Blind Estimation of FIR Channels in CDMA Systems with Aperiodic Spreading Sequences*

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Abstract

CDMA systems commonly use aperiodic spreading codes to distribute a signal spectrum uniformly over the channel bandwidth and differentiate neighboring cell sites. CDMA receivers often suffer from interference due to multipath fading. Blind signal estimation schemes cannot be used because they require periodic spreading sequences. RAKE receivers are often used, but they cannot fully exploit the rich structure of CDMA signals to minimize interference. This paper presents an iterative technique to estimate multipath parameters which can serve as a preprocessing step in a receiver to increase signal-to-interference ratio. We investigate the performance of the proposed method using computer simulations. Preliminary simulation results show an average of 10 dB gain on channel parameter estimation.

1 Introduction

The proliferation of wireless communication services have been stimulating unprecedented demands for scarce radio spectrum. Code-Division Multiple-Access (CDMA) systems have been proposed for high-capacity digital wireless networks. This has led to many algorithms which have been successfully developed on blind multiuser FIR channel estimation in CDMA systems [4, 8, 10, 11]. The blind estimation problem is to estimate FIR channel parameters without the use of training sequences. These methods, often called subspace-based algorithms, rely on the periodicity of spreading sequences to estimate the channel parameters. Furthermore, periodicity also simplifies the use of multi-user detection techniques [5, 3].

One of practical features of CDMA is the use of *aperiodic* spreading codes to distribute the signal spectrum over the bandwidth uniformly. Although the aperiodic spreading codes as used in the IS-95 standard [1] are beneficial to the soft capacity of CDMA systems, they prevent the use of existing signal reception and blind estimation schemes [8]. CDMA systems with aperiodic spreading sequences primarily employ RAKE receivers to estimate the channel parameters and alleviate multipath fading. RAKE receivers, however, cannot fully exploit the rich structure of CDMA signals.

In this paper, we will present an iterative technique to estimate multipath parameters in CDMA systems with aperiodic spreading sequences. Our estimation technique relies on the finite-alphabet structure of the information symbols and the known pseudo-noise (PN) spreading codes. Finite alphabet property structure of digital communication signals have been exploited in TDMA systems by several researchers [7, 12]. However, these methods are not directly applicable to CDMA systems because of the large number of users. Then the second property of CDMA signals, the knowledge of PN spreading codes, can be used to fill in the gap to estimate the channel parameters in conjunction with finite alphabet restoral techniques. These parameters can be used in a receiver to extract each symbol when the spreading code changes for each symbol. We investigate the performance of the proposed method via computer simulations.

2 Data Model

We describe an asynchronous uplink CDMA system with multiple receivers at the base station and model it as a multi-input multi-output (MIMO) system. First, we introduce the transmitted signal model which is a direct-

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* This work was sponsored in part by NSF CAREER Award under Grant MIP-9502695, Office of Naval Research under Grant N00014-95-1-0638, the Joint Services Electronics Program under Contract F49620-95-C-0045, Nortel, Inc., Southwestern Bell Technology Resources, Inc., and Texas Instruments. The United States Government is authorized to reproduce and distribute reprints for governmental purposes notwithstanding any copyright notation hereon. The second author was sponsored by the Defense Advanced Research Projects Agency (DARPA) and the US Army in the Composite CAD Program under DARPA Grant DAAB07-97-C-J007, and an NSF CAREER Award under grant MIP-9702707.

sequence CDMA signal given by

$$x(t) = c(t)\ s(t)\ e^{j2\pi f_c t} \tag{1}$$

where f_c is the carrier frequency of the transmitted signal, $s(t)$ is the binary message signal and $c(t)$ is a binary spreading sequence. An array of M antennas receives P signals through wireless channels. In the case of a multipath environment, the multipath channel between the ith user and the M-element antenna array at the base station can be characterized by a *composite vector* FIR channel [6]

$$\mathbf{h}_i(t) = \begin{bmatrix} h_{1,i}(t) \\ \vdots \\ h_{M,i}(t) \end{bmatrix} = \sum_{l=1}^{L_i} \mathbf{a}_i(\theta_l) p(t - \tau_i(l)) \tag{2}$$

