Full-diversity iterative MMSE receivers with space-time precoders over block-fading MIMO channels

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Abstract— **In this paper we study the performance of space-time bit-interleaved coded modulation (ST-BICM) over block-fading multi-input multi-output (MIMO) channels with iterative receivers based on minimum mean square error (MMSE) detection. We show how full diversity can be achieved with a special class of space-time precoders. Performance in terms of symbol error rate (SER) and word error rate (WER), obtained via Monte Carlo simulations, is shown.**

I. Introduction

Multiple-input multiple-output (MIMO) systems, obtained by using multiple antennas both at the transmitter and the receiver, have shown to provide high transmission rates over fading channels [20] and help in increasing the diversity order of signals over slow fading channels [7]. Achieving maximum diversity in uncoded systems requires the use of space-time codes together with maximum likelihood (ML) receivers [8]. Differently, in coded systems, *a posteriori* probability (APP) detectors are required to recover maximum diversity at the receiver end [9], [10]. In both cases, the complexity at the detector increases exponentially with the number of transmit antennas.

On the other hand, linear receivers for uncoded transmission over multiple-antenna quasi-static fading channels have been extensively studied [15], [18], [6], [11], [13]. The achieved diversity orders are far from being optimal, even with space-time precoders [14], [17].

In this work, we show that an iterative receiver can recover maximum diversity with a soft-input soft-output (SISO) linear detector [21] when coded modulation and space-time precoding are concatenated at the transmitter. We then study the outage probability [16] of such receivers that provide an information theoretic lower bound on the performance and thus give insight on the achievable diversity orders.

The paper is organized as follows: Section II gives the system model and the notations used in the rest of the paper; in Section III, we give the equations for the MMSE-based detector. The analysis of the diversity order for MMSE-based iterative receivers is provided in Section IV, and the design of space-time precoders for such receivers is proposed in Section V. In Section VI, symbol error rate (SER) and word error rate (WER) performance, obtained via Monte Carlo simulations, are shown. Finally, Section VII gives some concluding remarks.

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II. System Model

We consider a system transmitting via a space-time bit-interleaved coded modulation (ST-BICM) [4], [10] over a narrowband block-fading MIMO channel with n_t transmit antennas and n_r receive antennas. We assume that a codeword undergoes one single temporal channel realization. The discret-time model for the received signal is written as

$$\mathbf{y} = \mathbf{H}\mathbf{S}\mathbf{z} + \mathbf{w} \ , \tag{1}$$

where $\mathbf{y} \in \mathbb{C}^{sn_r}$ and $\mathbf{z} \in \Omega = (2^m - \text{PSK})^{sn_t}$ are the vectors of received and transmitted complex symbols, respectively, m being the number of bits per Phase Shift Keying (PSK) modulated symbol, and s being the time spreading of a space-time precoding matrix $\mathbf{S}$ of dimensions $sn_t \times sn_t$. The MIMO channel matrix $\mathbf{H}$ with dimensions $sn_r \times sn_t$ is diagonal and given by

$$\mathbf{H} = \mathbf{I}_s \otimes \mathcal{H} \ , \tag{2}$$

where $\mathbf{I}_s$ is the $s \times s$ identity matrix, and $\mathcal{H}$ has dimensions $n_r \times n_t$ and has independent complex Gaussian entries h_{ij} with zero mean and unit variance representing the channel gain from the jth transmit to the ith receive antennas. The length-sn_r vector of additive white Gaussian noise components $\mathbf{w}$ is assumed to be circularly symmetric with zero mean and variance N_0. Digital transmission operates as shown in Fig. 1: information bits are fed to an encoder of rate $R_c \leq 1$. The codeword $\mathbf{c}$ is first interleaved, fed to a 2^m-PSK mapper, and then space-time precoded. The space-time precoder combines sn_t PSK symbols over the n_t transmit antennas and over s time periods. The resulting frame is sent over the fading channel through the n_t transmit antennas, and the total transmission rate is: $R = mn_tR_c$. The channel coefficients are supposed to be perfectly known to the receiver, but not to the transmitter. At the receiver, a SISO linear detector, making use

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Fig. 1. Block diagram of the transmitter.

