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Dual-antenna-based blind joint hostile jamming cancellation and multi-user detection for uplink of asynchronous direct-sequence code-division multiple access systems

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Abstract: The authors investigate the problem of blind multi-user detection (MUD) for uplink of asynchronous direct-sequence code-division multiple access (DS-CDMA) systems with hostile jamming. To cope with the lack of prior knowledge of spread signals, hostile jamming and channel state information, the authors propose a scheme based on blind source separation (BSS) to solve this problem. Dual receive antennas are used in the proposed scheme. By exploiting the structure of the two received signals, a BSS model with dependent sources is formed, and then blind hostile jamming cancellation and MUD are obtained by solving this BSS problem. The proposed scheme does not require to know any information about the hostile jamming, and can work well under multiple kinds of hostile jamming. Simulation results further demonstrate that if such proposed approach is used to cancel hostile jamming and make MUD, then the bit-error-rate performance can be substantially improved as compared with earlier detectors.

1 Introduction

Direct-sequence code-division multiple access (DS-CDMA) technology forms the back bone of the third generation wireless communication systems and will also play an important role in future global wireless communication system, since it allows multiple users to share limited time and bandwidth resources.

A DS-CDMA signal is formed by multiplying each date symbol by a spreading sequence. Owing to the orthogonal property of the spreading sequences, each user signal of DS-CDMA system can be distinguished from the mixture of spread signals of all active users.

In practice, multiple access interference (MAI), arising from the non-orthogonality of spreading sequences, is a significant limiting factor for DS-CDMA communication system. Multi-user detection (MUD) technologies are promising technologies for mitigation MAI. In traditional MUD schemes, such as the decorrelating detector [1] and the minimum mean square error (MMSE) detector [2], either the knowledge of a training sequence or spreading sequence of the desired user is required.

Recently, the blind MUD technologies, which do not require to know any knowledge of desired user and training sequence, have been paid more attention. According to the approaches they employ, these detectors can be roughly divided into three categories: independent component analysis (ICA)-based detectors [3–5], constant modulus (CM)-based detectors [6–8] and tensor decomposition-based detectors [9, 10].

Although these blind MUD schemes are effective to suppress MAI in different situations, but the performance of these detectors will be severely degraded if there is hostile jamming in channel. Harmonic jamming, partial-band jamming and linear swept-frequency jamming are effective to jam CDMA communication systems [11, 12]. The detectors discussed above do not take the hostile jamming into consideration but treat it as received noise, so their performance will be severely degraded in hostile jamming dominant scenario. This calls for a more reliable blind MUD scheme to suppress the detrimental effect of hostile jamming, especially in military communications.

1.1 Main contribution

In this paper, we thus deal with the problem of blind MUD, which does not require the receiver to know any information about the desired user, in uplink of asynchronous CDMA communication system with unknown hostile jamming. Although the CM technology and the tensor decomposition technology are effective to deal with blind MUD problem, they are not valid in jamming dominant scenario. Since the CM property and the tensor structure may be not hold, when hostile jamming exists in system. In the uplink, every user signal and the hostile jamming experience different channels, so it is a challenging task to achieve MUD without prior information of user signals, the hostile jamming and the channels.

The lack of prior knowledge motivates us to employ blind source separation (BSS) technology, which has been introduced in blind MUD research in [3–5], to study this problem. The reason of using BSS technology rather than other approaches is that it has the ability to recover the original sources from their mixtures without knowing original sources and mixing system.

The main contribution in this paper is that we propose a blind joint hostile cancellation and MUD scheme for uplink of CDMA system. Two receive antennas are required in the proposed scheme. Specifically we introduce a MUD model that takes the effect of hostile jamming into consideration explicitly. According to the proposed MUD model with hostile jamming, we form an overdetermined or determined BSS model by exploiting the special structure of the two jammed signals, and then the jamming cancellation and MUD problem is transformed into a BSS problem. This BSS problem is different from that formed in [3–5], because the sources are not independent with each other, and so it can not be solved by using ICA approach. The BSS algorithm based on non-Gaussianity measure, which is proposed in [13], is used to solve this problem, and then jamming cancellation and MUD are obtained simultaneously.

There is almost no restriction on hostile jamming in the proposed schemes, so it adapts to multiple kinds of jamming, such as harmonic jamming, partial-band noise jamming, linear swept-frequency jamming and so on.

1.2 Related works

Investigations on blind MUD of DS-CDMA systems in the presence of hostile jamming have been carried out in [14–18]. They can be divided into two categories. One category detectors are only valid for downlink of CDMA systems, such as the detectors proposed in [14, 15]. These two schemes are ICA-assisted jamming cancellers, and require an antenna-array in receiver. At first they employ ICA to separate the jamming and the multi-user signal, and then realise MUD by using traditional detectors. These two schemes are applicable to additive white Gaussian noise (AWGN) channel and multi-path channel, respectively. The other category detectors, such as proposed in [16–18], are not only valid for downlink but also valid for uplink of CDMA systems. In [16], Ho *et al.* proposed a blind MUD scheme to combat partial-band jamming by a linear predictor. The scheme is impractical because it assumes that all user signals transmit through AWGN channel synchronously. The detectors proposed in [17, 18] are ICA-based detectors, which can be applied in multi-path channel situation. These two detectors only require single receive antenna. They approximate the hostile jamming by a signal which keeps constant during one symbol duration. By also transforming the MUD problem into a BSS problem, then they use the ICA to mitigate MAI, inter-symbol interference and hostile jamming simultaneously.

The difference between our work and the schemes proposed in [14, 15] is that our work is not only valid in downlink situation but also in uplink situation. In addition, our scheme only requires two receive antennas, but the number of antennas, which the detector in [15] requires, is larger than the number of paths of the multi-path channel. Although the detectors proposed in [17, 18] are also valid for both downlink and uplink of DS-CDMA system, the assumption that the jamming keeps constant during one symbol duration restricts their implementation. Our work is differentiated in that we treat the jamming as multiple signals by transforming it into parallel instead of approximating it as a signal that keeps constant during one symbol duration; therefore our scheme will perform better than the schemes proposed in [17, 18].

1.3 Paper organisation

The paper is organised as follows. In Section 2, we present the system model of multi-user DS-CDMA system with hostile jamming. Section 3 contains the theoretical basis on which the proposed schemes rely. In Section 4, performance of the proposed scheme is evaluated by simulation, and Section 5 concludes the paper.

Throughout this paper, all the vectors and matrices are denoted in boldface. $(\cdot)^{\mathrm{T}}$ denotes the transpose operation. $E(\cdot)$ denotes the expectation operation and $p(\cdot)$ represents the probability. $\mathbf{0}^{1\times d}$ denotes the $1 \times d$ zeros vector.

2 System model of asynchronous CDMA system with hostile jamming

Consider a K-user asynchronous DS-CDMA system, employing normalised spreading waveforms $s_1(t), s_2(t), \ldots, s_K(t)$, then the spread signal transmitted by the kth user can be described as

$$x_k(t) = \sum_{m=0}^{M-1} d_k(m) s_k\left(t - mT_s\right) \tag{1}$$

where $d_k(m)$ denotes the mth symbol sent by the kth active user.

