

Blind Interference Cancellation for MIMO Wireless Systems Based On ICA Algorithm.

**إلغاء التداخل الأعمى للأنظمة متعددة المداخل متعددة المخارج اللاسلكية بالاعتماد
على خوارزمية التحليل المستقل للعناصر**

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Abstract

In this paper, a new method for blind interference cancellation of Multiple Input Multiple Output (MIMO) wireless communication systems based on Independent Component Analysis (ICA) is proposed. A proposed ICA algorithm exploits the Higher Order Statistical (HOS) of the observation signals for blindly interference cancellation and signals estimation processes is presented. In contrast to other methods, the proposed method does not require any modification in transmission side or using the training sequences that usually costs a bandwidth. Simulation results show the ability of the proposed algorithm to cancel the interference effects of the multipath fading channel comparing with other ICA algorithms and conventional method.

Keywords: Blind Interference Cancellation, MIMO Wireless Systems, Blind Source Separation, Independent Component Analysis.

الخلاصة

في هذا البحث يتم تقديم طريقة جديدة لإلغاء تداخل الإشارات اللاسلكية للأنظمة متعددة المداخل متعددة المخارج اللاسلكية بالاعتماد على خوارزمية التحليل المستقل للعناصر بصورة عمياء. يتم استخدام خوارزمية مقترحة للتحليل المستقل للعناصر تعتمد على البناء الإحصائي لمصادر الإشارات المرسله لغرض تخمين وإلغاء تأثير التداخل الناتج من قناة الانتشار اللاسلكية متعددة المسارات على الإشارة المستلمة. تتميز الطريقة المقترحة بأنها لا تتطلب أي تعديل لجهاز الإرسال أو إرسال إشارات التدريب التي تقلل من عرض النطاق الترددي. وتوضح نتائج المحاكاة فوائد الخوارزمية المقترحة مقارنة مع أساليب تقليدية أخرى ومقارنة مع خوارزميات التحليل المستقل للعناصر الأخرى.

1- Introduction

Multiple Input Multiple Output (MIMO) wireless systems are shown to provide significantly higher data rate than Single Input Single Output (SISO) systems, these MIMO systems are used for wide wireless electronic applications [1]. Enhanced spectral efficiency and the bandwidth efficiency form very important factors for MIMO wireless systems [2]. One of the major limiting factors to bandwidth efficiency of MIMO systems is interference. Interference can originate from the other users in the same system, coexisting other systems and man made interferences. The randomness of the mobile propagation channels causing the Co-Channel Interference (CCI) while the multipath fading causing the Inter-Symbol Interference (ISI). Interference must be estimated and appropriately compensated for properly detection the received symbols; else, it will severely degrade the performance of the system. The interference cancellation forms a core part in receiver design [3].

The receivers are typically canceling the interference by utilizing the available knowledge about the interference structure. The more refined this knowledge is, the better performances of the receiver [4]. Typical assumptions on the nature of interference are that its components are Additive White Gaussian Noise (AWGN), or the interference is impulsive; such as the Multi-Access Interference (MAI) and ISI. Receivers for cancelling these classes of interference usually require Channel State Information (CSI) that traditionally can get based on training sequences methods [5,6]. Minimum Mean Squared Error (MMSE) detector is a good example of the training based methods [2].

Another class of receivers has evolved recently; it tends to make minimal assumptions on the interference structure [7]. These receivers are termed as blind receivers based on Blind Source Separation (BSS) techniques. BSS is commonly used to recover source of signals that have been mixed in some manner without explicit knowledge of either the mixing process or the source of signals [8]. Even though several blind approaches exist, most of these approaches are based on Second Ordered Statistics (SOS) [9].

The SOS based on Principal Component Analysis (PCA) is one method of BSS that used for blind channel estimation and interference cancellation of MIMO systems [10]. PCA used the eigenvalues analysis for selecting the most significance principal components to accomplish the interference cancellation process [10]. In case of deep fade channel, the interference cancellation based PCA may not be effective for some communication signals with small number of samples and not sufficient to constitute reliable statistics [11]. Most blind methods use conventional methods such as MMSE detector as their starting points, formulate adaptations of the blind detector [9], and hence do not fully harness the power of Higher-Order Statistics (HOS).

Papers [12, 13, 14, 15] address the issue of blind interference cancellation based on BSS. Where the ICA algorithms are used to cancel the interference signals originated from other users in array system in [12]. The ISI cancellation based on BSS algorithms for Space-Division Multiple Access (SDMA) of mobile system is introduced in [13]; the training sequences are used for elimination the ambiguity of BSS algorithm. The issue of semi-blind detection and CCI cancellation of MIMO system based on HOS is addresses in [14]. The performances comparison for the ICA algorithms in the present of interference is introduced in [15], the training sequences are used for introduced the user of interest.