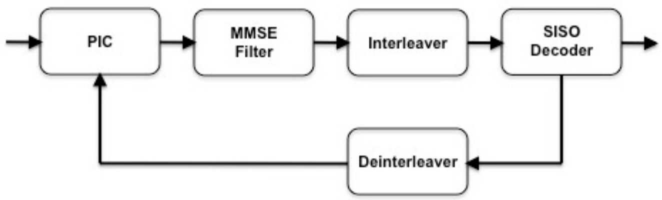

Fig. 2. Block diagram of the receiver.

of parallel interference cancellation (PIC) and minimum mean square error (MMSE) filtering, provides extrinsic probabilities on modulated symbols based on the received symbols, the channel matrix, and the *a priori* probabilities on coded bits fed back from the SISO decoder, as shown in Fig. 2.

III. Iterative MMSE-based Detector

At the output of the channel, the vector $\mathbf{y}$ is fed to a linear SISO detector [21], [19] that takes into account the *a priori* information fed from the SISO channel decoder. In the sequel, we denote

$$\mathbf{G} = \mathbf{HS} \ , \tag{3}$$

the channel seen by the PSK symbols. Now let $\bar{z}_j$ denote the *a priori*-based mean of the complex transmitted symbol z_j ($j = 1, \cdots, sn_t$) computed using the *a priori* probabilities $\pi(c_b)$ on coded bits fed back from the SISO decoder as

$$\bar{z}_j = \sum_{z_j} z_j \prod_{b=m.j}^{m.j+m-1} \pi(c_b) \ , \tag{4}$$

and define $\bar{\mathbf{z}}_j = \bar{\mathbf{z}} - \bar{z}_j \mathbf{e}_{sn_t}^j$ a vector containing the interference experienced by the jth symbol from the $sn_t - 1$ other symbols in the space-time vector, where the vector $\mathbf{e}_{sn_t}^j$ of length sn_t contains a value of 1 at position j and 0 elsewhere. The unbiased estimation of z_j is obtained (see [19]) via PIC

$$\tilde{\mathbf{y}}_j = \mathbf{y} - \mathbf{G}\bar{\mathbf{z}}_j \ , \tag{5}$$

and then via MMSE filtering

$$\tilde{z}_j = \mathbf{g}_j^\dagger \left(\mathbf{G}\Gamma_j\mathbf{G}^\dagger + N_0 \mathbf{I}_{sn_r} \right)^{-1} \tilde{\mathbf{y}}_j \ , \tag{6}$$

where $(\cdot)^\dagger$ is the transpose conjugate operator, $\mathbf{g}_j = \mathbf{G}\mathbf{e}_{sn_t}^j$, and Γ_j is a diagonal matrix whose nth entry is given by

$$\Gamma_{jn} = \begin{cases} 1 - |\bar{z}_n|^2 & n \neq j \\ 1 & n = j \end{cases} ,$$

and is computed at each iteration from the *a priori* probabilities fed from the SISO decoder.

IV. Diversity of MMSE-based Receivers

A. Non-iterative receiver for uncoded systems.

For uncoded systems, the MMSE-based detector has exactly the same expression as that of (6) without any prior knowledge on the symbol estimates, i.e. $\bar{z}_n = 0 \ \forall \ n$. The signal-to-interference-plus-noise ratio (SINR) of the jth symbol is thus computed as [15]:

$$\gamma_j = \mathbf{g}_j^\dagger \left(\hat{\mathbf{G}}_j \hat{\mathbf{G}}_j^\dagger + 2N_0 \mathbf{I}_{sn_r} \right)^{-1} \mathbf{g}_j \ , \tag{7}$$

where $\hat{\mathbf{G}}_j \in \mathbb{C}^{sn_r \times (sn_t - 1)}$ is obtained by removing column $\mathbf{g}_j$ from $\mathbf{G}$. The random variable in (7) has been shown to follow a χ^2 distribution with $2(n_r - n_t + 1)$ degrees of freedom [18], [6], [11], [13]. Hence, the maximum diversity order for uncoded systems with MMSE-based receivers over block-fading channels is

$$d_u = \lim_{\mathrm{SINR} \to \infty} \frac{-\log(P_e)}{\log(\mathrm{SINR})} = n_r - n_t + 1 \ , \tag{8}$$

where P_e is the error probability. Even with the use of a space-time code, uncoded systems with MMSE-based receivers cannot attain full diversity [14], [17]. Only for small transmission rates, i.e. with $R < n_t \log\left(\frac{n_t}{n_t - 1}\right)$, MMSE-based receivers can recover maximum diversity $d_{\max} = n_t n_r$.

