Blind Detection Method of MIMO – Space Time Coded Wireless Systems Based on ICA

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ABSTRACT

This paper presents a proposed blind detection method for Multiple Input Multiple Output-Space Time Coded (MIMO-STC) wireless systems based on Independent Component Analysis (ICA). The proposed method used the statistical independence of the sources of signals for blindly detection of STC signals. The original transmitted signals are estimated by gradient the kurtosis-based objective function of the received signals. In contrast to other approaches, the proposed method does not require any modification in transmission side or using the training sequences. Simulation results using MATLAB demonstrate competitive results for the proposed system comparing with conventional Minimum Mean Squared Error (MMSE) detector. Where at (10^{-7}) Bit Error Rate (BER) there is about (4 dB) and (7.5 dB) improvement in Signal to Noise Ratio (SNR) for the proposed system adopting Orthogonal Space-Time Block Coded (OSTBC) scheme with (6) receiving antennae comparing to the same system with (4) and (2) receiving antennae respectively.

Keywords: Blind Detection Methods, Independent Component Analysis, MIMO-STC Wireless Systems.

طريقة الكشف الأعمى لأنظمة الترميز الزمنية- متعددة المداخل متعددة المخارج اللاسلكية بالاعتماد على التحليل المستقل للعناصر

الخلاصة

في هذا البحث يتم تقديم طريقة استقبال عمياء لإشارات أنظمة الترميز الزمني متعدد المداخل متعدد المخارج بالاعتماد على طريقة التحليل المستقل للعناصر. يستغل المستلم المبني حسب على الطريقة المقترحة البناء الإحصائي لمصادر الإشارات المستلمة لغرض كشف الإشارات اللاسلكية لأنظمة الترميز بصورة عمياء. يتم تخمين الإشارات المرسلة باستخدام طريقة انحدار المعادلة الموضوعية للإشارات المستلمة. يتميز الأسلوب المقترح بأنه لا يتطلب أي تعديل لجهاز الإرسال أو إرسال إشارات التدريب. وتوضح المحاكاة المبرمجة بواسطة الماتلاب نتائج أداء تنافسية للطريقة المقترحة مقارنة مع نتائج أداء كاشف (MMSE) التقليدي. حيث يحقق المستلم المقترح ذو(6) هوائيات استلام وطريقة الترميز (OSTBC) ربح بحدود (4 dB) و (7.5 dB) مقارنة مع نفس المستلم لكن بعدد هوائيات استلام (4) و(2) على التوالي عند ($BER=10^{-7}$) .

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INTRODUCTION

Multiple Input Multiple Output (MIMO) wireless systems are shown to provide significantly higher data rate than Single Input Single Output (SISO) systems [1]. Enhanced spectral efficiency, increased capacity feature, the ability to tackle fading effects in multipath channels and the overall transmission performances improvements form very important factors for MIMO wireless systems [2].

MIMO systems used the Space-Time Coded (STC) schemes for approaching the information theoretic capacity limit of MIMO channels. Another benefit of STC is to transmit multiple copies of data stream across multiple antennae to exploit the various received versions of data to improve the reliability of data-transfer [3]. According to their coding schemes properties, different types of STC systems are designed such as, Orthogonal Space-Time Block Coded (OSTBC) systems [4],[5], Quasi-Orthogonal (QOSTBC) systems [6],[7] and Spatial Multiplexing (SM) [8] with different wireless communication applications.

In reception side of STC systems, the Channel State Information (CSI) must obtain in order to compensating the effects of wireless channel for recovering the original user's symbols properly [1]. The training sequences are commonly used for obtaining the CSI in the STC systems, the Zero Forcing (ZF) and the Minimum Mean Squared Error (MMSE) detectors are good examples of the training based method [9]. Nevertheless, using the training sequences reduces the bandwidth efficiency, and the limitation of the training sequences number, result in inaccurate channel estimations. Using such imperfect CSI at the receiver, in turn, can substantially reduce the performance of the conventional decoder [10].

The drawbacks of the training based methods have motivated an increasing interest in the development of blind STC symbols detection and channel estimation methods [10]. Blind Source Separation (BSS) based methods have been introduced for STC systems. The BSS based methods are able to obtain the CSI without using the training sequences, which costs extra bandwidth based on Higher Order Statistics (HOS) of the received signals [11].

