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BLIND MULTIUSER DETECTION BY KURTOSIS MAXIMIZATION FOR ASYNCHRONOUS MULTI-RATE DS/CDMA SYSTEMS

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ABSTRACT

In this paper, Chi and Chen's computationally efficient fast kurtosis maximization algorithm (FKMA) for blind source separation is applied to blind multiuser detection (BMD) for asynchronous multi-rate (variable processing gain or multi-code) DS/CDMA systems. The proposed blind multiuser detection algorithm, referred to as the BMD-FKMA, enjoys the fast convergence rate and computational efficiency of the FKMA. Furthermore, the BMD-FKMA in conjunction with the blind maximum ratio combining algorithm proposed by Chi *et al.* is considered for multi-rate DS/CDMA systems equipped with multiple receive antennas. Finally, some simulation results are provided to support the efficacy of the proposed BMD-FKMA and its performance as well as complexity improvements over some existing algorithms.

1. INTRODUCTION

Direct sequence/code division multiple access (DS/CDMA) has been widely used in multiuser communications (e.g. 2G, 3G and ultra wideband systems). With growing demands for multimedia services in wireless communication systems, there has been a need to provide a platform of multi-rate systems for the transmission of image, video, voice and data such as variable processing gain (VPG) and multi-code (MC) DS/CDMA systems which have been adopted for 3G wireless communication systems [1–3].

Multiple access interference (MAI) and intersymbol interference (ISI) are the two major problems encountered in the receiver design of both single-rate and multi-rate DS/CDMA systems [1–4]. In the presence of MAI and ISI, the nonblind linear minimum mean square error (MMSE) detector requires knowledge of the channel state information which can be estimated through the use of pilot signals or training sequences. However, pilot signal (or training sequence) transmission results in reduced spectral efficiency. Therefore, blind multiuser detection algorithms (BMDA) for multi-rate DS/CDMA systems are preferred, such as the blind minimum variance (MV) receiver proposed by Tsatsanis *et al.* [1], Ma and Tugnait's code-constrained inverse filter criteria (CC-IFC) algorithm [2], and the BMDA proposed by Chi *et al.* [3], called the BMDA-Chi in this paper.

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This paper applies the computationally efficient fast kurtosis maximization algorithm (FKMA) reported in [4], which is an iterative algorithm for blind source separation (or independent component analysis) and blind beamforming, to blind multiuser detection for multi-rate DS/CDMA systems equipped with multiple receive antennas.

2. SIGNAL MODEL

Consider an asynchronous VPG system [1–3] with a single receive antenna, a constant chip rate R (i.e., the same bandwidth for the all users) and G groups of users. All the K_i users of group i have the same data rate R_i where $R_i \neq R_j$ for all $i \neq j$. For notational clarity, let independent variables "n" and "k" denote symbol index and chip index, respectively, in all the discrete-time signals and channels throughout the paper. For ease of later use, some notations are defined as follows:

- P_i : $(= R/R_i)$ spreading factor of users in group i
- P : $(= \max_i\{P_i\})$ maximum spreading factor
- N_i : $(= P/P_i)$ number of "virtual users" (defined by (3) below) associated with each user in group i
- K : $(= \sum_{i=1}^{G} K_i)$ total number of users
- $\mathcal{K}$: $(= \sum_{i=1}^{G} K_i N_i)$ total number of virtual users
- $u_{ij}[n]$: symbol sequence of user j in group i
- $c_{ij}[k]$: spreading sequence associated with $u_{ij}[n]$
- $g_{ij}[k]$: multipath channel (FIR channel) of order $d_{ij} \leq \min_i\{P_i\}$ associated with $u_{ij}[n]$ [1,3,4].

The received discrete-time signal $y[k]$ in multi-rate form can be obtained through chip rate sampling of the received continuous-time signal as follows [3]:

$$y[k] = \sum_{i=1}^{G}\sum_{j=1}^{K_i}\sum_{n=-\infty}^{\infty} u_{ij}[n]h_{ij}[k-nP_i] + w[k] \quad (1)$$

where

$$h_{ij}[k] = \sum_{\tau=0}^{d_{ij}} c_{ij}[k-\tau]g_{ij}[\tau] \quad (2)$$

is the effective signature sequence associated with $u_{ij}[n]$.