where $p(t)$ is the pulse shaping function; $\tau_i(l)$ and $\mathbf{a}_i(\theta_l)$ are the delay and the array response vector of the lth multipath signal, respectively; and L_i is the total number of paths of ith user. Because we consider a multi-user system, a typical channel model described above is shown in Figure 1. In this model, the baseband signals from the antenna outputs of an asynchronous CDMA system with P users is written compactly as

$$\mathbf{y}(t) = \sum_{i=1}^{P} \sum_{n=-\infty}^{\infty} w_i(n)\ \mathbf{h}_i(t - nT) + \mathbf{v}(t) \tag{3}$$

where T is the chip period; $\mathbf{h}_i(t)$ is defined in (2); $\mathbf{v}(t)$ is the noise vector; and

$$w_i(k) = s_i(n) c_i(k - nL_c - k_i) \tag{4}$$

where $n = \lfloor \frac{k-k_i}{L_c} \rfloor$; k_i $(0 \leq k_i < L_c)$ is the chip delay index assumed to be known by the receiver in an asynchronous system.

3 Blind Estimation of FIR Channels in CDMA Systems

The blind estimation problem is to estimate FIR channel parameters without the use of training sequences. Note that many algorithms have been successfully developed on multiuser FIR channel estimation in CDMA systems with periodic spreading sequences [8, 4, 11, 10]. These methods often called subspace-based algorithms rely on the periodicity of spreading sequences in order to estimate the channel parameters. Furthermore, periodicity also simplify the use of multi-user detection techniques [5, 3]. However, these algorithms are only applicable to CDMA systems with periodic spreading sequences. Yet, many practical systems such as IS-95 use aperiodic spreading sequences to achieve uniform signal spectrum, identify cell cites uniquely, and obtain other desirable properties. A few algorithms have been developed on channel estimation to be used in such systems [2, 9, 6]. Here, we propose a method which provides promising signal estimates using the inherent structure information of CDMA signals.

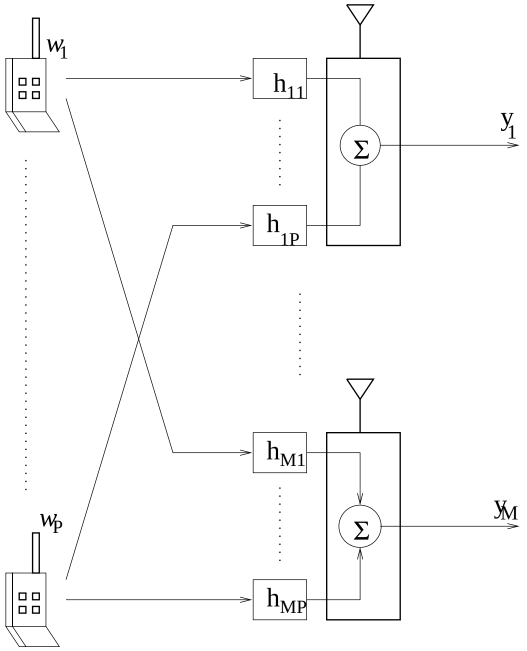


Figure 1. Channel Model in a P-User CDMA System with M-element Antenna Array

3.1 Channel Estimation Equations

In CDMA systems with aperiodic spreading sequences, RAKE receivers and 2-D RAKE receivers which is an extension to antenna array case are standard receivers which combine the spread signal constructively. Generally, channel parameters in RAKE receivers are determined using matched filters. Another method proposed in [6] estimate the channel parameters from the postdespreading data.

Our algorithm uses two different frameworks to capture the rich structure of CDMA signals. In the first framework, we construct the data matrix of the signal sampled at the chip rate

$$\mathbf{Y} = \mathbf{HW} = \begin{bmatrix} \mathbf{h}_1 & \mathbf{h}_2 & \cdots & \mathbf{h}_P \end{bmatrix} \begin{bmatrix} \mathbf{w}_1(N) \\ \mathbf{w}_2(N) \\ \vdots \\ \mathbf{w}_P(N) \end{bmatrix} \tag{5}$$

where $\mathbf{h}_i = [\mathbf{h}_i(L-1)\ \mathbf{h}_i(L-2)\ \cdots\ \mathbf{h}_i(0)]$; $\mathbf{w}_i$ is constructed as