Independent Component Analysis (ICA) is the major tool to perform the BSS [12]. ICA based on the assumption of mutual statistical independence between sources of signals, can be employed to estimate the original signals directly from the statistics of received signal. The blind signal's estimation can be done by maximizing the non-gaussianity of the received signals, without knowing the CSI, as long as the transmitted signals are linearly independent [13].

Blind signals estimation methods based on ICA have been investigated in many literatures for STC systems. These methods are either did not taking into account the specific structure of the STC signals as the methods in [14-15], or they are limited to a specific type of STC schemes as in [16-18].

Despite these literatures, none of the previous approaches is able to estimate the STC signals that transmitted over the MIMO channel without modification in transmission side or using the training sequence completely in blind fashion.

The aim of this paper is to detect the original STC transmitted signals blindly from the received observation signals only for different types of STC schemes. The STC signals that transmitted over the wireless MIMO channel are estimated based on ICA by gradient the kurtosis-based objective function of the observation signals. The proposed blind receiving system based on ICA is applied to different STC schemes and for different number of receiving antennae.

SYSTEM MODEL

The MIMO-STC transmission system with N_t transmit antennae and the proposing blind receiving system based ICA with N_r receiving antennae is illustrated in Figure (1). In transmission side, the user's data information are modulated and organized into blocks format. The block consists of N_s symbols during f time slots. The space-time encoder generates an $[N_t \times f]$ block matrix from a block s_i of N_s symbols, $s_i = [s_1, s_2, . . . , s_{Ns}]$, then transmits through the N_t antennae. The channel impulse responses remains constant during the duration of block of N_s symbols and vary independently from block to another. The block of coded data matrix, C, can be written as the following [19]

$$C = \sum_{i=1}^{Ns} G_i s_i \qquad \dots (1)$$

Where the $[N_t \times f]$ matrices G_i are the generating space-time coded matrices.

In reception side, the ICA block represents the first stage of the proposed blind receiving system, that received the observation signals through the N_r receiving antennae. The observation signals x_k are as the following:

$$x_k = [x_1, x_2, . . . , x_{Nr}] \qquad \dots (2)$$

Where k is the index of reception antennae (k = 1, 2, . . . , N_r). The b^{th} received observation block of signal $x_{b,k}$, that observed through the k receiving antenna can be written as:

$$\begin{aligned} x_{b,k} &= H_{k,j} C_{b,j} + n_b \\ &= \begin{bmatrix} H_{1,1} & \cdots & H_{1,N_t} \\ \vdots & \ddots & \vdots \\ H_{N_r,1} & \cdots & H_{N_r,N_t} \end{bmatrix} \begin{bmatrix} C_{b1} \\ \vdots \\ C_{bN_t} \end{bmatrix} + n_b \end{aligned} \qquad \dots (3)$$

Where j is the index of the transmission antennae (j = 1, 2, . . . , N_t). The matrix of the original coded source of signals that transmitted over the j transmit antenna, $C_{b,j}$, with size of $(N_t \times N_s)$ and the observation signals matrix $x_{b,k}$ with size of $(N_r \times N_s)$ are the complex valued baseband signals, while H with size of $(N_r \times N_t)$ is the channel impulse response matrix. The elements of H are independent identically distributed (i.i.d), with Rayleigh distributed for amplitude and uniformly distributed for phase. The n_b with size of $(N_r \times N_s)$ is the Additive White Gaussian Noise (AWGN), with a zero mean and unit variance. The ICA is aimed to extracting the original sources of signals from the received mixture of signals based on statistics of the received signals. In order to use the ICA to estimate the original signal without the knowledge of CSI the signals must be statistically independence with nongaussian distributions, and the number of receive antennae have to be equal or more than the number of transmit antennae. In addition, the average transmits power on each antenna is normalized to unity [13].