After transmitting through a multi-path fading channel with additive white Gaussian noise, whose impulse response is $g_k(t) = \sum_{l=1}^{L_k} a_{k,l}\delta\left(t - \tau_{k,l}\right)$, then the received base band signal because of the kth user can be modelled as

$$\begin{aligned} r_k(t) &= x_k(t) * g_k(t) \\ &= \sum_{m=0}^{m-1} d_k(m) \sum_{l=1}^{L_k} a_{kl} s_k\left(t - mT_{\mathrm{s}} - \tau_{kl}\right) \end{aligned} \tag{2}$$

where * denotes linear convolution operation, a_{kl} and τ_{kl} stand for the amplitude and delay of the kth user's lth path, respectively, L_k is the number of paths of the kth user, $\delta(t)$ is the unit impulse function, and T_{s} is the symbol interval. The spreading waveform $s_k(t)$ has the form

$$s_k(t) = \sum_{i=0}^{L_{\mathrm{c}}-1} c_k(i) h\left(t - iT_{\mathrm{c}}\right), \quad t \in \left[0, T_{\mathrm{s}}\right] \tag{3}$$

where L_{c} is the spreading factor, $\mathbf{c}_k = [c_k(0), c_k(2), \ldots, c_k(L_{\mathrm{c}} - 1)]$ is the spreading sequence of ±1's associated with the kth user, and $h(t)$ is the normalised chip waveform of duration $T_{\mathrm{c}} = T_{\mathrm{s}}/L_{\mathrm{c}}$.

Then the received multi-user signal in uplink can be expressed as follows

$$\begin{aligned} r(t) &= \sum_{k=1}^{K} r_k(t) \\ &= \sum_{k=1}^{K} \sum_{m=0}^{M-1} d_k(m) \sum_{l=1}^{L_k} a_{kl} s_k\left(t - mT_{\mathrm{s}} - \tau_{kl}\right) \end{aligned} \tag{4}$$

we make use of the following common assumptions:

- The transmitted symbols are zero-mean i.i.d. random variables with unit-variance. This assumption can be satisfied in practical system. Because the user signals are transmitted by different transmitters which are independent with each other. The assumption that the transmitted symbols are zero-mean random variables with unit-variance is not strict, because it can be satisfied by re-mean and whiten operation. The aim of this assumption is to overcome the scale ambiguous of BSS.

- The channels are quasi-static, which means they are time-invariant during the observation interval [19]. Hence the scheme which we will propose is suitable to the situation that channels change slowly.

Denote $\tau_{kl} = (d_{kl} + \varepsilon_{kl})T_c$, where d_{kl} is the maximum integer less than τ_{kl}/T_c, and $\varepsilon_{kl} \in [0, 1)$. If the maximum delay is less than one symbol duration, then $d_{kl} \le L_c - 1$, and so the samples of received signal in one symbol duration is related to two symbols of each user at most.

After chip-match filtering and sampling with chip rate, the sample vector of $\boldsymbol{r}(t)$ in the interval corresponding to the mth transmitted symbol can be written as [3]

$$\boldsymbol{r}(m) = \sum_{k=1}^{K} d_k(m-1) \sum_{l=1}^{L_k} a_{kl}\boldsymbol{s}_{kl}^{\text{down}} + \sum_{k=1}^{K} d_k(m) \sum_{l=1}^{L_k} a_{kl}\boldsymbol{s}_{kl}^{\text{up}} \tag{5}$$

where

$$\boldsymbol{r}(m) = \left[r(mT_s), r(mT_s + T_c), \ldots, r\left(mT_s + (L_c - 1)T_c\right)\right]^{\text{T}}$$

$$\boldsymbol{s}_{kl}^{\text{down}} = (1 - \varepsilon_{kl})\boldsymbol{c}^{\text{down}}(d_{kl}) + \varepsilon_{kl}\boldsymbol{c}^{\text{down}}(d_{kl} + 1)$$

$$\boldsymbol{s}_{kl}^{\text{up}} = (1 - \varepsilon_{kl})\boldsymbol{c}^{\text{up}}(d_{kl}) + \varepsilon_{kl}\boldsymbol{c}^{\text{up}}(d_{kl} + 1)$$

$$\boldsymbol{c}_{kl}^{\text{down}}(d_{kl}) = \left[c_k(L_c - d_{kl}), \ldots, c_k(L_c - 1), \boldsymbol{0}^{1\times(L_c - d_{kl})}\right]^{\text{T}}$$

and

$$\boldsymbol{c}_{kl}^{\text{up}}(d_{kl}) = \left[\boldsymbol{0}^{1\times d_{kl}}, c_k(0), \ldots, c_k(L_c - 1 - d_{kl})\right]^{\text{T}}$$

For simplification, define

$$\boldsymbol{g}_{2k-1} = \sum_{l=1}^{L_k} a_{kl}\boldsymbol{s}_{kl}^{\text{down}} \quad \boldsymbol{g}_{2k} = \sum_{l=1}^{L_k} a_{kl}\boldsymbol{s}_{kl}^{\text{up}}, \quad k = 1, \ldots, K \tag{6}$$

$$\boldsymbol{G} = [\boldsymbol{g}_1, \boldsymbol{g}_2, \ldots, \boldsymbol{g}_{2K}] \tag{7}$$

and

$$\boldsymbol{d}(m) = \left[d_1(m-1), d_1(m), \ldots, d_K(m-1), d_K(m)\right]^{\text{T}} \tag{8}$$

Thus, (5) can be rewritten as

$$\boldsymbol{r}(m) = \boldsymbol{G}\boldsymbol{d}(m) \tag{9}$$

Such a model could be extended to longer delay situation [20].

In addition, channel is assumed to contain a hostile jamming $j(t)$, which is independent with spread signals and also transmits through a multi-path channel. The impulse response of the multi-path channel is $g_j(t) = \sum_{l=1}^{L_J} b_l\delta\left(t - (l-1)T_c\right)$, where b_i stands for the received amplitude of the jamming's lth path. It is further assumed that L_J is no bigger than L_c, which means the duration of the impulse response of $g_j(t)$ is also shorter than one symbol interval.

Hence the total received signal at the receivers is the superposition of the multi-user signal $r(t)$, the hostile jamming and additive white Gaussian noise. After sampling with chip rate, the total received signal can be modelled as

$$z(kT_c) = r(kT_c) + \sum_{l=0}^{L_J - 1} b_l j(kT_c - lT_c) + n(kT_c) \tag{10}$$

where $z(kT_c)$ stands for the kth sample of the total received signal.

Now the sample vector of the received signal in the mth transmitted symbol duration can be written as

$$\boldsymbol{z}(m) = \boldsymbol{r}(m) + \boldsymbol{B}\boldsymbol{j}(m) + \boldsymbol{n}(m) \tag{11}$$

where

$$\boldsymbol{z}(m) = \left[z(mT_s), z(mT_s + T_c), \ldots, z\left(mT_s + (L_c - 1)T_c\right)\right]^{\text{T}}$$

$$\boldsymbol{j}(m) = \left[j\left(mT_s - (L_J - 1)T_c\right), \ldots, j(mT_s - T_c), j(mT_s), j(mT_s + T_c), \ldots, j\left(mT_s + (L_c - 1)T_c\right)\right]^{\text{T}}$$

$$\boldsymbol{B} = \begin{bmatrix} b_{L_J-1} & \cdots & b_0 & 0 & \cdots & 0 & 0 \\ 0 & b_{L_J-1} & \cdots & b_0 & \cdots & 0 & 0 \\ \vdots & \ddots & \ddots & \ddots & \ddots & \vdots & \vdots \\ 0 & \cdots & 0 & b_{L_J-1} & \cdots & b_0 & 0 \\ 0 & 0 & \cdots & 0 & b_{L_J-1} & \cdots & b_0 \end{bmatrix}_{L_c\times(L_c+L_J-1)}$$

and

$$\boldsymbol{n}(m) = \left[n(mT_s), n(mT_s + T_c), \ldots, n\left(mT_s + (L_c - 1)T_c\right)\right]^{\text{T}}$$