$$\begin{bmatrix} w_i(1) & w_i(2) & \cdots & w_i(NL_c-L+1)\\ w_i(2) & w_i(3) & \cdots & w_i(NL_c-L+2)\\ \vdots & \vdots & \cdots & \vdots \\ w_i(L) & w_i(L+1) & \cdots & w_i(NL_c)\end{bmatrix}$$

where $w_i(n)$ is found using (4) with transmitted symbols and aperiodic spreading sequences. Note that we know most of $\mathbf{W}$ due to the known PN spreading sequence which is the output of a data scrambler. If we solve (5), we get

$$\mathbf{H} = \mathbf{Y}\mathbf{W}^{\dagger} \tag{6}$$

where the operator $(\cdot)^{\dagger}$ denotes the pseudo-inverse. In the second framework, we stack the spatial data samples so that the data matrix $\mathcal{Y} = \begin{bmatrix} \mathbf{y}^1 & \mathbf{y}^2 & \cdots & \mathbf{y}^M \end{bmatrix}^T$ (the superscript denotes the antenna index) can be represented as

$$\mathcal{Y} = \underbrace{\begin{bmatrix} \mathcal{G}_1 & \cdots & \mathcal{G}_P \end{bmatrix}}_{\mathcal{G}} \underbrace{\begin{bmatrix} \mathbf{s}_1^T \\ \vdots \\ \mathbf{s}_P^T \end{bmatrix}}_{\mathbf{S}} \tag{7}$$

where $\mathbf{s}_i = [s_i(1) \ \cdots \ s_i(N)]$. Then, we continue to describe

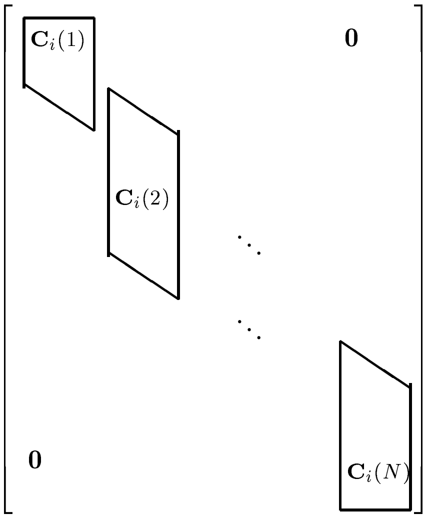
$$\mathcal{G}_i = \underbrace{\begin{bmatrix} \mathcal{C}_i & & \mathbf{0} \\ & \ddots & \\ \mathbf{0} & & \mathcal{C}_i \end{bmatrix}}_{M \text{ blocks}} \begin{bmatrix} \mathcal{H}_i^1 \\ \vdots \\ \mathcal{H}_i^M \end{bmatrix} \tag{8}$$

where

$$\mathcal{H}_i^m = \underbrace{\begin{bmatrix} \mathbf{h}_i^m & & \mathbf{0} \\ & \ddots & \\ \mathbf{0} & & \mathbf{h}_i^m \end{bmatrix}}_{N \text{ blocks}} \tag{9}$$

and $\mathbf{h}_i^m = \begin{bmatrix} h_i^m(L-1) & \cdots & h_i^m(0) \end{bmatrix}^T$. The kernel matrix $\mathcal{C}_i$ is defined as the shifted blocks of the PN spreading sequences

$\mathcal{C}_i =$



. (10)

Note that each block covers one symbol period and has Toeplitz structure due to the convolution effect of the FIR channel. Upper and lower blocks may be also partial because of the asynchronous operation of the uplink. Thus, a complete block of $\mathbf{C}_i(n) \ \ n = 0, \ldots, N-1$ can be written as

$$\underbrace{\left.\begin{bmatrix} 0 & \cdots & 0 \\ \cdots & \ddots & \cdots \\ c_i(nL_c+1) & \ddots & 0 \\ \vdots & \ddots & c_i(nL_c+1) \\ c_i(nL_c+L_c) & \ddots & \vdots \\ 0 & \ddots & c_i(nL_c+L_c) \\ \vdots & \cdots & 0 \\ 0 & \cdots & 0 \end{bmatrix}\right\} 2L_c}_{L \text{ columns}} \tag{11}$$

