JAMMER MITIGATION IN DS-CDMA ARRAY SYSTEM USING INDEPENDENT COMPONENT ANALYSIS

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ABSTRACT

In this paper we consider blind interference mitigation in direct sequence spread spectrum communication system under intentional jamming. Recent work [1] presents a general framework in which blind source separation (BSS) techniques are utilized to enhance conventional detection. However, only second order statistics were utilized which makes the scheme vulnerable to temporally uncorrelated information or jamming signals. In this paper we remove this disadvantage by utilizing BSS based on independent component analysis (ICA). Numerical examples are given to evaluate achieved performance gains.

1. INTRODUCTION

Interference mitigation techniques in spread spectrum (SS) communications have been under active research due to the inevitable gains in the overall system performance and capacity [2]. Although bandwidth expansion gives an inherent temporal mitigation capability for SS communications, usually called a processing gain, additional techniques are needed. This is because bandwidth expansion results in bandwidth dependent mitigation capability. Interference mitigation techniques, however, alleviate the need for wider spectrum for reliable communications.

Considering commercial cellular SS communication systems we can distinguish many types of interferences, starting from multiuser interference inside each sector in a cell to inter-operator interference. Unintentional jamming can also be present due to co-existing systems at the same band, whereas intentional jamming arises mainly in military applications. In direct sequence (DS) SS communication systems, RAKE [3] is the traditional receiver. It relies only on processing gain and frequency diversity, and is thus vulnerable in the presence of jamming. Jamming can be mitigated e.g. by the use of multiple antenna sensors utilizing spatial diversity. Multiple sensors enable the use of directional antennas, which can point their beam to a specific direction to reduce the interference level for a desired user. Direction-of-arrival (DOA) estimation thus becomes a requiste task for conventional array receivers.

DOA estimation can be relaxed, however, as was proposed recently in [1], by using blind source separation (BSS) techniques [4]. Motivation for applying BSS techniques in array signal processing arises especially from the potential performance gains that can be achieved when applied to uncalibrated arrays. In [1] the idea was to separate the information bearing and jammer signal from the received array data before conventional detection. From BSS point of view, the received array data is a mixture of signals received from different directions, the mixture being determined by the angles of arrivals. The task of BSS was then to separate from the DOA-dependent mixture a set of DOA-independent signals. However, only second order statistics were utilized which makes the scheme vulnerable to signals having low temporal correlation. This is the case especially when data modulation is turned on or if jamming is either pulsed in nature or unlocked to the carrier frequency.

In this paper we consider BSS based on independent component analysis (ICA) [5] to enable adequate jammer mitigation also in the presence of signals with low temporal correlation. Continuous wave (CW) jamming is considered both at the carrier frequency and with a frequency offset. The latter case, together with data modulation, is demonstrated especially to study the behavior of the scheme when signals are less correlated in time.

2. SYSTEM MODEL

A standard spread spectrum system with direct sequence spreading is assumed. In addition we assume a single tone continuous wave jammer to cause an intentional interference for the system.

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Suppose $r(t)$ is the baseband spread spectrum signal. When transmitting the signal a carrier frequency f_c is used, so that the transmitted DSB-modulated signal is equal to $r(t)e^{j2\pi f_c t}$. The jammed signal received at the nth antenna element ($n = 1, \ldots, N$) is then (assuming ideal channel for a while for notational simplicity)

$$y_n(t) = r(t)e^{j2\pi f_c t}e^{j(n-1)\theta_r} + j(t)e^{(n-1)j\theta_r}, \quad (1)$$

where

$$j(t) = \sqrt{J}e^{j(2\pi f_j t+\phi)} \quad (2)$$

is the CW jammer. Power, frequency and phase of the jammer are denoted by J, f_j and ϕ, respectively. The phase is assumed to be uniformly distributed over $[0, 2\pi)$. Variables θ_r and θ_j are related to the directions of arrival for information and jammer signal, respectively, and their form depends on the antenna configuration. For example, for an uniform linear array with N elements and half a carrier wavelength spacing, $\theta = \pi \sin(\alpha)$, where α is the true direction of arrival.