The symbol sequence $u_{ij}[n]$ can be decomposed into N_i virtual users' subsequences as follows:

$$u_{ij}^{(l)}[n] = u_{ij}[nN_i + l - 1], \quad l = 1,\ 2,\ ...,\ N_i \quad (3)$$

and the associated spreading sequence $c_{ij}^{(l)}[k]$ of length P is given by

$$c_{ij}^{(l)}[k] = \begin{cases} c_{ij}[k-(l-1)P_i], & (l-1)P_i \le k \le lP_i - 1 \\ 0, & \text{otherwise.} \end{cases} \quad (4)$$

Then $y[k]$ (see (1)) in multi-rate form can also be converted into a single-rate form as follows:

$$y[k] = \sum_{i=1}^{G}\sum_{j=1}^{K_i}\sum_{l=1}^{N_i}\sum_{n=-\infty}^{\infty} u_{ij}^{(l)}[n] h_{ij}^{(l)}[k-nP] + w[k] \quad (5)$$

where

$$h_{ij}^{(l)}[k] = \sum_{\tau=0}^{d_{ij}} c_{ij}^{(l)}[k-\tau] g_{ij}[\tau] \quad (6)$$

is the effective signature sequence associated with $u_{ij}^{(l)}[n]$.

Define $\mathbf{0}_p$ as a $p \times 1$ zero vector and

$$q = \max_{ij}\{d_{ij}\} \le \min_i\{P_i\} \le P_i \quad (7)$$

$$\mathbf{g}_{ij} = (g_{ij}[0], g_{ij}[1], ..., g_{ij}[d_{ij}], \mathbf{0}^{\mathrm{T}}_{(q-d_{ij})})^{\mathrm{T}} \quad (8)$$

$$u_{ij,m}^{(l)}[n] = u_{ij}^{(l)}[n-m], \quad m = -1,\ 0,\ 1 \quad (9)$$

$$\mathbf{c}_{ij}^{(l)} = (c_{ij}^{(l)}[0], c_{ij}^{(l)}[1], ..., c_{ij}^{(l)}[P-1])^{\mathrm{T}} \quad (10)$$

$$\mathbf{h}_{ij,m}^{(l)} = \begin{cases} (\mathbf{0}_P^{\mathrm{T}}, h_{ij}^{(l)}[0], ..., h_{ij}^{(l)}[q-1])^{\mathrm{T}}, & m=-1 \\ (h_{ij}^{(l)}[0], ..., h_{ij}^{(l)}[P+q-1])^{\mathrm{T}}, & m=0 \\ (h_{ij}^{(l)}[P], ..., h_{ij}^{(l)}[P+q-1], \mathbf{0}_P^{\mathrm{T}})^{\mathrm{T}}, & m=1. \end{cases} \quad (11)$$

It can be easily shown, by (6) and (11), that

$$\mathbf{h}_{ij,m}^{(l)} = \mathbf{C}_{ij,m}^{(l)} \mathbf{g}_{ij}, \quad (12)$$

where $\mathbf{g}_{ij}$ is given by (8) and

$$\mathbf{C}_{ij,m}^{(l)} = \begin{cases} (\widetilde{\mathbf{c}}_{ij,0}^{(l)}, \widetilde{\mathbf{c}}_{ij,1}^{(l)}, ..., \widetilde{\mathbf{c}}_{ij,q}^{(l)}), & m=-1 \\ (\mathbf{c}_{ij,0}^{(l)}, \mathbf{c}_{ij,1}^{(l)}, ..., \mathbf{c}_{ij,q}^{(l)}), & m=0 \\ (\bar{\mathbf{c}}_{ij,0}^{(l)}, \bar{\mathbf{c}}_{ij,1}^{(l)}, ..., \bar{\mathbf{c}}_{ij,q}^{(l)}), & m=1 \end{cases} \quad (13)$$

in which

$$\widetilde{\mathbf{c}}_{ij,r}^{(l)} = (\mathbf{0}_P^{\mathrm{T}}, c_{ij,r}^{(l)}[0], ..., c_{ij,r}^{(l)}[q-1])^{\mathrm{T}} \quad (14)$$

$$\begin{aligned}\mathbf{c}_{ij,r}^{(l)} &= (c_{ij,r}^{(l)}[0], c_{ij,r}^{(l)}[1], ..., c_{ij,r}^{(l)}[P+q-1])^{\mathrm{T}} \\ &= (\mathbf{0}_r^{\mathrm{T}}, (\mathbf{c}_{ij}^{(l)})^{\mathrm{T}}, \mathbf{0}^{\mathrm{T}}_{(q-r)})^{\mathrm{T}} \end{aligned} \quad (15)$$

$$\bar{\mathbf{c}}_{ij,r}^{(l)} = (c_{ij,r}^{(l)}[P], ..., c_{ij,r}^{(l)}[P+q-1], \mathbf{0}_P^{\mathrm{T}})^{\mathrm{T}}. \quad (16)$$