Despite these literatures, none of their approaches are able to cancel the effects of interference signals causing by the fading channel or originating from other users in the MIMO systems completely in blind fashion. However, the principle of applying ICA towards interference cancellation of MIMO system has not been very clearly addressed before since the ICA was not developed for this purpose, i.e., it used for blind signals estimation.

In this paper, a new method based on proposed ICA algorithm for blind interference cancellation and signals estimation of MIMO systems is introduced. The proposed algorithm is used for blind interference cancellation based on HOS of the received observation signals only. The proposed method helping to conserve bandwidth since it does not require using the training sequences or knowledge the channel conditions.

2- ICA Technique

ICA technique is aimed to extracting the original sources of signals from the received mixture of signals based on statistically independency of the received observation signals [8]. The ICA needs to receive mixtures from several independent observations from multiple received antennae for performing the blind signals estimation. If (s) is the original source of signals, (A) is the mixing matrix (that represented the wireless channel's effects in communication applications), and (x) be the observation signals, the noiseless ICA model can be represented as the following

$$x = As \quad \dots (1)$$

The object of ICA is to recover the original signals (s) from the mixed signals (x) by estimating the separation matrix (W) that cancelled the effects of mixing matrix. The estimated signals (\hat{s}) are

$$\hat{s} = Wx = W(As) = (WA)s \quad \dots(2)$$

In order to use ICA technique to estimate the original transmitted signal without the knowledge of CSI [8], the transmitted signals must be statistically independence with nongaussian distributions, the number of receive antennae have to be equal or more than the number of transmit antennae.

3- System Model

The proposed MIMO system model with (K) transmit and (R) receive antennae is illustrated in Fig.(1). The user's data information is digitally modulated and transmitted over the multipath fading channel, assuming that (M) transmitted signals; each signal consists of (T) samples. The variable (a_{klm}) represented the attenuation factor of the (l^{th}) channel path, which is a complex number and vary from signal to another, (L) is the number of the channel paths, (t) is the signal duration, (z) denotes the AWGN, with a zero mean and unit variance. The $y_r[n]$ received signal via the (r^{th}) reception antennae ($r=1,2, \dots, R$) had the following form [11]

$$y_r[n] = \sum_{k=1}^K \sum_{m=1}^M b_{kml}[n] \sum_{l=1}^L a_{klm} + z[n] \quad \dots (3)$$

where (b_{kml}) represent the (m) signal that transmitting via (k^{th}) antennae through the (l) channel path. Due to ISI causing by the multipath channel effects, the vector of the received signal might contain symbols related to other signals. Assuming that the path delays, (d_{kl}) of the signals are within one signal duration. Using processing window length of three signal ($3t$), the vector of one received signals is included in the three successive signals $b[n-1]$, $b[n]$ and $b[n+1]$, which represented the “early”, “middle” and “late” parts of the received signals, respectively. According to this assumption, the received signal including the multipath interference effects has the form [7],

$$y_r[n] = \sum_{k=1}^K \sum_{l=1}^L a_{kl} (b_k[n-1] + b_k[n] + b_k[n+1]) + z[n] \quad \dots (4)$$

where $b_k[n] = [b_k[1], b_k[2], \dots, b_k[T]]$
 $b_k[n-1] = [b_k[T-d_{kl}+1], \dots, b_k[T], 0, \dots, 0]$
 $b_k[n+1] = [0, \dots, 0, b_k[1], \dots, b_k[T-d_{kl}]]$

Equation (4) can be rewritten in a matrix form as the following [16]:

$$Y_r = B_n A + z \quad \dots (5)$$

In this representation, (B_n) matrix contains the vectors of the received signals depends on the symbols of the signals and on the channel's paths via their delays, while (A) contains the path strengths and depends on the channel's paths via their numbers, and gains as the following:

$$B_n = [\dots, b_k[n-1], b_k[n], b_k[n+1], \dots], \quad A = \sum_{l=1}^L a_{kl}$$

The signals transmitted by independent transmitters act as independent components and inputs of different antennas in MIMO system as observations. Hence, the signal by independent transmitters can be separated using ICA technique. The model of the MIMO system describes by equation (5) is similar to the general model of ICA given in equation (1). Therefore, ICA technique can be used for extracting the user's signals and cancel the effects of the multipath interferences.

