Asian Journal of Information Technology 6 (3): 323-328, 2007

Performance Study of Receiver Based on Independent Component Analysis in CDMA Systems

Abdelkrim Hamza and Salim Chitroub
Signal and Image Processing Laboratory, Electronics and Computer Science,
Faculty, U.S.T.H.B. P.O. Box 32, 16111, Algiers, Algeria

Abstract: To improve the performances of the wireless mobile communication system, a statistical method is illustrated in this study. It consists in separating the signals at the reception of the communication systems which are based on the Code Division Multiple Access technology. The idea is to optimize the separation of the various users sharing the same frequency and temporal resources using the emergent statistical method called Independent Component Analysis (ICA). ICA makes it possible to extract the emitted signals that are as statistically independent as possible. Bit error rate and the signal to noise ratio are used as criteria for evaluating the performances of the ICA receiver. Adding White Gaussian Noise to input signal channel and the Rayleigh channel (fading channel) cases have been considered. A comparative study with the conventional receivers such as the RAKE, the Matched filter (Mf) and the Minimum Mean-Squared Error is carried out. The obtained results show the superiority of ICA receiver compared to the MF receiver.

Key words: Digital communication, signal processing, Blind Source Separation (BSS), statistical independence, interference cancellation

INTRODUCTION

In the field of the mobile telecommunication systems, the technology of Code Division Multiple Access (CDMA) is a strong candidate for the evolution of the wireless digital communication systems. The Wideband CDMA (WCDMA) systems were already selected to solve the problem of air interface in Universal Mobile Telecommunication Services (UMTS), which provide a multitude of services, particularly of multimedia and data transmission with high flow. In fact, one of the principal challenges that faced the evolution of the wireless telecommunication systems is the effective use of the available band-width. The demands to provide a sufficient quality and capacity to the services with high flows are in increase.

The need to take account of the multiple users who want both to reach the same channel and to share in an optimal way the resources of bandwidth has contributed to the emergence of the CDMA-based systems. Indeed, the CDMA-based systems solve partially this problem since they make it possible to all the users simultaneously to reach the totality of the band by exploiting the technique of spectral spreading. The speakers are distinguished in the reception by distinct specific codes. The codes are specified using the principle of the orthogonal codes. However, the orthogonality principle of the codes might not be efficient because of several practical considerations and consequently the separation of the emitted signals becomes very difficult (Lee *et al*., 1999; Moshavi, 1996; Cristescu *et al*., 2000; Waheed *et al*., 2003). In fact, the Multiple Access Interferences (MAI) and the Inter Symbol Interferences (ISI) are the principal causes of the inefficiency of the separation process. The MAI are due to the fact that the signals are transmitted at the same time and in the same frequency band. Meanwhile, the ISI are due to the several trajectories of the signal propagation in the channel. This phenomenon becomes significant in the case of the systems with a high flow. Moreover, the transmission problems such as fading, losses of synchronization, interferences... etc., makes this technique very complex. The receivers such as the RAKE and the Matched Filter (MF), which take into account only the frequency diversity, become unsatisfactory in the case of loss of orthogonality. One of the solutions consists in studying the structure of MAI in order to eliminate them. Nevertheless, the high cost in term of computation time could generate sub-optimal detectors such as in the case of the Minimum Mean-Squared Error (MMSE) receiver. Blind Source Separation (BSS) techniques, recently developed in the signal processing community, could be

Corresponding Author: Abdelkrim Hamza, Signal and Image Processing Laboratory, Electronics and Computer Science, Faculty, U.S.T.H.B. P.O. Box 32, 16111, Algiers, Algeria

considered since only the knowledge of the desired user signatures is required for separating the emitted signals (Dahmane, 2005). In this context, a new axe of research to improve the separation and detection of the telecommunication signals is recently launched in the community.

The remainder of this study is structured as follows. The next study is devoted to describe the Independent Component Analysis (ICA) method and how it can be applied for CDMA signal separation. After an overview of ICA methods, the application model of ICA for CDMA-based system is detailed in this study. We present the structures of the different receivers used in this study.