A discrete-time instantaneous (or memoryless) multiple-input multiple-output (MIMO) signal model can be obtained through a polyphase decomposition as follows:

$$\begin{aligned}\mathbf{y}[n] &= (y[nP], y[nP+1], ..., y[nP+P+q-1])^{\mathrm{T}} \\ &= \sum_{i=1}^{G}\sum_{j=1}^{K_i}\sum_{l=1}^{N_i}\sum_{m=-1}^{1} \mathbf{h}_{ij,m}^{(l)} u_{ij,m}^{(l)}[n] + \mathbf{w}[n] \\ &= \mathbf{H}\mathbf{u}[n] + \mathbf{w}[n] \end{aligned} \quad (17)$$

where $\mathbf{w}[n]$ is a $(P+q)\times 1$ white Gaussian noise vector, $\mathbf{u}[n]$ is a $(3\mathcal{K})\times 1$ vector composed of $3\mathcal{K}$ sources $u_{ij,m}^{(l)}[n]$'s and $\mathbf{H}$ is a $(P+q)\times(3\mathcal{K})$ MIMO channel matrix composed of $3\mathcal{K}$ column vectors $\mathbf{h}_{ij,m}^{(l)}$'s. Three worthy remarks about the preceding instantaneous MIMO signal model are as follows:

($\mathcal{R}1$) One can observe, by (4) and (10) to (16), that $\mathbf{h}_{ij,-1}^{(l)} = \mathbf{0}_{P+q}$ for all $2 \le l \le N_i$ and $\mathbf{h}_{ij,1}^{(l)} = \mathbf{0}_{P+q}$ for $1 \le l \le N_i - 1$ for the VPG system. Therefore, by removing these zero column vectors, the channel matrix $\mathbf{H}$ reduces to a $(P+q)\times(\mathcal{K}+2K)$ matrix instead of a $(P+q)\times(3\mathcal{K})$ matrix, and then the associated signal vector $\mathbf{u}[n]$ consists of only $(\mathcal{K}+2K)$ $(\le 3\mathcal{K})$ components out of all the $3\mathcal{K}$ sources $u_{ij,m}^{(l)}[n]$'s.

($\mathcal{R}2$) The inputs (sources) $\mathbf{u}[n]$ of the instantaneous MIMO signal model (see (17)) consist of not only $u_{ij,0}^{(l)}[n] = u_{ij}^{(l)}[n]$ but also the associated ISI, i.e., $u_{ij,m}^{(l)}[n] = u_{ij}^{(l)}[n-m]$ for $m \neq 0$ (see (9)), and therefore not all the source signals in $\mathbf{u}[n]$ are mutually statistically independent random processes.

($\mathcal{R}3$) For an asynchronous MC system [2, 3], a high rate symbol sequence $u_{ij}[n]$ can be converted into N_i symbol subsequences $u_{ij}^{(l)}[n]$'s (i.e., N_i virtual users), as defined by (3), each assigned by a distinct spreading sequence $c_{ij}^{(l)}[k]$ (with the same processing gain $P = R/\min_i\{R_i\}$). All the N_i virtual users' spreading signals are superimposed prior to transmission. Following the same modeling procedure of the VPG system, one can also obtain an instantaneous MIMO signal model $\mathbf{y}[n]$ which has exactly the same form as given by (17) for the MC system except that $\mathbf{h}_{ij,m}^{(l)} \neq \mathbf{0}_{P+q}$ for all i, j, m, and l, and $d_{ij} \le P$ (rather than $d_{ij} \le \min_i\{P_i\}$ as in the VPG system).

3. PROPOSED BMDA

The *kurtosis* of a zero-mean random variable z is known to be

$$C_4\{z\} = E\{|z|^4\} - 2(E\{|z^2|\})^2 - |E\{z^2\}|^2.$$

The proposed BMDA, referred to as BMD-FKMA, comprises source extraction using FKMA followed by user identification under the following three assumptions:

($\mathcal{A}1$) The unknown $\mathbf{H}$ (which is a $(P+q)\times(\mathcal{K}+2K)$ channel matrix for the VPG system, or a $(P+q)\times(3\mathcal{K})$ channel matrix for the MC system) is of full column rank with $(P+q) \ge (\mathcal{K}+2K)$ for the VPG system or with $(P+q) \ge (3\mathcal{K})$ for the MC system.

($\mathcal{A}2$) $u_{ij}[n]$ for all i and j are independent identically distributed (i.i.d.) nonGaussian with zero mean and $C_4\{u_{ij}[n]\} \neq 0$.

($\mathcal{A}3$) $\mathbf{w}[n]$ is zero-mean Gaussian, and statistically independent of $\mathbf{u}[n]$.

As mentioned in ($\mathcal{R}2$), not all the source signals in $\mathbf{u}[n]$ are mutually independent sources. Nevertheless, Assumption ($\mathcal{A}2$) implies the following fact.

Fact 1: $\mathbf{u}[n]$ *for each fixed* n is a zero-mean nonGaussian random vector with all the random components of $\mathbf{u}[n]$ being mutually statistically independent.

