JAMMER CANCELLATION IN DS-CDMA ARRAYS: PRE AND POST SWITCHING OF ICA AND RAKE

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Abstract. In this paper Independent Component Analysis (ICA) is considered for blind interference cancellation in a direct sequence spread spectrum communication system utilizing antenna arrays. Recently, an ICA-assisted interference canceler was proposed [1]. This receiver structure is an extension to the framework proposed in [2], in which blind source separation (BSS) techniques were utilized to the jammer mitigation problem. A common feature for both is that they apply an advanced pre-processing tool to offer an unjammed signal for conventional detection. However, it is not always desirable to apply the pre-processing tool, since it might even cause additional interference if the jammer is weak or absent. What would make the receivers more practical is to switch the additional canceler active only whenever it is expected to improve conventional detection. In this paper we compare two possible switching strategies at both ends of the receiver chain, pre and post switching schemes, and evaluate their impacts to the overall performance improvement of the array receiver.

INTRODUCTION

Independent Component Analysis (ICA) [3] is a fairly new statistical technique which has recently drawn a lot of attention both in the neural network and signal processing communities. 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 $x_1(t), \dots, x_m(t)$ at the time instant t are assumed to be linear combinations of n unknown but statistically

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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.

We 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 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 $x_i(t)$.

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 [4]. 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 [2, 5] 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 [2] the idea of applying blind source separation (BSS) techniques before conventional detection [6]. 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 [2] 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 [2] 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. These problems were circumvented in [1] and [7], where independent component analysis was utilized instead of second-order blind source separation techniques.

The standard receiver used in DS-CDMA communications is the RAKE detector [9], which consists of a bank of matched filters. RAKE uses prior knowledge on the desired user's code, and it can be applied also when a jammer signal is present. However, RAKE does not exploit independence of the information bearing signal from the jamming signal in any way. In this work, we try to utilize the available information as well as possible by combining RAKE and ICA sequentially when it is reasonable.

It should be noted that all the BSS/ICA-based receivers mentioned above are still impractical as such in the sense that they employ a BSS/ICA block even though it is not sure whether it is always desirable. In fact, if the jammer is weak or even absent, the additional BSS/ICA jammer cancellation block might even cause addition interference for the information bearing signal. This question was raised in [8], in which the additional ICA-based interference canceler was activated adaptively based on the quality of received training symbols. In this paper we further develop these ideas and compare two different switching strategies, namely pre and post switching schemes, which correspond to two different switching criteria between ICA-assisted and conventional RAKE detection in the array receiver chain.

SYSTEM MODEL

In this application, a standard spread spectrum system [9] 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 [3], Chapter 23 for an introduction)

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

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, $d \in \{0, \ldots, (C-1)/2\}$, 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 [9, 3].

We assume further that the received signal $r(t)$ in (2) is jammed by a signal $q(t)$, which has the form

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

Here $\delta_p(t) = 1$ with a probability p during a symbol. Jamming corresponds to a continuous wave when $p = 1$ and pulsed wave at the symbol level otherwise. The above two methods are not necessarily the only means of jamming, but they surely are the very common cases. 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 ($n = 1, \ldots, N$) before the down-conversion can be written as

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

where $r(t)$ is the baseband spread spectrum signal that is DSB modulated at a carrier frequency f_c [9]. 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

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

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

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

where

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

and $\mathbf{n}(t)$ is the additive white Gaussian noise (AWGN) vector. This model has the same form as (1) with two independent sources and $\mathbf{A} = \Theta$.

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 $\mathbf{W}$ [3, 5]. 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 [12, 3, 11]. 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 [3]. Some other ICA algorithms developed for complex mixtures, for example JADE [3], were also tried, and they performed equally well. Alternatively, one could apply a complex version of the neural natural gradient algorithm [5].

In most ICA methods, the data are first pre-whitened spatially. This makes the subsequent separation task easier, because the separating matrix is constrained to be orthogonal [3]. In whitening, the observed mixtures $\mathbf{r}(t)$ are transformed linearly so that their components become uncorrelated and have unit variance:

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

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

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

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 [3].

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 [12, 3]

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

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 [12]. These typically apply slower growing nonlinearities which are more robust against outliers and impulsive noise in the data. In addition to 10, the columns of $\mathbf{w}_i^+$ must be orthonormalized after each step.

PRE AND POST SWITCHING OF ICA AND RAKE

ICA inherently has two indeterminacies, which must be taken into account in the design of the ICA-assisted receiver. First of all, the sources can only be estimated up to a permutation, so some criterion must be chosen for the selection of the desired source. Second, a scalar can be exchanged between the source and the respective column of the mixing matrix, possibly introducing a phase reversal for the estimated source. Training symbols or a preamble was used in [1, 7] to solve these problems.

The same training symbols can also be used to determine whether the additional jammer cancellation by ICA is desirable or not. In general, this decision can be made either before or after ICA has been active, see Figs. 1 and 2. Here the switching between ICA-RAKE and RAKE branches is based on the preamble sequence matching. In the pre-switching scheme, the switch decides if there is a need to separate the jammer by ICA prior to conventional detection, or if the convential detection alone is performed. In the post-switching scheme, however, both ICA-RAKE and RAKE branches are active, but the final output of the receiver is chosen to be that branch which results in higher correlation with the training symbols.