ICA FOR CDMA-BASED SIGNAL SEPARATION

Recently, Blind Source Separation (BSS) by ICA has received attention because of its potential applications in various domains. As the name implies, ICA is to find the transformation such that the resulting components are as statistically independent from each other as possible. It takes into account of higher order statistical properties and its components are mutually independent with respect to these higher order statistics. ICA can be carried out by using many different methods.

The statistical-algebraic algorithms are cumulate-based methods. They use joint diagonalizing of a set of fourth-order cumulate matrices and exploit their algebraic properties. The algebraic-based algorithms typically require extensive batch computations using estimated higher-order statistics. ICA is also suitable for neural network implementation and different theories recently proposed for that purpose lead to the same iterative learning algorithm. Lee *et al*. (2000) review those theories and suggest that information theory can be used to unify several lines of research. Different automatic neural network based algorithms for ICA are reviewed in (Lee *et al*., 1999, 2000; Hyvarinen, 1999). The most popular of them is the Fast-ICA algorithm that is based on a fixed-point iteration and uses a deflation scheme to calculate components sequentially (Ristanieni *et al*., 2002; Hyvarinen, 1999). It has contributed to the application of ICA to large-scale problems due to its computational efficiency. Another popular algorithm of ICA is the Info-max algorithm that maximizes the joint entropy of the components (Dahmane, 2005; Duran and Cruces, 2003). It has a simple neural network architecture and can deal with either sub-Gaussian or super-Gaussian components by adaptively switching between them. Because of its speed and simplicity properties, the Fast-ICA algorithm is used for elaborating the ICA-based receiver to separate the emitted signals. However, the mathematical details of this algorithm are out of the scope of this study and the reader could consulte, for more details, the following reference (Cardoso, 1998).

Note that the most application of ICA so far has been on blind signal separation of unknown source signals from their linear mixture for which ICA obviously is useful. The use of ICA for digital communication has been limited. We believe that ICA can be useful in telecommunication domain. In this study, we will demonstrate some potential advantages of ICA in interference cancellation for an optimal separation of CDMA signals.

General ICA model : Under some statistical assumptions and in the environment in which a white additive noise that affected the data is supposed, the general ICA model for the BSS problems can be formulated in the matrix notation in the following form:

$$R = GB + N \tag{1}$$

where R is the observed data vector, G is the mixture matrix that we look for it and B is the vector of the non Gaussian signals (sources) that are supposed to be unknown. The vector N is a realization of the White Gaussian process of the additive noise.

The sources are estimated by using only the vector of the observations. The ICA algorithms consist of looking for the inverse of the mixture matrix and hence the sources could be obtained by computing the following form of the produce: $\hat{B} = \tilde{G}^{-1}R$, where $\hat{B}$ and $\tilde{G}$ are the estimated sources and the estimated mixture matrix, respectively.

CDMA system model: ICA supposes that the emitted signals are non-Gaussian and statistically independent. These assumptions are realised for CDMA-based transmission systems. In fact, without a priori knowledge of the nature of the emitted signals as well as the parameters of the propagation channels, there are criteria that can be used for detecting the desired signals by using only the a priori information of the code of the desired user. The recourse to the training sequence, which has an affect in reducing the effectiveness of the transmission system, could be now avoided.

There are other reasons that justify the use of the ICA for optimizing the signal separation of CDMA-based systems. First, ICA could be used to reduce the near-fact effect. Second, the ICA model does not need the knowledge of all the parameters of the system. Third, it is possible to consider a hybrid receiver made of a ICA receiver and another type of receiver at the same time.

To start, here is a description of the model for the transmission channel. This model is that of a downlink CDMA. Let K is the number of the system users. Thus, the received signal has the following form (Ekiei and Yongacoghe, 2004):

$$r(t)=\sum_{k=1}^{K}\sum_{n=0}^{N-1}A_k b_k(n)\sum_{l=1}^{L}h_{k,l}(n)s_k(t-nT-\tau_l)+n(t) \quad (2)$$

where $s_k(t)$ is the sequence of the signatures assigned to the k^{th} user in the channel, N represents the total number of symbols during the interval of observation and K represents the total number of users. The constant L represents the number of path per symbol. $b_k(n)$ represents the n^{th} symbol of the data transmitted by the k^{th} user. A_k represents the energy of the signal of the user. The $h_{l,k}(n)$ represents the fading factor for the l^{th} transmission path, which is supposed to be constant during the block of N symbols of data. The length of the sequence chip is C. τ_l is the time of transmission for the l^{th} transmission path and T is the symbol period. n(t) is the Gaussian noise and σ^2 is its energy. The model can be represented in the following compact form:

$$r = SHAb + \eta \quad (3)$$

where the received signal is such as:

$$r=\left(r(0)^t, r(1)^t,...,r(N-1)^t\right)^t \quad (4)$$

$$r(n)=\left(r(T_c(nN+1)),...,r(T_c(n+1)N)\right)^t \quad (5)$$

$$s=\left(s(0),s(1),...,s(N-1)\right) \quad (6)$$

$$S(n)=\left(s_{1,1}(n),...,s_{1,L}(n),...,s_{K,L}(n)\right) \quad (7)$$

$$H=\text{diag}\left(H(0),H(1),...,H(N-1)\right) \quad (8)$$

$$H(n)=\text{diag}\left(h_1(n),h_2(n),...,h_K(n)\right) \quad (9)$$

$$h_K(n)=\left(h_{K,1}(n),...,h_{K,L}(n)\right)^t \quad (10)$$

The matrix A is given by:

$$A=\text{diag}\left(A(0),A(1),...,A(N-1)\right) \quad (11)$$

$$A(n)=\left(A_1,A_2,...,A_K\right) \quad (12)$$

The transmitted symbols are:

$$b=\left(b(0)^t,b(1)^t,...,b(N-1)^t\right)^t \quad (13)$$

$$b(n)=\left(b_1(n),b_2(n),...,b_K(n)\right)^t \quad (14)$$

In the following sub-section, we show how the ICA model could be considered for modelling the CDMA systems.

ICA model for CDMA system: We observe that G = SHA depends on the codes and on the profits of the paths. The matrix B depends only on the symbols transmitted by the user (Lupas and Verdu, 1980). The model of the CDMA system describes by (3) is similar to the general model of ICA given in (1). By supposing that the various sequences transmitted by the users are statistically independent, the Eq. 2 represents the linear standard model of ICA (Ristanieni *et al.*, 2002; Duran and Cruces, 2003) expressed in the form of matrices, where B is a matrix whose columns are the source vectors, R is the observation matrix whose columns are the observed data vectors and G is the unknown matrix of mixture.

In this study, a blind separation method of CDMA signals by using the ica is presented. A comparative study, in order to show the advantages and possibly the disadvantages of this method, is carried out. For that, two cases have been considerate: the case of the Add White Gaussian Noise to input signal (awgn) channel and the case of the Rayleigh channel (fading channel). A comparative study with the conventional receivers such as the RAKE, Matched Filter (MF) and the Minimum Mean-Squared Error (MMSE) is then realised.

RECEIVER STRUCTURES IN CDMA

A particular interest in MF, RAKE and MMSE receivers, respectively is done. In the case of AWGN, receiver MF minimizes the probability of error (Cristescu *et al.*, 2000). This is not valid any more as soon as the signal is corrupted by the MAI which are caused by the correlation between the desired signal and the signals from the other users. MAI becomes problematic when the number of users increases. Another alternative consists then of the application of the multi–user detectors (Tugnait and Li, 2001; Cardoso, 1998) that are characterized by a detection of all the output signals of the MF filter. However, this detection presents the disadvantage of an exponential increase in computation cost proportional to the number of users (Ekici and Yongacoghe, 2004). The MMSE receiver is a sub-optimal detector because of the complexity that linearly increases with the number of users (Waheed *et al.*, 2003; Rajw and Ristaniemi, 2002; Duran and Cruces, 2003).

The model described in (2) could be used for deducing the forms of the linear detectors such as MF, RAKE and MMSE.

Conventional receivers: The MF receiver uses the sequence of the signatures to produce the best possible estimate of the desired signal, but without take in consideration the presence of MAI. In the Direct Sequence CDMA (DS-CDMA) system, the MF receiver for the K^{th} user takes the following form (Lupas and Verdu, 1989):

$$\hat{b}_{k,n,MF} = s_k^t r_n \quad (15)$$

where $\hat{b}_{k,n}$ represents the estimated symbol of the K^{th} user at the instant n and s_k^t represents the identification code of the K^{th} user.