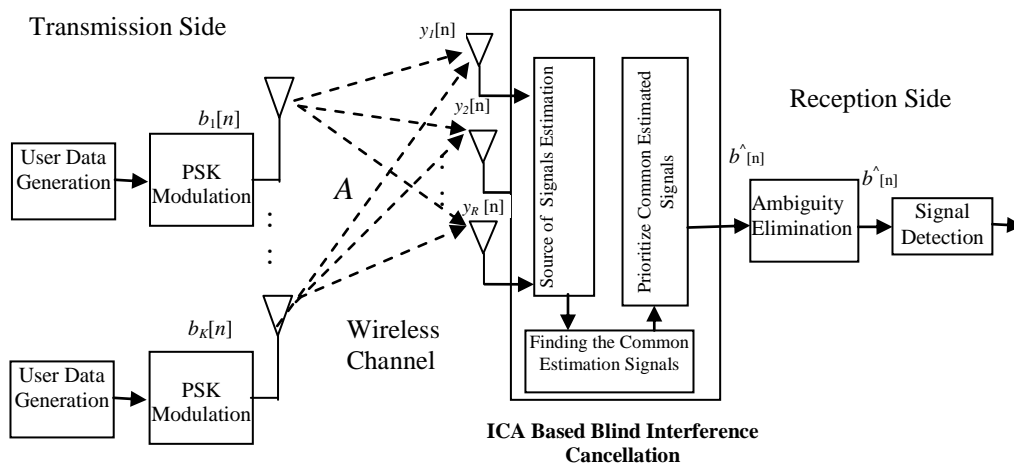


Fig.(1) Proposed System Model for Blind Interference Cancellation and Signals Estimation based ICA.

4- The Proposed Method for Blind Interference Cancellation and Signal Estimation Based on ICA

The idea of the proposed method is to first estimation all the source of signals form the received observation mixture based on proposed ICA algorithm (which denoted here as pICA) by determining the separation matrix (W). The order of the estimated signals by each run of pICA is different because of randomly initialize of pICA algorithm. Nevertheless, if the information contained in an estimated signal is significant, such an estimated signal will always appear in each run. With this assumption, if the pICA algorithm is keep running to find common estimated signals over all the runs until common estimated signals remain unchanged, in which case the process is terminated. The common estimated signals then prioritizing according to their HOS for choosing the (m) desired signals estimated by pICA algorithm and cancel the other component that represent the interference signals.

The first step of the proposed method for blind interference cancellation and user's signal estimation is the blind estimation process of all source of signals form the received observation signals based on pICA algorithm as the following:

The separation matrix W estimation of the pICA algorithm is performed based on maximizing the nongaussianity of the observation signals principle [8]. The Kurtosis $K[s]$ is one measure of nongaussianity of a random variable s , which is defined for a complex data as the following [8]

$$K[s] = E[|s|^4] - 2(E[|s|^2])^2 - E[ss]E[s^*s^*] \quad \dots (6)$$

where $(.)^*$ corresponds to the complex conjugate. Since the kurtosis of most of digital modulation (ASK, PSK and QAM) is negative, therefore, the estimation of the separation matrix (W) is performed by minimizing the objective function $J(W)$ under the unitary constraint ($WW^H = I_R$). The estimation of (W) by minimizing the proposed objective function $J(W)$ which based on the kurtosis of the estimated signals $\hat{b}[n]$ can be expressed as the following [11]

$$W = \left\{ \min_W J(W) = \sum_{j=1}^M K[\hat{b}[n]] \right. \quad \dots (7)$$

The minimization of the objective function $J(W)$ is performed by computation the gradient of the objective function, so the objective function Γ_w is define as

$$\Gamma_w = \frac{\partial J(W)}{\partial W} = K(w^H \hat{b}[n]) [E\{\hat{b}[n](w^H \hat{b}[n])^3\} - 3w\|w\|^2] \quad \dots (8)$$

where (w) is one vector of the separation matrix (W) . Since the optimization of the objective function Γ_w is under the unitary constraint $(WW^H = I_R)$, the gradient of the objective function must be complemented by projecting (W) on the unit sphere after every step, which performed by dividing (W) by its norm. To further simplify computation of the Γ_w , the latter term in brackets in equation (8) can be omitted since it does not change the direction of the norm of (w) . This is because only the direction of (w) interesting, and any change in the norm is insignificant because the norm is normalized to unity anyway, thus the final proposed Γ_w is obtained as:

$$\Gamma_w = \frac{\partial J(W)}{\partial W} = K(w^H \hat{b}[n]) [E\{\hat{b}[n](w^H \hat{b}[n])^3\}] \quad \dots (9)$$

The second step of the proposed method is by running the pICA algorithm several times, each time with different randomly initializing of W for estimating common signals for all pICA algorithms' runs. Where two estimated signals for different runs, $\hat{b}_i[n]$ and $\hat{b}_j[n]$ are considered distinct if the Spectral Angle Mapper (SAM) between their corresponding vectors $v_i[n]$, and $v_j[n]$ is greater than a prescribed threshold ε .