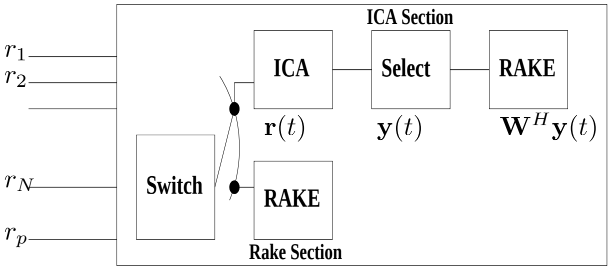

Figure 1: Pre-ICA-RAKE Switching Configuration. $r_1 \dots r_N$ is the received data, r_p is the preamble sequence used for switching between the two sections, $\mathbf{W}$ is the orthogonal separating matrix.

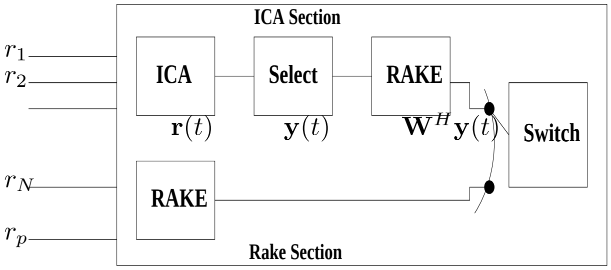

Figure 2: Post ICA-RAKE Switching Configuration. $r_1 \dots r_N$ is the received data, r_p is the preamble sequence used for switching between the two sections, $\mathbf{W}$ is the orthogonal separating matrix.

SIMULATION RESULTS

The simulation environment was an AWGN channel [13] with a known path delay. The DS-CDMA system consisted of $K = 8$ users, and each user was spread with short Gold codes of length $C = 31$. Each data block was assumed to have $M = 200$ QPSK symbols. Downlink data was considered during the simulations. During each simulation, a desired user was chosen randomly, and jammer power, measured as the Signal-to-Jammer Ratio (SJR) was defined with respect to this user. Standard RAKE was used when the number of antenna elements was $N_a = 1$ (single element array), while maximal ratio combining (MRC) was used when the array elements exceeded 1. A maximum of $N_a = 3$ elements was used. The pre and post ICA Switch employed FastICA, and when the number of antenna elements exceeded 2, the data dimension was reduced during the whitening process, as described in Section 3. The results are based on 3000 independent runs. The results are compared against standard RAKE, RAKE with maximal ratio combining, and against ICA-RAKE without any switching. The jammer was either locked to the carrier frequency or had a frequency offset, when the jamming was continuous. In the case of a pulsed jammer, the jammer was unlocked. Pre-switching involved activation of the ICA-RAKE branch only if more than 10% of the training symbols were erroneously estimated by RAKE. Post-switching involved switching at the decision device, where either the soft decision outputs of the ICA-RAKE branch or the RAKE branch were decoded, based on the errors with respect to the training sequence.

In the continuous wave setting, the SJR varied against a constant SNR of 10 dB. The achieved bit-error-rate (BER) and block-error-rate (BLER) were calculated. Fig. 3 shows the achieved BER in the case of a locked jammer. All ICA versions achieve around 5 dB gain compared to RAKE or MRC. While ICA without switching saturates beyond 5 dB, pre-switching now switches to the RAKE portion of the receiver and hence its performance is similar to MRC beyond 5 dB. Post-switching on the other hand performs at least 1 dB better than pre-switching, and starts to saturate much later. The BLER curves in Fig. 4 show that post-switching is better than pre-switching by at least 3 dB everywhere. Pre-switching performs well under heavy jamming, but the performance of post-switching is better over the whole range.

Using a pulsed jammer which had a frequency offset resulted in the bit and block error rates shown in Figs. 5 and 6. Pre-switching is equivalent to MRC in this case, while post-switching results in a gain of 1 dB in the -15 to 5 dB region, as seen in the BER curves. In fact the BLER curves show that post-switching outperforms pre-switching by at least 2 dB when the target is 10^{-1} and provide a better performance in the area of high jamming.

Increasing the number of antenna elements gives results comparable to the two-antenna case and are not shown here.

CONCLUSIONS

In this paper, we considered the effect of switching between a blind separation algorithm and a standard RAKE receiver with multiple antenna elements at both ends of the receiver chain. This formed the pre and post ICA-RAKE-Switch receiver. The switch can mitigate the effects of a correlated or uncorrelated jammer in a direct sequence spread spectrum system, with the use of independent component analysis. Pre-switching was less complex, and more effective than MRC in the case of a continuous wave jammer, while post-switching worked better in all cases, especially when the jammer was pulsed in nature. Both methods provided around 5 dB gain over conventional methods, during the period of heavy jamming. This was evident in all the BER and BLER curves.

