SUPPRESSION OF BIT-PULSED JAMMER SIGNALS IN DS-CDMA ARRAY SYSTEM USING INDEPENDENT COMPONENT ANALYSIS

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ABSTRACT

In this paper, Independent Component Analysis is considered for blind suppression of interference caused by bit-pulsed jamming in a direct sequence spread spectrum communication system. A framework for applying blind techniques to the jammer mitigation problem was earlier introduced in [1]. However, the scheme proposed there is based on second-order statistics only, and has serious practical limitations. For example, it fails for temporally uncorrelated data which is commonplace in CDMA communications. This paper extends the framework by taking into account both data modulation and temporally uncorrelated jamming, and removes the uncorrelatedness limitation by employing independent component analysis instead of second-order statistics. Computer simulations show that the proposed method performs better than the well-known RAKE method, which is the standard choice for suppressing jammer signals.

1. INTRODUCTION

Independent Component Analysis (ICA) [2] is a fairly new statistical technique which has recently drawn a lot of attention. The goal of ICA is to express a set of observed signals or random variables as linear combinations of statistically independent components, which are often called sources or source signals. In standard linear ICA, the m observed signals $x_1(t), \ldots, x_m(t)$ at the time instant t are assumed to be linear combinations of n unknown but statistically independent source signals $s_1(t), \ldots, s_n(t)$ at the time t. The ICA problem is blind, because not only the source signals but also the mixing coefficients are unknown.

Introduce the data vector $\mathbf{x}(t) = [x_1(t), \ldots, x_m(t)]^T$ for the observed signals $x_i(t)$ at time t, and similarly the source vector $\mathbf{s}(t) = [s_1(t), \ldots, s_n(t)]^T$ for the source signals $s_j(t)$. Then the instantaneous noisy linear ICA mixture model is given by

$$\mathbf{x}(t) = \mathbf{A}\mathbf{s}(t) + \mathbf{n}(t) \tag{1}$$

Here the $m \times n$ unknown but constant mixing matrix $\mathbf{A}$ contains the mixing coefficients, and $\mathbf{n}(t)$ denotes the additive noise vector at time t. We make the standard assumptions that $\mathbf{A}$ has full rank, and that $n \leq m$, meaning that there are at most as many source signals $s_j(t)$ as mixtures $x_i(t)$.

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In this particular context, $\mathbf{x}(t)$ is the received mixture of information signals $\mathbf{s}(t)$. In a multiple antenna system, $\mathbf{A}$ is the Direction-of-Arrival (DOA) matrix, which mixes the signals received from different directions by their angles of arrival. Since it is assumed that the source signals $s_j(t)$ are statistically independent, the above model can be used to separate them to obtain the desired information signal. Occasionally, unintentional jamming can also be present due to co-existing systems at the same band. Jamming can be mitigated by using multiple antenna sensors utilizing spatial diversity [5]. These sensors enable the use of directional antennas, which can point their beam to a specific direction to reduce the interference for the desired signal. Hence DOA estimation becomes a prerequisite task for conventional array receivers.

Classical techniques used in array processing require that the DOA matrix $\mathbf{A}$ is completely known except for the angles of arrival. This in turn requires exact prior knowledge of the positions of the receiving antenna sensors. Blind techniques [1, 3] relax this stringent requirement, making it possible to achieve performance gains when applied to uncalibrated arrays in which the positions of sensors are known only roughly or not at all.

It is quite realistic to assume that the jammer signal is independent of the information bearing signal. Observing this, Belouchrani and Amin first presented in [1] the idea of applying blind source separation (BSS) techniques before conventional detection. BSS techniques were used to separate a set of DOA independent source signals $\mathbf{s}(t)$ from their DOA dependent mixtures $\mathbf{x}(t)$. However, the work described in [1] is rather preliminary in several aspects. For example, data modulation is omitted completely, which is an unrealistic assumption from practical point of view. Furthermore, resorting to second-order temporal statistics only, makes the scheme introduced in [1] vulnerable to signals having low temporal correlations. Such cases are commonplace in DS-CDMA communication systems, appearing for example when the signals are modulated or when the jammer is pulsed in nature or not locked to the carrier frequency.