B. Iterative receiver for coded systems.

With an iterative receiver, soft information is exchanged between the detector and the channel decoder, and interference between transmit antennas can be removed more efficiently. First, let us consider the channel seen at the output of the linear detector for every symbol, provided that the interference is totally removed between symbols. We have that

$$\tilde{z}_j = \mu_j z_j + w_j \ , \tag{9}$$

with the mean μ_j written as

$$\mu_j = \mathbf{g}_j^\dagger \left(\mathbf{g}_j \mathbf{g}_j^\dagger + 2N_0 \mathbf{I}_{sn_r} \right)^{-1} \mathbf{g}_j \tag{10}$$

$$= \mathbf{g}_j^\dagger \Omega_j^{-1} \mathbf{g}_j \ . \tag{11}$$

The matrix Ω_j is an $sn_r \times sn_r$ Hermitian matrix. For $n_r > 1$ the matrix is non-singular, due to $N_0 > 0$, and thus invertible. After eigenvalue decomposition, Ω_j can be written as

$$\Omega_j = \mathbf{D}_j \Lambda_j \mathbf{D}_j^{-1} \ , \tag{12}$$

where $\mathbf{D}_j$ is an $sn_r \times sn_r$ rotation matrix containing the eigenvectors of Ω_j, and the non-zero diagonal entries λ_i of Λ_j are the corresponding eigenvalues. Then, the inverse of Ω_j may be written as

$$\Omega_j^{-1} = \mathbf{D}_j^{-1} \Lambda_j^{-1} \mathbf{D}_j = \mathbf{D}_j^\dagger \Lambda_j^{-1} \mathbf{D}_j \ . \tag{13}$$

Now inserting (13) into (11), we obtain

$$\mu_j = \mathbf{g}_j^\dagger \mathbf{D}_j^\dagger \Lambda_j^{-1} \mathbf{D}_j \mathbf{g}_j = \mathbf{f}_j^\dagger \Lambda_j^{-1} \mathbf{f}_j \ . \tag{14}$$

The distribution of $\mathbf{g}_j$ being invariant after rotation, $\mathbf{g}_j$ and $\mathbf{f}_j$ have the same distribution, and we thus obtain that

$$\mu_j = \mathbf{f}_j^\dagger \Lambda_j^{-1} \mathbf{f}_j = \sum_{i=1}^{sn_r} \frac{|f_i|^2}{\lambda_i} \ , \tag{15}$$

and follows a χ^2 distribution with $2sn_r$ degrees of freedom. This means that, if the *a priori* information fed from the channel decoder is perfectly reliable, maximum diversity $n_t n_r$ is attained when using a full-spreading space-time rotation, i.e. assuming $s = n_t$. In other words, without a space-time rotation, the receiver sees n_t interfering single-input multiple-output fading subchannels carrying each a diversity order of $1 \times n_r$. With a space-time precoder, the receiver sees sn_t interfering single-input multiple-output fading subchannels having each a diversity order of $1 \times sn_r$. Hence, all PSK symbols can potentially achieve full diversity at a cost of a stronger interference. For this reason, the choice of the space-time rotation that allows for interference suppression is crucial.

V. Design of space-time precoders.

As explained in the previous section, each transmitted symbol z_j achieves full diversity when a full-spreading space-time rotation is used, provided that the interference is totally removed. For this reason, the critical part of the detector in (6) is the interference cancellation operation, given by

$$\tilde{\mathbf{y}}_j = \mathbf{y} - \mathbf{G}\bar{\mathbf{z}}_j = \mathbf{G}\left(\mathbf{z} - \bar{\mathbf{z}}_j\right) + \mathbf{w} \ . \tag{16}$$

In order to better analyze the equivalent channel matrix $\mathbf{G}$, we write the space-time rotation matrix as

$$\mathbf{S} = \begin{bmatrix} \theta^1_{1,1} & \theta^1_{1,2} & \cdots & \theta^1_{1,sn_t} \\ \vdots & \vdots & \ddots & \vdots \\ \theta^1_{n_t,1} & \theta^1_{n_t,2} & \cdots & \theta^1_{n_t,sn_t} \\ \theta^2_{1,1} & \theta^2_{1,2} & \cdots & \theta^2_{1,sn_t} \\ \vdots & \vdots & \ddots & \vdots \\ \theta^2_{n_t,1} & \theta^2_{n_t,2} & \cdots & \theta^2_{n_t,sn_t} \\ \vdots & \vdots & \ddots & \vdots \\ \theta^s_{1,1} & \theta^s_{1,2} & \cdots & \theta^s_{1,sn_t} \\ \vdots & \vdots & \ddots & \vdots \\ \theta^s_{n_t,1} & \theta^s_{n_t,2} & \cdots & \theta^s_{n_t,sn_t} \end{bmatrix} , \tag{17}$$