Substitute (9) into (11), then (11) can be rewritten as

$$\boldsymbol{z}(m) = \boldsymbol{A}\tilde{\boldsymbol{d}}(m) + \boldsymbol{n}(m) \tag{12}$$

where

$$\boldsymbol{A} = [\,\boldsymbol{G} \quad \boldsymbol{B}\,]_{L_c\times(2K+L_c+L_J-1)} \tag{13}$$

and

$$\tilde{\boldsymbol{d}}(m) = \begin{bmatrix} \boldsymbol{d}(m) \\ \boldsymbol{j}(m) \end{bmatrix}_{(2K+L_c+L_J-1)\times 1} \tag{14}$$

Note that (12) can be treated as an underdetermined BSS model with L_c observations and $2K + L_c + L_J - 1$ sources, and $\boldsymbol{A}$, $\tilde{\boldsymbol{d}}(m)$ and $z(m)$ stand for unknown mixing matrix, unknown source vector and observation vector, respectively.

3 Blind joint jamming cancellation and multi-user detection (BJCMUD)

In this section, we explore the approach to realise BJCMUD by exploiting dual receive antennas.

We assume that each spread signal and the hostile jamming are received by two antennas after transmitting through different multi-path channels. For simplicity, we further assume that the orders of the two multi-path channels, which the hostile jamming transmits through, are same. If the orders are not same, then L_J denotes the larger one. According to (9) and (11), after chip-matched filtering and chip-rate sampling, the two received signal vectors can be written as

$$\boldsymbol{z}_p(m) = \boldsymbol{G}_p\boldsymbol{d}(m) + \boldsymbol{B}_p\,\boldsymbol{j}(m) + \boldsymbol{n}_p(m), \qquad p = 1, 2 \tag{15}$$

To construct a determined or overdetermined BSS model, we construct a new received signal vector by concatenating $z_1(m)$ and $z_2(m)$ together

$$\tilde{z}(m) = \begin{bmatrix} z_1(m) \\ z_2(m) \end{bmatrix} \tag{16}$$

Substituting (15) into (16), we obtain

$$\begin{aligned}\tilde{z}(m) &= \begin{bmatrix} \boldsymbol{G}_1 & \boldsymbol{B}_1 \\ \boldsymbol{G}_2 & \boldsymbol{B}_2 \end{bmatrix}\begin{bmatrix} \boldsymbol{d}(m) \\ \boldsymbol{j}(m) \end{bmatrix} + \begin{bmatrix} \boldsymbol{n}_1(m) \\ \boldsymbol{n}_2(m) \end{bmatrix} \\ &= \tilde{\boldsymbol{A}}\tilde{\boldsymbol{d}}(m) + \tilde{\boldsymbol{n}}(m) \end{aligned} \tag{17}$$

where

$$\tilde{\boldsymbol{A}} = \begin{bmatrix} \boldsymbol{G}_1 & \boldsymbol{B}_1 \\ \boldsymbol{G}_2 & \boldsymbol{B}_2 \end{bmatrix}_{2L_c \times (2K + L_c + L_J - 1)} \tag{18}$$

and

$$\tilde{\boldsymbol{n}}(m) = \begin{bmatrix} \boldsymbol{n}_1(m) \\ \boldsymbol{n}_2(m) \end{bmatrix}_{2L_c \times 1} \tag{19}$$

Note that (17) can also be treated as a BSS model, and $\tilde{\boldsymbol{A}}$, $\tilde{\boldsymbol{d}}(m)$ and $\tilde{z}(m)$ stand for unknown mixing matrix, unknown source vector and observation vector, respectively. In this model the jamming is equivalently treated as $L_c + L_J - 1$ sources, so the number of total equivalent sources is $2K + L_c + L_J - 1$, and the number of observations is $2L_c$. If it satisfies that

$$K \le \left\lfloor \frac{L_c - L_J + 1}{2} \right\rfloor \tag{20}$$

then (17) is an overdetermined or determined linear instantaneous BSS model that is solvable. $\lfloor x \rfloor$ describes the nearest integers less than or equal to x.

By above analysis, the MUD of asynchronous DS-CDMA system with one hostile jamming can be achieve by solving the BSS problem described in (17), and the hostile jamming can be cancelled simultaneously. The system model of the proposed BJCMUD scheme can be described by Fig. 1.

Fig. 1 shows the system model of the proposed scheme that can be disassembled into four steps. First, the spread signals are generated according to (1) and the hostile jamming is generated by a jammer; Second, they are mixed while transmitting through their respective multi-path channels; Third, two mixed signals $z_1(t)$ and $z_2(t)$ are received by two receive antennas, whose samples can be described by (10); Finally, the blind joint hostile jamming cancellation and MUD is carried out. In the system model, we ignore the up-conversion and down-conversion operations to simplify the processing, because up or down conversion will not affect the processing results. Next, we will introduce the proposed blind joint hostile jamming cancellation and MUD algorithm in detail.

In the instantaneous mixing model shown in (17), the equivalent sources vector $\tilde{\boldsymbol{d}}(m)$ contains $\boldsymbol{d}(m)$ and $\boldsymbol{j}(m)$. Conventionally, to solve such problem always relies on the ICA method, which requires the sources to be independent. However, even though the assumption that $d_i(m)$, $d_j(m)$ and $j(t)$ are independent from each other is tenable, and $d_i(m)$ and $d_i(m-1)$ are mutually independent because of the characteristic of i.i.d, the independence among each entries