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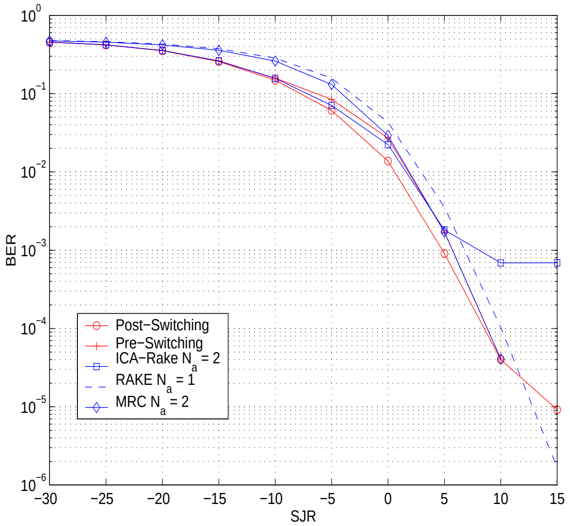

Figure 3: Bit-error-rate as a function of SJR at an average SNR = 10 dB. This system had $K = 8$ users of equal strength in an AWGN channel with a continuous wave jammer, that was locked to the center frequency. The antenna was a 2 element array. ICA-RAKE does not involve any switching, while pre and post ICA-RAKE switching involved switching at either ends.

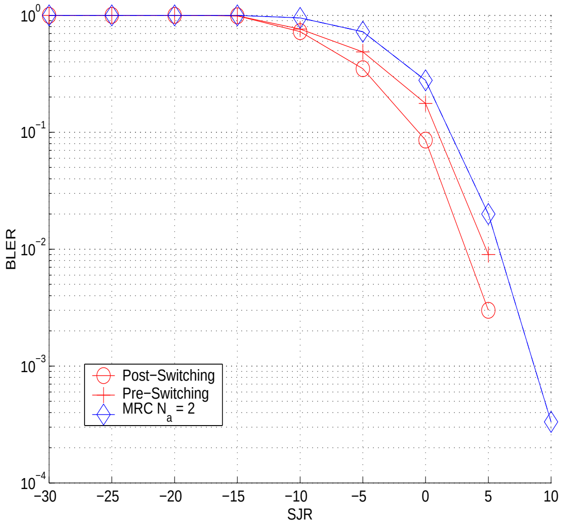

Figure 4: Block-error-rate as a function of SJR at an average SNR = 10 dB. This system had $K = 8$ users of equal strength in an AWGN channel with a continuous wave jammer, that was locked to the center frequency. The antenna was a 2 element array.

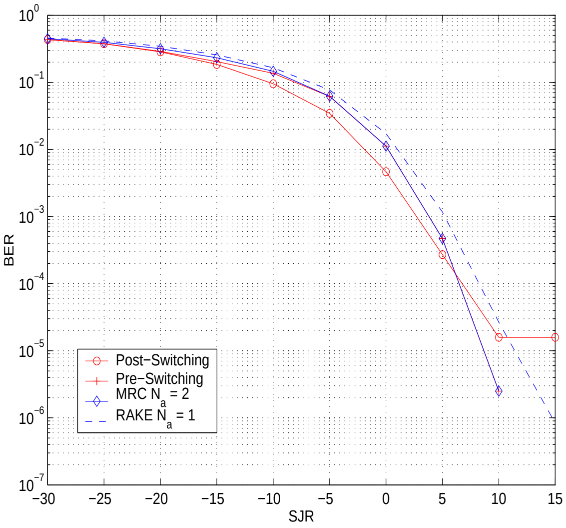

Figure 5: Bit-error-rate as a function of SJR at an average SNR = 10 dB. This system had $K = 8$ users of equal strength in an AWGN channel with a bit-pulsed jammer, that had a frequency offset. The antenna was a 2 element array.

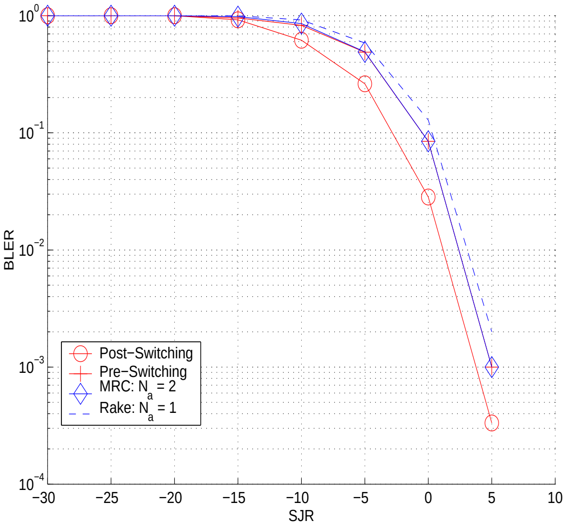

Figure 6: Block-error-rate as a function of SJR at an average SNR = 10 dB. This system had $K = 8$ users of equal strength in an AWGN channel with a bit-pulsed jammer, that had a frequency offset. The antenna was a 2 element array.