor m is chosen according to $m = \lceil \frac{P+K}{P-K} \rceil \iota$ [4]. Using these quantities and separating terms corresponding to known and unknown users' signals, equation (6) can be written as,

$$\mathbf{r}[i] = \tilde{\mathbf{H}}\tilde{\mathbf{b}}[i] + \bar{\mathbf{H}}\bar{\mathbf{b}}[i] + \sigma \mathbf{n}[i], \tag{7}$$

where $\tilde{\mathbf{H}}$ and $\bar{\mathbf{H}}$ are composite signal waveform matrices of known and unknown users. $\tilde{\mathbf{b}}[i]$ and $\bar{\mathbf{b}}[i]$ are derived from **b**[i] for known and unknown users respectively.

The soft interference cancellation at the first stage of the proposed receiver is similar to what is proposed in [2]. Suppose that at the first stage of the receiver we have available *a priori* log likelihood ratios $L^{pri}_{Det}(k,i)$ of known users' transmitted symbols. The soft estimate of the known user's transmitted symbol is given by

$$\hat{b}_k[i] = E\{b_k[i]\} = \tanh\left(\frac{L^{pri}_{Det}(k,i)}{1+exp(L^{pri}_{Det}(k,i))}\right). \quad (8)$$

The partially interference-canceled signal corresponding to the kth user's symbol is then obtained by subtracting out a soft-estimate of MAI of known users, as

$$\mathbf{r}_k[i] = \mathbf{r}[i] - \tilde{\mathbf{H}}\hat{\tilde{\mathbf{b}}}_k[i], \quad (9)$$

where $\hat{\tilde{\mathbf{b}}}_k[i] = \hat{\tilde{\mathbf{b}}}[i] - \hat{b}_k[i]\mathbf{e}_{\tilde{K}\iota+k}$, and $\mathbf{e}_{\tilde{K}\iota+k}$ is an $\tilde{K}(m+\iota)$ vector of all zero except for the single unity element at the $\tilde{K}\iota+k$ position. $\hat{b}_k[i]$ is the soft estimate of the kth user's symbol, and $\hat{\tilde{\mathbf{b}}}[i]$ is a vector of the soft estimate of known users' coded bits. We further define $\tilde{\mathbf{r}}_k[i] = \tilde{\mathbf{H}}(\tilde{\mathbf{b}}[i] - \hat{\tilde{\mathbf{b}}}_k[i]) + \sigma\mathbf{n}[i]$ to be the component of $\mathbf{r}_k[i]$ in (9) consisting of signals from known users plus noise.

In order to further suppress the MAI from known users and unknown users a combined instantaneous linear MMSE filter $\mathbf{w}_k[i]$ is applied to $\mathbf{r}_k[i]$, such that

$$z_k[i] = \mathbf{w}_k[i]^H\mathbf{r}_k[i]. \quad (10)$$

The purpose of using group-blind MMSE filtering is to suppress the remaining MAI from known users based on the spreading sequences and channel characteristics of these users and to suppress the interference from other unknown users using subspace-base blind method. The weight vector of the group-blind linear MMSE detector for user k $(1 \le k \le \tilde{K})$ is given by $\mathbf{w}_k[i] = \tilde{\mathbf{w}}_k[i] + \bar{\mathbf{w}}_k[i]$, where $\tilde{\mathbf{w}}_k[i] \in$ range$(\tilde{\mathbf{H}})$, and $\bar{\mathbf{w}}_k[i] \in$ {range$(\mathbf{H}) \cap$ null$(\tilde{\mathbf{H}}^H)$} such that

$$\tilde{\mathbf{w}}_k[i] = \arg\min_{\mathbf{w}\in \text{ range}(\tilde{\mathbf{H}})} E\{|b_k[i] - \mathbf{w}^H\tilde{\mathbf{r}}_k[i]|^2\}, \quad (11)$$

$$\bar{\mathbf{w}}_k[i] = \arg\min_{\mathbf{w}\in\Omega} E\{|b_k[i] - (\mathbf{w}+\tilde{\mathbf{w}}_k[i])^H\mathbf{r}_k[i]|^2\}, \quad (12)$$

where $\Omega \triangleq$ {range$(\mathbf{H}) \cap$ null$(\tilde{\mathbf{H}}^H)$}. Considering the following equalities,

$$E\{\mathbf{r}_k[i]\mathbf{r}_k[i]^H\} = \tilde{\mathbf{H}}\Delta_k[i]\tilde{\mathbf{H}}^H + \bar{\mathbf{H}}\bar{\mathbf{H}} + \sigma^2\mathbf{I}_{Pm}, \quad (13)$$

$$E\{\tilde{\mathbf{r}}_k[i]\tilde{\mathbf{r}}_k[i]^H\} = \tilde{\mathbf{H}}\Delta_k[i]\tilde{\mathbf{H}}^H + \sigma^2\mathbf{I}_{Pm}, \quad (14)$$

$$E\{b_k[i]\tilde{\mathbf{r}}_k[i]\} = \tilde{\mathbf{H}}\mathbf{e}_{\tilde{K}\iota+k}, \quad (15)$$

and

$$\Delta_k[i] \triangleq Cov\{\tilde{\mathbf{b}}[i] - \tilde{\mathbf{b}}_k[i]\}. \quad (16)$$