3.1. Extraction of Source Signals

Assume that the desired user is user 1 in group 1, i.e., $u_{11}[n]$ (decomposed into $u_{11}^{(l)}[n]$, $l = 1, 2, ..., N_1$ (see (3))) is the symbol sequence of interest. Our goal is to design a $(P+q)\times 1$ linear combiner $\mathbf{v}$ such that its output

$$e[n]=\mathbf{v}^{\mathrm{T}}\mathbf{y}[n] \tag{18}$$

approximates one of the N_1 subsequences $u_{11,0}^{(l)}[n]=u_{11}^{(l)}[n]$, $l=1,\,2,\,...,\,N_1$ (see (9)). The FKMA [4] finds an optimum $\mathbf{v}$ by maximizing the following objective function [2–5]

$$J(\mathbf{v})=J(e[n])=\frac{|C_4\{e[n]\}|}{E^2\{|e[n]|^2\}}, \tag{19}$$

which is also the magnitude of normalized kurtosis of $e[n]$. It is also known [5] that under the assumption $(\mathcal{A}1)$, the noise-free assumption, and Fact 1, the optimum $e[n]$ by maximizing $J(e[n])$ (see (19)) is exactly one source signal in $\mathbf{u}[n]$ except for an unknown scale factor. Therefore, for finite SNR, the iterative FKMA can be applied to obtain one source estimate

$$e[n]\simeq\alpha_{ij,m}^{(l)}u_{ij,m}^{(l)}[n], \tag{20}$$

where the subscripts i, j, m and the superscript l are unknown, and $\alpha_{ij,m}^{(l)}$ is an unknown scale factor.

A well-designed initial condition for $\mathbf{v}$ is needed so that $e[n]\simeq\alpha_{11,0}^{(\ell)}u_{11,0}^{(\ell)}[n]=\alpha_{11}^{(\ell)}u_{11}^{(\ell)}[n]$ for some ℓ. Next, let us present how to find a good initial condition for $\mathbf{v}$. Let

$$\mathbf{v}_{\mathtt{t}}=\left(\mathbf{0}_{\mathtt{t}}^{\mathrm{T}},(\mathbf{c}_{11}^{(\ell)})^{\mathrm{T}},\mathbf{0}_{(q-\mathtt{t})}^{\mathrm{T}}\right)^{\mathrm{T}} \tag{21}$$

where $\mathbf{c}_{11}^{(\ell)}$ is given by (10) and

$$\tau=\arg\max_{\mathtt{t}}\{J(\mathbf{v}_{\mathtt{t}}),\ \mathtt{t}=0,\ 1,\ ...,\ q-1\}. \tag{22}$$

With the suggested initial condition $\mathbf{v}^{(0)}=\mathbf{v}_\tau$ and (17) substituted into (18), one can obtain

$$\begin{aligned}e[n]=&\mathbf{v}_\tau^{\mathrm{T}}\mathbf{y}[n]=\sum_{i=1}^{G}\sum_{j=1}^{K_i}\sum_{l=1}^{N_i}\sum_{m=-1}^{1}\eta_{ij,m}^{(l)}u_{ij,m}^{(l)}[n]+\mathrm{w}[n]\\=&\eta_{11,0}^{(\ell)}u_{11,0}^{(\ell)}[n]+\mathrm{ISI}+\mathrm{MAI}+\mathrm{w}[n]\end{aligned} \tag{23}$$

where $\mathrm{w}[n]=\mathbf{v}_\tau^{\mathrm{T}}\mathbf{w}[n]$, $\eta_{ij,m}^{(l)}=\mathbf{v}_\tau^{\mathrm{T}}\mathbf{h}_{ij,m}^{(l)}$ and

$$|\eta_{11,0}^{(\ell)}|\simeq\beta_1|g_{11}[\tau]|\gg|\eta_{ij,m}^{(l)}|\ \forall(i,j,m,l)\neq(1,1,0,\ell), \tag{24}$$

where $\beta_1=P_1$ and $\beta_1=P$ for the VPG system and MC system, respectively, and we have used (11) and (12) in the derivation of (24). From (18) and (24), one can infer that $g_{11}[\tau]$ is basically the strongest path in $g_{11}[k]$ and the ISI and MAI in $e[n]$ have been substantially suppressed, thus efficiently leading to the optimum $e[n]=\widehat{u}_{11,0}^{(\ell)}[n]=\widehat{u}_{11}^{(\ell)}[n]$. However, even with the use of the above initial condition $\mathbf{v}_\tau$, it cannot be guaranteed that $(i,j,m,l)=(1,1,0,\ell)$, and therefore (i,j,m,l) still needs to be identified.