The RAKE receiver is deduced from the MF receiver for the detection of the powerful signals of type multi- ways. The MMSE Receiver is the most powerful one for the DS-CDMA systems (Tugnait and Li, 2001; Cardoso, 1998; Gupta and Santhanam, 2004). This receiver has the following structure:

$$\hat{b}_{k,n,MMSE} = s_k^t V D^{-1} V^t r_n \quad (16)$$

where D and V represent the eigenvalues and the eigenvectors matrices, respectively, of the estimated auto-correlation matrix of the signals (Moshavi, 1996).

ICA receiver: We have used the Fas-tICA algorithm for elaborating the ICA receiver of CDMA signals (Waheed *et al.*, 2003; Dahmane, 2005; Ristanini and Joutsensalo, 2000). Fast-ICA, recently developed in the literature, is a very powerful algorithm for the non-Gaussian source separation. It is based on the principle of the fixed point algorithm. The training process of the neural network of Fast ICA consists of looking for the directions of the vectors w in which the statistical independence between the outputs of the network is maximized. Given the input vector data of the network, X, the output vector of the network is such as $g_i(w_i^T x)$, where g_i is the non-linear scalar function.

The algorithm for extracting the first component can be then formulated as follows:

- Randomly choose the initial vector w.
- Set $w^+ = E(x.g(w^T x)) - w.E(g^6(w^T x))$.
- Set $w = w^+ / \|w^+\|$.
- If the network does not converge, repeat the steps 2 and 3.

Convergence means that the values of w (old and new) go in the same direction i.e. becomes below the convergence criterion between the two iterations.

To estimate several components, we need to use the above algorithm with several neurons of the weight vectors $w_1,\dots,w_n$. So that the vectors do not converge towards the same maximum, we must impose the projections $w_1^T x,\dots, w_n^T x$ to be uncorrelated after each iteration. There are several methods for constraining the outputs of the network to be uncorrelated. Among them, we present here the Gram-Schmidt method. In this method, after the estimation of the p independent components ($w_1,\dots,w_p$), we use the algorithm of the fixed point to consider the (p+1)th component, i.e., vector w_{p+1} and after each iteration we make the subtraction from the vector w_{p+1} the projections $w_{p+1}{}^T w_j w_j$, (j=1…p) and we renormalize w_{p+1}, so we have:

$$\text{Set } W = W \Big/ \sqrt{\|WW^T\|} \cdot$$

$$\text{Set } W = \frac{3}{2} W - \frac{1}{2} W.W^T.W \cdot$$

The algorithm finds the separation matrix W of the sources. The performance of this algorithm depends on the choice of the function g. The components are sequentially extracted. Thus, we obtain a considerable profit in performances if we extract only some components.

We note that the whitening phase is a common preprocessing step of any ICA algorithm. This step consists of making the components of the input data vectors mutually uncorrelated and normalizes their variances to unity. The whitened data matrix is computed as follows:

$$V = \Lambda^{-1/2} U_s^t R \quad (17)$$

Where Λ is the diagonal matrix containing the eagen values of the estimated data correlation matrix R and U is the matrix containing the respective eigenvectors in the same order.

RESULTS AND DISCUSSION

We will compare the performances of the receivers in context CDMA in the case of the AWGN and in the case of the fading channel with L varying from 3 to 6 paths. We suppose for reasons of simplicity that the transmission (Gold code spreading sequence) is made in a synchronous way and in downlink. The number K of users varies from 20 to 50 and for a factor of spreading C of 31, 256 and 512. The criterion taken into account to analyse the performances of the various receivers is the BER. All the system parameters are assumed to be known. Also, we have used the SNR as performance criterion and the its values vary from 0 to 20 dB.

Figure 1 illustrates the BER performances of the MMSE receiver with C = 512 and for K equal to 20, 30 and 50, respectively. We observe the good behaviour of this receiver that reaches a BER of 10^{-4} starting from a SNR equal to 8 dB. We observe also a low convergence at low SNR values. The MMSE offers better performances at large SNR values. Figure 2 shows the performances of the RAKE receiver with C = 31 and K = 10 with a fading channel. We observe the degradation of the performances when the number of path increases. For L = 1 (which correspond to AWGN channel) we obtain the best performance of this type of receiver since it reaches a BER of 10^{-4} starting a SNR equal to 10 dB. Finally we note in Fig. 3, when C = 31 and K = 10, that ICA receiver has a low convergence comparable to the RAKE receiver and the MMSE receiver but it is better than the MF receiver.

