ICA Based Blind MIMO OFDM Receiver

ICA Based Blind MIMO OFDM Receiver

Mohammad Reza Alsharif[1], Mahdi Khosravy[1] and Katsumi Yamashita[2]
[1]Department of Information Engineering, University of the Ryukyus, Okinawa, Japan
[2]Graduate School of Engineering, Osaka Prefecture University, Osaka, Japan
E-mail : [1]k078661@eve.u-ryukyu.ac.jp, asharif@ie.u-ryukyu.ac.jp,
[2]yamashita@eis.osakafu-u.ac.jp

Abstract

This paper proposes an ICA-based MIMO-OFDM system which efficiently overcomes problems inherent to ICA by using a precise and robust signal reconstruction method. It exploits the predetermined characteristics introduced to transmitted signals by a convolutional encoder at the transmitter to solve permutation indeterminacy, amplitude scaling ambiguity and phase distortion. Since, the introduced characteristics are only dependent on the convolutional code, despite the previous method, the proposed method is channel independent and robust. Moreover, the method is precise, because the accuracy of the introduced characteristics are fulfilled by an optimized convolutional code. We have compared the performance of the proposed MIMO-OFDM system with joint detection (JD) method which estimates the channels by using two training OFDM blocks. Although the JD method is a training based method, the performance of the proposed blind method is favorably comparable over slowly varying channels, and it dominates JD method over fast varying channels.

1 Introduction

Orthogonal frequency division multiplexing (OFDM) has become a popular technique for transmission of signals over wireless channels. The combination of OFDM with multiple-input multiple-output (MIMO) transceiver structure has been promised as a strong candidate for future forth generation (4G) communications [1]. Besides the advantages of a MIMO-OFDM system, deploying blind channel estimation increases the spectral efficiency of the system, since no training data is required.

The separation of multiuser signals in a MIMO-OFDM system at each frequency bin (FB) level has been represented by [2] as an instantaneous blind source separation (BSS) problem in complex domain. But the reconstruction of the multiuser data separated by BSS suffers from permutation indeterminacy, amplitude scaling ambiguity and phase distortion ambiguity which these problems are inherent to complex BSS [3]. Furthermore, the general complexity of BSS algorithms is another important issue that should be practically modified.

This paper proposes an efficient blind multiuser detection and channel estimation technique for MIMO-OFDM systems based on independent component analysis (ICA) [4]. The proposed ICA based MIMO-OFDM system efficiently overcomes the problems of deploying ICA. To solve indeterminacies inherent to ICA, it deploys the precoding solution in [5]. To reduce the complexity of ICA algorithm it uses a concatenate structure wherein a fast BSS approach [6] is used to approximate a separating matrix as starting point of ICA.

The organization of the paper is as follows. Section 2 presents the proposed ICA based multiuser detection in a MIMO-OFDM system. Section 3 explains briefly instantaneous BSS and the used method for reducing BSS complexity. Section 4 provides the simulation results, and finally, section 5 concludes the paper.

2 The Proposed Method

Consider a multiuser MIMO-OFDM system with M_T transmit antennas and M_R receive antennas. The symbols of each user are convolutional encoded by an FIR pre-filter at the transmitter as follows

$$S_i(kN+m) \quad = \quad \sum_{l=0}^{L_f-1} c(l)D_i(kN+m-l) \tag{1}$$

where $D_i(kN+m)$ are information symbols of the i^{th} user, and $S_i(kN+m)$ are their encoded symbols. L_f is the length of the filter and $c(.)$ are its coefficients. R_0 the auto-correlation of No.m FB track of i^{th} encoded user symbol-block and R_1 the correlation between its m^{th} and $m+1^{st}$ FB tracks are respectively as follows

$$\begin{aligned} R_0 &= E\left[|S_i(kN+m)|^2\right] \\ &= c^2(0)+\cdots+c^2(L_f-1) \end{aligned} \tag{2}$$

$$\begin{aligned} R_1 &= E\left[S_i(kN+m)S_i^*(kN+m)\right] \\ &= c(0)c(1)+\cdots+c(L_f-2)c(L_f-1) \end{aligned} \tag{3}$$