The solution to equation (11) is given by

$$\tilde{\mathbf{w}}_k[i] = \tilde{\mathbf{H}}(\Delta_k[i]\tilde{\mathbf{H}}^H\tilde{\mathbf{H}} + \sigma^2\mathbf{I}_{\tilde{K}(m+\iota)})^{-1}\mathbf{e}_{\tilde{K}\iota+k}. \quad (17)$$

To solve the optimization problem (12), we first introduce the projection matrix $\mathbf{P}$, which is defined in a way that projects any signal onto the null subspace of $\tilde{\mathbf{H}}^H$; in this way $\mathbf{P}$ is defined as follow

$$\mathbf{P} \triangleq \mathbf{I}_{Pm} - \tilde{\mathbf{H}}(\tilde{\mathbf{H}}^H\tilde{\mathbf{H}})^{-1}\tilde{\mathbf{H}}^H. \quad (18)$$

The autocorrelation matrix for $\mathbf{r}[i]$ is equal to

$$E\{\mathbf{r}[i]\mathbf{r}[i]^H\} = \tilde{\mathbf{H}}\tilde{\mathbf{H}}^H + \bar{\mathbf{H}}\bar{\mathbf{H}}^H + \sigma^2\mathbf{I}_{Pm}. \quad (19)$$

It is then easily seen that the matrix $\mathbf{P}E\{\mathbf{r}[i]\mathbf{r}[i]^H\}\mathbf{P}$ has an eigen-structure of the form

$$\mathbf{P}E\{\mathbf{r}[i]\mathbf{r}[i]^H\}\mathbf{P} = \begin{bmatrix}\bar{U}_s & \bar{U}_n & \bar{U}_0\end{bmatrix}\begin{bmatrix}\bar{\Lambda}_s & \mathbf{0} & \mathbf{0}\\ \mathbf{0} & \bar{\Lambda}_n & \mathbf{0}\\ \mathbf{0} & \mathbf{0} & \mathbf{0}\end{bmatrix}\begin{bmatrix}\bar{U}_s^H\\ \bar{U}_n^H\\ \bar{U}_0^H\end{bmatrix}$$

where $\bar{\Lambda}_s \triangleq diag[\lambda_1, ..., \lambda_{(K-\tilde{K})(m+\iota)}]$, and $\bar{\Lambda}_n \triangleq \sigma^2\mathbf{I}_{Pm-K(m+\iota)}$, with $\lambda_i > \sigma^2$ for $i = 1, ..., (K-\tilde{K})(m+\iota)$. The column of $\bar{U}_s$ form an orthogonal basis of the subspace range$(\mathbf{H}) \cap$ null$(\tilde{\mathbf{H}}^H)$.

An approximation for autocorrelation matrices $E\{\mathbf{r}[i]\mathbf{r}[i]^H\}$ and $E\{\mathbf{r}_k[i]\mathbf{r}_k[i]^H\}$ can be formed as follows

$$\mathbf{C}_r \triangleq E\{\mathbf{r}[i]\mathbf{r}[i]^H\} \approx \frac{1}{M}\sum_{i=0}^{M-1}\mathbf{r}[i]\mathbf{r}[i]^H, \quad (20)$$

$$\mathbf{C}_{r_k}[i] \triangleq E\{\mathbf{r}_k[i]\mathbf{r}_k[i]^H\} \approx \mathbf{C}_r - \tilde{\mathbf{H}}\tilde{\mathbf{H}}^H + \tilde{\mathbf{H}}\Delta_k[i]\tilde{\mathbf{H}}. \quad (21)$$

The solution to equation (12) is given by

$$\bar{\mathbf{w}}_k[i] = -\bar{U}_s\bar{\Lambda}_s^{-1}\bar{U}_s^H\mathbf{C}_{r_k}[i]\tilde{\mathbf{w}}_k[i]. \quad (22)$$

The combined group-blind MMSE filter is defined as

$$\begin{aligned}\mathbf{w}_k[i] =& \tilde{\mathbf{w}}_k[i] + \bar{\mathbf{w}}_k[i],\\ =& (\mathbf{I}_{Pm} - \bar{U}_s\bar{\Lambda}_s^{-1}\bar{U}_s^H\mathbf{C}_{r_k}[i])\tilde{\mathbf{H}}\\ &\times(\Delta_k[i]\tilde{\mathbf{H}}^H\tilde{\mathbf{H}} + \sigma^2\mathbf{I}_{\tilde{K}(m+\iota)})^{-1}\mathbf{e}_{\tilde{K}\iota+k}.\end{aligned} \quad (23)$$