In the reception the signal is down-converted to the baseband, which yields

$$\begin{aligned} \hat{r}_n(t) &= y_n(t)e^{-j2\pi f_c t} && (3)\\ &= r_n(t)e^{j(n-1)\theta_r} && (4)\\ &+ \sqrt{J}e^{j(2\pi(f_j-f_c)t+\phi)}e^{j(n-1)\theta_j}. && (5) \end{aligned}$$

Thus, CW jamming introduces a bias with a constant amplitude but a varying phase determined by the frequency offset. If the jammer is locked to the carrier frequency, i.e. $f_j = f_c$, then the contribution of the jammer reduces to $\sqrt{J}e^{j\phi}e^{j(n-1)\theta_j}$, which means that the phase of the bias is determined by DOA and the initial phase difference of the carrier and jammer's tone.

The information bearing signal is assumed to be DS-CDMA signal in the downlink (e.g. base-to-mobile) channel. Thus, the data describing received block of M symbol have the form

$$r(t) = \sum_{m=1}^{M}\sum_{k=1}^{K} a\, b_{km} s_k(t - mT - d) + n(t) \quad (6)$$

in which the symbols b_{km} are sent for K users via the channel characterized by a complex path gain a and path delay d. For notational simplicity, the path delay is assumed to be discretized, and hence $d \in \{0, \ldots, (C-1)/2\}$. The delay is assumed to remain constant during the block of interest, say M data symbols. $s_k(\cdot)$ is kth user's binary chip sequence, supported by $[0, T)$, where T is the symbol duration and $n(t)$ is gaussian noise.

With a simple manipulation the received antenna data can be represented more compactly as

$$\mathbf{r}(t) = [r_1(t) \cdots r_N(t)]^T = \Theta[r(t)\ j(t)]^T + \mathbf{n}(t), \quad (7)$$

where

$$\Theta = \begin{bmatrix} 1 & 1 \\ e^{j\theta_r} & e^{j\theta_j} \\ \vdots & \vdots \\ e^{j(N-1)\theta_r} & e^{j(N-1)\theta_j} \end{bmatrix} \quad (8)$$

and $\mathbf{n}$ is the additive white gaussian noise (AWGN).

3. JAMMER REJECTION USING BLIND SOURCE SEPARATION TECHNIQUES

Using the terms of blind source separation (BSS) the data model (7) is a noisy mixing model with a mixing matrix Θ and sources $r(t)$,$j(t)$. The goal of BSS is to find the unmixing mapping, say $\mathbf{W}$, using only the observations $r(t)$ such that $\mathbf{W}\mathbf{r}(t)$ would recover the set of original sources as well as possible.

To cope with signals which have low temporal correlation we consider BSS based on independent component analysis (ICA) [5] in which the statistical independence of the original signals will be utilized in the separation process. We apply FastICA [6] algorithm for complex mixtures [5, 7]. It is based on fourth order statistics and is one of the fastest and simplest methods for linear BSS.

FastICA as well as many other methods for BSS includes a whitening step for the data [5]. This helps to reduce the number of unknowns in the mixing matrix, so that the remaining mixture can be modeled by a simpler orthonormal matrix. More precisely, whitening is a linear transform which de-correlates the observed mixtures, and normalizes the component variances to unity. This linear mapping can always be accomplished e.g. by the means of eigenvalue decomposition. For sampled data this yields a transformation

$$\mathbf{y}[t] = \mathbf{T}\mathbf{r}[t]. \quad (9)$$

Here $\mathbf{T} \stackrel{\text{def}}{=} \mathbf{\Lambda}_s^{-\frac{1}{2}}\mathbf{U}_s^H$, where $\mathbf{\Lambda}_s$ and $\mathbf{U}_s$ correspond to the principal eigenvalues and -vectors of the data autocorrelation matrix $E\{\mathbf{r}[t]\mathbf{r}[t]^H\}$, respectively.

