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A two-stage Independent Component Analysis-based method for blind detection in CDMA systems

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ABSTRACT

We propose an ICA-based method for blind detection of users in asynchronous DS-CDMA communications systems with multipaths channels with the only knowledge of the desired user's code. The method can handle both the uplink and the downlink situations, since it does not require the synchronism between users. We convert the received cyclostationary signal into an observations vector that follows the ICA model with instantaneous mixture. The selection of the estimated source is carried out by means of the desired user's code. Unlike previous works, we avoid to project the results after each iteration. Instead, we introduce a preprocessing based on a linear transformation of the data that enforces the extraction vector to lie in the desired user's subspace. The detection is done in two stages. The second stage is a fine tuning in which the constraint is removed from the data in order to obtain more accurate results. Computer simulations show that the proposed method compares favorably with other well-known methods, in terms of mean-square error (MSE) of the output, symbol error rate and robustness against the near-far problem.

1. Introduction

Blind Signal Separation (BSS, also Blind Source Separation) is a technique that aims at the recovery of a set of signals (sources) that have been linearly mixed into a set of observations without the knowledge of the mixing system or of the sources. When the goal is to retrieve a subset of the sources the technique is called Blind Signal Extraction (BSE, also Blind Source Extraction). As a particular case of BSE we can consider the estimation of a single source.

In order to achieve this blind recovering, it is necessary to exploit some *a priori* information about the sources. One property that has received especial attention is the independence of the sources, which leads to the Independent Component Analysis (ICA) [1–3]. In recent years several ICA algorithms and criteria have been proposed for complex-valued sources, some of them based on higher-order cumulants [2,4–8] and others based on nonlinearities of the outputs that try to approximate either the probability density function of the sources (like in the ML and Infomax criteria) or the output's negentropy [9–13].

The blind detection of communications signals is an application of BSS and BSE methods for complex-valued sources. In digital communications there are two types of interferences: co-channel interference (CCI), due to the sharing of the same time-frequency-code slots by the users; and inter-symbol interference (ISI), due to the multipath channels [14]. The blind detection process equalizes the channels, avoiding training sequences used by supervised detectors, and allowing a more efficient use of the channel bandwidth [15–18]. As it was shown by several authors [8,19–21] blind detection can be seen as a BSS or BSE problem where the mixing system depends on the impulsive response of the channels.

In the case of CDMA (Code Division Multiple Access) systems, users share the same time and frequency slots, but have different codes [22]. Traditionally the blind detection of users in CDMA systems has been considered from the point of view of the blind deconvolution or equalization, and several methods have been proposed exploiting the signal subspace generated by the desired user's code [23–25], like MMSE-based algorithms [24,26], those based on the inverse filter criterion [27,28] or on the constant modulus algorithm (CMA) [29]. Some authors also consider the use of multiple antennas [26,30–33] in order to exploit spatial diversity. Inverse filter criterion (IFC) has received a particular attention because of its ability to suppress both MAI (multi-access interference, also MUI, multiuser interference) and ISI in CDMA systems. In IFC approaches the CDMA system is interpreted as a linear and convolutive MIMO (multiple inputs multiple outputs) system, and the optimum equalizer is achieved based on several criteria that exploit either second-order statistics (SOS) [34–36] or higher-order statistics (HOS) [27,28,37,38].

Exploiting the strong connection between blind equalization and ICA, several authors have considered the blind detection in

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CDMA systems as an ICA problem [21,39–42]. The use of ICA is justified by the non-Gaussianity of communications signals, the mutual independence between the symbols sequences corresponding to different users and the independence between symbols for a certain sequence. Several ICA-based methods have been proposed for the downlink [21,39,40], thus assuming the synchronism between users and the absence of near-far problem (i.e., equal power for all users' contributions). These methods combine classical detectors with ICA-based stages. Other authors have proposed ICA-based methods for the uplink [41,42]. In [41] FastICA is used for simultaneous separation of all users, then using the correlation with the codes to identify each user. Peng et al. [42] use the FKMA (Fast Kurtosis Maximization Algorithm) proposed by Chi and Chen [43].

In previous works [8,44] we proposed an ICA-based method for blind detection of users in DS-CDMA systems considering the asynchronism between users, the near-far problem and multipath channels. Exploiting the cyclostationarity of the received signal and the multipath channels we converted the original cyclostationary and convolutive MISO model (multiple inputs single output) into a linear and instantaneous MIMO model, which corresponds to a linear and instantaneous mixture of sources. This method used a constraint based on the desired user's code related to those proposed in the context of blind equalization [26,27,37]. Like in these previous works, the constraint had to be applied as a projection of the results after each iteration of the algorithm.

In the present paper we propose a novel method that incorporates a new constraint which is applied to the data rather than to the results. This implies a reduction of the data dimension by means of a linear transformation of the observations vector which projects it onto the subspace associated to the desired user's code, thus avoiding the need of a projection of the results after each iteration. The proposed method is aimed at the recovering of the symbols sequence of a desired user whose spreading code is known. This estimation is made with the aid of a BSE algorithm for the extraction of one source.