$$\boldsymbol{X}(m) = \mathbb{H}(m)\boldsymbol{S}(m) + \boldsymbol{Z}(m), \tag{9}$$

with

$$\begin{aligned}
\boldsymbol{X}(m) &= [X_1(kN+m), X_2(kN+m), \cdots, X_{M_R}(kN+m)]^T \\
\boldsymbol{S}(m) &= [S_1(kN+m), S_2(kN+m), \cdots, S_{M_T}(kN+m)]^T \\
\boldsymbol{Z}(m) &= [Z_1(kN+m), Z_2(kN+m), \cdots, Z_{M_R}(kN+m)]^T
\end{aligned}$$

$$\mathbb{H}(m) = \begin{pmatrix} \boldsymbol{H}_{11}(m,m) & \boldsymbol{H}_{12}(m,m) & \cdots & \boldsymbol{H}_{1M_T}(m,m) \\ \boldsymbol{H}_{21}(m,m) & \boldsymbol{H}_{22}(m,m) & \cdots & \boldsymbol{H}_{2M_T}(m,m) \\ \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{H}_{M_R1}(m,m) & \boldsymbol{H}_{M_R2}(m,m) & \cdots & \boldsymbol{H}_{M_RM_T}(m,m) \end{pmatrix}$$

---

where $E[.]$ is the expectation with respect to k. Eqs. (2) and (3) have been obtained in the Appendix. The prefilter coefficients are optimized for the least possible error of average phase of R_1, that is used for removing phase distortion induced by ICA. We have proved in [5] that this optimization aim is obtained by the following criteria

$$\begin{aligned}
&[c(0), c(1), \cdots, c(L_c-1)] \\
&= argmin_{c(.)}\left(\frac{[\sum_{l=0}^{L_c-1} c(l)]^2}{\sum_{l=0}^{L_c-1} c(l)c(l+1)}\right).
\end{aligned} \tag{4}$$

By solving the above optimization problem subjected to $\sum_{l=0}^{L_f-1} c(l) = 1$, the optimized coefficients are obtained as $[\frac{1}{3}\ \frac{1}{2}\ \frac{1}{6}]$. Note that R_0 and R_1 are only dependent on the coefficients of the convolutional code. These two characteristics will be respectively used for solving the amplitude scaling ambiguity and permutation indeterminacy at the receiver. As it is seen the phase of R_1 which conveys the average difference between the phases of adjacent FB tracks, is zero. This characteristic will be used to solve the phase distortion problem. The N-length k^{th} OFDM symbol block of each i^{th} user

$$\boldsymbol{S}_i^{(k)} = [S_i(kN), S_i(kN+1), \cdots, S_i(kN+N-1)]^T \tag{5}$$

is modulated by an N-point IDFT to

$$\boldsymbol{s}_i^{(k)} = [s_i(kN), s_i(kN+1), \cdots, s_i(kN+N-1)]^T \tag{6}$$

where $i = 1, 2, \cdots, M_T$.

After adding the cyclic prefix (CP) with the length L_{cp} to avoid inter-symbol interference (ISI), the modulated signals are transmitted. The transmitted signals pass through different propagation channels and they are received by No.j antenna at the receiver. After removal of the CP and demodulation by N-point DFT, the received N-length data symbol block by the j^{th} antenna at time k is

$$\boldsymbol{X}_j^{(k)} = \sum_{i=1}^{M_T} \boldsymbol{H}_{ji}\boldsymbol{S}_i^{(k)} + \boldsymbol{Z}_j^{(k)} \tag{7}$$

where $\boldsymbol{Z}_j^{(k)}$ represents zero-mean white Gaussian noise. Because of the orthogonality among the subcarriers, $\boldsymbol{H}_{ji}$ becomes an $N \times N$ diagonal matrix of channel gains between i^{th} transmit antenna and j^{th} receive antenna. The received signal of m-th subcarrier at the j-th antenna in Eq. (7) can be rewritten as

$$\begin{aligned}
&X_j(kN+m) \\
&= \sum_{i=1}^{M_T} \boldsymbol{H}_{ji}(m,m)S_i(kN+m) + Z_j(kN+m) \\
&\qquad 0 \le m \le N-1.
\end{aligned} \tag{8}$$

For the all receive antennas ($1 \le j \le M_R$), we obtain the Eq.(9) (top of this page).