Now let us present how to identify (i,j,m,l) from $e[n]$ given by (20) and the following channel estimate $\widehat{\mathbf{h}}_{ij,m}^{(l)}$ [4,5]:

$$\widehat{\mathbf{h}}_{ij,m}^{(l)}=\frac{E\{\mathbf{y}[n]e^*[n]\}}{E\{|e[n]|^2\}}\quad\text{(by (17) and (20))} \tag{25}$$

$$\simeq\frac{\mathbf{h}_{ij,m}^{(l)}}{\alpha_{ij,m}^{(l)}}=\frac{1}{\alpha_{ij,m}^{(l)}}\mathbf{C}_{ij,m}^{(l)}\mathbf{g}_{ij}.\quad\text{(by (12))} \tag{26}$$

Let $\mathbf{b}=(b_1,b_2,...,b_p)^{\mathrm{T}}$ be a $p\times 1$ vector and

$$\Lambda(\mathbf{b})=\Lambda(\beta\mathbf{b})=\frac{\sum_{i=1}^{p}|b_i|^4}{(\sum_{i=1}^{p}|b_i|^2)^2},\ \forall\beta\neq 0 \tag{27}$$

which is also an "entropy measure" of a finite sequence b_i and $0\le\Lambda(\mathbf{b})\le 1$ (with minimum entropy corresponding to $\Lambda(\mathbf{b})=1$) [4]. Let

$$\mathbf{a}_{\mathrm{ij,m}}^{(\mathrm{l})}=\left(\mathbf{C}_{\mathrm{ij,m}}^{(\mathrm{l})}\right)^{\mathrm{H}}\cdot\widehat{\mathbf{h}}_{ij,m}^{(l)},\quad\forall\mathrm{i,j,m,l}. \tag{28}$$

By the fact that $c_{ij}[k]$ is a pseudonoise sequence and by (11), (12), (13), (26) and (28), one can easily prove that as $\mathbf{h}_{ij,m}^{(l)}\neq\mathbf{0}_{P+q}$,

$$\mathbf{a}_{\mathrm{ij,m}}^{(\mathrm{l})}\simeq\begin{cases}\beta_i\mathbf{g}_{ij}/\alpha_{ij,0}^{(l)},\ (\mathrm{i,j,m,l})=(i,j,0,l)\\ \mathrm{diag}\{q,...,1,0\}\mathbf{g}_{ij}/\alpha_{ij,-1}^{(l)},\ (\mathrm{i,j,m,l})=(i,j,-1,l)\\ \mathrm{diag}\{0,1,...,q\}\mathbf{g}_{ij}/\alpha_{ij,1}^{(l)},\ (\mathrm{i,j,m,l})=(i,j,1,l)\end{cases} \tag{29}$$

where $\beta_i=P_i$ for the VPG system and $\beta_i=P$ for the MC system, and that as $\mathbf{h}_{ij,m}^{(l)}\neq\mathbf{0}_{P+q}$, $\mathbf{a}_{\mathrm{ij,m}}^{(\mathrm{l})}$ approximates to a finite random sequence for $(\mathrm{i,j,m,l})\neq(i,j,m,l)$, implying

$$\Lambda(\mathbf{a}_{ij,m}^{(l)})\simeq\Lambda(\mathbf{g}_{ij})\gg\Lambda(\mathbf{a}_{\mathrm{ij,m}}^{(\mathrm{l})}),\ \forall(\mathrm{i,j,m,l})\neq(i,j,m,l). \tag{30}$$

Then, the proposed user identification algorithm (UIA) for identifying the (i,j,m,l) associated with the $e[n]=\widehat{u}_{ij,m}^{(l)}[n]$ is as follows.

(U1) Compute $\Lambda(\mathbf{a}_{\mathrm{ij,m}}^{(\mathrm{l})})$ for all i, j, m, l using (25), (27), and (28).

(U2) Identify (i,j,m,l) by

$$\left(\widehat{i},\widehat{j},\widehat{m},\widehat{l}\right)=\arg\max_{(\mathrm{i,j,m,l})}\left\{\Lambda\left(\mathbf{a}_{\mathrm{ij,m}}^{(\mathrm{l})}\right)\right\}. \tag{31}$$

If $(\widehat{i},\ \widehat{j},\ \widehat{m},\ \widehat{l})=(1,1,0,\ell)$, then the desired source estimate $e[n]=\widehat{u}_{11,0}^{(\ell)}[n]=\widehat{u}_{11}^{(\ell)}[n]$ is obtained, otherwise, one has to update $\mathbf{y}[n]$ by $\mathbf{y}[n]-\widehat{\mathbf{h}}_{ij,m}^{(l)}e[n]$ (cancellation or deflation processing) and then repeat the preceding signal processing (source extraction followed by user identification) until an estimate $\widehat{u}_{11}^{(\ell)}[n]$ is obtained (except for a scale factor).