The paper is organized as follows. Section 2 describes the signal model and notation that we use. Section 3 describes the conversion of the original MISO model into a linear and instantaneous MIMO model. In Section 4 we propose a linear transformation of the data in order to enforce the extraction of the desired user. The proposed blind detection method is introduced in Section 5. In Section 6 we present a set of computer experiments in order to illustrate the theoretical results. Finally, in Section 7 we summarize the main conclusions of our work.

2. Signal model and notation

Let us consider the sources vector $\mathbf{s}(k) = [s_1(k), \ldots, s_N(k)]^{\mathrm{T}}$ containing a set of N complex-valued sources with zero mean and unit variance that are mixed by a linear and instantaneous mixing system in a noisy environment to yield a vector of M observations $\mathbf{x}(k) = [x_1(k), \ldots, x_M(k)]^{\mathrm{T}}$, given by

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

where $\mathbf{A} \in \mathbb{C}^{M\times N}$ is the constant matrix that represents the mixture and $\mathbf{n}(k)$ the noise vector. In BSS problems, the vector of outputs or estimated sources, $\mathbf{y}(k)$, is computed by means of a separation matrix, $\mathbf{B}$, by the expression[1] $\mathbf{y}(k) = \mathbf{B}^{\mathrm{H}}\mathbf{x}(k)$. However, in BSE problems for the recovering of only one source, the output signal, $y(k)$, is a scalar signal, and is obtained by means of an extraction vector, $\mathbf{b}$, as $y(k) = \mathbf{b}^{\mathrm{H}}\mathbf{x}(k)$. In fact, each column of a separation matrix in a BSS problem can be considered as the extraction vector that provides one of the outputs in a BSE problem.

A common preprocessing is the prewhitening of the observations in order to obtain a new data vector, $\mathbf{z}(k) = \mathbf{W}\mathbf{x}(k)$, whose covariance, $E[\mathbf{z}\mathbf{z}^{\mathrm{H}}]$, is the identity matrix of dimension $N \times N$. $\mathbf{W}$ is called the prewhitening matrix. In this case, the output signal is computed as $y(k) = \mathbf{u}^{\mathrm{H}}\mathbf{z}(k)$, where $\mathbf{u}$ is the unit-norm extraction vector (enforcing the output to have unit variance). The overall transfer vector from the sources to the output is defined by the row vector $\mathbf{g}^{\mathrm{H}} = \mathbf{u}^{\mathrm{H}}\mathbf{W}\mathbf{A}$.

In communication systems the sources vector consists of shifted versions of the user's symbols sequences. We will consider a DS-CDMA system with N_u active users, whose respective symbol sequences are $\{b_j(k)\}$, $\forall j = 1, \ldots, N_u$. Each symbol sequence consists of zero-mean i.i.d. (independent and identically distributed) complex-valued symbols (quadrature modulation is considered). For different users, the sequences are also mutually independent. The spreading sequence of the jth user is given by its code's vector $\mathbf{c}_j = [c_j(N_c - 1) \ \cdots \ c_j(0)]^{\mathrm{T}}$ and has a duration of exactly one symbol, thus resulting in a process gain of N_c chips/symbol. For synchronous CDMA systems, orthogonal codes (e.g., Walsh codes) are able to remove the multiuser interference (MUI) when there are not multipath channels. However, for asynchronous CDMA systems, it is usual to take pseudorandom sequences for the users' codes (e.g., Gold codes), since it is not possible to guarantee the orthogonality between codes for any delay [22].

In these conditions, the signal transmitted by the jth user is

$$\hat{x}_j(m) = \sum_{l=-\infty}^{\infty} b_j(l)c_j(m - lN_c), \quad j = 1, 2, \ldots, N_u. \tag{2}$$

Let us denote by $a_j(m)$ the impulse response of the channel from the jth transmitter to the receiver, sampled at the chip interval, T_c, where $m \in \mathbb{Z}$. For now this impulse response can be considered of infinite length, i.e., $-\infty < m < \infty$. In general, at the uplink this impulse response is different for different users, and it includes the effects of chip-matched filtering at the receiver [45], but not the transmission delay (modulus N_c) of the jth user, d_j (asynchronism between users is assumed). Without loss of generality, we can consider $0 \leqslant d_j \leqslant N_c - 1$. Therefore the contribution of the jth user at the receiver is given by

$$\tilde{x}_j(m) = \sum_{l=-\infty}^{\infty} a_j(l)\hat{x}_j(m - d_j - l). \tag{3}$$

By grouping the effects of the code and the channel into the effective channel

$$h_j(m) = \sum_{l=0}^{N_c-1} c_j(l)a_j(m - l), \tag{4}$$

we can rewrite the contribution of the jth user at the receiver as

$$\tilde{x}_j(m) = \sum_{l=-\infty}^{\infty} b_j(l)h_j(m - d_j - lN_c). \tag{5}$$

The contributions of all users are superimposed at the receiver in the presence of additive white Gaussian noise, $n(m)$, so that the received signal is given by

$$\begin{aligned}\tilde{x}(m) &= \sum_{j=1}^{N_u} \tilde{x}_j(m) + n(m) \\ &= \sum_{j=1}^{N_u} \sum_{l=-\infty}^{\infty} b_j(l)h_j(m - d_j - lN_c) + n(m).\end{aligned} \tag{6}$$

[1] The superscripts $()^*$, $()^{\mathrm{T}}$, $()^{\mathrm{H}}$ denote conjugate, transpose and conjugate transpose, respectively.