Blind Multiuser Detection For Uplink CDMA Systems With Aperiodic Spreading Codes

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Abstract—This paper considers blind multiuser detection for uplink long code DS-CDMA systems. In this research, by taking the spread and scrambled chip-rate signals as the inputs, the long code CDMA system is characterized with a time invariant multiple-input multiple-output (MIMO) model. Under this framework, multistep linear predictor-based (MSLP) method is applied to transform the system model from convolutive mixture mode to instantaneous mixture mode. As a result, classic independent component analysis methods can be used to recover the signals. Because the chip level signals are taken as the inputs, the proposed method supports multi-rate transmission inherently. Simulation examples are provided to illustrate the proposed approach.

Index Terms—DS-CDMA, blind estimation, multistep linear prediction.

I. INTRODUCTION

CDMA has been identified as the multiple access technique for the next generation cellular communication systems. In DS-CDMA systems, signals of multiple users are transmitted over the same frequency band simultaneously. Therefore, in addition to the intersymbol interference (ISI) and interchip interference caused by multipath propagation, the system has to combat multi-user interference (MUI) or multiple-access interference (MAI). Compared with conventional single user detectors where MUI is modeled as Gaussian noise, significant improvement can be achieved with multiuser detector where MUI is an explicit part of the signal model.

In literature [1], if the spreading sequences are periodic and repeat every information symbol, the system is referred to as short-code CDMA, and if the spreading sequences are aperiodic or essentially pseudo-random, it is known as long-code CDMA. Since multiuser detection relies on the cyclostationarity of the received signal, which is significantly complicated by the time-varying modeling of the long-code system, research on multiuser detection has largely been limited to short code CDMA. On the other hand, long-code is widely used in virtually all operational and commercially proposed CDMA systems due to its performance stability in frequency fading environment and better information security.

Recently, multiuser detection methods targeted at long-code CDMA systems have been proposed [2], [3], [4], [5], [6], [7], [8], [9], [10]. Algorithms proposed in [2]-[7] are based on time-varying channel modeling with symbol rate input, following a symbol-by-symbol process or a frame-by-frame strategy. Algorithms proposed in [8]-[10] are based on time-invariant channel modeling by taking the chip rate signals as inputs. In [9], [10], transmission induced cyclostationary is exploited for multiuser detection, but the drawback is that the spreading codes need to be non-constant modulus, which causes inconvenience for practical design. To overcome this obstacle, instead of using only second-order statistics as in [9], [10], in this paper following [11], higher-order statistics are exploited so that multiuser separation no longer requires the spreading code to be non-constant modulus. In this paper, first, multistep linear predictors-based method is applied to transform the system model to instantaneous mixture mode. Secondly, as in [12], [11], joint approximate diagonalization of eigen-matrices (JADE) algorithm is used to estimate the channels. Finally, MMSE equalizer is designed to recover the input signals. In the third generation wireless systems, multi-rate transmission is required to support variable quality of service. Because the chip level MIMO model is applied in this paper, the proposed method supports...
multi-rate transmission inherently.

II. SYSTEM MODEL

Consider a multi-rate uplink DS-CDMA system with $M$ users. Assume each base station has $K$ receive antennas. The structure of the system is illustrated in Figure 1. Let $\{u_m(k)\}$ and $c_m \ (m = 1, \ldots, M)$ denote the symbol stream and spreading code of user $m$ respectively with

$$c_m := [c_m(0), c_m(1), \ldots, c_m(N_m - 1)], \quad (1)$$

where $N_m$ is the processing gain of user $m$, which could be distinct for different users. The spread signal of user $m$ is given by:

$$r_m(k) := [r_m(kN_m), \ldots, r_m(kN_m + N_m - 1)] = u_m(k)[c_m(0), \ldots, c_m(N_m - 1)]. \quad (2)$$