where the entries $\theta^\ell_{u,v}$ are complex numbers. We then have the equation (18) at the top of the next page where each Φ_p is an $n_t \times sn_t$ matrix. Now let us compute the covariance matrix of the equivalent channel matrix $\mathbf{G}$ as

$$\mathbf{C} = \mathbb{E}\left[\mathbf{G}\mathbf{G}^\dagger\right] = \mathbb{E}\begin{bmatrix} \Phi_1\Phi_1^\dagger & \cdots & \Phi_1\Phi_s^\dagger \\ \vdots & \ddots & \vdots \\ \Phi_s\Phi_1^\dagger & \cdots & \Phi_s\Phi_s^\dagger \end{bmatrix} . \tag{19}$$

In order for the interference encountered by the sn_t PSK symbols to be independent, the covariance matrix $\mathbf{C}$ should be a scaled identity matrix. First, by considering the block-diagonal part of $\mathbf{C}$, i.e. the entries at $\Phi_p\Phi_p^\dagger$, only diagonal terms remain as channel coefficients are independent. Second, for the off-block-diagonal entries of $\mathbf{C}$ to be null, i.e. for $\Phi_p\Phi_q^\dagger$ $\forall \ p \neq q$, the s sub-parts of every column in $\mathbf{S}$ should be orthogonal to each other, i.e.

$$< \mathbf{\Theta}^b_r, \mathbf{\Theta}^d_r >= 0 \ \ \forall \ r, b \neq d \ , \tag{20}$$

with

$$\mathbf{\Theta}^b_r = \left[\theta^b_{1,r}, \cdots, \theta^b_{n_t,r}\right]^t \ , \tag{21}$$

where $(\cdot)^t$ denotes the transpose operator. Finally, the space-time precoder should ensure that the sn_t transmitted symbols encounter the same residual interference-plus-noise variance. The reason is that usually, in multi-user detection, PIC is most efficient when all the users have equal power [22]. It is thus necessary that the symbols at the output of the equivalent channel $\mathbf{G}$ have equal power so that, after PIC, they face residual interference having the same variance. This property is ensured if the s sub-parts of every column of the space-time rotation $\mathbf{S}$ have equal norm, and we thus obtain that $\mathbf{G}\left(\mathbf{z} - \bar{\mathbf{z}}_j\right) \sim \mathcal{N}\left(0, \left(\mathbf{\Theta}^b_r\right)^\dagger \mathbf{\Theta}^b_r \mathbf{I}_{sn_t}\right) \forall \ r, b$. If this property is not ensured, a situation similar to the near-far problem in multi-user detection will occur, in which the dominance of certain sub-channels over others leads to performance degradation [23]. Moreover, the equal-norm property of the subparts of every column leads to the fact that the eigenvalues of Ω_j will be all equal and thus the coding gain is enhanced, as shown with APP detectors in [9]. The equal-norm and orthogonal sub-parts conditions, called the “Genie conditions” in [3], are also necessary for optimal iterative APP detection and decoding over MIMO channels. They also correspond to the properties of Unitary Trace-Orthogonal Space-Time Block Codes [14] that allow for optimal uncoded performance of MMSE receivers. Finally, it should be noted that, as detection complexity in (6) is proportional to s, partial-spreading rotations (with $s < n_t$) can be used at the cost of lower diversity orders. *Dispersive Nucleo Algebraic* (DNA) space-time precoders [9], that exist for $s \in [1, \cdots, n_t]$ and satisfy the “Genie conditions”, allow to achieve a diversity order of sn_r over MIMO channels with MMSE-based detectors as well.

VI. Simulation Results

In this section, SER and WER performance in the uncoded and coded cases, respectively, of ST-BICM with MMSE-based receivers are shown. The space-time precoders are the full-rate DNA precoders that satisfy the properties of Section V. We consider Quadrature Phase Shift Keying (QPSK) modulation with Gray mapping, thus the extrinsic probabilities at the output of the detector are given by

$$\xi(c_{2n}) = 2\Re(\tilde{z}_n) - 1 \ , \quad \xi(c_{2n+1}) = 2\Im(\tilde{z}_n) - 1 \ , \tag{22}$$

with $n = 0, \cdots, N/2 - 1$, and where N is the number of bits per codeword.