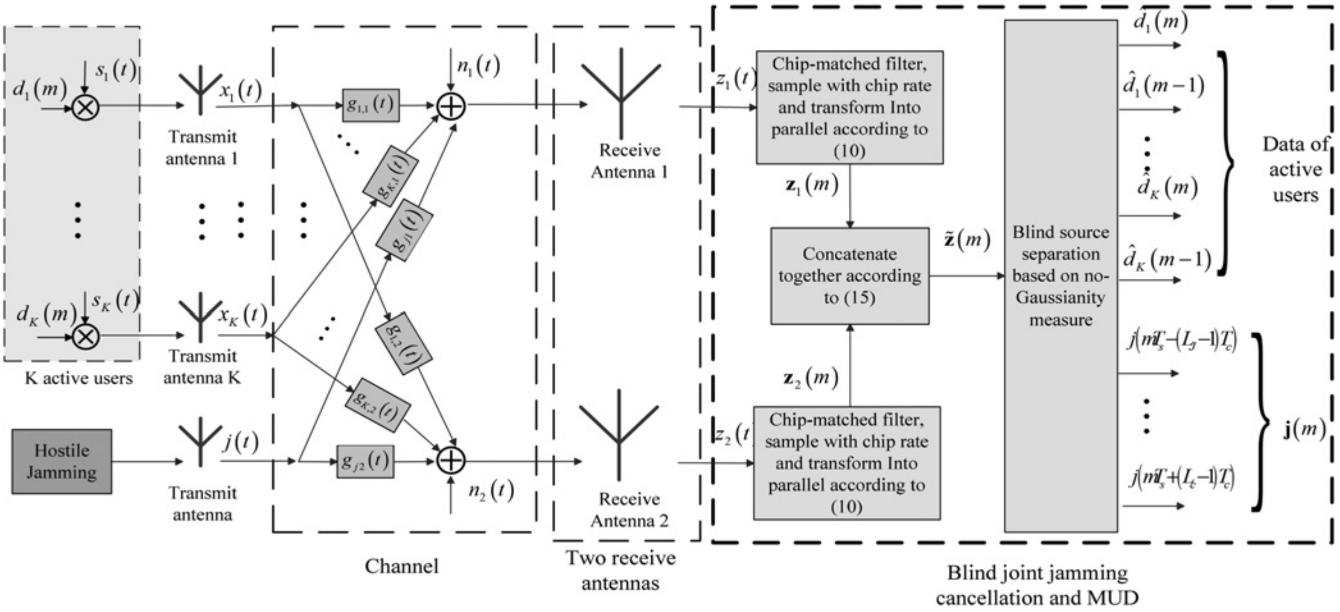

Fig. 1 *System model of BJCMUD scheme*

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of $\boldsymbol{j}(m)$ is not guaranteed, which means the ICA-based algorithm is invalid in this situation. Fortunately, other works [13, 21, 22] provide solutions to the BSS problem for the special case of statistically dependent sources. The joint block diagonalisation (JBD) [21] is the extension of joint approximate diagonalisation of eigen-matrices (JADE) which can separate the sources from different independent tuples even though there are dependent sources from the same one. However, it is invalid if the number of sources from each tuple is not uniform. Caiafa and Proto [13] proved that the non-Gaussianity measure is still effective for dependent sources instead of the minimisation of mutual information ones. Novey and Adali [22] extended this non-Gaussianity measure to the complex situation. Therefore the approach based on non-Gaussianity measure will be used to solve the BSS problem described in (17).

To solve the BSS problem based on non-Gaussianity measure, we need to search for the linear combinations of equivalent observations that give the source estimates with maximum non-Gaussianity. Consequently, a cost function is required to quantise the non-Gaussianity. In this paper, we choose the L2-Euclidean distance non-Gaussianity measure as the cost function [13], which is denoted by

$$\Gamma\left(p_y\right) = \int_{\Upsilon} \left[\Phi(y) - p_y(y)\right]^2 dy \tag{21}$$

where Υ is the range of variable y, $p_y(y)$ is the distribution, which is unknown in this situation, and $\Phi(y)$ is the Gaussian probability distribution function (pdf)

$$\Phi(y) = N(0, 1) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{1}{2}y^2\right) \tag{22}$$

To calculate the $L2$-Euclidean distance, we must obtain the estimation of $p_y(y)$. In this paper, the non-parametric technique, namely Parzen window, is applied to estimate $p_y(y)$, the Gaussian kernel of which is as follows [13]

$$\hat{p}(y) = \frac{1}{Mh} \sum_{m=0}^{M-1} \Phi\left(\frac{y - y(m)}{h}\right) \tag{23}$$

As a result, (21) can be rewritten as

$$\Gamma\left(p_y\right) = \int \Phi^2(y)\,\mathrm{d}y - 2\int \Phi(y) p_y(y)\,\mathrm{d}y + \int p_y^2(y)\,\mathrm{d}y \tag{24}$$

Replacing $p_y(y)$ with $\hat{p}(y)$, then (24) becomes

$$\Gamma\left(\hat{p}_y\right) = \frac{1}{2\sqrt{\pi}} + \Gamma_1\left(\hat{p}_y\right) + \Gamma_2\left(\hat{p}_y\right) \tag{25}$$

where

$$\begin{aligned}\Gamma_1\left(\hat{p}_y\right) &= -2\int \Phi(y)\hat{p}_y(y)\,\mathrm{d}y \\ &= -\frac{2}{M\sqrt{h^2+1}} \sum_{m=0}^{M-1} \Phi\left(\frac{y(m)}{\sqrt{h^2+1}}\right)\end{aligned} \tag{26}$$

and

$$\begin{aligned}\Gamma_2\left(\hat{p}_y\right) &= \int \hat{p}_y^2(y)\,\mathrm{d}y \\ &= \frac{2}{M^2\sqrt{h^2+1}} \sum_{m=0}^{M-1}\sum_{n=0}^{M-1} \Phi\left(\frac{y(n) - y(m)}{\sqrt{2}h}\right)\end{aligned} \tag{27}$$

Set h to be $10.6 \times M^{-1/5}$ to guarantee the minimum mean integrated square error in the pdf estimation [13].

Since the maximum NG method requires the sources have unit-variance and the BSS model described in (17) may be overdetermined, we need to spatially whiten the observations. By this way, the scaling ambiguity disappears, but the sign changing is unavoidable. Fortunately, such problem can be solved by other techniques such as different coding. In this paper, we implement Karhunen–Loeve transformation spatial filter on the observation vector $\tilde{\boldsymbol{z}}(m)$ to obtain a new set of spatially uncorrelated observations

$$\hat{\boldsymbol{z}}(m) = \boldsymbol{V}\Lambda^{-1/2}\boldsymbol{V}^T\tilde{\boldsymbol{z}}(m) \tag{28}$$

where $\boldsymbol{\Lambda}$ is a diagonal matrix containing the largest $2K + L_c + L_J - 1$ eigenvalues of $\boldsymbol{R}_{\tilde{z}\tilde{z}} = E[\tilde{z}\tilde{z}^T]$, and $\boldsymbol{V}$ is formed by the corresponding eigenvectors. Now, if we define $\boldsymbol{W}$ to be the desired unmixing matrix after obtaining the spatially whitened observation vector $\hat{\boldsymbol{z}}(m)$, each row of it must be unit-norm. The problem is reduced to searching $2K + L_c + L_J - 1$ different local maxima of the NG measure $\Gamma(p_y)$, where y is a linear combination of the whiten observations

$$y(m) = w_1\hat{z}_1(m) + w_2\hat{z}_2(m) + \cdots + w_N\hat{z}_N(m) \tag{29}$$

and $N = 2K + L_c + L_J - 1$ denotes the number of whitened observations.

Since $\sum_{i=1}^{N} w_i^2 = 1$, the whole space of vector solutions for the rows of matrix $\boldsymbol{W}$ can be generated by $N - 1$ hyper-spherical angles, which is denoted as follows

$$\boldsymbol{w}^{\mathrm{T}} = \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_N \end{bmatrix} = \begin{bmatrix} \cos\theta_1 \\ \sin\theta_1\cos\theta_2 \\ \vdots \\ \prod_{n=1}^{N-2}\sin\theta_n\cos\theta_{N-2} \\ \prod_{n=1}^{N-1}\sin\theta_n \end{bmatrix} \tag{30}$$

Let us define

$$\boldsymbol{\theta} = \left[\theta_1, \theta_2, \ldots, \theta_{N-1}\right]^{\mathrm{T}} \tag{31}$$

To search the local maxima, a gradient ascend algorithm is enough to guarantee the convergence. Therefore we need to calculate the marginal derivatives of $\Gamma(p_y)$ with respect to the angles vector $\boldsymbol{\theta}$, which can be denoted as follows

$$\begin{aligned}\frac{\partial\Gamma(p_y)}{\partial\boldsymbol{\theta}} &= \left[\frac{\partial\Gamma(p_y)}{\partial\theta_1}, \frac{\partial\Gamma(p_y)}{\partial\theta_2}, \ldots, \frac{\partial\Gamma(p_y)}{\partial\theta_{N-1}}\right]^{\mathrm{T}} \\ &= \frac{\partial\Gamma(p_y)}{\partial\boldsymbol{w}}\frac{\partial\boldsymbol{w}}{\partial\boldsymbol{\theta}}\end{aligned} \tag{32}$$

where

$$\frac{\partial \boldsymbol{w}}{\partial \boldsymbol{\theta}} = \begin{bmatrix} \frac{\partial w_1}{\partial \theta_1} & \cdots & \frac{\partial w_1}{\partial \theta_{N-1}} \\ \vdots & \ddots & \vdots \\ \frac{\partial w_N}{\partial \theta_1} & \cdots & \frac{\partial w_N}{\partial \theta_{N-1}} \end{bmatrix}_{N\times(N-1)} \tag{33}$$