The scrambling process is achieved by

$$s_m(n) := r_m(n)d_m(n), \quad (3)$$

where $d_m(k)$ is a pseudo-random long code. Let $g_p(l)$ denote the channel impulse response between user $m$ and the $p$th receive antenna of the base station. Thus, the received signal at antenna $p$ can be represented as

$$y_p(n) = \sum_{j=1}^{M} \sum_{l=0}^{L-1} g_{j}^{(p)}(l)s_j(n - l) + w_p(n), \quad (4)$$

where $w_p(n)$ is the additive noise at $p$th antenna. Define

$$s(n) := [s_1(n), s_2(n), \ldots, s_M(n)]^T \quad (5)$$

and the received signal vector

$$y(n) = [y_1(n), y_2(n), \ldots, y_K(n)]^T, \quad (6)$$

then the time invariant MIMO model can be obtained as

$$y(n) = \sum_{l=0}^{L-1} H(l)s(n - l) + w(n)$$

$$= y_s(n) + w(n), \quad (7)$$

where

$$H(l) = \begin{bmatrix}
g_1^{(1)}(l) & g_2^{(1)}(l) & \cdots & g_M^{(1)}(l) \\
g_1^{(2)}(l) & g_2^{(2)}(l) & \cdots & g_M^{(2)}(l) \\ \vdots & \vdots & \ddots & \vdots \\
g_1^{(K)}(l) & g_2^{(K)}(l) & \cdots & g_M^{(K)}(l)
\end{bmatrix} \quad (8)$$

and $w(n) = [w_1(n), w_2(n), \ldots, w_K(n)]^T$.

Note that $N_m \ (m = 1, \ldots, M)$ could be distinct for different users. This model is suitable for both single-rate and multi-rate CDMA systems.

III. TRANSFORMATION TO INSTANTANEOUS MIXTURE MODEL

As can be seen, the model shown in the previous section is a convolutive mixture model. In this section, multistep linear predictors-based (MSLP) method is applied to transform it to an instantaneous mixture model, so that some classic independent component analysis methods can be applied. The implementation of MSLP is based on following assumptions:

(A1) The symbol sequences $\{u_m(k)\}_{m=1}^{M}$ are zero mean, mutually independent, i.i.d., and $|u_m(k)| = 1$;

(A2) The scrambling sequences $\{d_m(k)\}_{m=1}^{M}$ are mutually independent i.i.d. BPSK sequences, independent of the information sequences;

(A3) The noise sequences $\{w_{j}(k)\}_{j=1}^{K}$ are zero mean Gaussian, independent of the information sequences, with $E\{w(n+k)w(n)\} = \sigma^2_w I_K \delta(k)$;

(A4) $\text{Rank}\{H(z)\} = M$ for $z \neq 0$, including $z = \infty$.

From (A1-A2) and (2)(3), it can be obtained that

$$R_a(n, k) := E\{s(n)s^H(n - k)\} = I_M \delta(k). \quad (9)$$

Where $I_M$ is the $M \times M$ identity matrix. That is, $s_m$ is zero mean and white. Based on the multistep linear prediction principle, as proposed in [11], the noise-free channel output $y_s(n)$ can be represented as

$$y_s(n) = \sum_{i=l}^{L_l} A_i^{(l)} y_s(n - i) + e(n|n - l), \quad (l = 1, 2, \ldots). \quad (10)$$

And the linear prediction coefficient matrices $A_i^{(l)}$, $i = l, \ldots, L_l$, satisfy

$$[A_l^{(l)}, A_{l+1}^{(l)}, \ldots, A_{L_l}^{(l)}] R_{y_s}(L_l - l)$$

$$= [R_{y_s}(l), R_{y_s}(l + 1), \ldots, R_{y_s}(L_l)], \quad (11)$$
where $R_{yz}(k) = E\{y_s(n+k)y_s^H(n)\}$, and $\mathcal{R}_{yz}(L_l - l)$ is an $[(L_l - l + 1)K] \times [(L_l - l + 1)K]$ matrix, with its $(i,j)$th block be $R_{yz}(j-i)$. A solution to (11) is

$$[A^{(l)}_1, A^{(l)}_2, \ldots, A^{(l)}_{L_l}] = [R_{yz}(l), R_{yz}(l+1), \ldots, R_{yz}(L_l)]R_{yz}^\#(L_l - l)$$

where $R_{yz}^\#(L_l - l)$ denote the pseudoinverse of $R_{yz}(L_l - l)$. The prediction error $e(n|n-l)$ is given by

$$e(n|n-l) = \sum_{i=0}^{l-1} H(i)s(n-i).$$

Define $\bar{e}_i(n) := e(n|n-l) - e(n|n-l+1)$, and let

$$\mathbf{E}(n) := [\bar{e}_0^T(n+d), \bar{e}_0^T(n+d-1), \ldots, \bar{e}_0^T(n+1), e^T(n|n-1)]^T.$$  

Choose $d = L - 1$, then it follows from (13) that

$$\mathbf{E}(n) = [\mathbf{H}(d)^T, \mathbf{H}(d-1)^T, \ldots, \mathbf{H}(0)^T]^T \mathbf{s}(n)$$

$$:= \hat{\mathbf{H}} \mathbf{s}(n).$$

Clearly, this is an instantaneous mixture model.