It is clear From Eq. (9) that once the output signals of the DFT modulation are arranged in accordance with the index of subcarriers (m), the MIMO channel in the described system is presented as an instantaneous mixture. Therefore, the blind multiuser detection in this MIMO-OFDM system can be split into N BSS problems to obtain N un-mixing matrices related to N subcarriers ($0 \le m \le N-1$). Note that because of complex nature of symbols, the complex BSS should be applied over each FB track mixtures.

After solving the N complex ICA problems related to N subcarriers in Eq. (9) the separated FB tacks are obtained as

$$\boldsymbol{Y}(m) = \boldsymbol{W}(m)\boldsymbol{X}(m) \tag{10}$$

where $\boldsymbol{W}(m)$ is the un-mixing matrix related to m^{th} subcarrier. But even after successful separation by ICA, permutation indeterminacy, amplitude scaling ambiguity and phase distortion are new problems which necessitate user reconstruction as a post-BSS task.

It can be shown that the auto-correlation of adjacent p^{th} and $p+1^{st}$ FB tracks recovered by complex BSS is as follows

$$E[Y_i(kN+p)Y_l^*(kN+p+1)] = \begin{cases} 0 & \text{if } i \neq l, \\ R_1 A_{ip} A_{l,p+1} e^{(\theta_{ip}-\theta_{l,p+1})} \neq 0 & \text{if } i = l\,. \end{cases} \quad (11)$$

where R_1 is a nonzero known value from Eq.(3), i and l are unknown user ownership indices, A_{ip} and $A_{l,p+1}$ are unknown scaling amplitudes, θ_{ip} and $\theta_{l,p+1}$ are unknown phase distortions. As it is seen in Eq.(11) the cross-correlation between adjacent FB tracks of the same user is a nonzero value, while it is zero for adjacent FB tracks of different users. Therefore, by doing a correlation-based grouping in the sequence from No.1 FB to No.$(N-1)$ FB, the permutation corrected multiuser symbols $\dot{Y}_i(kN+m)$ will be obtained. After permutation alignment, the auto-correlation of the No.p FB track of i^{th} user symbol-block will be

$$\begin{aligned} \phi_{ip}^{ip} &= E[Y_i(kN+p)Y_i^*(kN+p)] \\ &= A_{ip}^2 R_0 \end{aligned} \quad (12)$$

where A_{ip} is unknown amplitude scaling. So, by having R_0 from Eq.(2) the amplitude scaling of $\dot{Y}_{ip}$ can be corrected as follows

$$\ddot{Y}_i(kN+m) = \sqrt{\frac{R_0}{\phi_{im}^{im}}}\,\dot{Y}_i(kN+m). \quad (13)$$

After permutation alignment and amplitude scaling correction, the phase deviation of each FB track with respect to its following one can be obtained as follows

$$\begin{aligned} \phi_{i,p+1}^{ip} &= E[\ddot{Y}_i(kN+p)\ddot{Y}_{i,p+1}^*(kN+p+1)] \\ &= e^{(\theta_{ip}-\theta_{i,p+1})} R_1 \end{aligned} \quad (14)$$

where θ_{ip} and $\theta_{i,p+1}$ are their unknown phase distortions. Since, the phase of R_1 is zero with the least estimation error,

$$e^{j(\theta_{ip}-\theta_{i,p+1})} = e^{j\angle\phi_{i,p+1}^{ip}} = \frac{\phi_{i,p+1}^{ip}}{|\phi_{i,p+1}^{ip}|}. \quad (15)$$

Therefore by multiplying $\ddot{Y}_i(kN+p+1)$ by $\frac{\phi_{i,p+1}^{ip}}{|\phi_{i,p+1}^{ip}|}$, its phase deviation will be the same as $\ddot{Y}_i(kN+p)$. By doing this operation from No.1 FB to No.$N-1$ FB, each FB track is adjusted to its preceding FB track which was adjusted to its prior one. So, the phase distortion of all FB tracks become θ_{i1}, that is a case similar to uncertain carrier phase in single carrier system. The same unknown resultant phase deviation for all symbols of the user can be eliminated by noncoherent detection [7]. At this point all OFDM user signals have been reconstructed, and they are ready to be transferred to user identification unit. Fig. 1 shows the proposed ICA based MIMO-OFDM system.