In Fig. 3, SER performance of the “Genie-aided” MMSE-based detector for uncoded transmission is shown over the 4×1 narrowband block-fading channel, in which interference was removed in the simulation, i.e. we set : $\bar{z}_j = z_j \ \forall j$ in (6). The three curves represent transmissions without rotation ($s = 1$),

$$\mathbf{G} = \mathbf{HS} = \begin{bmatrix} \Phi_1 \\ \vdots \\ \Phi_s \end{bmatrix} = \begin{bmatrix} \sum_{a=1}^{n_t} h_{1,a}\theta_{a,1}^1 & \sum_{a=1}^{n_t} h_{1,a}\theta_{a,2}^1 & \cdots & \sum_{a=1}^{n_t} h_{1,a}\theta_{a,sn_t}^1 \\ \vdots & \vdots & \ddots & \vdots \\ \sum_{a=1}^{n_t} h_{n_r,a}\theta_{a,1}^1 & \sum_{a=1}^{n_t} h_{n_r,a}\theta_{a,2}^1 & \cdots & \sum_{a=1}^{n_t} h_{n_r,a}\theta_{a,sn_t}^1 \\ \sum_{a=1}^{n_t} h_{1,a}\theta_{a,1}^2 & \sum_{a=1}^{n_t} h_{1,a}\theta_{a,2}^2 & \cdots & \sum_{a=1}^{n_t} h_{1,a}\theta_{a,sn_t}^2 \\ \vdots & \vdots & \ddots & \vdots \\ \sum_{a=1}^{n_t} h_{n_r,a}\theta_{a,1}^2 & \sum_{a=1}^{n_t} h_{n_r,a}\theta_{a,2}^2 & \cdots & \sum_{a=1}^{n_t} h_{n_r,a}\theta_{a,sn_t}^2 \\ \vdots & \vdots & \ddots & \vdots \\ \sum_{a=1}^{n_t} h_{1,a}\theta_{a,1}^s & \sum_{a=1}^{n_t} h_{1,a}\theta_{a,2}^s & \cdots & \sum_{a=1}^{n_t} h_{1,a}\theta_{a,sn_t}^s \\ \vdots & \vdots & \ddots & \vdots \\ \sum_{a=1}^{n_t} h_{n_r,a}\theta_{a,1}^s & \sum_{a=1}^{n_t} h_{n_r,a}\theta_{a,2}^s & \cdots & \sum_{a=1}^{n_t} h_{n_r,a}\theta_{a,sn_t}^s \end{bmatrix}, \quad (18)$$

partial-spreading DNA rotation ($s = 2$), and full-spreading DNA rotation ($s = 4$). In each case, a diversity order of sn_r is achieved, thus a full-spreading rotation is required to recover maximum diversity.

WER performance of ST-BICM for a codeword length of $N = 1024$ are shown for 2×1 and 2×2 narrowband block-fading MIMO channels in Figs. 4 and 5, respectively. The code used is the 16-state non-recursive non-systemmatic convolutional code with generator polynomials $(23, 35)_8$, and the interleavers are pseudo-randomly generated. The comparison of MMSE-based receivers for different space-time precoders is made with outage probability. In both Figs. 4 and 5, maximum diversity $d_{\max} = sn_r$ is achieved with the DNA rotation given by:

$$\mathbf{S} = \frac{1}{2} \begin{bmatrix} 1 & e^{j2\pi/15} & e^{j4\pi/15} & e^{j6\pi/15} \\ 1 & je^{j2\pi/15} & -e^{j4\pi/15} & -je^{j6\pi/15} \\ e^{j6\pi/15} & -e^{j8\pi/15} & e^{j10\pi/15} & -e^{j12\pi/15} \\ -e^{j6\pi/15} & je^{j8\pi/15} & e^{j10\pi/15} & -je^{j12\pi/15} \end{bmatrix},$$

and performance less than 2 dB from outage probability is achieved, while the receivers fail to remove the interference with both a random rotation [12] and the Golden code rotation.