In this paper, we apply independent component analysis, enabling jammer mitigation in the presence of modulated signals jammed with a bit-pulsed jammer. Jamming can appear at the carrier frequency and also with a frequency offset. Both the jammer and information signals are temporally uncorrelated, so that Belouchrani's and Amin's method [1] will not work. In another paper [6], we have considered the case where the jammer signal is temporally correlated but the information signal is uncorrelated due to the data modulation.

2. SYSTEM MODEL

In this application, a standard spread spectrum system [7] with direct sequence spreading is assumed. Since a downlink channel is of prime interest here (e.g. base-to-mobile), the data describing the received block of M symbols is of the form (see [2], Chapter 23 for an introduction)

$$r(t) = \sum_{m=1}^{M} \sum_{k=1}^{K} a\, b_{km} s_k(t - mT - d) + n(t) \qquad (2)$$

where the symbols b_{km} are sent to K users via a channel characterized by a complex path gain a and a path delay d. It is assumed that the delay d is discrete, $d \in \{0, \dots, (C-1)/2\}$, and remains constant for every block of M data symbols. Furthermore, $s_k(\cdot)$ is kth user's binary chip sequence, supported by $[0, T)$, where T is the symbol duration and $n(t)$ is Gaussian noise [7, 2].

We assume further that the received signal $r(t)$ in (2) is jammed by a bit-pulsed jamming signal $q(t)$. The jammer signal has the form

$$q(t) = \delta_p(t)\sqrt{Q}e^{j(2\pi f_q t + \phi)} \qquad (3)$$

where $\delta_p(t) = 1$ with a probability p during a symbol. The power, frequency, and phase of the jammer signal are denoted respectively by Q, f_q, and ϕ. The phase is assumed to be uniformly distributed over the interval $[0, 2\pi)$.

Assuming an antenna array, the received signal at the nth antenna element $(n = 1, \dots, N)$ before the down-conversion can be written as

$$y_n(t) = r(t)e^{j2\pi f_c t}e^{j(n-1)\theta_r} + q(t)e^{j(n-1)\theta_q} \qquad (4)$$

where $r(t)$ is the baseband spread spectrum signal that is DSB modulated at a carrier frequency f_c [7]. Variables θ_r and θ_q are related to the directions of arrival of the information signal $r(t)$ and the jammer signal $q(t)$ respectively, and their form depends on the antenna configuration.

This signal is down-converted to the baseband, yielding

$$\begin{aligned} \hat{r}_n(t) &= y_n(t)e^{-j2\pi f_c t} = \\ r(t)e^{j(n-1)\theta_r} &+ \delta_p(t)\sqrt{Q}e^{j(2\pi(f_q - f_c)t+\phi)}e^{j(n-1)\theta_q} \end{aligned} \qquad (5)$$

Thus the bit-pulsed jammer 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 so that $f_q = f_c$, then the contribution of the jammer reduces to $\delta_p(t)\sqrt{Q}e^{j\phi}e^{j(n-1)\theta_q}$. This means that the phase of the bias is determined by DOA and the initial phase difference of the carrier and jammer's tone.

Using this definition the received antenna data can be more appropriately represented as

$$\mathbf{r}(t) = [r_1(t) \cdots r_N(t)]^T = \Theta[r(t)\, q(t)]^T + \mathbf{n}(t) \qquad (6)$$

where

$$\Theta = \begin{bmatrix} 1 & 1 \\ e^{j\theta_r} & e^{j\theta_q} \\ \vdots & \vdots \\ e^{j(N-1)\theta_r} & e^{j(N-1)\theta_q} \end{bmatrix} \qquad (7)$$

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

3. JAMMER MITIGATION USING ICA

The aim of ICA and BSS methods is to estimate using only the observation vectors $\mathbf{r}(t)$ a de-mixing or separating matrix $\mathbf{W}$ [2, 3]. This matrix should be such that the vector $\mathbf{Wr}(t)$ of estimated sources or independent components recovers the original sources and the jammer signal as well as possible.