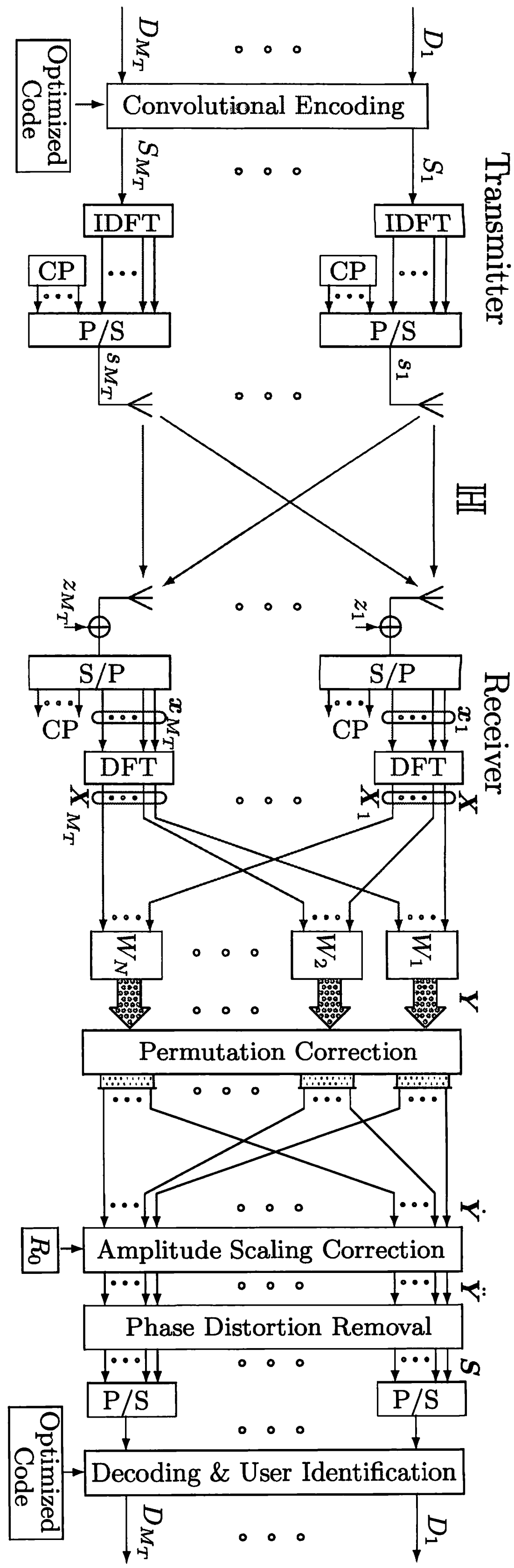

Figure 1: The Proposed ICA based MIMO-OFDM system

3 Blind Source Separation

Here we face the instantaneous form of BSS. The mixing process is described as

$$\boldsymbol{x}(t) = \boldsymbol{A}\boldsymbol{s}(t) + \boldsymbol{n}(t) \tag{16}$$

where an n-dimensional vector $\boldsymbol{s}(t) = [s_1(t), \cdots, s_n(t)]^T$ of independent sources is mixed by an $m \times n$ matrix $\boldsymbol{A}$, and $\boldsymbol{x}(t) = [x_1(t), \cdots, x_m(t)]^T$ is observed. BSS problem is looking for the best $n \times m$ separation matrix $\boldsymbol{W}$ to extract signals $\boldsymbol{y}(t)$ as much as possible close to unknown source signals. Without any prior knowledge of $\boldsymbol{s}$(t) and $\boldsymbol{A}$ except the independence assumption for source signals, $\boldsymbol{y}(t)$ is recovered by BSS as follows

$$\boldsymbol{y}(t) = \boldsymbol{W}\boldsymbol{x}(t) \tag{17}$$

where $\boldsymbol{y}(t) = [y_1(t), \cdots, y_n(t)]^T$.