If we use the equation 7 to solve for $\mathbf{S}$, then we get

$$\mathbf{S} = \mathcal{G}^{\dagger}\mathcal{Y}. \tag{12}$$

These solutions for $\mathbf{H}$ in (6) and $\mathbf{S}$ in (12) allow us to use both frameworks to exploit the discrete-alphabet property of CDMA signals and knowledge of spreading codes. We adopt an Iterative Least Squares with Projection (ILSP) algorithm originally developed by [7] for TDMA systems. The basic concept is to update $\mathbf{S}$ iteratively, which updates $\mathbf{W}$ and $\mathbf{H}$, under the constraint that the information symbols $\mathbf{S}$ are from finite-alphabets. Given an initial estimate of transmitted symbols, we first use (6) to find the estimate of $\mathbf{H}$. Using this estimate of $\mathbf{H}$, we form an estimate of $\mathcal{G}$ to find $\mathbf{S}$. Then, we project $\mathbf{S}$ to the closest alphabet values. We perform these operations based on iterative least-squares and projection techniques, we continue them until $\mathbf{S}$ or $\mathbf{H}$ converge. Note that $LP \leq NL_c$ should be satisfied in order to compute $\mathbf{H}$.

3.2 Algorithm Outline

We assume finite alphabet symbols *i.e.*, binary-phase-shift-keying (BPSK). Algorithm can be outlined as follows:

1. Randomly choose $\mathbf{S}_0$ and set $l = 0$
2. $l := l + 1$
   (a) $\begin{bmatrix} \mathbf{h}_{1,l} & \cdots & \mathbf{h}_{P,l} \end{bmatrix} = \mathbf{Y}\mathbf{W}_l^{\dagger}$ where

$$\mathbf{W}_l = \begin{bmatrix} \mathbf{w}_{l,1}(NL_c) \\ \vdots \\ \mathbf{w}_{l,P}(NL_c) \end{bmatrix}$$

and $\mathbf{w}_{i,l}$ can be constructed as

$$\begin{bmatrix} w_{i,l}(1) & w_{i,l}(2) & \cdots & w_{i,l}(N-L+1) \\ w_{i,l}(2) & w_{i,l}(3) & \cdots & w_{i,l}(N-L+2) \\ \vdots & \vdots & \ldots & \vdots \\ w_{i,l}(L) & w_{i,l}(L+1) & \cdots & w_{i,l}(N) \end{bmatrix}$$

where $w_{i,l}(n)$ is found using (4) with estimated symbols and aperiodic spreading sequences.

(b) Construct $\mathcal{G}_l$ with the estimated channel parameters and PN sequences using (7), (8), and (10).

(c) $\mathbf{S}_{l+1}$ is estimated through

$$\mathbf{S}_{l+1} = \mathcal{G}_l^\dagger \mathcal{Y}.$$

(d) Project $[s_{l,i}(k)]$ to closest discrete values.

3. Continue until $\mathbf{S}_{l+1} - \mathbf{S}_l = \mathbf{0}$.

At each iteration, two least squares problems are solved. The advantages of this method are full exploitation of CDMA structure, simultaneous estimation of all channel parameters, and increase in system performance. The disadvantage is increased computational complexity over a RAKE receiver.

4 Computer Simulations

We conduct computer simulations to compare the performance of conventional RAKE receivers and the proposed method. In the simulations for each user, the multipath delay and the number of multipath components were uniformly distributed within $[0,\ 3T]$, and $[1,\ 10]$, respectively. We use the principal component (PC) algorithm proposed in [6] in the RAKE receiver to estimate channel parameters and information symbols. In the first scenario, we compare our method with RAKE receiver in a single receiver case. We simulate a single receiver CDMA system with $L_c = 16$, $P = 8$ and SNR $= 15$ dB. The spreading code for each user was randomly generated. In the simulation setup, we assumed that CDMA signals are synchronous. In our algorithm, we only used 6 symbol lengths of data, however, we let the RAKE receiver use 40 symbols. Upper plots in Figure 2 show processing results. Note that Figure 2 shows the symbols for all users because we limit our operation to short data sequences. Figure 3 compares the mean square errors of the proposed channel estimation and PC algorithm. we see that the proposed method offers better channel estimation. As an example of the application of our approach to a multi-receiver system, consider the simulation results presented in the lower part of Figure 2. Two receiver antennas are employed in a 13-user system. Comparing these plots, we can see that an increase in the number of users has a negligible effect on the performance of channel vector estimation and equalization. We list the average number of iterations in Table 1 in these two experiments. We see that the convergence is very fast.