There exists different versions of FastICA algorithms depending on the selected objective function [5]. The core of the FastICA algorithm which is applied here is to update the ith column $\mathbf{w}_i$ of $\mathbf{W}$ according to

$$\mathbf{w}_i^+ = E\{\mathbf{y}[t](\mathbf{w}_i^H\mathbf{y}[t])^*|\mathbf{w}_i^H\mathbf{y}[t]|^2\} - \gamma\mathbf{w}_i, \quad (10)$$

where $'+'$ denotes updated value, and γ is 2 (resp. 3) for complex (resp. real) valued signals. E stands for expected value which is taken from the available set of samples $\mathbf{y}[t]$.

After ICA there are two tasks to do: a selection among separated sources because only one source corresponds to the information bearing signal, and estimation of the channel. Recall that both tasks are due to the inherent indeterminacies of ICA: the sources can be estimated only up to a permutation, and a complex scalar can be exchanged between a source and related column of the mixing matrix [5]. Proper initialization would alleviate these drawbacks [7], but here it would require DOA estimation. To prevent increase in computation we take advantage of training symbols, or a preamble, which are often implemented to help channel estimation. Here the preamble is used for both conventional matched filter -based channel estimation and for identification of the desired source. Latter is based on matching between the preamble and corresponding portion of the estimated sequence of symbols. Finally, conventional detection is performed for the selected source resulting in a so-called ICA-RAKE receiver structure.

4. NUMERICAL EXPERIMENTS

We test the algorithms using simulated DS-CDMA downlink data with AWGN channel. Path delay is assumed to be known. A system with $K = 8$ users is considered, and short Gold codes of the length $C = 31$ are used. The length of the data block is $M = 200$ QPSK symbols. Signal-to-Jammer Ratio (SJR) and Signal-to-Noise Ratio (SNR) are defined with respect to the monitored user, which is chosen randomly. The number of antenna elements is $N_a = 1 - 3$. The results are based on 3000 independent runs. As reference methods we use traditional RAKE for single antenna reception and RAKE with maximal ratio combining (MRC) for multiple receive antennas.

First, SNR is fixed to 10 dB, and the achieved bit-error-rate (BER) and block-error-rate (BLER) are presented as a function of SJR in Figs. 1 and 2, respectively. In this case the jammer is assumed to operate exactly at the carrier frequency. Fig. 1 shows that the BER behavior of ICA-RAKE is quite equal to the MRC with $N_a = 2$ antennas up to -10 dB after which it saturates. Saturation is expected due to the fixed level of thermal noise. However, Fig. 1 doesn't tell the whole truth, as can be seen in Fig. 2, which shows that ICA-RAKE is able to enhance the BLER-behavior. Compared to MRC with $N_a = 3$ antennas, approximately a 3 dB gain is achieved when taking either 10^{-1} or 10^{-2} as target BLER.

Second, the same setting is used as previously but the jammer is now unlocked. The frequency offset is set to $f_j - f_c = \frac{1}{200T_s}$, where T_s is the duration of a symbol. This results in a total phase shift of 2π during $M = 200$ symbols. Figs. 3 and 4 shows the BER and BLER curves, respectively. Now, ICA-RAKE performs clearly the best up to $0 - 5$ dB depending on whether 2 or 3 antennas are in use. For example, with $N_a = 3$ antennas ICA-RAKE gives a 5 dB gain when 10^{-1} is taken as a targer BER. BLER behavior is quite the same, the gains being over 2 dB at the BLER levels of 10^{-1} and 10^{-2}.