The third step of the proposed method is prioritize the pICA's common estimated signals according to the following criterion [8] for that combines third and fourth orders of statistics in order to find the common estimated signals

$$J(\hat{b}_q) = \left(\frac{1}{12}\right)[\Re_q^3]^2 + \left(\frac{1}{48}\right)[\Re_q^4 - 3]^2 \quad \dots (10)$$

where $\Re_q^3 = E\{\hat{b}_q^3\} = (1/T) \sum_{n=1}^T (\hat{b}_q[n])^3$ and $\Re_q^4 = E\{\hat{b}_q^4\} = (1/T) \sum_{n=1}^T (\hat{b}_q[n])^4$ are the sample means of third and fourth orders of statistics of the estimated signals, q is the algorithms' run index ($q=1,2,\dots,Q$).

The proposed method is described in the following steps for a fixed step size (μ) :

1. Initialization the maximum number of the pICA algorithms' run Q , set $q=0$
2. Initializing the separation matrix W randomly.
3. Set the objective function $J_{old} \leftarrow J(W)$.
4. Computing the gradient of the objective function Γ_w according to the equation (9).
5. Updating W in the direction of the negative gradient, $W \leftarrow W - \mu \Gamma_w$.
6. Normalizing W based on unitary constraint, $W \leftarrow W / \|W\|$.
7. If the objective function is not converged $J_{old} - J(W) < \varepsilon$ (where ε is a very small threshold value), then go back to step 2.
8. Estimating the set of signals: $\hat{b}[n] = W^H \times Y_r$.
9. Formed each estimated signal $\hat{b}[n]$ as a vector, denoted by $v_q[n]$.
10. If $q < 1$ go to step 2. Otherwise, continue.
11. Find the set of the common vectors for all runs of algorithm up to q^{th} run.
12. If the set of the common vectors does not appear for all pICA runs go to step 2, otherwise, the algorithm is terminated.
13. Prioritize the common vectors in accordance with the $J(\hat{b}_q)$ magnitude of equation (10).
14. Select the (m) desired vectors of signals with the largest $J(\hat{b}_q)$ to perform blind interference cancellation process.

The estimated user's signals $\hat{b}[n]$ is estimated up to a permutation and phase rotation ambiguities, because of the ambiguity problems of the ICA algorithm. Where $\hat{b}[n]$ is not the same as the

transmitted signal $b[n]$, there exists ambiguity matrix G comparing with the original transmitted signals $b[n]$ as [17]

$$\hat{b}[n] = G \times \hat{b}[n] \quad \dots (11)$$

The ambiguity matrix (G) is composed by two indeterminacies as the following [17]

$$G = P \times D \quad \dots (12)$$

where (P) is the ($m \times m$) permutation ambiguity matrix, and (D) is the ($m \times m$) phase rotation ambiguity matrix. Considering the set of all possible calculated ambiguities matrices (L) as the following [17]

$$L = P \times D \quad \dots (13)$$

The ambiguities elimination step of the proposed method is represent by post-multiplying the estimated signals $\hat{b}[n]$ by (L_F) where

$$L_F = \arg \min_{L \in G} \|\hat{b}[n] - \hat{b}[n] \times L\|^2 \quad \dots (14)$$

The final estimated signals $\hat{b}_F[n]$ is defined as the following

$$\hat{b}_F[n] = L_F \times \hat{b}[n] \quad \dots (15)$$

In addition to the pICA algorithm, this paper focuses on three of BSS algorithms that can be applied in MIMO systems for the purpose of performances comparison, including the Joint Approximate Diagonalization of Eigen-matrices (JADE) [18], FastICA [19] and the Temporal Decorrelation SEPARation (TDSEP) algorithm [20]. The BSS algorithms are originally invented for blind signals estimation, the pICA algorithm's steps (1,9,10,11,12,13,14) are applied with JADE, FastICA and TDSEP algorithms in order to used them for blind interference cancellation.