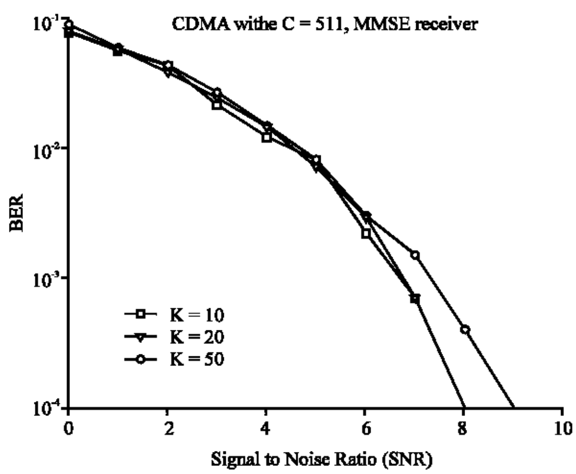

Fig. 1: BER versus SNR for the MMSE receiver

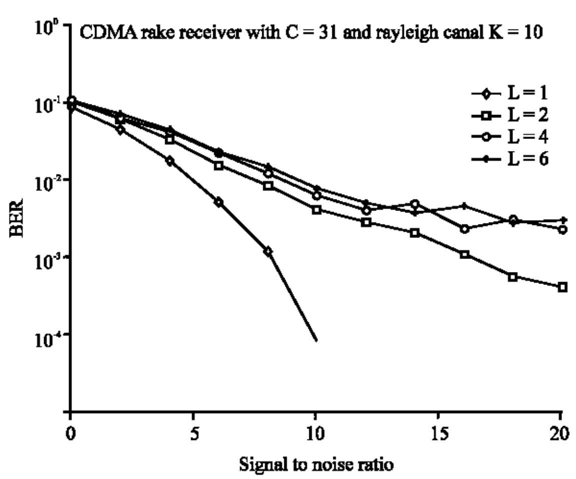

Fig. 2: BER versus SNR for the RAKE receiver

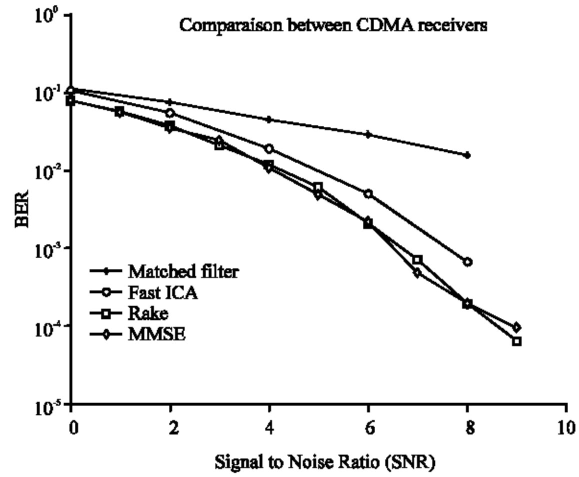

Fig. 3: BER versus SNR for the MF receiver, the ICA receiver, the RAKE receiver and the MMSE receiver

CONCLUSION

We have addressed in this study the possibility of application of the emergent statistical method, called ICA, in digital communications. We have presented the ICA receiver in order to perform the optimal separation of CDMA signals. We have exposed the ICA receiver based on the popular algorithm Fast ICA. We have also shown the performances of the conventional receivers, such as the RAKE, the MMSE and the MF receivers, in the CDMA systems in order to perform a comparative study. The simulations and the obtained results show that the ICA receiver give better performances compared to the MF receiver. We justify this superiority of ICA receiver by the fact that the MF receiver can not process the presence of ISI and MAI, while the powerful of the ICA receiver resides in its ability to eliminate the presence of the ISI as well as the MAI. According to the simulations and the results given in this paper, we envisage in the future investigations to use some mixture structures of the receivers such as RAKE+ICA or MMSE+ICA because we believe that these hybrid structures could improve the general performances of the CDMA-based systems by exploiting the advantages of each of the receivers.

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