3.2. Recovery of the Desired User's Data Sequence

To obtain $\widehat{u}_{11}[n]$ from the estimates $\widehat{u}_{11}^{(l)}[n]$, $l=1,\,2,\,...,\,N_1$, requires only the estimation of relative scale factors defined as

$$\lambda_{11}^{(l)}=\alpha_{11}^{(1)}/\alpha_{11}^{(l)},\quad l=1,\ 2,\ ...,\ N_1. \tag{32}$$

Then, a chip-rate channel estimate $\widehat{g}_{11}^{(l)}[k]$ can be easily obtained via

$$\begin{aligned}\widehat{\mathbf{g}}_{11}^{(l)}&=(\widehat{g}_{11}^{(l)}[0],\widehat{g}_{11}^{(l)}[1],...,\widehat{g}_{11}^{(l)}[q])^{\mathrm{T}}=\left(\mathbf{C}_{11,0}^{(l)}\right)^{\mathrm{H}}\widehat{\mathbf{h}}_{11,0}^{(l)}\\&\simeq\beta_1\cdot\mathbf{g}_{11}/\alpha_{11}^{(l)}\quad\text{(by (13) and (26))}\end{aligned} \tag{33}$$

where the approximation $(\mathbf{C}_{11,0}^{(l)})^{\mathrm{H}}\mathbf{C}_{11,0}^{(l)}\simeq\beta_1\mathbf{I}$ (identity matrix) has been used in the derivation of (33) since $c_{ij}^{(l)}[k]$ is a pseudonoise sequence. Therefore, the parameter $\lambda_{11}^{(l)}$ can then be estimated by

$$\lambda_{11}^{(l)} = \frac{\widehat{g}_{11}^{(l)}[k_{11}^{(l)}]}{\widehat{g}_{11}^{(1)}[k_{11}^{(1)}]} \tag{34}$$

where

$$k_{11}^{(l)} = \arg\max_{k} \left\{ \left| \widehat{g}_{11}^{(l)}[k] \right| \right\}. \tag{35}$$

Finally, by (20), (34) and (3), we obtain the symbol sequence estimate of the desired user as follows:

$$\widehat{u}_{11}[n] = \lambda_{11}^{(l)} \cdot \widehat{u}_{11}^{(l)}[\widetilde{n}] \simeq \alpha_{11}^{(1)} u_{11}[n] \tag{36}$$

where $l = (n \text{ modulo } N_1) + 1$ and $\widetilde{n} = (n - l + 1)/N_1$, and $\alpha_{11}^{(1)}$ is the unknown scale factor in the estimate $\widehat{u}_{11}[n]$. Let us summarize the proposed BMD-FKMA as follows:

Proposed BMD-FKMA:

(S1) As presented in Section 3.1, obtain $\widehat{u}_{11}^{(l)}[n]$, $l = 1, 2, ..., N_1$ using the FKMA and the proposed UIA.

(S2) As presented in Section 3.2, obtain $\widehat{u}_{11}[n]$ from $\widehat{u}_{11}^{(l)}[n]$, $l = 1, 2, ..., N_1$ using (36).

Let us conclude this section about the proposed BMD-FKMA with the following three remarks.

($\mathcal{R}4$) The CC-IFC algorithm, BMDA-Chi, and the proposed BMD-FKMA are devised by maximizing $J(e[n])$ given by (19). However, the CC-IFC algorithm and BMDA-Chi obtain $e[n] = \boldsymbol{v}^{\mathrm{T}}[n] * \boldsymbol{y}[n]$ where $\boldsymbol{v}[n]$ is an FIR equalizer of length L and $\boldsymbol{y}[n] = (y[nP], ..., y[nP+P-1])^{\mathrm{T}}$ is a $(P \times \mathcal{K})$ convolutional MIMO model rather than an instantaneous MIMO model. Therefore, the total number of unknown parameters in $\boldsymbol{v}[n]$ for the CC-IFC algorithm and BMDA-Chi is $PL \gg (P+q)$ (that in $\mathbf{v}$ for the BMD-FKMA) as $L \geq 2$ (since $q \leq P_i \leq P$ for the VPG system and $q \leq P$ for the MC system). Thus, the computational complexities of the CC-IFC algorithm and BMDA-Chi are significantly higher than that of the BMD-FKMA.

($\mathcal{R}5$) The proposed BMD-FKMA, which also enjoys the merits of super-exponential convergence rate and guaranteed convergence of the FKMA, is also applicable to both VPG and MC systems as long as the discrete-time signal vector $\mathbf{y}[n]$ given (17) is obtained.

($\mathcal{R}6$) Suppose that the receiver is equipped with $\Bbbk > 1$ antennas and $e_k[n] \simeq \alpha_k u_{11}[n]$, $k = 1, ..., \Bbbk$ are the associated estimates of $u_{11}[n]$ obtained by the proposed BMD-FKMA. One can use the blind maximum ratio combining algorithm (also using FKMA) reported in [4] to obtain $\widehat{u}_{11}[n] = \sum_{k=1}^{\Bbbk} v_k e_k[n]$ with maximum antenna gain (i.e. maximum signal-to-interference-plus-noise ratio (SINR) as obtained by the nonblind MMSE combiner which requires α_k given in advance).