From now on SJR is fixed to -5 dB and SNR is varied from -20 to 20 dB. Figs. 5 and 6 shows the BER and BLER curves, respectively, for locked CW jammer. The results

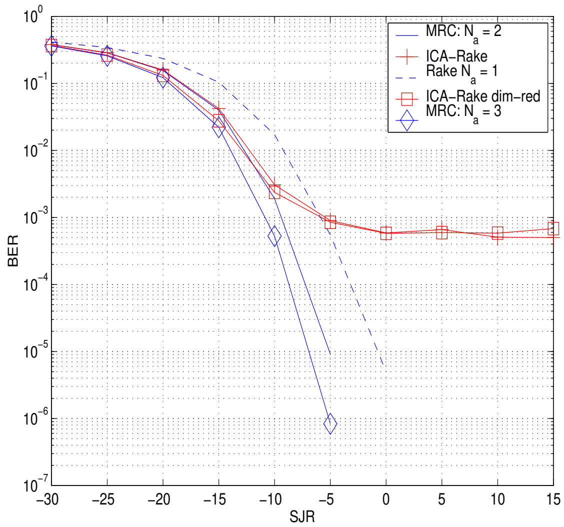

Fig. 1. Bit-error-rate as a function of SJR. The system includes $K = 8$ users of equal strength in AWGN channel and with locked CW jammer. Average signal-to-noise ratio is 10 dB and BPSK modulation is used. ICA-RAKE uses $N_a = 2$ antenna elements while the case $N_a = 3$ includes dimension reduction using whitening.

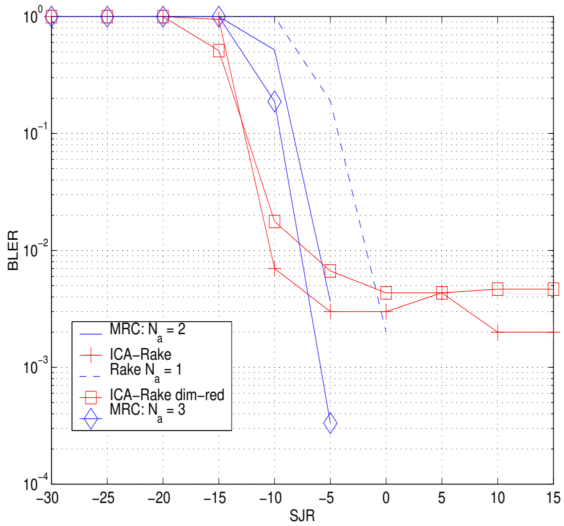

Fig. 2. Block-error-rate as a function of SJR. The system includes $K = 8$ users of equal strength in AWGN channel and with locked CW jammer. Average signal-to-noise ratio is 10 dB and BPSK modulation is used. ICA-RAKE uses $N_a = 2$ antenna elements while the case $N_a = 3$ includes dimension reduction using whitening.

are similar to the SJR variation case. ICA-RAKE is comparable with MRC with two antennas up to 5 dB, whereas MRC with 3 antennas gives the best performance. However, once again, gains are achieved from BLER behavior; if two antennas are in use ICA-RAKE gives nearly 5 dB gain at BLER level of 10^{-1} and 1 dB gain at 10^{-2} BLER level, and if three antennas are used the gain is over 2 dB at both BLER levels.

Finally, Figs. 7 and 8 shows the BER and BLER curves for unlocked CW jammer. Here the differences are the most visible. With 2 antennas only ICA-RAKE reaches BER level of 10^{-1} with SNR lower than 20 dB, and with 3 antennas ICA-RAKE gives nearly a 10 dB gain.

5. CONCLUSIONS

In this paper we considered jammer mitigation in direct sequence spread spectrum communication system under intentional continuos wave jamming by using blind separation techniques in array reception. Especially, higher order statistics were utilized in order to cope with signals of low temporal correlation. The performance of so-called ICA-RAKE receiver structure was found adequate by numerical simulations. Namely, BLER performance was improved especially when strong jamming/thermal noise existed, giving usually $1-5$ dB gains in terms of SJR/SNR at BLER levels of 10^{-1} and 10^{-2}, depending on the jamming frequency.