IV. BLIND CHANNEL IDENTIFICATION AND EQUALIZATION

In this section, a simulation example is provided – joint approximate diagonalisation of eigen-matrices (JADE) [12] is applied to estimate the channels, and MMSE equalizer is designed based on the channel estimation.

A. Channel Estimation Using JADE

From (9) and (15), it follows that

$$\mathbf{R}_{EE}(0) = E\{\mathbf{E}(n)\mathbf{E}^H(n)\} = \hat{\mathbf{H}} \hat{\mathbf{H}}^H.$$  

Except for the one user case, $\hat{\mathbf{H}}$ cannot be uniquely determined from (16), since $\mathbf{H} \mathbf{H}^H = \mathbf{B} \mathbf{B}^H \mathbf{H} \mathbf{H}^H$ for any unitary $\mathbf{B}$. Thus, higher order statistics has to be exploited.

First, find a $M \times (KL)$ whitening matrix $\mathbf{W}$ which satisfies $\mathbf{I}_M = \mathbf{W} \mathbf{R}_{EE}(0) \mathbf{W}^H = \mathbf{W} \hat{\mathbf{H}} \hat{\mathbf{H}}^H \mathbf{W}^H$.

Let $\lambda_i$ $(i = 1, \ldots, M)$ denote the eigenvalues of $\mathbf{R}_{EE}(0)$, and $\mathbf{v}_i$ $(i = 1, \ldots, M)$ denote the corresponding orthonormal eigenvectors. We choose $\mathbf{W} = \Gamma^{-1} \mathbf{V}^H$, where $\Gamma = \text{diag}(\sqrt{\lambda_1}, \ldots, \sqrt{\lambda_M})$ and $\mathbf{V} = [\mathbf{v}_1, \ldots, \mathbf{v}_M]$. Then the whitening process is carried out as

$$\mathbf{z}(n) := \mathbf{W} \mathbf{E}(n) = \hat{\mathbf{H}} \mathbf{s}(n).$$

Let $\mathbf{U} := \mathbf{W} \hat{\mathbf{H}}$, and observe that $s_j(n)$ are non-Gaussian, then the JADE algorithm proposed in [12] can readily be applied to estimate $\mathbf{U}$. After $\mathbf{U}$ is estimated, the channel estimates $\hat{\mathbf{H}}$ can be obtained as $\hat{\mathbf{H}} = \mathbf{W}^\# \mathbf{U}$

B. MMSE Equalization

If we select the equalizer length $L_e = d$, the MMSE equalizer with delay $d$ is given by

$$\mathbf{F}_e := [F_e^H(0), F_e^H(1), \ldots, F_e^H(L_e-1)]^H = \mathbf{R}_{yz}^L \hat{\mathbf{H}}$$

where $\mathbf{R}_{yz}^L := E\{y^T(n), \ldots, y^T(n-L_e + 1)\}^T \mathbf{y}(n), \ldots, \mathbf{y}(n-L_e + 1)\}$. The equalization output is given by

$$\hat{s}(n-d) = \sum_{k=0}^{L_e-1} F_e^H(k) y(n-k).$$

V. SIMULATION EXAMPLE

In this section, a simulation example is provided to illustrate the proposed approach. Uplink CDMA systems with four receive antennas and two users were considered. Each user transmitted QPSK symbols with equal power. The spreading sequences and scrambling sequences were randomly generated. The processing gain of the basic rate user is $N = 16$. Each subchannel has four paths, which are uniformly distributed in one basic-rate symbol period. In this example, the additive noise is white Gaussian. SNR refers to chip level signal-to-noise ratio with respect to the desired user. The equalizers were designed based on 256 symbols, and were applied to 1024
symbols to calculate the normalized symbol mean square error SMSE. SMSE and MSE of channel estimation (CHMSE) were further averaged over 100 Monte Carlo runs. In this example, one user transmitted at basic symbol rate, and the other user transmitted at two times the basic rate. The estimation results of the high rate user are shown in Figure 2 and Figure 3.

REFERENCES