There are a lot of BSS methods. Here, we have deployed independent component analysis ICA with Kullback-Leibler contrast function. Because, it is known as the best performance BSS method. Since, the nature of symbols is complex, the extension of Kullback-Leibler (KL) ICA to complex domain is used [3]. For fast convergence of ICA algorithm, natural gradient learning algorithm (NGLA) [8] is used. NGLA has a hardware-friendly iterative structure that qualifies it as a better choice.

For more reducing the BSS complexity, an initial approximate to separating matrix is obtained by a low performance fast BSS method. Then the approximated matrix is given to Kullback-Leibler complex ICA as initial value. In this way NGLA starts with an initial separating matrix, and after a few iterations the high performance separating matrix is obtained. For the first step, we have used improved Stone's BSS [6] that is extended to complex domain. Stone BSS [9] is a fast method based on predictability maximization with scaling characteristics of $O(M_R^3)$. By applying two-stepped BSS, number of iterations is reduced in average from 130 to 30 iterations per each separation procedure.

4 Simulation results

This section provides the simulation results of evaluation of performance of the proposed multiuser detection method. All results are compared with the joint detection (JD) method [10] over typical urban (TU) and hilly terrain (HT) channels. In the JD method, the channels are estimated using two training OFDM blocks. Then all user signals are recovered based on the obtained channel estimates, where zero-forcing algorithm is used for joint detection. In our evaluation, different $M_T \times M_R$ configurations of receiving 2 or 3 transmitted user signals by 2, 3, 4 or 6 antennas are employed. All OFDM parameters are the same for both methods. Signal constellation is DQPSK. The number of subcarries is 64, and cycling prefix is 8. Carrier frequency and system bandwidth are respectively 0.5 GHz and 0.5 MHz.

Figs. 2 and 3 demonstrate the comparison of the proposed method with JD method respectively in slowly fading ($f_d = 1.0 \times 10^{-6}$) and fast fading conditions ($f_d = 1.5 \times 10^{-4}$). f_d is the maximum Doppler frequency normalized with symbol rate. As it is seen, the performance of the proposed blind method is favorably comparable over slowly varying channels, and it is better than JD method over fast varying channels. Because the JD method can not accurately approximate the channels during the entire frame in fast variation of channels, while the proposed method does not require channel state information.

5 Conclusion

In this paper, we have proposed an efficient ICA based blind multiuser detection method for MIMO-OFDM systems. The problems inherent to complex ICA have been successfully solved in the proposed method. Furthermore, ICA complexity has been substantially reduced. Since, the coefficients of pre-filter are optimized, the introduced characteristics to transmitted symbols are accurate and the method is precise. On the other hand, it is robust and channel independent because the characteristics of the transmitted signals only depends on the optimized pre-filter coefficients. Computer simulations also demonstrates the efficiency of the proposed method.

Appendix

The auto-correlation of an FB track of encoded OFDM symbols by FIR pre-filter of Eq.(1) can be written as

$$R_0 = E\left[\left|\sum_{l=0}^{L_f-1} c(l) D_i(kN+m-l)\right|^2\right]. \tag{18}$$

where L_f and $c(.)$ are respectively the length and coefficients of the FIR pre-filter. $E[.]$ is the expectation with respect to k. Since $D_i(kN+m)$ is an information symbol modulated by an M-PSK constellation, R_0 can