4.1- JADE Algorithm [18]

JADE algorithm principle for signals estimation is based on diagonalization of higher-order cumulate matrices of the observation signals [18]. The fourth-order cumulate of a random variable (x) is defined as

$$Q(x) = E[x^4] - 3(E[x^2])^2 \quad \dots (16)$$

where $E[x^2]$ is the variance of (x). The objective function of the JADE algorithm (J_{JADE}) is based on minimization the off-diagonal elements of the cumulate matrices

$$J_{JADE} = \sum_{m=1}^M \text{OffDiag}(UQ(m)U^T) \quad \dots (17)$$

(U) is an orthogonal matrix. The separation matrix (W) is estimated based on minimization the off diagonal elements of cumulates matrix by eigenmatrices of the observation signals [18].

4.2- FastICA Algorithm [19]

FastICA algorithm is based on the principle of maximizing the nongausinaty of the estimated components. The objective function of the FastICA algorithm ($J_{FastICA}$) is based on maximization some function (G), where (G) is a twice continuously differentiable nonlinear function with ($g = G'$) and ($g = G''$) for the first and second derivative of (G). Function (g) is called the nonlinearity, one standard nonlinearities used in FastICA algorithm as the following [19]

$$g(x) = \tanh(x) \quad \dots (18)$$

The update for the separation matrix (W) is

$$W^+ \leftarrow E\{g(W^T x)x\} - E\{g'(W^T x)\}x \quad \dots (19)$$

4.3- Temporal Decorrelation SEPARation (TDSEP) Algorithm [20]

TDSEP algorithm is proposed for a mixed signals represented a time series (i.e., had a time structures), or for the independent components are correlated over time. The idea of the TDSEP algorithm is to use the different covariance between the received signals for different time delays (τ) and simultaneously diagonalize all the corresponding delayed covariance matrices based on the assumptions for separation are that the independent components have different autocovariances [20]. The autocovariance C_x^τ of the observation signals x for a time delays (τ) is

$$C_x^\tau = E[x(t)x(t-\tau)^T] \quad \dots (20)$$

The objective function [20] of the TDSEP algorithm is based on minimizing the sum of the off-diagonal elements of several delayed covariances of the estimated components,

$$J_{TDSEP} = \sum_{\tau \in S} \text{off}(WC_\tau^x W^T) \quad \dots (21)$$

where (C_τ^x) is the delayed covariance matrix and S is the set of chosen time delays (τ).

5- Simulation Results

The performances of the proposed method are evaluated through a computer simulation using the M-file of MATLAB environment. The channel is modulated as a multipath Rayleigh fading with zero mean and unit variance with (L) of (5) paths. The transmitted signals are a PSK modulation of (1000) symbols for each signal, the threshold value ϵ equal to (10^{-5}). The receiving system adopted pICA, FastICA, JADE, TDSEP algorithms for performances comparison; the MMSE detector based equalization with perfect CSI is used as benchmark.

Fig. (2) illustrates the performance differences (as Signal to Interference Ratio (SIR) versus BER) of the ICA algorithms and MMSE detector with K and R of (2) antennae. It is seen that the pICA algorithm provides the best results compared with FastICA, JADE and TDSEP and comparable to the results of the MMSE detector. Where, at (20 dB) SIR, the pICA had a (3×10^{-5}) BER, comparing with (10^{-5}) BER for MMSE detector while FastICA, TDSEP, JADE algorithms had a BER (8×10^{-5} , 2×10^{-4} , 2×10^{-3}) respectively.

Fig. (3) shows the performance comparison (as SIR versus BER) of the MIMO systems with R of (2) and (4) reception antennae. The pICA outperforms other ICA algorithms and performs comparably with results of the MMSE detector having similar number of R . Clearly, it can be seen from the BER curves in Fig. (3) that pICA provides an advantage of (7), (15) dB over FastICA, JADE algorithms with R of (2) antennae and BER of (10^{-4}).

The plot of the number of transmission antennae (K) verses the Performance Index (PI) is given in Fig. (4), the PI defined by [9]:

$$PI = \frac{1}{m} \sum_{i=1}^m \left\{ \left(\sum_{k=1}^m \frac{|g_{ik}|}{\max_j |g_{ij}|} - 1 \right) + \left(\sum_{k=1}^m \frac{|g_{ki}|}{\max_j |g_{ji}|} - 1 \right) \right\} \quad \dots(22)$$

where m is the number of sources of signal, g_{ij} is the (i, j) element of the global system matrix [$G = WA$] and ($\max_j g_{ij}$) represents the maximum value among the elements in the i^{th} row vector of G , ($\max_j g_{ji}$) is the maximum value among the elements in the i^{th} column vector of G . Form the figure it can be seen that, when K is increased, the pICA algorithm outperforms FastICA, TDSEP, JADE algorithms. For K of (10) elements antennae, the pICA had PI of (21) in comparing with (25), (42), (45) for FastICA, TDSEP, JADE algorithms.