Since

$$\begin{aligned} \frac{\partial \Gamma(p_y)}{\partial \boldsymbol{w}} &= \frac{\partial \Gamma_1(p_y)}{\partial \boldsymbol{w}} + \frac{\partial \Gamma_2(p_y)}{\partial \boldsymbol{w}} \\ &= \frac{2}{M\sqrt{h^2+1}} \sum_{m=0}^{M-1} y(m)\Phi\left(\frac{y(m)}{\sqrt{h^2+1}}\right)\hat{\boldsymbol{z}}(m) \\ &\quad + \frac{\sqrt{2}}{M^2 h} \sum_{m=0}^{M-1} \frac{\hat{\boldsymbol{z}}(m)}{\sqrt{2h}} \sum_{n=0}^{M-1} \left(\frac{y(n)-y(m)}{\sqrt{2h}}\right)\Phi\left(\frac{y(n)-y(m)}{\sqrt{2h}}\right) \end{aligned} \tag{34}$$

then the update of $\boldsymbol{\theta}$ can be denoted by

$$\boldsymbol{\theta}^{(n+1)} = \boldsymbol{\theta}^{(n)} - \frac{\partial \Gamma(p_y)}{\partial \boldsymbol{w}} \frac{\partial \boldsymbol{w}}{\partial \boldsymbol{\theta}} \tag{35}$$

After achieving $\hat{\boldsymbol{\theta}}$, an unmixing vector $\hat{\boldsymbol{w}}$ can be obtained by substituting $\hat{\boldsymbol{\theta}}$ into (30), and one equivalent source can be estimated by

$$\hat{y}(m) = \hat{\boldsymbol{w}}\hat{\boldsymbol{z}}(m) \tag{36}$$

Before searching the new one, we should remove the non-Gaussian structure related to this source. In this paper, we choose the technique which is introduced by Friedman [23].

Now, let us roughly analyse the complexity of the algorithm. Obviously, it is computational complexity increases linearly with the number of equivalent sources. Moreover,it is shown in (34) that a total number of $M + M^2$ calculations of Gaussian function are needed to estimate one equivalent source in every iteration. The quadratic term M^2 may be a problem for the case of a large sample data size. A technique, introduced by Silverman in [24], can be implemented to reduce the computational complexity by taking advantage of the fast Fourier transform properties.

After estimating all the equivalent sources, we should pick out the symbols send by each active user from all estimated sources. Considering the assumption about the symbol $d_k(m)$ and the special structure of the equivalent sources vector $\tilde{\boldsymbol{d}}(m)$, the covariance matrix of $\tilde{\boldsymbol{d}}(m)$ has the following form

$$\begin{aligned} \boldsymbol{R}_{\tilde{d}\tilde{d}} &= E\left(\tilde{\boldsymbol{d}}(m)\tilde{\boldsymbol{d}}^{\mathrm{T}}(m)\right) \\ &= \begin{bmatrix} \boldsymbol{I}^{2K\times 2K} & \boldsymbol{0}^{2K\times(L_J+L_c-1)} \\ \boldsymbol{0}^{(L_J+L_c-1)\times 2K} & \boldsymbol{R}_{jj} \end{bmatrix} \end{aligned} \tag{37}$$

where $\boldsymbol{R}_{jj} = E(\boldsymbol{j}(m)\boldsymbol{j}^{\mathrm{T}}(m))$. $\boldsymbol{R}_{jj}$ is not a diagonal matrix, if $j(t)$ is not white. According to this, we can extract all data signals by distinguish $2K$ rows or columns, in which there is only one dominant entry, from the covariance matrix of the estimated sources vector $\hat{\boldsymbol{y}}(m)$. Then we can divide the $2K$ data signals into K couples, by exploit the dependent between $d_k(m)$ and $d_k(m-1)$.

By above derivation, we realise the BJCMUD in BSS way by using two receive antennas. If the number of active users K is larger than $\lfloor (L_c - L_J + 1)/2 \rfloor$, more receive antennas is needed to construct an over-determined or determined BSS model, and the number of antennas required is

$$P \geq \left\lfloor \frac{2K + L_J - 1}{L_c} \right\rfloor + 1 \tag{38}$$

where P is the number of antennas.

It is easy to extend the method to the situation that multiple hostile jammings coexist in system. Assuming that there are Q hostile jammings and K active users coexist in system, and the largest orders of the multi-path channels, which the qth hostile jamming transmits through is $L_{J,q}$, then the number of receive antennas required to construct an overdetermined or determined linear instantaneous BSS model is show as follows

$$P \geq \left\lfloor \frac{\sum_{q=1}^{Q}\left(L_{J,q} - 1\right) + 2K}{L_c} \right\rfloor + Q \tag{39}$$

After chip-match filtering, chip rate sampling and S/P transformation, the BSS model can be formed by concatenating the P receive vectors together, and blind jamming cancellation and MUD can be realised in the same way.

Although the proposed algorithm is aiming at uplink of DS-CDMA system, it is also valid for downlink. In downlink, the base station transmits all user signals together. After transmitting through a multi-path channel, the received multi-user signal can be expressed as follows [15]

$$r(t) = \sum_{k=1}^{K}\sum_{m=0}^{M-1} d_k(m) \sum_{l=1}^{L} a_l s_k\left(t - mT_s - \tau_l\right) + n(t) \tag{40}$$

where α_l and τ_l stand for the received amplitude and delay of the lth path, respectively.

The difference between (40) and (4) is that all user signals experience the same channel. Therefore if we set all a_{kl} and τ_{kl} equally in (3), then the receive model of uplink becomes that of downlink. Moreover the proposed algorithm does not depend on the channels, so it is also effective for downlink.

4 Simulation and discussion

In this section, Monte Carlo simulations have been carried out to verify the performance of the proposed jamming cancellation and MUD scheme for CDMA uplink with a hostile jamming.

All simulations are carried out according to the architecture shown in Fig. 1. In the first step, the user signals are simulated as BPSK signals with bit rate $R_b = 1000$ bit/s, which are spread with m-sequences of length $L_c = 31$. Three different models have been used to generate the hostile jamming:

- Model $J1$: The hostile jamming $j(t)$ is modelled as the following single harmonic [19]

$$j(t) = A\cos\left(2\pi f_\Delta t + \phi(t)\right) \tag{41}$$

where A is the amplitude, $f_\Delta = 50$ Hz describes the jamming frequency offset from the carrier frequency, and $\phi(t)$ is the phase error, which is uniformly distributed on $[0, 2\pi]$.

- Model $J2$: The hostile jamming $j(t)$ is a partial-band jamming, which is modelled by band-limit Gaussian noise [25]. To describe the ratio of the hostile jamming bandwidth W_J to the signal bandwidth W, we define

$$\eta = W_J / W \tag{42}$$

- Model $J3$: The hostile jamming $j(t)$ is modelled as linear swept-frequency jamming [26], whose jamming frequency swipes from 0 to 31 000 Hz periodically

$$j(t) = A\cos\left(2\pi f_0 t + \frac{\pi W_s}{T_{\mathrm{SF}}} t^2\right) \tag{43}$$

where A is the amplitude, $f_0 = 0$ is the initial frequency, $W_s = 31\,000$ Hz is the swept-frequency bandwidth, and T_{SF} is the scan period of the linear swept-frequency signal.