It can be shown that the extrinsic log likelihood ratio corresponding to the kth user signal $k \in \{1, ..., \tilde{K}\}$, delivered by the soft instantaneous group-blind MMSE filter is given by [2]

$$L^{ext}_{Det}(k,i) = \frac{4\Re\{z_k[i]\}}{1-\mu_k[i]}, \quad (24)$$

where $\mu_k[i] = \mathbf{w}_k[i]^H\tilde{\mathbf{H}}\mathbf{e}_{\tilde{K}\iota+k}$. The set of soft outputs $\{L^{ext}_{Det}(k,i)\}$ are next deinterleaved and passed on to the bank of single-user channel decoders to serve as *a priori* information. Applying the turbo principle, after an initial detection of blocks of received symbols from known users, block-wise detection and decoding operation are performed simultaneously for known users, on the same set of received data. A suitably chosen termination criterion (i.e. specific number of iterations), stops the iteration process.

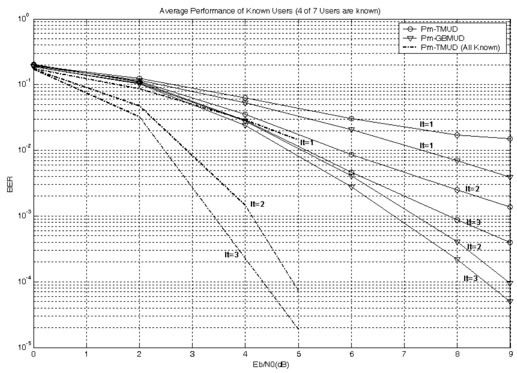

Fig. 1. Performance Comparison, 4 of 7 users are known

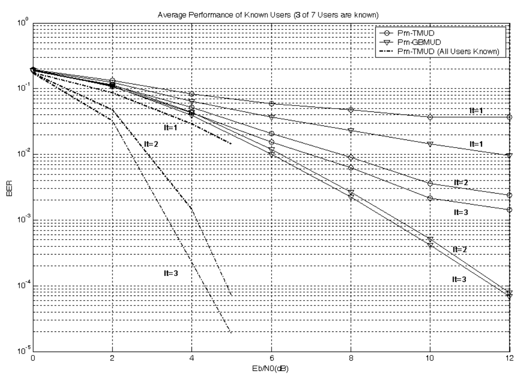

Fig. 2. Performance Comparison, 3 of 7 users are known

4. SIMULATION RESULTS

We present bit error rate (BER) performance results by simulating data transmission using the receiver introduced in section III. We consider an asynchronous CDMA system with seven users ($K = 7$). The number of known users in this system are 4, or 3, as noted on the figures. The user spreading sequences are sequences of length 7, the number of paths between each user and the base station is $L_k = 3$, and the maximum delay in symbol interval is 1. All users employ the same rate $1/2$ recursive systematic convolutional encoder with generator matrix $g = [23, 35]$ in octal notation. The block size of information bits for each user is 128, and the chip pulse waveform is raised cosine with roll-off factor of 0.5. For the sake of comparison, in each figure, we have included three sets of graphs, the proposed method (Pm-GBMUD), and the conventional turbo multiuser detector as proposed in [2], in the presence and absence of unknown interference. The sampling rate at the output of the matched filter is T_c/p where $p = 3$ for our method as well as the conventional turbo multiuser detector.

Fig.1 and 2 illustrate the average bit error rate performance of known users in the presence of 3 and 4 unknown users, respectively. As shown in these figures, the conventional Pm-TMUD tends to exhibit an error floor at high SNR. This is mostly because the detector fails to suppress the multiple access interference from unknown users, while the proposed method continues to provide the lower BER as the SNR increases.

5. CONCLUSION

We have proposed an iterative multiuser receiver for the uplink of block coded CDMA systems in multipath channels. The proposed scheme suppresses the effect of MAI from unknown users in systems with high intercell interference. The modified scheme performs the interference suppression and channel decoding in two different stages. More specifically, after soft interference cancellation on known users coded bits, the resulting soft information is sent to a combined group-blind multiuser detector. The proposed group-blind filter satisfies the MMSE criterion in a way that it suppresses the remained MAI from known users base on the spreading sequences and the channel characteristics of these users, while suppressing the MAI from other unknown users, using subspace based blind method. Simulation results show that the proposed method significantly outperforms systems that ignore the effect of interference from unknown users.

6. REFERENCES

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