In our experiments, we applied the so-called FastICA algorithm for complex mixtures [10, 2, 9]. FastICA is a fast method for performing linear ICA, which is in its basic form based on the simple fourth-order statistics kurtosis. However, other forms of the algorithm employing more robust lower-order statistics exist [2]. Some other ICA algorithms developed for complex mixtures, for example JADE [2], were also tried, and they performed equally well.

In most ICA methods, the data are first prewhitened spatially. This makes the subsequent separation task easier, because the separating matrix is constrained to be orthogonal [2]. In whitening, the observed mixtures $\mathbf{r}(t)$ are transformed linearly so that their components become uncorrelated and have unit variance:

$$\mathbf{y}(t) = \mathbf{Tr}(t), \qquad \mathrm{E}\{\mathbf{y}(t)\mathbf{y}(t)^H\} = \mathbf{I} \qquad (8)$$

Here $\mathbf{y}(t)$ is the whitened data vector, $\mathbf{T}$ a whitening transformation matrix, $\mathbf{I}$ the unit matrix, and H denotes complex conjugation and transposition. Whitening is often carried out via principal component analysis (PCA), which yields for complex data the transformation matrix

$$\mathbf{T} = \Lambda_s^{-\frac{1}{2}}\mathbf{U}_s^H \qquad (9)$$

There the matrices Λ_s and $\mathbf{U}_s$ respectively contain the eigenvalues and eigenvectors of the autocorrelation matrix $\mathrm{E}\{\mathbf{r}(t)\mathbf{r}(t)^H\}$ of the received data vectors $\mathbf{r}(t)$. When PCA is used for whitening, it is easy to reduce the dimensionality of the data vectors simultaneously if desirable; see [2].

The FastICA algorithm is then used to separate the sources from their whitened mixtures $\mathbf{y}(t)$. The core of this algorithm is updating of the ith column $\mathbf{w}_i$ of the orthogonal separating matrix $\mathbf{W}$ according to [10, 2]

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

where $\mathbf{w}_i^+$ is the updated value of $\mathbf{w}_i$, and * denotes complex conjugation. The constant γ is 2 for complex-valued signals, and 3 for real ones. In practice, the expectation E in (10) is replaced by computing the respective average over the available set of whitened data vectors $\mathbf{y}(t)$. The update rule (10) uses the standard cubic nonlinearity arising from the maximization of the kurtosis, but other versions of the complex FastICA algorithm exist, too [10]. These typically apply slower growing nonlinearities which are more robust against outliers and impulsive noise in the data.

Due to the inherent indeterminacies of ICA [2], two additional tasks must be performed. These are selection of the desired information bearing signal among the separated sources, and estimation of the channel. ICA can estimate the source signals only up to a permutation, and a complex scaling factor can be exchanged between a source and the respective column of the mixing matrix [2]. To mitigate this, a short sequence of training symbols forming a preamble is used. The preamble is used for both conventional

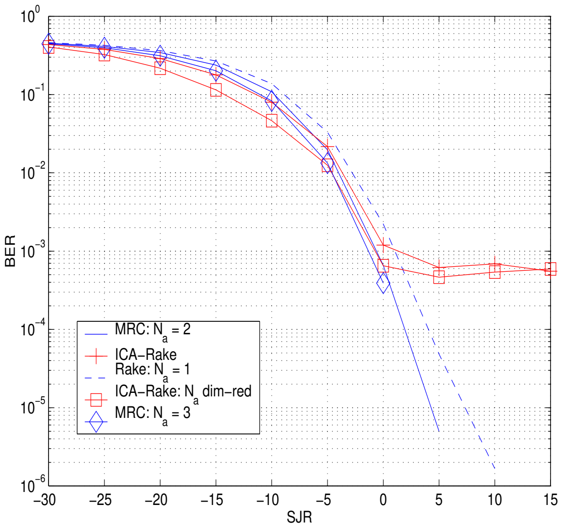

Fig. 1. Bit-error-rate as a function of SJR at an average SNR = 10 dB for $K = 8$ users of equal strength in an AWGN channel with bit-pulsed jamming and BPSK modulation. ICA-RAKE uses $N_a = 2$ antenna elements, while $N_a = 3$ includes reduction of dimension by one in the whitening stage.