The next simulation example is primarily presented to compare the proposed method with the RAKE receiver employing a single antenna and a two-element antenna array. As shown in Figure 4, the proposed method outperforms the RAKE receivers at least in this particular example. In this simulation, we managed 200 runs with $L_c = 13$.

5 Conclusions

We present a new approach for blind estimation of FIR channels in CDMA systems with aperiodic spreading sequences. After deriving two frameworks to exploit the structure information of CDMA signals efficiently, we develop an iterative technique based on iterative least-squares and projection. We perform computer simulations to demonstrate the effectiveness of the purposed scheme over existing methods. Our future directions include proving a necessary and sufficient condition for identifiability.

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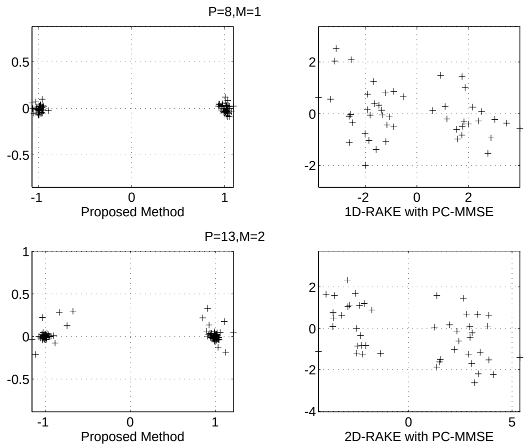

Figure 2. Signal constellations: 1-D RAKE, 2-D RAKE and our iterative method for the 1-D (M=1) and 2-D (M=2) cases. The RAKE receivers use the Principal Components (PC) Minimum Mean Square Error (MMSE) method.

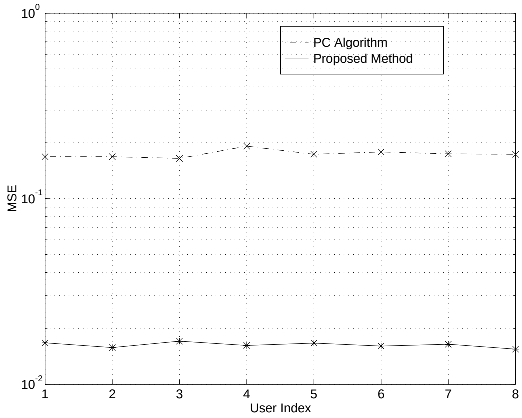

Figure 3. Comparison of the Principal Component (PC) method and our method for eight users at SNR=15 dB

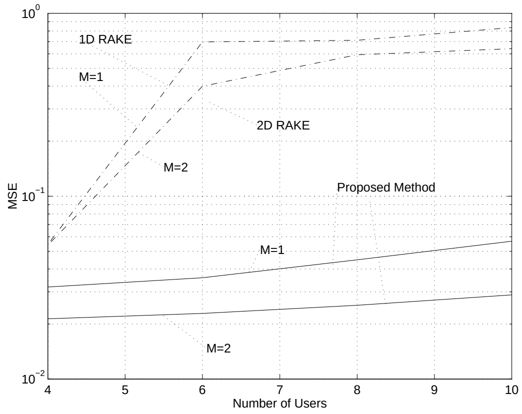

Figure 4. MSE vs. number of users using different receivers: 1-D RAKE, 2-D RAKE and our iterative method for the 1-D (M=1) and 2-D (M=2) cases.

# of Users	M=1	M=2
4	3.06	2.86
6	3.83	3.19
8	4.44	3.45
10	-	3.89
12	-	4.23
14	-	4.56
16	-	5.11

Table 1. Average number of iterations vs. number of antennas and users