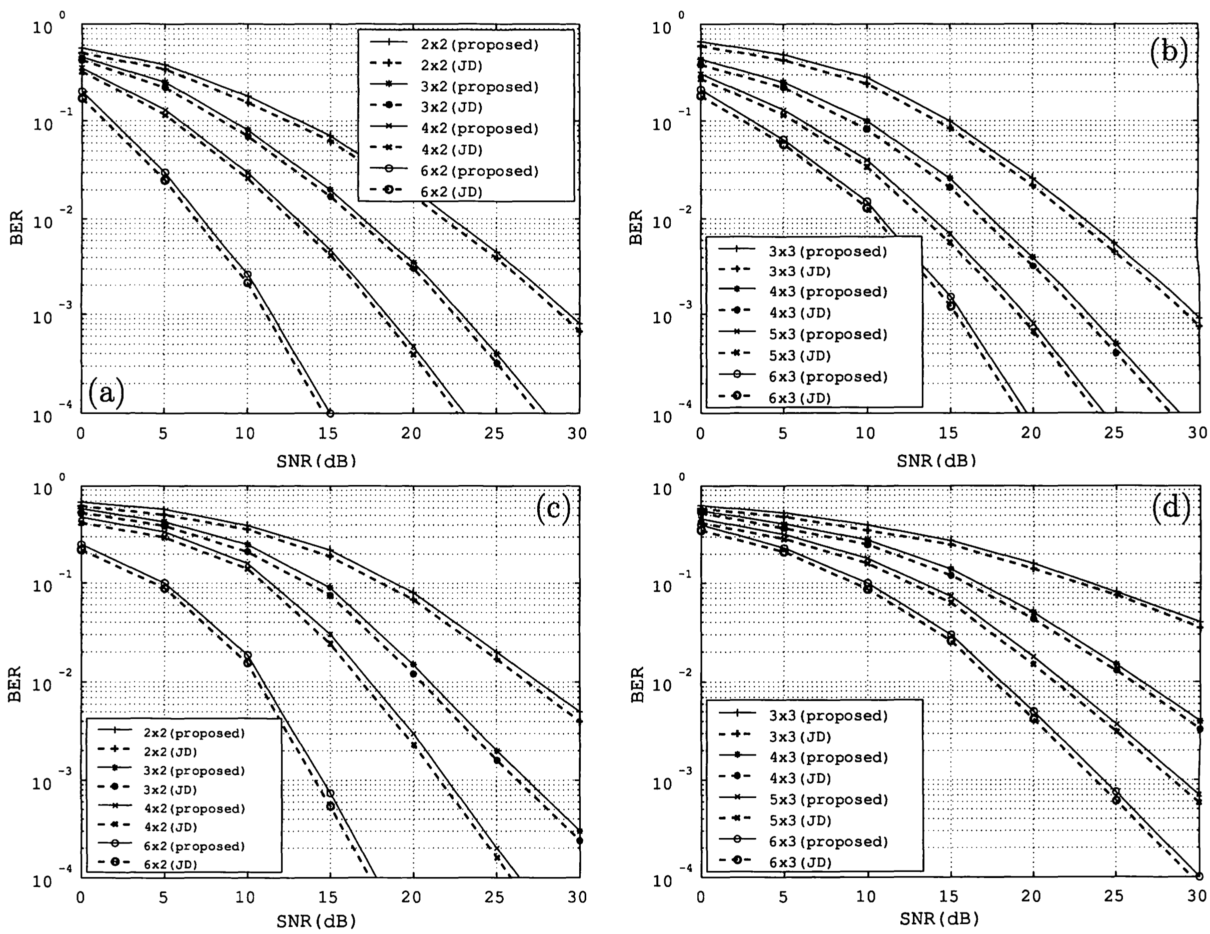

Figure 2: BER comparison for different values of $M_R \times M_T$ while $f_d = 1.0 \times 10^{-6}$ over (a & b) tipycal urban channel, (c & d) hilly terrain channel.

be written as

$$\begin{aligned} R_0 &= E\left[\left| \sum_{l=0}^{L_f-1} c(l) cos\alpha_{m-l,k} + j \sum_{l=0}^{L_f-1} c(l) sin\alpha_{m-l,k} \right|^2\right] \\ &= E\left[\left| \sum_{l=0}^{L_f-1} c(l) cos\alpha_{m-l,k} \right|^2\right] + E\left[\left| \sum_{l=0}^{L_f-1} c(l) sin\alpha_{m-l,k} \right|^2\right] \end{aligned} \quad (19)$$

where $\alpha_{k,m-l}$ is the phase of $D_i(k, m-l)$. From the above equation, it can be obtained