The ICA stage of the proposed receiving system consists mainly of whitening and estimation signals processes. The Principal Component Analysis (PCA) is a common method that frequently used for whitening the received signals through the estimation the whitening matrix *V*. The whitening matrix *V* is obtained based on the Eigen Value Decomposition (EVD) analysis of the autocorrelation matrix R_{xx} of received signals x_b as the following [13]

$$\begin{aligned} R_{xx} &= E[x_b x_b^H] \\ &= HE[C_b C_b{}^H]H^H \\ &= U\Lambda^{1/2} \end{aligned} \quad \dots (4)$$

where U is the $N_r \times N_t$ matrix of eigenvectors of R_{xx} and Λ is the $N_t \times N_t$ diagonal matrix of eigenvalues of R_{xx}. The autocorrelation matrix R_{xx} of the received observation signals can be also analysis as

$$\begin{aligned} R_{xx}(k) &= E[x_b x_b^H] \\ &= HE[C_b C_b^H]H^H \\ &= HH^H \end{aligned} \quad \dots (5)$$

The whitening matrix is given by [13]

$$V = \Lambda^{-1/2} U^H \quad \dots (6)$$

From equation (4) and (5) the estimated channel matrix $\hat{H}$ can be expressed as

$$\hat{H} = U\Lambda^{1/2} W^H \quad \dots (7)$$

where W is the $N_t \times N_t$ full rank separation matrix which is assumed to be the inverse of mixing matrix (wireless channel effects) *H*. The whitened received block of signals Y_b is given by

$$Y_b = V_b \; x_b \quad \dots (8)$$

Form equation (3) and (8), it can be shown that, the whitened received block of signals Y_b is given by

$$\begin{aligned} Y_b &= U^H \Lambda^{-1/2} C_b U \Lambda^{1/2} W^H + n_b \\ &= C_b W^H + n_b \end{aligned} \qquad \text{… (9)}$$

The second process of the proposed method is the determination of the separation matrix *W*, where *W* is unknown at the blind receiving side. The estimation of *W*, is performed by maximizing the statistical independence of the estimated signals by maximizing the statistical independence of these signals. The Kurtosis $K[s]$ is one measure of nongaussianity of a random variable *s* and it chosen as proposed measurement due to its simple calculation form the received signals directly. The Kurtosis $K[s]$ is defined for a complex data as the following [13]

$$K[s] = E[|s|^4] - 2(E[|s|^2])^2 - E[ss]E[s^* s^*] \qquad \text{… (10)}$$

Where $(.)^*$ corresponds to the complex conjugate and $E[\cdot]$ is the expectation operator.

The idea of the proposed blind detection method is as the following: the ICA stage of the receiving system performed the whitening process on the observation signals to eliminate the signal's components that consist of noise only. Then the separation matrix *W* estimation is performed based on HOS of the whitening signals Y_b by gradient the kurtosis based objective function. The estimated *W* is used for decoding the estimated signals and estimation the channel matrix. Other steps are used for elimination the ambiguities of the estimated signals (as illustrated in the Appendix A later).

The separation matrix *W* is estimated by optimization (maximizing or minimizing) the objective function $J(W)$, which is based on kurtosis of the estimated signals $\hat{s}_b$. Since the kurtosis of most of the digital modulation (ASK, PSK and QAM) is negative, therefore, the proposed optimization approach is performed by minimizing the objective function $J(W)$ which is depends on *W* under the unitary constraint $WW^H = I_{N_t}$. The estimation of *W* by minimizing the proposed objective function $J(W)$ can be expressed as the following

$$W = \begin{cases} \min\limits_{W} \quad J(W) = \sum_{k=1}^{Ns} K[\hat{s}_b] \end{cases} \qquad \text{… (11)}$$

The minimization of the objective function *J(W)* is performed by computation the gradient of the objective function. The gradient of the objective function Γw is defined as

$$\Gamma w = \frac{\partial J(W)}{\partial W} = K(w^H \hat{s}_b)[E\{\hat{s}_b (w^H \hat{s}_b)^3\} - 3w\|w\|^2] \qquad \text{… (12)}$$

Where (w) is one row of the separation matrix W. Since the optimization of the objective function Γw is under the unitary constraint $WW^H = I_{N_t}$, 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 Γw, the latter term in brackets in equation (12) can be omitted since it does not chance 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, Γw is obtaining as the following:

$$\Gamma w = \frac{\partial J(W)}{\partial W} = K(w^H \hat{s}_b)[E\{\hat{s}_b w^H \hat{s}_b{}^3\}] \quad \dots (13)$$

The original block of symbols can be recovered using space-time decoder after compensate the effects of channel. The space-time decoder computes an inverse matrix of the generating matrix to compensate the effect of the space-time coding. The final estimated signal is compute by

$$\hat{s}_F = D_b W^T \hat{s}_b \quad \dots (14)$$

Where the $(Ns \times N_t\ f)$ matrix D denotes the pseudo-inverse of the STC generating matrix G and $\hat{s}_b$ is the estimated symbols of the block b.