4. SIMULATION RESULTS

Consider a six-user asynchronous dual rate DS/CDMA system with $K_1 = K_2 = 3$ and $R_1 = 2R_2$. For the VPG system, the spreading sequences for group 1 are Gold codes with $P_1 = 31$ while those for group 2 with $P_2 = 62$ are formed by two Gold codes of length 31. For the MC system, all the $c_{ij}^{(l)}[k]$'s (with the spreading factor $P = 62$) are also formed by two Gold codes of length 31. The synthetic signal $\mathbf{y}[n]$ (see (17)) and $\boldsymbol{y}[n] = (y[nP], ..., y[nP+P-1])^{\mathrm{T}}$ were generated with $u_{ij}[n]$ being a binary sequence of ± 1 and a 3-path channel for each user. The parameter $q = \max_{ij}\{d_{ij}\} = 10$ was used in the simulation. Then $\mathbf{y}[n]$ was processed by the proposed BMD-FKMA and MV receiver [1], and $\boldsymbol{y}[n]$ was processed by CC-IFC algorithm [2] and BMDA-Chi [3] with the length $L = 3$ for the $P \times 1$ FIR equalizer $\mathbf{v}[n]$. Assume that the desired user's power is E_1 and all the other users have the same signal power E.

Figures 1(a) (for NFR $= E/E_1 = 0$ dB) and 1(b) (for NFR $= 10$ dB) show the simulation results (output SINR versus the desired user's SNR (input SNR) for low rate data length $N = 2500$) obtained by all the algorithms under test for the VPG system with one receive antenna employed. The corresponding results for the MC system are shown in Figs. 1(c) and 1(d). One can see, from Figs. 1(a) and 1(b), that the performance of the proposed BMD-FKMA (◯) and the CC-IFC algorithm (△) are close to that of the nonblind MMSE detector (solid line), slightly superior to that of the BMDA-Chi (◊) and much better than that of the MV receiver (□) for the VPG system. The same conclusion applies to Figs. 1(c) and 1(d) (the MC system) except that the BMDA-Chi performs much better than the MV receiver, but much worse than the other three algorithms for NFR $= 10$ dB. On the other hand, Figs. 2(a) and 2(b) show some results (output SINR versus low rate data length N for input SNR $= 10$ dB) for NFR $= 0$ dB and NFR $= 10$ dB, respectively. One can observe, from Figs. 2(a) and 2(b), that the performance of the proposed BMD-FKMA is slightly superior to that of the BMDA-Chi and the blind CC-IFC algorithm and much better than that of the blind MV receiver with larger performance difference for smaller N. The same conclusion applies to Figs. 2(c) and 2(d) (the MC system) except that the BMDA-Chi, again, performs much better than the MV receiver, but much worse than the other three algorithms for NFR $= 10$ dB.

Figure 3 shows the output SINR versus input SNR for NFR $= 0$ dB and NFR $= 10$ dB, associated with the BMDA-Chi (dashed line) and the proposed BMD-FKMA (solid line) using multiple receive antennas. One can see, from Fig. 3, that approximately a 3 dB and a 6 dB performance gain (antenna gain) are obtained by the BMD-FKMA with 2 antennas (△) and 4 antennas (□), respectively, for both the VPG system and the MC system. This observation also applies to BMDA-Chi except the case of NFR $= 10$ dB for the MC system (Fig. 3(d)). For this case, the proposed BMD-FKMA significantly outperforms the BMDA-Chi, although the former slightly outperforms the latter for the other cases (Figs. 3(a)-3(c)).

5. CONCLUSION

We have presented a BMDA, BMD-FKMA, using FKMA reported in [4] for asynchronous multi-rate (VPG or MC) DS/CDMA systems equipped with a single or multiple antennas, which also shares the fast convergence rate and computational efficiency of the FKMA (see ($\mathcal{R}5$)). Some simulation results demonstrate that the proposed BMD-FKMA performs nearly best over all the cases (finite data length, finite SNR, and different NFRs) among all the blind algorithms (BMD-FKMA, BMDA-Chi [3], MV receiver [1], and CC-IFC algorithm [2]) under test, and meanwhile its computational complexity is much lower than that of BMDA-Chi and CC-IFC algorithm because of much smaller number $P + q = 62 + 10 = 72 \ll PL = 62 \times 3 = 186$ of equalizer coefficients used (see ($\mathcal{R}4$)).