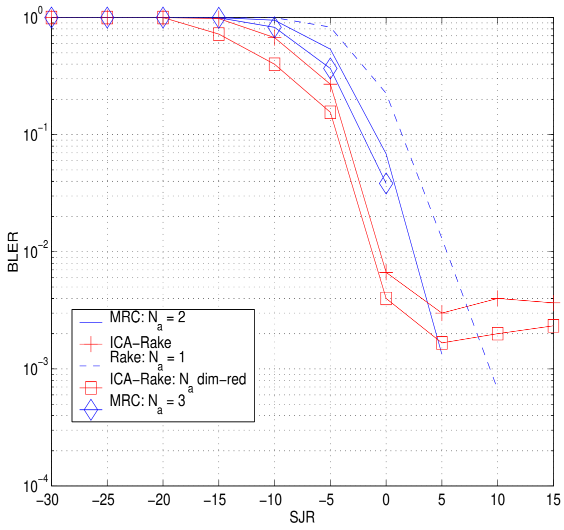

Fig. 2. Block-error-rate as a function of SJR at an average SNR = 10 dB using $K = 8$ users of equal strength in an AWGN channel with bit-pulsed jamming and BPSK modulation. ICA-RAKE uses $N_a = 2$ antenna elements, while $N_a = 3$ includes reduction of dimension by one in the whitening stage.

matched filter based channel estimation [7] and for identifying the desired source. This in turn takes place by matching the preamble with the corresponding portion of the estimated symbols. Finally, conventional detection is performed for the selected source. This leads to our ICA-RAKE receiver structure, where the well-known and robust RAKE method [4, 7] is used for conventional detection. Other methods developed for multi-user detection [11] could be used after ICA, too. However, here the prime interest is ICA and its cabability to mitigate jammer signals prior to actual detection. Since RAKE is the most popular receiver structure in practice, it was chosen for studying the gain of ICA pre-processing in a realistic setting.

Actually, the method developed here is semi-blind, requiring some prior information on the desired user. This is typically the case in communications problems like the one considered here.

4. SIMULATION RESULTS

Our ICA-RAKE method was tested and compared with other methods using simulated DS-CDMA downlink data with AWGN channel [7, 11], with a known path delay. A system with $K = 8$ users was considered, spread with a short Gold Code of length $C = 31$ [4, 7]. The length of the data block was $M = 200$ QPSK symbols. The monitored user was chosen randomly, and the signal-to-noise ratio (SNR) and the signal-to-jammer ratio (SJR) were defined with respect to this desired user. The probability that a bit is jammed was chosen to be $p = 0.5$. The number of elements N_a in the antenna varied from 1 to 3. The case $N_a = 1$ corresponds to the standard RAKE (no array, one sensor only), and using more than $N_a = 3$ antenna elements does not help any more. The results are based on 3000 independent runs. They were compared with the traditional RAKE detector for a single antenna, and with RAKE using maximum ratio combining (MRC) [4] for multiple antennas.

First, the SJR of the jammer locked to the carrier frequency was varied by keeping the SNR fixed to 10 dB, and the achieved bit-error-rate (BER) as well as block-error-rate (BLER) were calculated. The results are shown respectively in Figs. 1 and 2. Figure 1 shows that the two-antenna ICA-RAKE combination performs comparably with the MRC having similar dimensions in the region of high jamming (up to SJR = 0 dB). Beyond SJR = 0 dB, the curves saturate due to the fixed level of thermal noise. When the number of antenna elements is increased, the ICA-RAKE combination with whitening outperforms the MRC with $N_a = 3$ antenna elements by at least 2dB in the SJR region between -10 dB and -5 dB. Inspection of the BLER curves in Fig. 2 reveals that the ICA-RAKE combination is superior to the conventional RAKE or the MRC-RAKE by as much as 6 dB or 3 dB when either 10^{-2} or 10^{-1} is used as the target block-error-rate.