THE PROPOSED MIMO-STC BLIND DETECTION METHOD BASED ON ICA

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

1. Compute R_{xx} and perform the eigenvalue decomposition according to the equation (4).
2. Compute the whitened block of signals Y_b according to the equation (9).
3. Initialize the separation matrix W randomly.
4. Calculate the estimated signals $\hat{s}_b$ as the following: $\hat{s}_b = W^T Y_b$
5. Set the objective function $J_{old} \leftarrow J(W)$.
6. Compute the gradient of the objective function Γw according to the equation (12).
7. Updating W in the direction of the negative gradient, $W \leftarrow W - \mu \Gamma w$
8. Normalizing W based on unitary constraint, $W \leftarrow W / \|W\|$
9. If the objective function is not converged $J_{old} - J(W) < \varepsilon$ (where ε is a threshold value), then go back to step 5.
10. Estimate the channel matrix $\hat{H}$ according to the equation (7), and the original block of symbols according to the equation (14).

The estimated signals $\hat{s}_F$ and the channel matrix $\hat{H}$ are estimated up to a permutation and phase rotation ambiguities, because of the ambiguity problems of the

ICA. The estimated signal $\hat{s}_F$ is not the same as the original transmitted signal s_b, there exists an ambiguities comparing with the original transmitted signals s_b. The error minimization between the estimated signals matrix and original signals matrix is proposed for elimination the ambiguities problems of the ICA.

For the blind algorithms, there is no guarantee that the algorithm will find the global minimum. So, for avoiding converges to a local minimum the performances of the proposed method are evaluated using the multistart initialization. Where, the proposed method runs several times with new random starting points and selects the estimated separation matrix W which minimizes the objective function Γw.

SIMULATION RESULTS

The performances of the proposed method are evaluated through a computer simulation using the M-file programming of MATLAB. The performances of the MIMO-STC system with proposed ICA blind receiver were quantified through

1- The average Bit Error Rate (BER) that obtained after the signal detection process.

2- The Normalized Mean Square Error (NMSE) that obtained after the channel matrix estimation.

For each SNR, two thousand independent simulations were performed to approximate the BER and NMSE. The transmitted signals are a PSK modulation of (1000) symbols for each block of signals. The threshold value ε is (10^{-5}) and the step size (μ) is (0.1). Considering the MIMO system, with (2) transmit antennae and (2),(4),(6) receive antennae. The MMSE detector with perfect CSI is used as benchmark.

In the following, the performances of the proposed system are presented for the following type of STC schemes at transmission side: OSTBC, QOSTBC, STBC and SM.

Considering the OSTBC as coding scheme at first, the performance of the proposed system comparing to MMSE detector with perfect CSI is shown in Figure (2). For a BER of (1×10^{-7}), the proposed system with (Nr=2) receiving antennae had a SNR of nearly (9 dB) comparing to (8 dB) obtained by the MMSE detector with same number of antennae. For the systems with (4) reception antennae, SNR is improved to nearly (5.5 dB) for the proposed system comparing with (4 dB) for the MMSE detector. For the systems with (6) reception antennae, the SNR is improved to (1.5 dB) for the proposed system and (1 dB) for the MMSE detector for the same value of BER. It can be seen that the proposed ICA system with N_r of (6) had gain of (7.5 dB) SNR and about (4 dB) gain achieved over the same system with N_r of (2) and (4) receiving antennae for BER of (10^{-7}).

For the QOSTBC coding scheme, the performances comparison of the systems is shown in Figure (3). For (1×10^{-7}) BER and systems with (2) receiving antennae, the MMSE detector had a SNR of (8.8 dB), while the proposed system had a SNR of (9.2 dB). For the systems with (4) reception antennae, the SNR is improved to (5.5 dB) for the proposed system and (5 dB) for the MMSE detector. For the same systems with (6) reception antennae, the SNR is improved to (2.8 dB) for the proposed system and (2 dB) for the MMSE detector. The proposed ICA system with (6) receiving antennae had a gain of (6.5 dB) and nearly (3.7 dB) SNR over the same system with (2) and (4) receiving antennae respectively for (10^{-7}) BER.