6. REFERENCES

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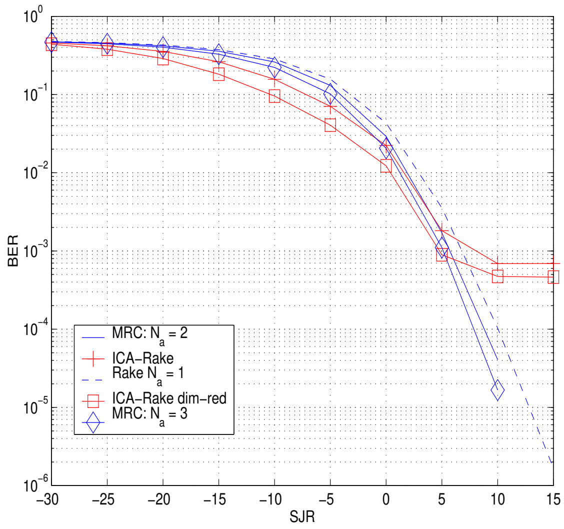

Fig. 3. Bit-error-rate as a function of SJR. The system includes $K = 8$ users of equal strength in AWGN channel and with unlocked jammer. Average signal-to-noise ratio is 10 dB and BPSK modulation is used. ICA-RAKE uses $N_a = 2$ antenna elements while the case $N_a = 3$ includes dimension reduction using whitening.

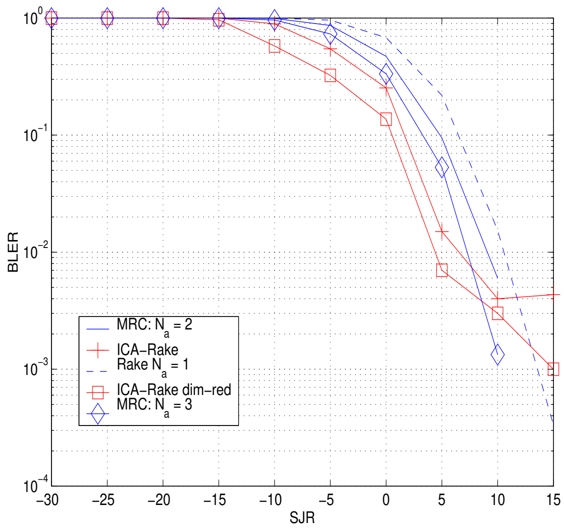

Fig. 4. Block-error-rate as a function of SJR. The system includes $K = 8$ users of equal strength in AWGN channel and with unlocked jammer. Average signal-to-noise ratio is 10 dB and BPSK modulation is used. ICA-RAKE uses $N_a = 2$ antenna elements while the case $N_a = 3$ includes dimension reduction using whitening.

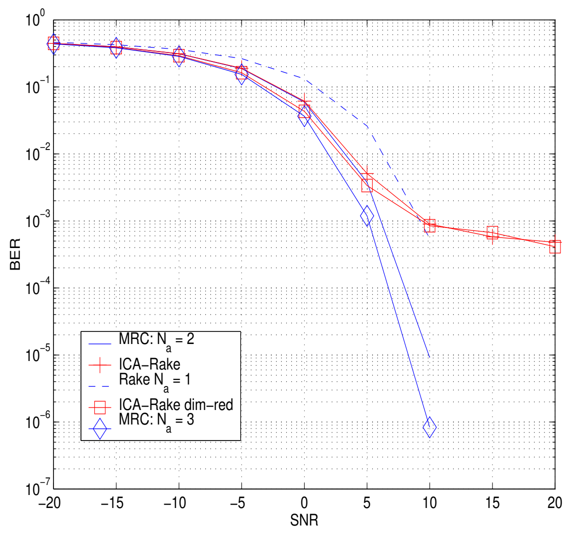

Fig. 5. Bit-error-rate as a function of SNR. The system includes $K = 8$ users of equal strength in AWGN channel and with locked CW jammer.. Average signal-to-jammer ratio is -5 dB and BPSK modulation is used. ICA-RAKE uses $N_a = 2$ antenna elements while the case $N_a = 3$ includes dimension reduction using whitening.