Finally the performance of pICA algorithm with K and R of (2),(4),(6) antennae verses BER is shown in Fig. (5), from the figure it can be shown that as number of signal's samples increased, the BER curves improving. Because the statistical independence is easier to establish with large number of samples of signals.

It is obvious from the previous results that, the pICA algorithm outperforms the other ICA algorithms, for all different performances measurements, Fast-ICA algorithm had an improvement performances, while JADE algorithm had a degradation performances. The pICA algorithms had a better capability for tracking the multipath channel type and cancel the effects of interference on processing signal.

6- Conclusions

This paper proposed a blind interference cancellation method for MIMO wireless communication systems using ICA. The proposed method performs a blind interference cancellation process based on HOS of the received observation signals only. The proposed method is applicable to the multipath fading channel case and does not require using the training sequences that usually costs extra bandwidth. The proposed method has good performances close to the conventional MMSE detector with perfect CSI, showing the ability to mitigate the channel effects.

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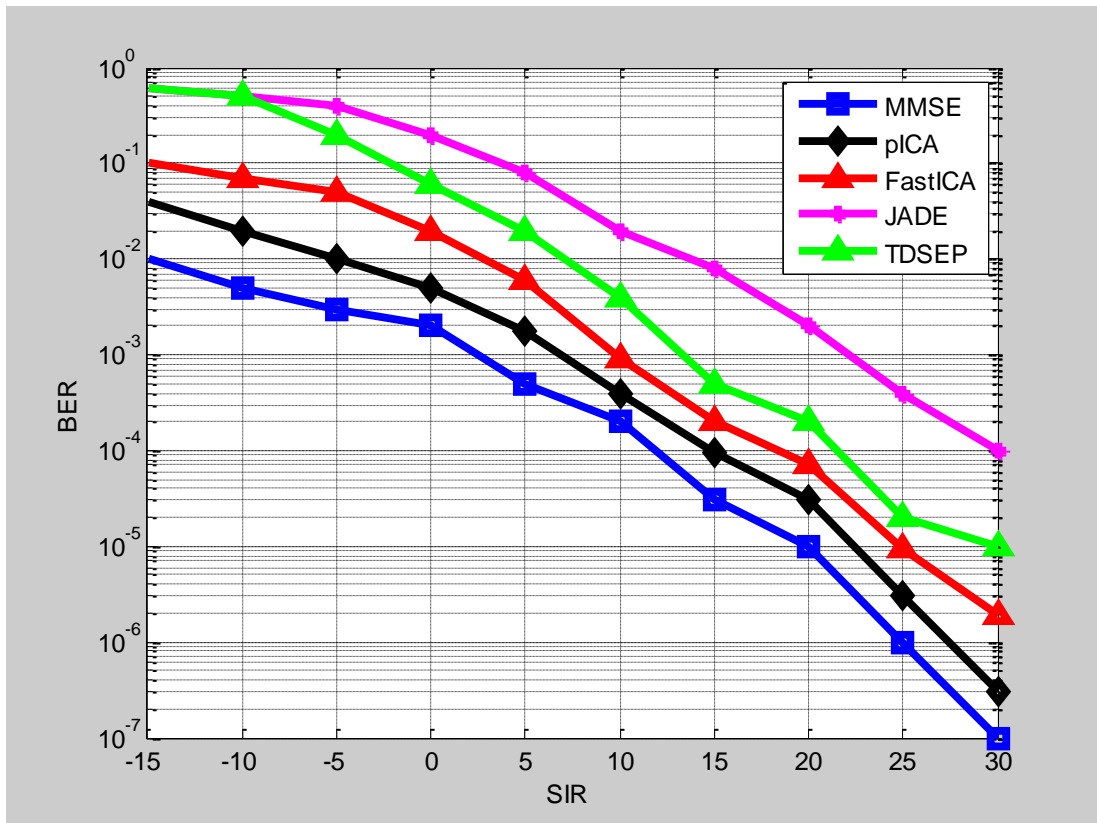


Fig. 2. SIR versus BER Performances over Multipath Fading Channel ($K=2, R=2$).