Figure (4) illustrates the performances comparison of the proposed system and the MMSE detector adopting the STBC scheme. For the systems with (4) receiving antennae and (1×10^{-7}) BER, SNR for the proposed system is observed to be (8 dB) and MMSE detector gives nearly (7 dB). At (1×10^{-7}) BER and (6) receiving antennae, the proposed system is give SNR of (5 dB) while the MMSE detector give SNR of (4.2 dB). The ICA system with *Nr* of (6) had gain of (3 dB) over the system with *Nr* of (4) receive antennae at BER of (10^{-7}).

For the SM coding scheme, the performances comparison of the two systems is shown in Figure (5). For the systems with (2) receiving antennae and (1×10^{-6}) BER, the SNR for the proposed system is observed to be (11 dB) and MMSE detector gives nearly (10 dB). While for the systems with (4) receiving antennae and (1×10^{-7}) BER, SNR for the proposed system is observed to be (9.5 dB) and MMSE detector gives nearly (9 dB). At (1×10^{-7}) BER and the systems with (6) receiving antennae, the proposed system is give SNR of (7 dB) while the MMSE detector give SNR of (6 dB). The systems with (2) receiving antennae are performed poorly. It can be observed that at BER of (10^{-7}), the proposed system with (6) receive antennae had a gain about (2.5 dB) relative to the ICA systems with *Nr* of (4).

It should be noted form the previous figures that the ICA blind system achieves near-optimal performance especially at high SNRs since their BERs are vary close to the ones of the MMSE detector. The best performance is obtained for the maximum number of receiving antennae (N_r=6) for all type of STC schemes, which is expected due to improve the reliability of signals transmission. The simulations results showed that significant SNR gain could be achieved by increasing the number of receiving antennae.

The systems with OSTB coded schemes had the best performances comparing with other coded schemes for all number of receiving antennae. This is due mainly to the orthogonality property of the encoding generating matrix, where the transmitted blocks of signal from each antenna are orthogonal to each other. The systems with SM coded scheme had the worst performances due to the inter channel interference between the transmitted signals. The QOSTBC system's performances are lower bounded by the one of the OSTBC system due to the partial orthogonallity exhibited by the transmitted signals of this system.

Figure (6) display the performances comparison of the MMSE detector and the proposed system (as SNR verses NMSE) adopting the OSTBC, QOSTBC, STBC and SM coded schemes. Considering the MIMO system, using (2) antennae at transmission and reception. For NMSE of (1×10^{-6}), the proposed ICA system with OSTBC scheme had a SNR of (9 dB) comparing with (11 dB) related to the QOSTBC scheme and (14 dB) related to the STBC. For the SM coded scheme proposed system achieved (15 dB) SNR for the same value of NMSE. It can be seen from Figure (6) that the proposed blind ICA system with OSTBC scheme outperforms other systems adopting other coding schemes. At NMSE of (10^{-6}) the proposed system with OSTBC scheme achieved gain of (2 dB) over the ICA system with QOSTBC, and achieving gain of (5 dB) over the system with STBC scheme at NMSE of (10^{-6}). There are slight differences between the results of the ICA system and the results of the MMSE detector for each type of STC schemes due to the capability of the proposed ICA system to reduce the effects of noisy fading channel.

It can be seen from all the previous results, that the proposed system had good performances results comparing with conventional MMSE detector with perfect CSI, showing the ability to the resolve ambiguities effectively, and the ability of the ICA to reduce the channel effects. With increasing the number of receiving antennae, the performances of the ICA systems improve due to receiving multiple copies of transmit signals.

CONCLUSIONS

This paper proposed a blind detection method for MIMO-STC wireless systems based on ICA. The proposed method performed the signals detection and channel estimation processes blindly. The proposed method is based on statistical independence assumption of the transmitted signals only and has good performances close to the results of the conventional MMSE detector with perfect CSI showing the ability to reduce the channel effects. Simulation results demonstrates that, the proposed system with (6) receiving antennae acts better than the systems with fewer number of receiving antennae for all type of STC schemes.