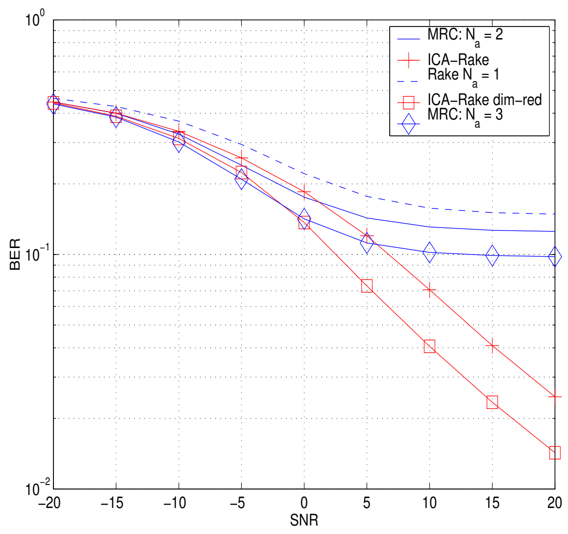

Fig. 7. Bit-error-rate as a function of SNR. The system includes $K = 8$ users of equal strength in AWGN channel and with unlocked CW jammer.. Average signal-to-jammer ratio is -5 dB and BPSK modulation is used. ICA-RAKE uses $N_a = 2$ antenna elements while the case $N_a = 3$ includes dimension reduction using whitening.

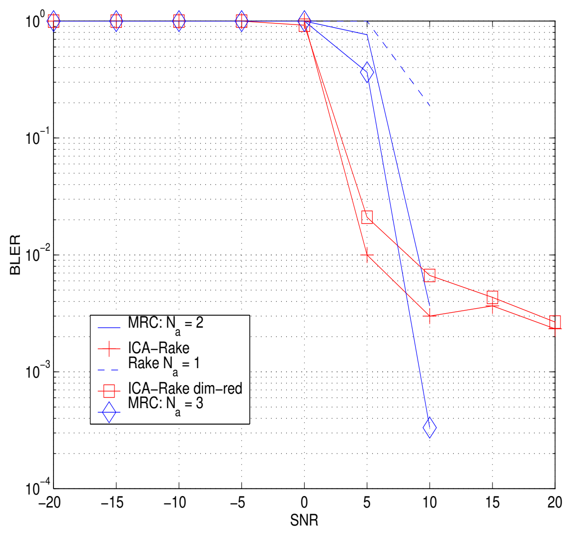

Fig. 6. Block-error-rate as a function of SNR. The system includes $K = 8$ users of equal strength in AWGN channel and with locked CW jammer.. Average signal-to-jammer ratio is -5 dB and BPSK modulation is used. ICA-RAKE uses $N_a = 2$ antenna elements while the case $N_a = 3$ includes dimension reduction using whitening.

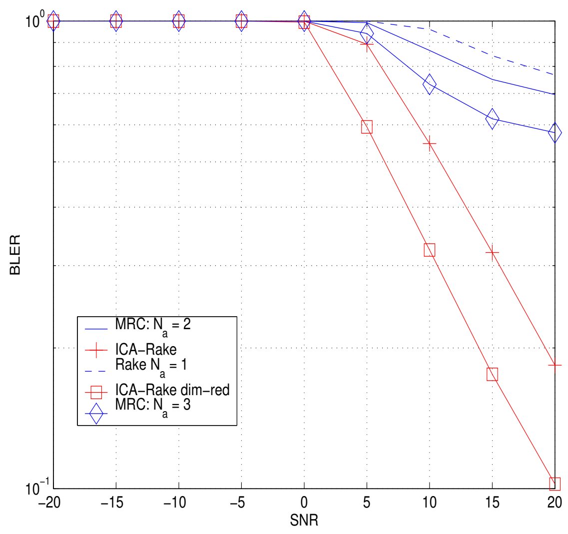

Fig. 8. Block-error-rate as a function of SNR. The system includes $K = 8$ users of equal strength in AWGN channel and with unlocked CW jammer.. Average signal-to-jammer ratio is -5 dB and BPSK modulation is used. ICA-RAKE uses $N_a = 2$ antenna elements while the case $N_a = 3$ includes dimension reduction using whitening.