In the second step, the channels which the user signals and hostile jamming transmit through are generated. Specifically, the number of paths that each user signal transmits to each receive antenna is $L_k = 6$, and the corresponding delay is uniformly distributed on $[0, (L_c - 1)T_c]$. The channels that hostile jamming transmits to each antenna are formed by two FIR filters whose orders are $L_J = 6$ and entries are randomly drawn from a zero-mean Gaussian process. All channels are fixed and normalised in all simulations. Two observation signals are obtained in the third step, and the proposed algorithm is used to realise blind joint hostile jamming cancellation and MUD in the fourth step.

In all simulations, we assume that all the users have identical power. The signal-to-noise ratio (SNR) is defined as the ratio of the power of single user to the power of received noise, and the signal-to-jamming ratio (SJR) is defined as the ratio of the power of single user to the power of hostile jamming, namely

$$\mathrm{SNR} = \frac{E\left(x_k(t)^2\right)}{E\left(n(t)^2\right)}$$

and

$$\mathrm{SJR} = \frac{E\left(x_k(t)^2\right)}{E\left(j(t)s^2\right)}$$

Fig. 2 shows the bit-error-rate (BER) against JSR performance of BJCMUD algorithm under three kinds of hostile jamming. The numbers of active users are five, and SNR is −8 dB. For the sake of comparison, the result of using the conventional MMSE detector [2], which requires the prior knowledge of spreading sequences, and the ICA-SIC (successive interference cancellation) detector [18], which is a blind jamming cancellation and MUD scheme with single receive antenna, are also plotted. The partial-band jamming and the linear swept-frequency jamming are generated according to Model J2 and Model J3 with $\eta = 0.25$ and $T_{\mathrm{SF}} = 0.01s$, respectively. It can be observed that the BER performance of BJCMUD algorithm is superior to that of MMSE detector and ICA-SIC detector, because the BJCMUD algorithm treats the hostile jamming as $L_c + L_J - 1$ sources which need to be estimated whereas the MMSE detector treats the hostile jamming as receive noise. Although the ICA-SIC detector treats the hostile jamming as a source which need to be estimated, it requires the jamming keeps constant during one symbol interval, and the three kinds of jamming are not satisfied. It can also be observed that the performance of the proposed algorithm is different under three kinds of hostile jamming, and the performance under single harmonic jamming and linear

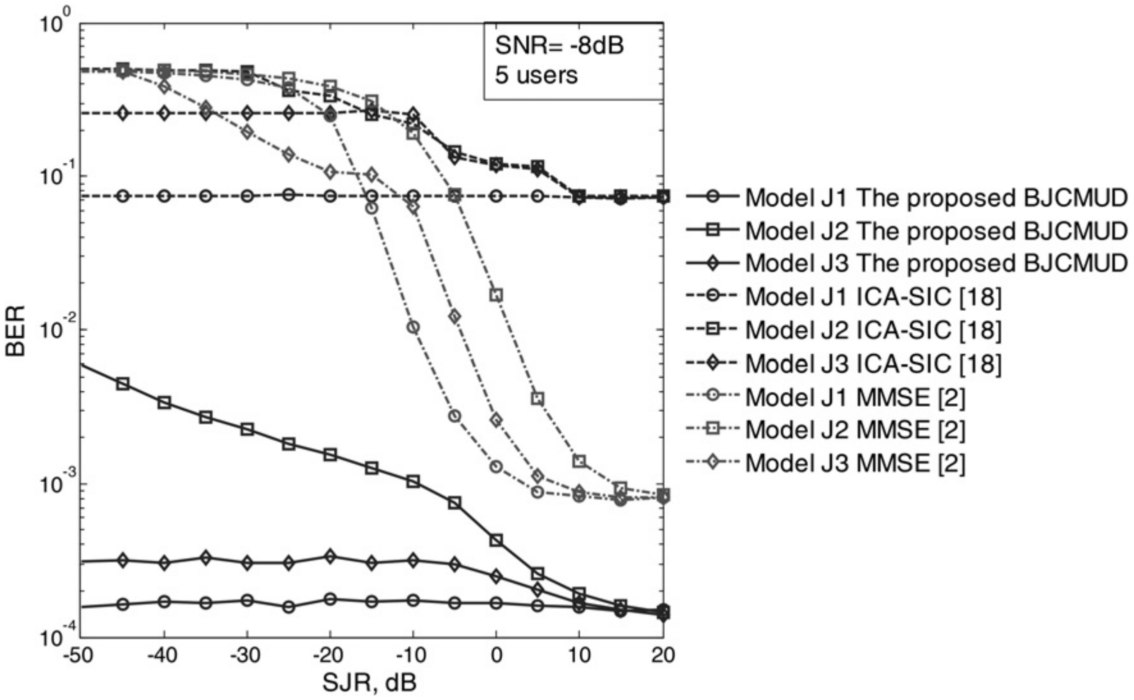

Fig. 2 *BER against JSR performance of BJCMUD algorithm under three kinds of hostile jamming with five active users and SNR = −8 dB*

swept-frequency jamming, which keeps almost stable on all range of SJRs, is superior to that under partial-band jamming.

The performance of BJCMUD algorithm under three kinds of hostile jamming is simulated specifically and the results are shown from Figs. 3–8. In Fig. 3, the first hostile jamming model has been used, whereas in Figs. 4 and 5 the second hostile jamming model has been applied. In Fig. 6–8, the third hostile jamming model is employed.

Fig. 3 shows the BER against SNR or SJR performance of BJCMUD algorithm with various number of active users under a single harmonic jamming. As can be expected in any multi-user system, the BER performance decreases as the number of active users increasing. It is shown in Fig. 3*a* that the BER performance of ten active users loses ~2 dB compared with that of single active user when the BER is 10^{-4}. Fig. 3*b* shows that BER performance keeps almost stable on all range of SJRs, which means the algorithm is insensitive to the power of single harmonic jamming.

Fig. 4 shows the BER against SNR or SJR performance of BJCMUD algorithm with various number of active users under a partial-band jamming with $\eta = 0.25$. As shown in Fig. 4*a* the BER performance also decreases as the number of active users increasing, and the BER performance of 10 active users loses ~4 dB compared with that of single active user when the BER is 10^{-4}. As shown in Fig. 4*b*, unlike the performance under single harmonic jamming, the performance under partial-band jamming is gradually deteriorated as the SJR decreasing.

The BER performance of BJCMUD algorithm against the bandwidth of partial-band jamming is shown in Fig. 5.