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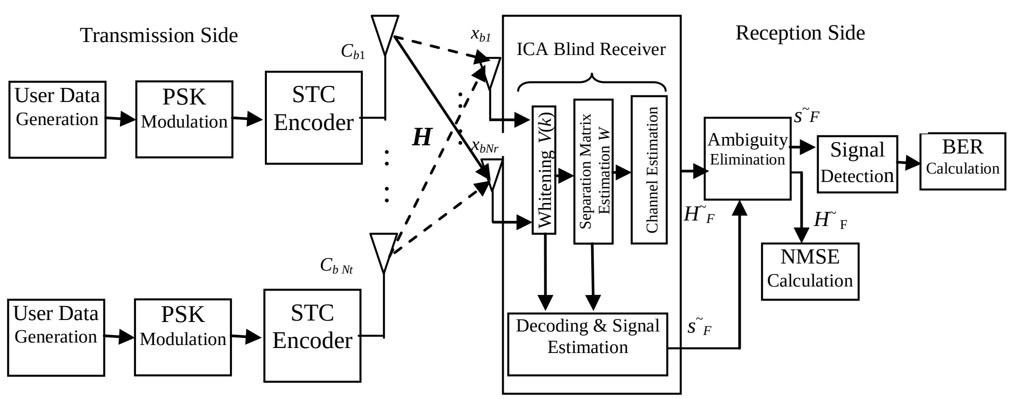

Figure (1) The Proposed Wireless MIMO-STC System Model with ICA based Blind Receiving System Structure.

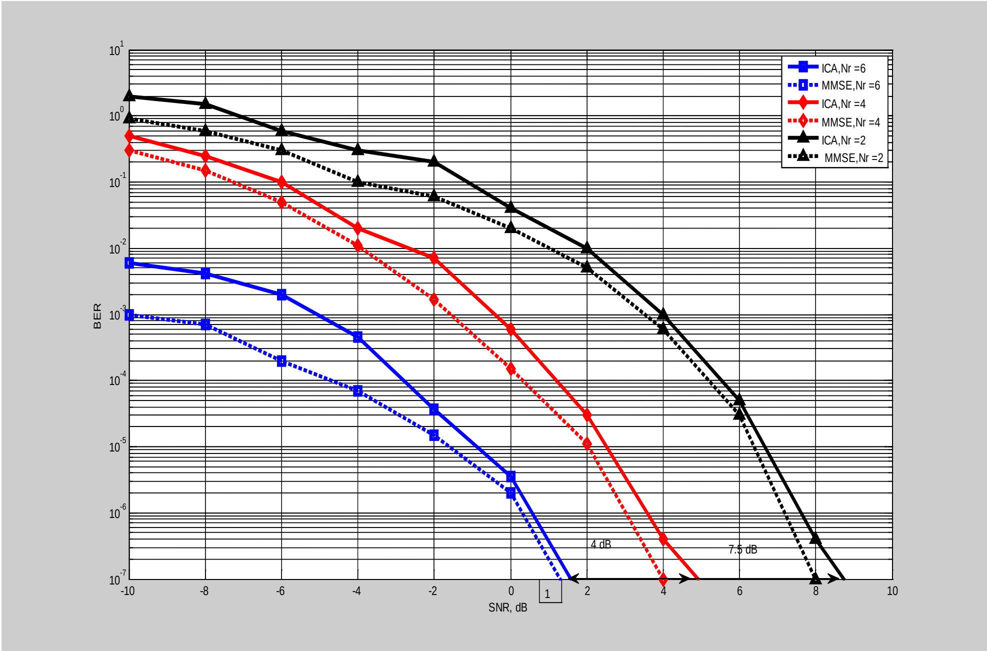

Figure (2) OSTBC: SNR verses BER Performance Comparison for (N_t=2, N_r=2,4,6).