$$R_0 = \sum_{l=0}^{L_f-1} c^2(l) + E\left[\sum_{l_i=0}^{L_f-1} \sum_{l_j=0}^{L_f-1} {}^{l_i \neq l_j} 2c(l_i)c(l_j) cos(\alpha_{m-l_i,k} - \alpha_{m-l_j,k}) \right] \quad (20)$$

mehdi Let $\alpha_{l_i l_j} = \alpha_{k,m-l_i} - \alpha_{k,m-l_j}$, Since the used PSK modulation is without initial phase, it can be shown that $\alpha_{l_i l_j}$ is the phase of a point in the same constellation, and there is equal probability for $\alpha_{l_i l_j} = \alpha_1$ and $\alpha_{l_i l_j} = \alpha_2$, where $cos\alpha_1 = -cos\alpha_2$. Therefore, the expectation of second term of Eq.(20) is zero, and Eq.(2) is obtained.

Similarly, the correlation between m^{th} and $m+1^{st}$ FB tracks is

$$R_1 = \sum_{l=0}^{L_f-2} c(l)c(l+1) + E\left[\sum_{l_i=0}^{L_f-1} \sum_{l_j=0}^{L_f-1} {}^{l_j \neq l_i+1} c(l_i)c(l_j) e^{j(\alpha_{l_i} - \alpha_{l_j})} \right] \quad (21)$$

where $E[.]$, $c(.)$ and L_f are the same as used in Eq.(18). Since, constellation points are symmetrically located around the unit circle, and $e^{j(\alpha_{l_i} - \alpha_{l_j})}$ equals each of them with equal probability, the second term in Eq.(21) equals zero, and Eq.(3) is concluded.