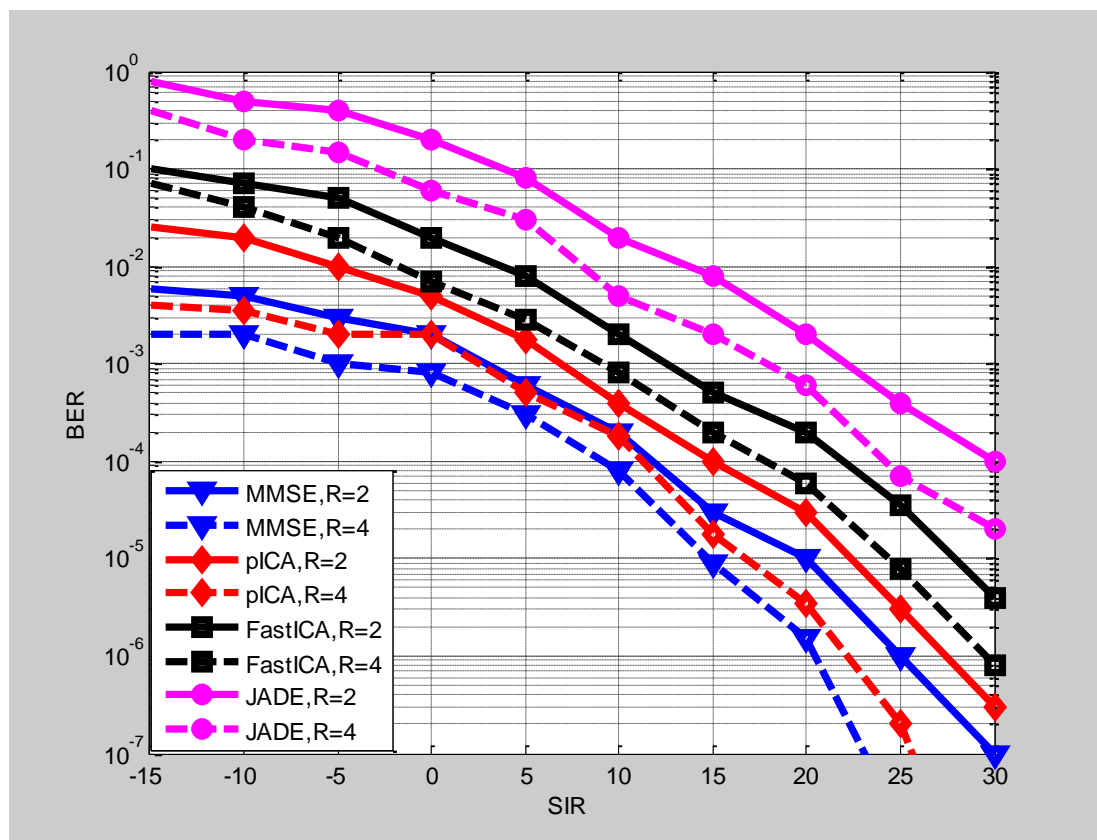


Fig. 3. SIR versus BER Performance over Multipath Fading Channel ($K=2, R=2,4$)