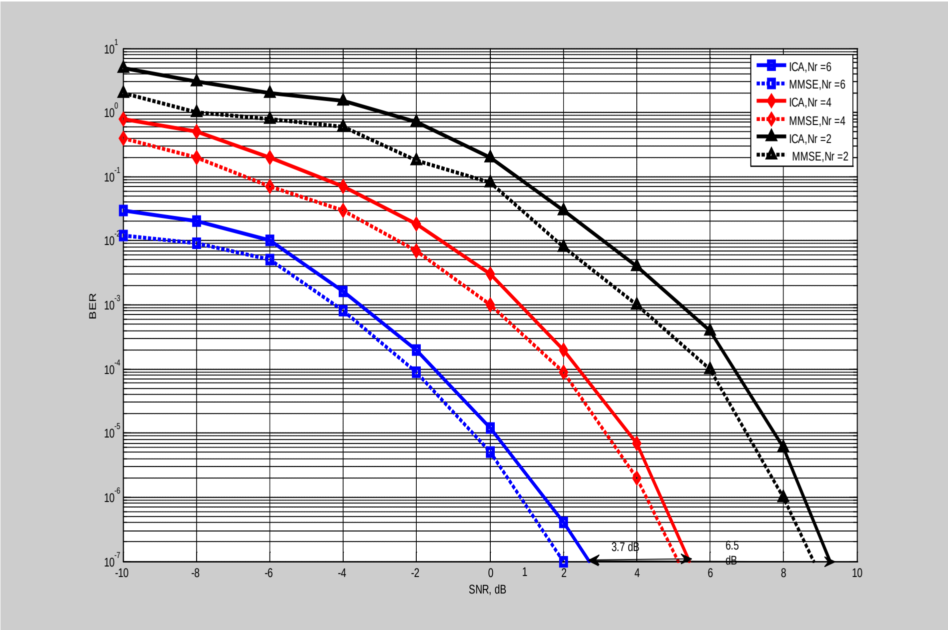

Figure (3) QOSTBC: SNR verses BER Performance Comparison for (N_t=2, N_r=2,4,6).

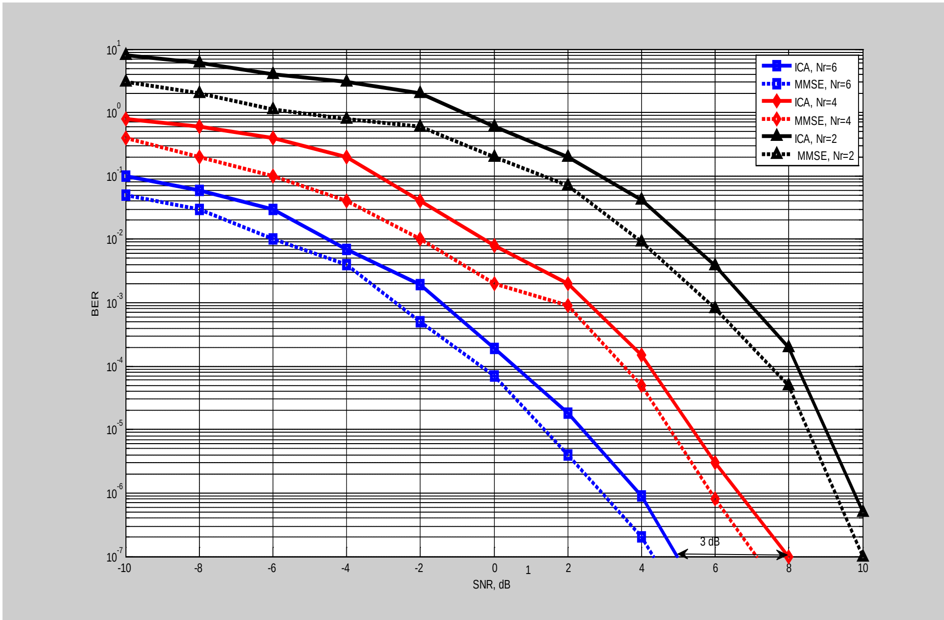

Figure (4) STBC: SNR verses BER Performance Comparison for (N_t=2, N_r=2,4,6).

