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A clustering approach for the blind separation of multiple finite alphabet sequences from a single linear mixture

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Abstract

In this paper, we treat the blind separation problem of binary signals and multilevel PAM signals from a single real mixture or a single complex mixture, respectively. Our approach is based on the clustering of the observation values and the close relationship between the position of the cluster centers and the mixing coefficients. Under mild assumptions, our mathematical formulation yields two deterministic algorithms for the blind estimation of the mixing operator. In the real mixture case we derive a finite, recursive algorithm exploiting the arrangement of the centers along the 1-D line, while in the complex mixture case we exploit the properties of the convex hull of the 2-D data cloud to estimate the mixing parameters. In the absence of noise and for any number of sources, both methods yield perfect results. Following the parameter estimation step, the source symbols can be estimated using a nearest neighbor rule. In the noisy case, our error analysis shows that the parameter estimation error increases smoothly with the noise power, while the source estimate bit error rate depends on relative size of the noise power and the minimum distance between the cluster centers.
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Keywords: Blind source separation; BSS; Finite alphabet signals; Single mixture; Overdetermined mixtures

1. Introduction

The blind separation of signals from a set of observed linear mixtures with constant coefficients is known as blind signal separation from instantaneous mixtures (BSS-IM). This problem finds applications under a variety of contexts. For example, in the reverse link model of wireless, multiuser communications, n user signals arrive at the base station impinging on an array of $M_a > 1$ antennas. Each antenna records a mixture of the signals affected by multipath results such as delay spread, frequency spread, and angle spread. A core problem in multiuser blind equalization/signal separation is the estimation of the sources using

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just the antenna baseband data sampled at a suitable rate. If the delay spread is negligible and the sources are synchronized, then the baseband data model takes the form of a linear combination of the sources with constant, complex mixing coefficients [1]. Even though the BSS-IM problem seems simplistic it is important because realistic FIR-MIMO equalization scenarios allowing large delay spread, unsynchronized sources and arbitrary modulation functions can be reduced to the above problem. An important and special case is the one where the sources transmit symbols from a finite alphabet (FA). In particular, binary antipodal symbols $\{-1, +1\}$ appear in many digitally modulated schemes such as, binary phase shift keying (BPSK) [2], direct-sequence CDMA [3], BSS-IM for FA signals has attracted a lot of attention and various algorithms have been proposed in the literature, especially for binary sources, including, ILSE, ILSP, [4], ACMA [5], SD [6,7], AMiSRoF [8], etc.

Digital communications is not the only reason for our interest in BSS-IM. In fact, there is a fast growing literature on the problem of blind source separation (BSS) from real or complex instantaneous mixtures. Traditional approaches are usually based on appropriate statistical problem formulations. Higher-order statistics are used in the independent component analysis (ICA) method which assumes that the sources are white, independent random sequences [9,10]. Second-order statistics can be also used provided that the source signals are colored [11]. These methods have found applications in array signal processing [12], speech separation [13], medical signal processing [14], industrial fault detection [15], feature extraction for image and speech data [16–18], etc. For a thorough discussion of ICA, BSS and related topics see [19,20].

In this paper, we study the BSS-IM problem for binary antipodal sources or M-ary PAM sources under the constraint that there is only one available mixture although there are $n > 1$ sources. The importance of the problem is obvious since the reduction of the number of sensors affects the cost and the complexity of the blind signal separation system. The separation of more sources than mixtures is attracting increasing attention in recent years. One of the first approaches was proposed by Belouchrani and Cardoso [21]. This method is based on the FA property of the sources and offers the maximum likelihood estimation of the mixing parameters using the EM algorithm. Although it is primarily concerned with the case where the number of observations is greater or equal to the number of sources the authors present an example where the algorithm works with 2 observations and 3 sources. However, our simulations show that with 1 mixture and $n > 2$ sources the method does not perform well because the EM algorithm is very often trapped in local minima. Since good initial conditions are difficult to derive the algorithm does not seem to be a promising candidate for this case. Another approach based on self-organizing maps (SOMs) was presented in [22]. Again the method is designed primarily for problems with equal numbers of sources and mixtures. Performance decreases rapidly when the number of sensors m becomes smaller than the number of sources n. For example, after 1000 trials of the algorithm with $m = 1$ and $n = 4$ no source signal was recovered for 989 times. The problem of nonlinear BSS was treated in [23,38] using a maximum likelihood approach. In the case of binary sources the method can work for $n > m$ and it becomes similar to [21]. The same drawbacks as discussed above apply to this method as well. More recently, Lee et al., [24] proposed a gradient learning algorithm for the maximization of the data likelihood function. The method applies to continuous signals and can successfully separate up to 4 speech signals from 2 mixtures. For binary sources the method becomes similar to the maximum likelihood approach in [21].

Our approach is not based on the optimization of signal statistics but on the clustering of the observed data. We use the FA property of the sources to obtain a theory which relates the position of the cluster centers with the mixing coefficients. We will find that the problem is more combinatorial in nature rather than stochastic. Preliminary results of this research have been presented elsewhere [25,26] for the special case of binary antipodal sources and one real mixture. Li

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