6. REFERENCES

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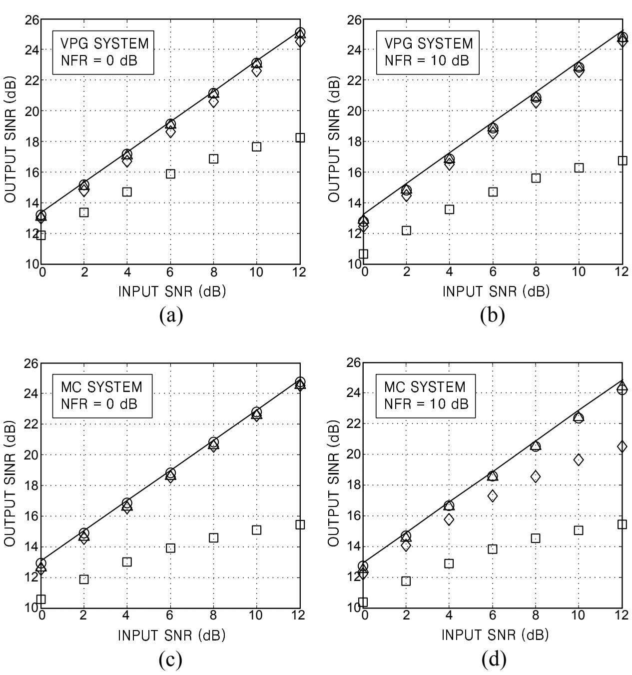

Figure 1. Simulation results (output SINR versus input SNR for low rate data length $N = 2500$) associated with the nonblind MMSE detector (solid line), the proposed BMD-FKMA (◯), the BMDA-Chi (◊), and the blind CC-IFC algorithm (△) and MV receiver (□) with one antenna used.

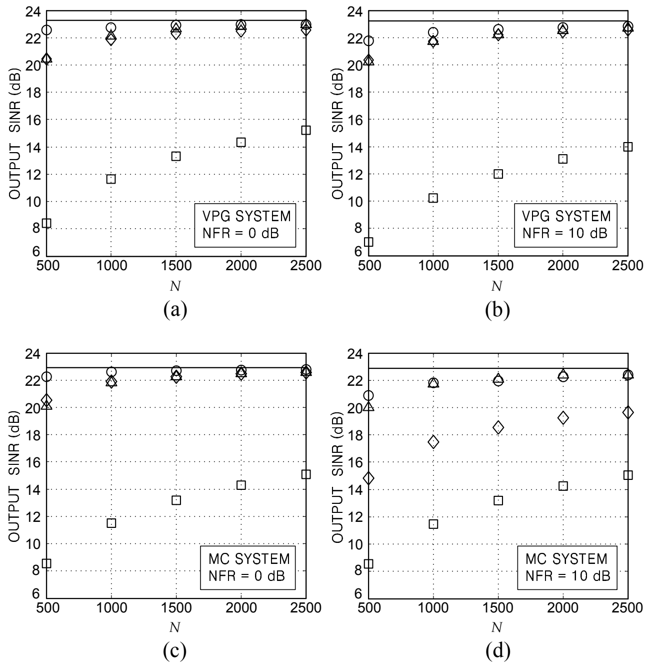

Figure 2. Simulation results (output SINR versus low rate data length N for input SNR = 10 dB) associated with the nonblind MMSE detector (solid line), the proposed BMD-FKMA (◯), the BMDA-Chi (◊), and the blind CC-IFC algorithm (△) and MV receiver (□) with one antenna used.

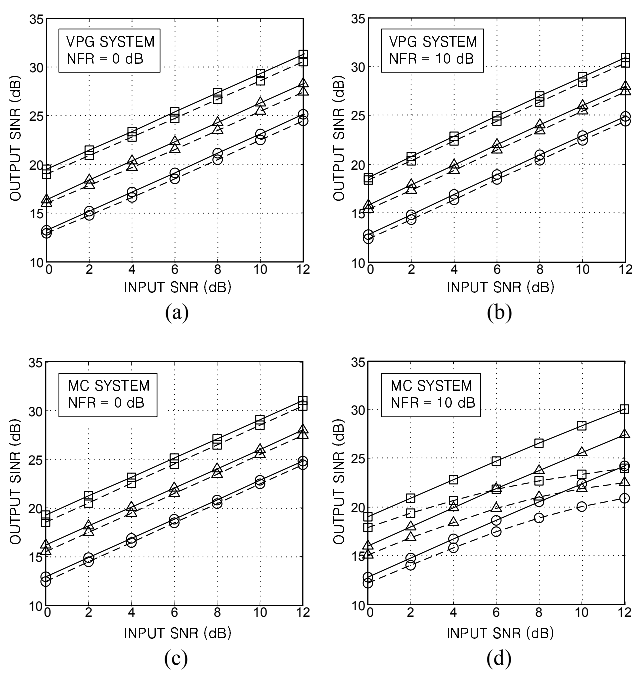

Figure 3. Simulation results (output SINR versus input SNR for low-rate data length $N = 2500$) associated with the proposed BMD-FKMA (solid line) and the BMDA-Chi (dashed line) with 1 (◯), 2 (△), and 4 (□) antennas used.