In another series of simulations, the signal-to-jammer ratio was fixed at the constant value SJR = -5 dB, and the signal-to-noise ratio was varied. Figures 3 and 4 show the respective bit-error-rate and block-error-rate curves. The results are qualitatively similar as in the previous case of fixed SNR. ICA-RAKE performs equally well as MRC with $N_a = 2$ elements up to 5 dB, and provides a nearly 3 dB performance gain over conventional RAKE. However, the BLER curves in Figure 4 reveal an interesting behavior. With $N_a = 2$ antenna elements, ICA-RAKE provides a nearly 3 dB performance gain over MRC at the BLER level of 10^{-1}, and 2 dB gain at the BLER level of 10^{-2}. When the number of antenna

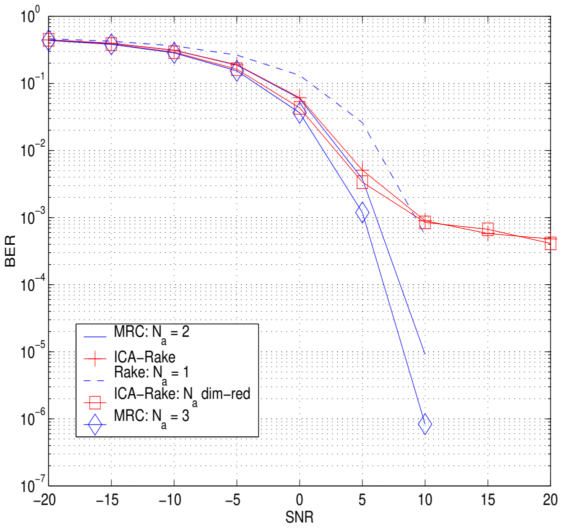

Fig. 3. Bit-error-rate as a function of SNR at an average SJR = -5 dB for $K = 8$ users of equal strength in an AWGN channel with bit-pulsed jamming and BPSK modulation. ICA-RAKE uses $N_a = 2$ antenna elements, while $N_a = 3$ includes reduction of dimension by one in the whitening stage.

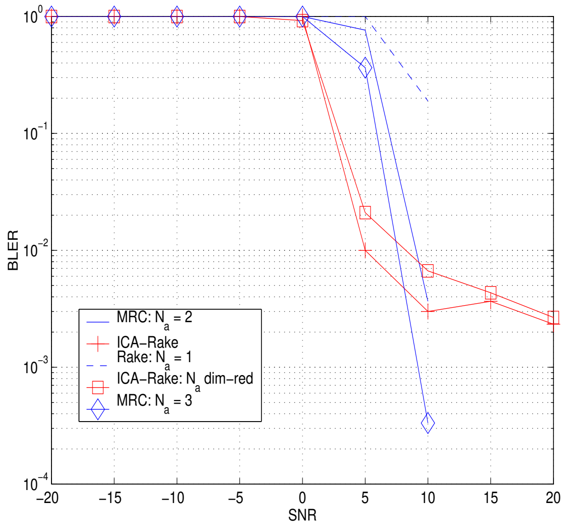

Fig. 4. Block-error-rate as a function of SNR at an average SJR = -5 dB for $K = 8$ users of equal strength in an AWGN channel with bit-pulsed jamming and BPSK modulation. ICA-RAKE uses $N_a = 2$ antenna elements, while $N_a = 3$ includes reduction of dimension by one in the whitening stage.

elements is increased, ICA-RAKE has a comparable performance up to a BLER level of 10^{-2}.

5. CONCLUSION

Jamming problems are important in DS-CDMA communications because both intentional and unintentional jamming can occur in several practical circumstances. In this paper, we have considered suppression of a bit-pulsed jammer signal in a direct sequence spread spectrum communication system (DS-CDMA). The proposed method is based on independent component analysis (ICA) applied to sensor array signals. If the signals have low temporal correlations, ICA using higher order statistics performs well. The performance of our ICA-RAKE receiver structure was comparable or better than its MRC equivalents under severe jamming, and provided a nearly 3 to 5 dB gain over the compared methods when the block-error-rate was fixed to 10^{-1} or 10^{-2}. The work presented here can be extended in several ways by considering different types of jamming and information signals.

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