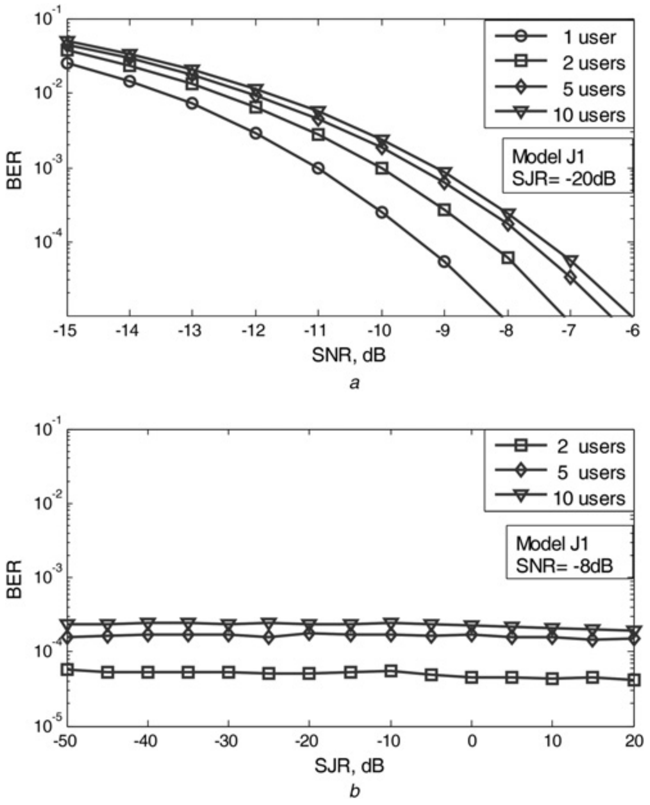

Fig. 3 *BER against SNR or SJR performance of BJCMUD algorithm with various number of active users under a single harmonic jamming*

a BER against SNR with SJR = −20 dB
b BER against SJR with SNR = −8 dB

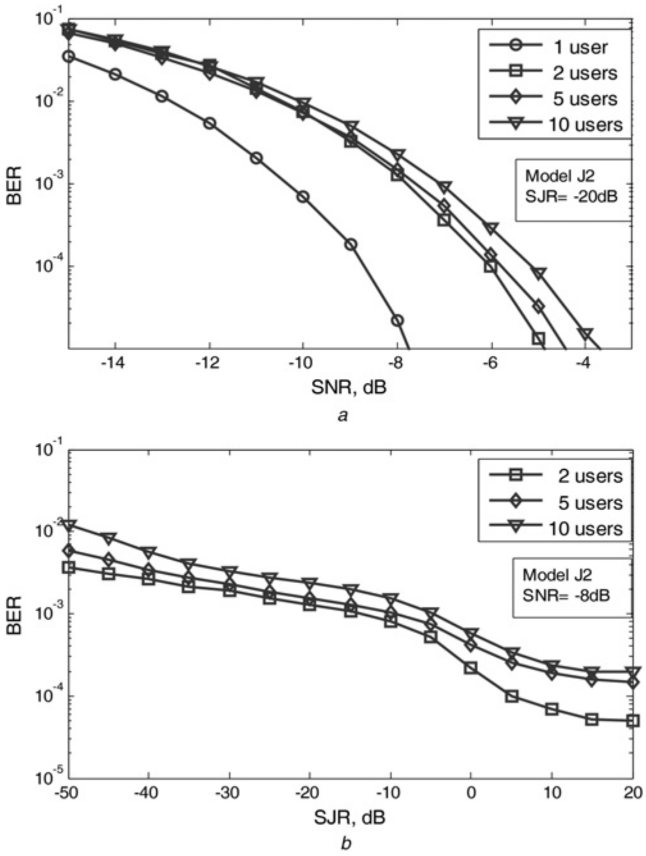

Fig. 4 *BER against SNR or SJR performance of BJCMUD algorithm with various number of active users under a partial-band jamming with η = 0.25*

a BER against SNR with SJR = −20 dB
b BER against SJR with SNR = −8 dB

As shown in Fig. 5, the BER increases as the increasing of the bandwidth of partial-band jamming, and the performance keeps almost constant when η is > 0.7. This is because the Gaussianity of the equivalent sources formed by hostile jamming increases as the increasing of bandwidth, then the separation performance of BSS based on non-Gaussianity measure will be deteriorated.

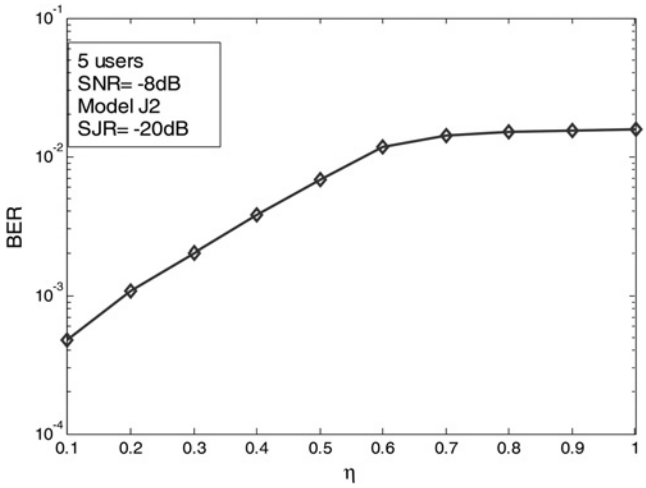

Fig. 5 *BER against η performance of BJCMUD algorithm under partial-band jamming with five active users, SNR = −8 dB and SJR = −20 dB*

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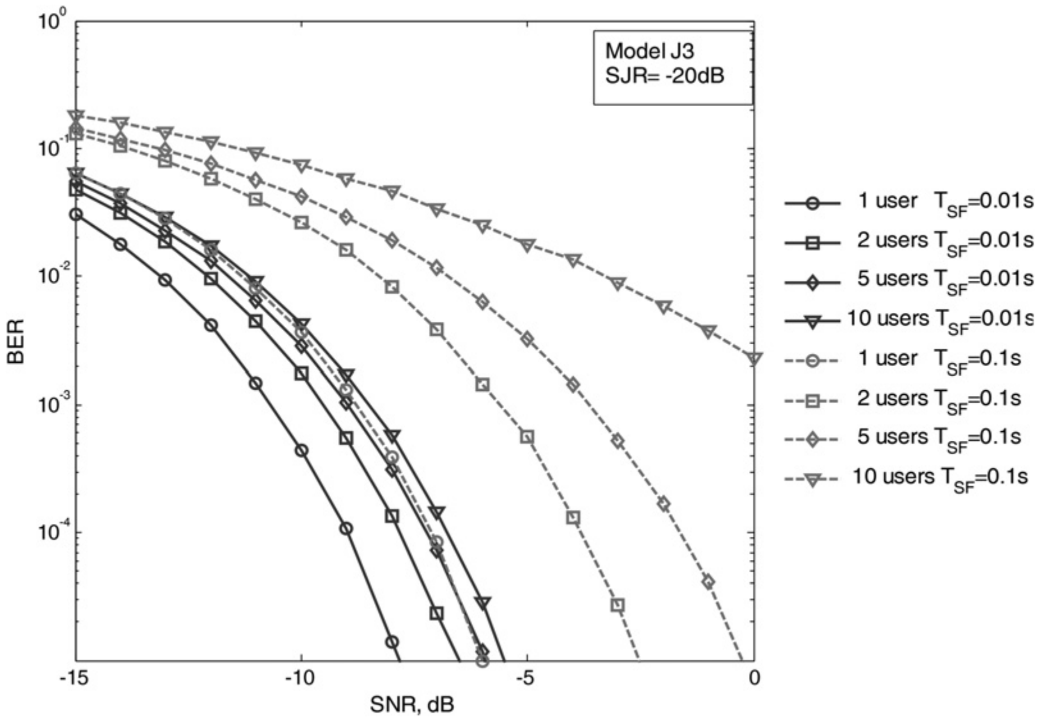

Fig. 6 *BER against SNR performance of BJCMUD algorithm with various number of active users under a linear swept-frequency jamming with SJR = −20d for T_{SF} = 0.01s and T_{SF} = 0.1s*

Figs. 6 and 7 show the BER against SNR and SJR performance of BJCMUD algorithm with various numbers of active users under a linear swept-frequency jamming, respectively. As shown in Figs. 6 and 7, the BER performance with $T_{\rm SF} = 0.01s$ is close to that under a single harmonic jamming, whereas the performance with $T_{\rm SF} = 0.1s$ is much worse. It is shown in Fig. 7 that the BER performance with $T_{\rm SF} = 0.01s$ keeps almost stable on all range of SJRs, whereas the BER performance with $T_{\rm SF} = 0.1s$ is close to that with $T_{\rm SF} = 0.01s$ when SJR is < 0 dB, but it rapidly increases to another error floor, which is much higher than the original floor.