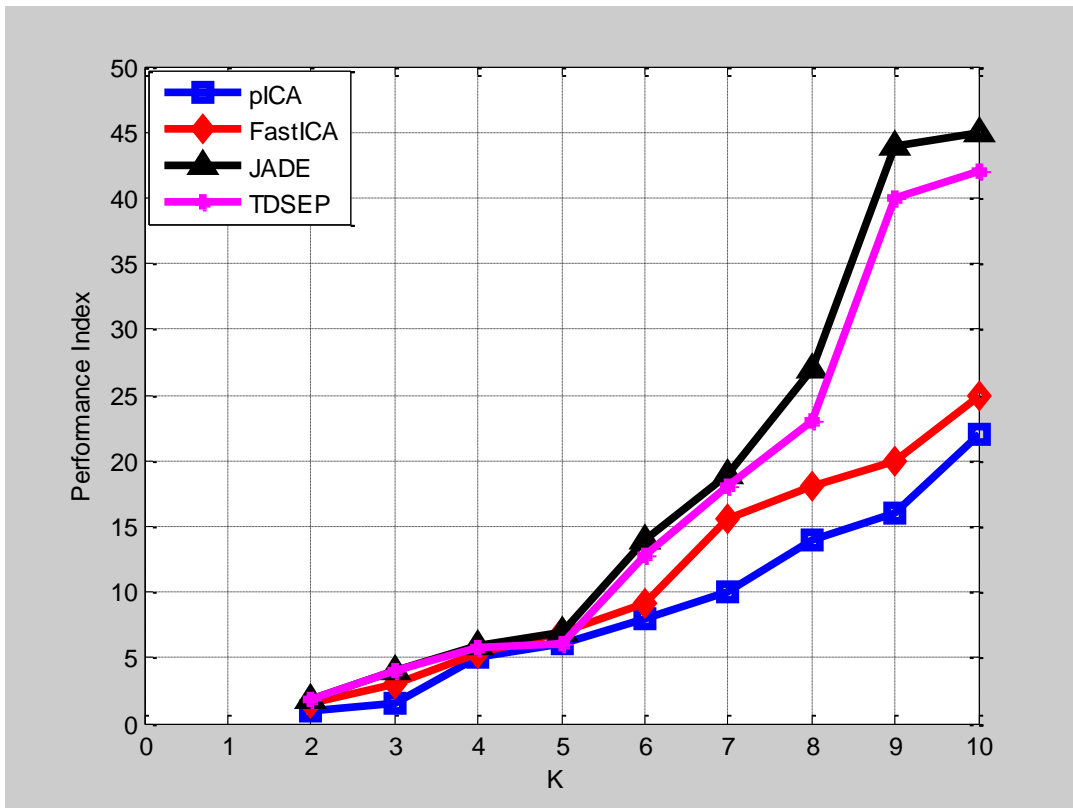


Fig. 4. (*K*) versus (*PI*) Performance over Multipath Fading Channel (*R*=2).

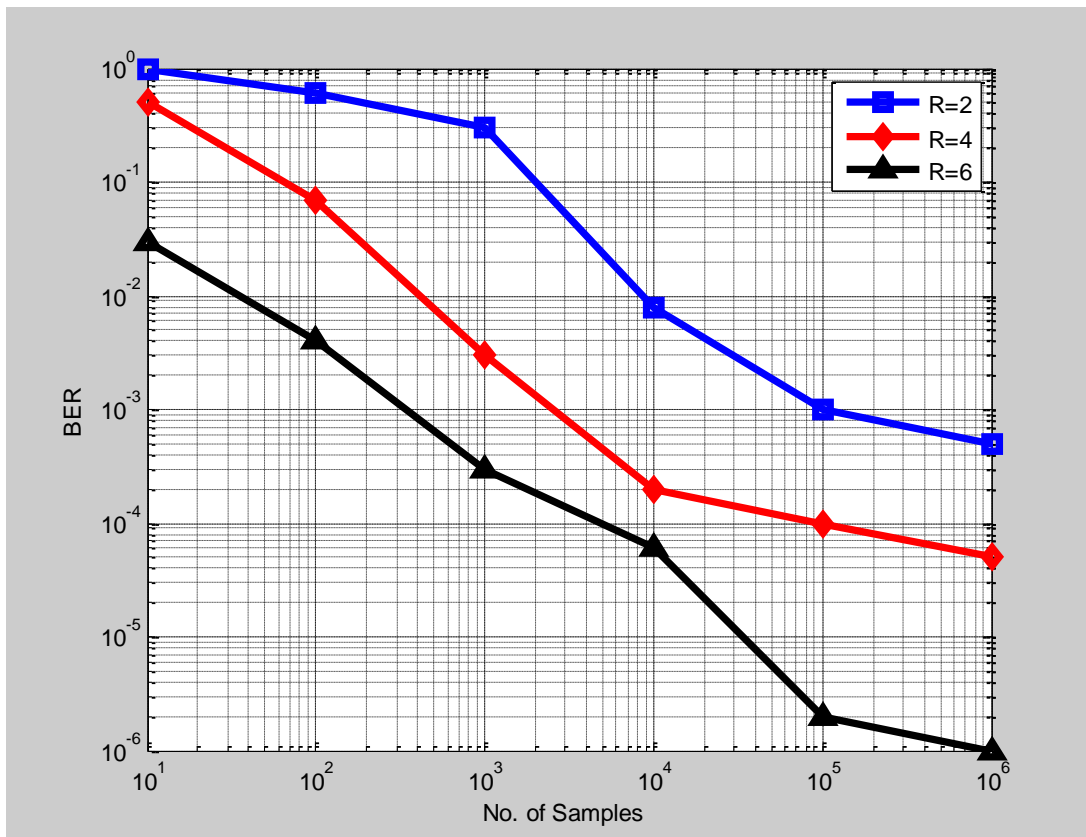


Fig. 5. No. of Samples versus BER Performance of (pICA) Algorithm over Multipath Fading Channel.