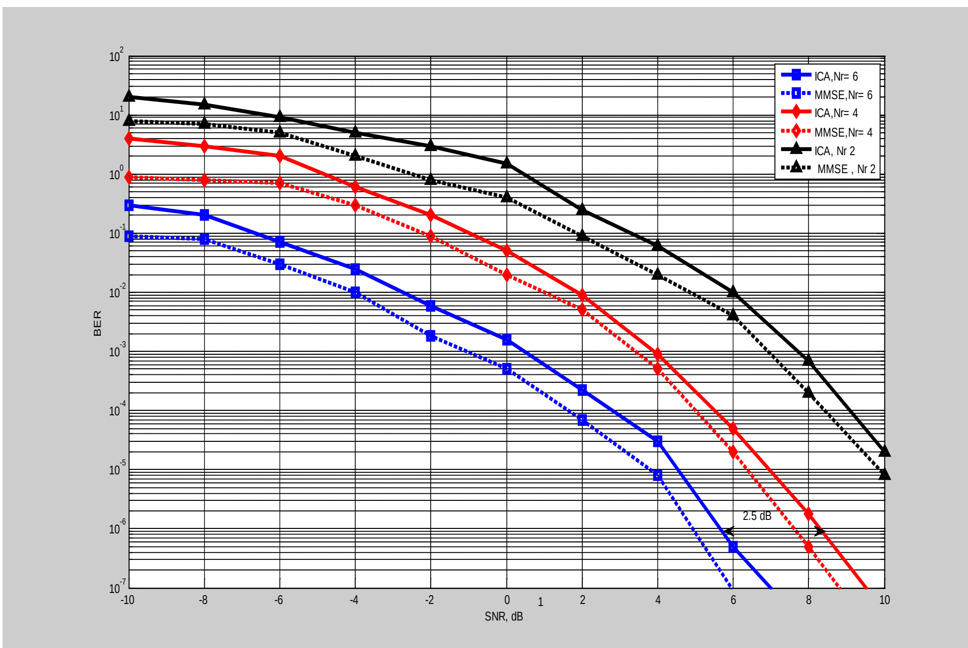

Figure (5) SM: SNR verses BER Performance Comparison for (N_t=2, N_r=2,4,6).

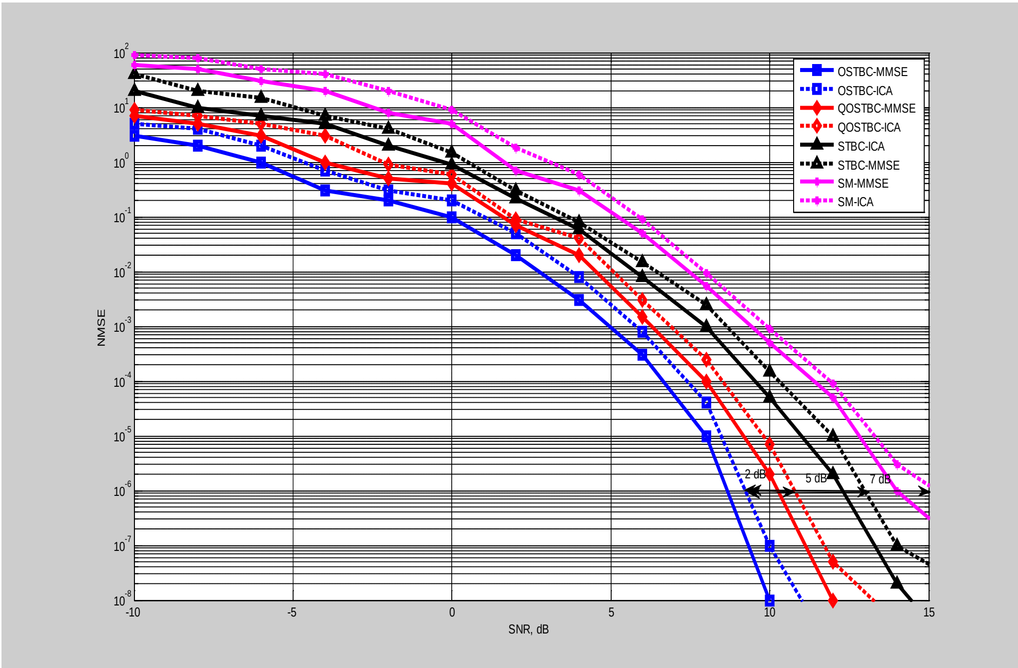

Figure (6) SNR verses NMSE Performance Comparison for (N_t=2, N_r=2).