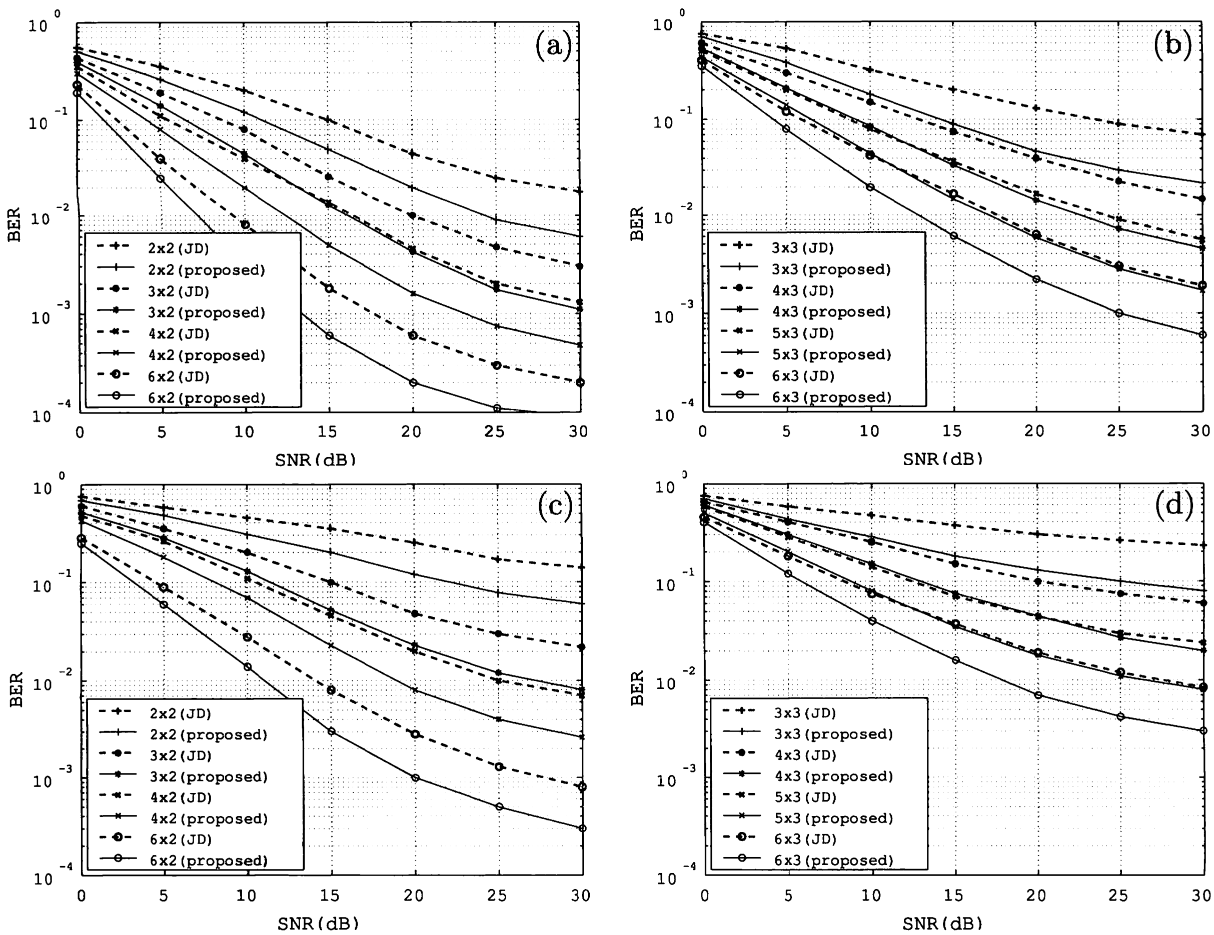

Figure 3: BER comparison for different values of $M_R \times M_T$ while $f_d = 1.5 \times 10^{-4}$. over (a & b) tipycal urban channel, (c & d) hilly terrain channel.

References

[1] Hemanth Sampath, Shilpa Talwar, Jose Tellado, Vinko Erceg and Arogyaswami Paulraj, "A fourth-generation MIMO-OFDM broadband wireless system: design, performance, and field trial results" , *IEEE Commun. Mag.*, vol. 40, no. 9, pp. 143–149, Sep. 2002.

[2] Chiu Shun Wong, Dragan Obradovic, Nilesh Madhu, "Independent component analysis (ICA) for blind equalization of frequency selective channels" *in Proc. 13th IEEE Workshop Neural Networks Signal Processing*, pp. 419-428, 2003.

[3] Paris Smaragdis, "Blind separation of convoluted mixtures in frequency domain", *J. Neurocomputing*, vol. 22, Issues 1–3, pp. 21–34, 1998.

[4] Aapo Hyvrinen, Juha Karhunen, Erkki Oja, *Independent Component Analysis*, John Wiley, New York, 2001.

[5] Mahdi Khosravy, Mohammad Reza Alsharif , Bin Guo, Hai Lin and Katsumi Yamashita, "A Robust and Precise Solution to Permutation Indeterminacy and Complex Scaling Ambiguity in BSS-based Blind MIMO-OFDM Receiver", *in ICA 2009, T. Adali, (Eds.) , Springer-Verlags Lecture Notes in Computer Science, LNCS 5441*, pp. 670-677, 2009.

[6] Mahdi Khosravy, Mohammad Reza Alsharif, Katsumi Yamashita, "A Probabilistic Short-length Linear Predictability Approach to Blind Source Separation" *in 23rd International Technical Conference on Circuits/Systems, Computers and Communications (ITC-CSCC2008)*, pp. 381–384, Yamaguchi, Japan, July, 2008.

[7] Richard Van Nee, Ramjee Prasad, *OFDM for Wireless Multimedia Communications*, Artech House, 2000.

[8] S. Amari, A. Cichocki and H. H. Yang,"A New Learning Algorithm for Blind Signal Separation", *Advances in Neural Information Processing Systems 1996*, Vol.8, MIT Press, Cambridge MA, pp. 757-763, 1996.

[9] James V. Stone, "Blind source separation using temporal predictability", *Neural computation*, 13(7), pp. 1559–1574, 2001.

[10] Alexandros Sklavos, Tobias .E. Costa, Harald Haas, and Egon Schulz, "Joint detection in multi-antenna and multi-user OFDM systems", *in multi-carrier Spread-Spectrum and Related Topics*, K.Fazel, S. Kaiser, Eds. Boston, MA: Kluwer, 2002.