To further evaluate the impact of the scan period $T_{\rm SF}$ on the performance of the proposed algorithm under linear swept-frequency jamming, the performance under various scan period is simulated. The Fig. 8 shows the BER against $T_{\rm SF}$ performance of BJCMUD algorithm for Model J3 under the condition of SJR = −20 dB and five active users with SNR = −8 dB. It can be observed that the BER increases from 10^{-4} to 10^{-2} rapidly as $T_{\rm SF}$ changing from 0.001 to 0.035s, keeps constant when $T_{\rm SF}$ increases from 0.036 to 10s, and decreases from 10^{-2} to 10^{-4} as $T_{\rm SF}$ increasing from 10 to $10^4 s$.

The explanation of this phenomenon is that the performance of BJCMUD is concerned with the scan period

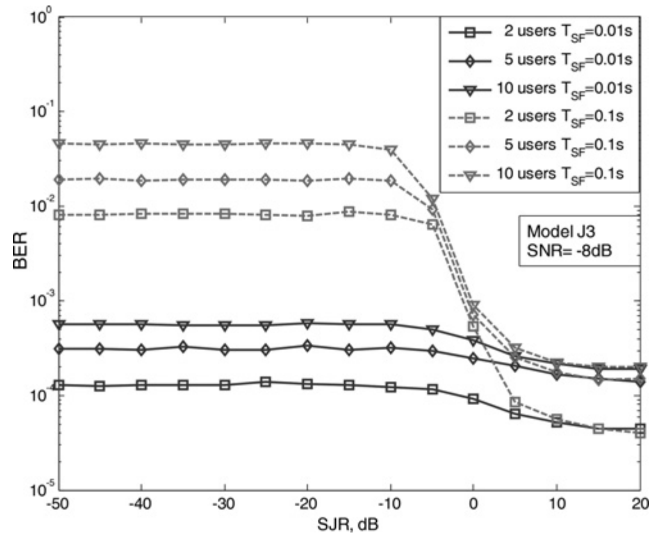

Fig. 7 *BER against SJR performance of BJCMUD algorithm with various number of active users under a linear swept-frequency jamming with SNR = −8 dB for T_{SF} = 0.01s and T_{SF} = 0.1s*

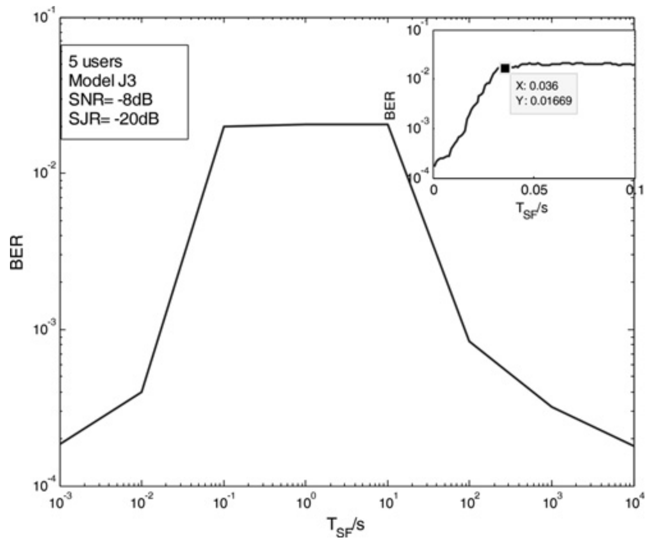

Fig. 8 *BER against T_{SF} performance of the proposed algorithm under a linear swept-frequency jamming*

T_{SF}. Assume that the scan period T_{SF} is HT_S, where H is a positive integer, then the period of the jamming vector $\boldsymbol{j}(m)$ is H, and the covariance matrix of $\boldsymbol{j}(m)$ can be expressed as

$$\boldsymbol{R}_{\mathbf{jj}} = E\big(\boldsymbol{j}(m)\boldsymbol{j}^{\mathrm{T}}(m)\big) = \frac{1}{H}\sum_{m=1}^{H}\boldsymbol{j}(m)\boldsymbol{j}^{\mathrm{T}}(m) \qquad (44)$$

Hence the number of non-zero eigenvalues of $\boldsymbol{R}_{\mathbf{jj}}$, which is denoted as F, is predicatively no larger than the minor one between H and $L_c + L_J - 1$. According to primary components analysis, the equivalent sources formed by $\boldsymbol{j}(m)$ can be reconstructed by F sources which are uncorrelated. Then the number of equivalent sources contained in $\tilde{\boldsymbol{d}}(m)$ can be further reduced from $2L_{\mathrm{c}}$ to $2K+F$ by whiten operation described in (28) without performance loss. In these simulation, as T_{SF} increasing from 0.001 to 0.035s, F increase from 1 to 35, so the number of equivalent sources formed by $j(t)$ also increase from 1 to 35. Moreover the performance of BSS degrades as the number of sources increasing, so the BER increases as the T_{SF} increasing from 0.001 to 0.035s. When $T_{\mathrm{SF}} \geq 0.036s$, F equals to $L_{\mathrm{c}} + L_J - 1$, namely $\boldsymbol{R}_{\mathbf{jj}}$ is full-rank. Therefore the numbers of the equivalent sources in these situations are identical, which means the separation performances should be similar. As shown in Fig. 8, the BER actually keeps stable with $0.036s \leq T_{SF} < 10s$, which coincides with the discussion above, but the BER begins to decrease when $T_{\mathrm{SF}} > 10s$, and falls to the BER of single harmonic jamming when T_{SF} is 10^4s. The reason is that the received jamming in the observation interval becomes more and more similar to a single harmonic jamming as the increasing of T_{SF}, which means F decreases gradually. Therefore the number of equivalent sources formed by $j(t)$ decreases and the BER falls. When T_{SF} increases to 10^4s, the received jamming in observation interval can be approximated by a harmonic jamming and F decreases to 1, so it achieves the BER of single harmonic jamming.

5 Conclusions

A novel blind joint interference cancellation and MUD algorithm, which does not require any knowledge about spread signals, hostile jamming and channel state information, has been proposed for uplink of DS-CDMA systems operating in the presence of unknown hostile jamming. Unlike most of the existing MUD techniques developed for unknown hostile jamming case, the proposed algorithm is applicable to more general hostile jamming and only requires two receive antennas. By transforming the receive model into an overdetermined or determined BSS model with dependent sources, the blind jamming cancellation and MUD are obtained by using BSS algorithm based on non-Gaussianity measure simultaneously. The scheme can be easily extend to the situation that multiple hostile jammings coexist in system. Numerical experiments have revealed the robustness of the proposed scheme against the unknown hostile jamming.

In addition, the proposed algorithm can be associated with other mitigation technologies, such as interleaving and channel coding. If Interleave and channel code are used at both transmitter and receiver, the performance will be further enhanced.

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