VII. Conclusions

We have proposed a communication system based on ST-BICM capable to achieve maximum diversity over narrowband block-fading MIMO channels with MMSE-based iterative receivers. The diversity is collected at the linear detector, and under specific properties of the space-time rotation, the channel decoder is capable of removing the interference between the transmitted symbols. We have shown SER and WER performances, obtained via Monte Carlo simulations, in the cases of uncoded and coded transmissions, respectively.

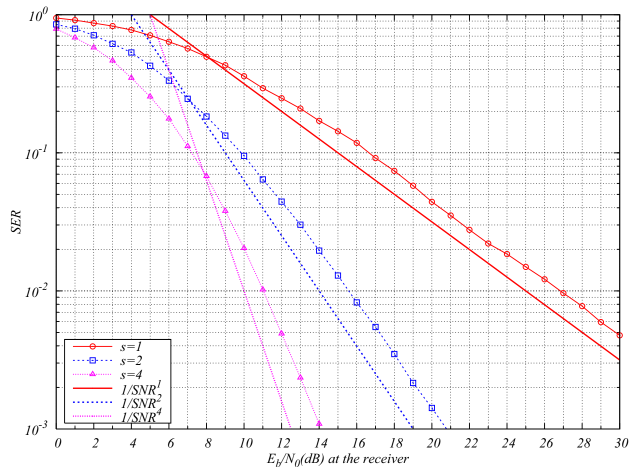

Fig. 3. MMSE detector, uncoded transmission, $n_t = 4$, $n_r = 1$, DNA precoders.

References

[1] L. Bahl, J. Cocke, F. Jelinek, and J. Raviv, "Optimal decoding of linear codes for minimizing symbol error rate," *IEEE Trans. Inf. Theory*, vol. 20, no. 2, pp. 284–287, Mar. 1974.

[2] J.C. Belfiore, G. Rekaya, and E. Viterbo, "The golden code: a 2x2 full-rate space-time code with nonvanishing determinants," *IEEE Trans. Inf. Theory*, vol. 51, no. 4, pp. 1432–1436, Apr. 2005.

[3] J.J. Boutros, N. Gresset, and L. Brunel, "Turbo coding and decoding for multiple antenna channels," *IEEE Int. Symp. Turbo Codes & Related Topics*, 2003.

[4] G. Caire, G. Taricco, and E. Biglieri, "Bit-interleaved coded modulation," *IEEE Trans. Inf. Theory*, vol. 44, no. 3, pp. 927–946, Mar. 1998.

[5] A. Dejonghe and L. Vandendorpe, "Turbo-equalization for multilevel modulation: an efficient low-complexity scheme," *IEEE Int. Conf. Comm. (ICC)*, 2002.

[6] A. Fasano and S. Barbarossa, "Iterative MMSE decoder for trace-orthogonal space-time coding," *IEEE Int. Conf. Acoustics, Speech, Sig. Proc. (ICASSP)*, 2006.

[7] G.J. Foschini and M.J. Gans, "On limits of wireless communications in a fading environment when using multiple antennas," *Wireless Pers. Comm., Springer*, vol. 6, no. 3, pp. 311–335, Mar. 1998.

[8] D. Gesbert, M. Shafi, D. Shiu, P.J. Smith, and A. Naguib, "From theory to practice: an overview of MIMO space-time coded wireless systems," *IEEE J. Sel. Areas Comm.*, vol. 21, no. 3, pp. 281–302, Mar. 2003.

[9] N. Gresset, "New space-time coding techniques with bit-interleaved coded modulations," *Ph.D. Thesis*, ENST, Paris, 2004.

[10] N. Gresset, L. Brunel, and J.J. Boutros, "Space–time coding techniques with bit-interleaved coded modulations for MIMO block-fading channels," *IEEE Trans. Inf. Theory*, vol. 54, no. 5, pp. 2156–2178, May 2008.

[11] A. Hedayat and A. Nosratinia, "Outage and diversity of linear receivers in flat-fading MIMO channels," *IEEE Trans. Sig. Proc.*, vol. 55, no. 12, pp. 5868–5873, Dec. 2007.

[12] G. Kraidy, N. Gresset and J.J. Boutros, "Information theoretical versus algebraic constructions of linear unitary precoders for non-ergodic multiple antenna channels," *Canadian Workshop Inf. Theory*, 2005.

[13] K.R. Kumar, G. Caire, and A.L. Moustakas, "Asymptotic performance of linear receivers in MIMO fading channels," *IEEE Trans. Inf. Theory*, submitted, `http://arxiv.org/abs/0810.0883`.

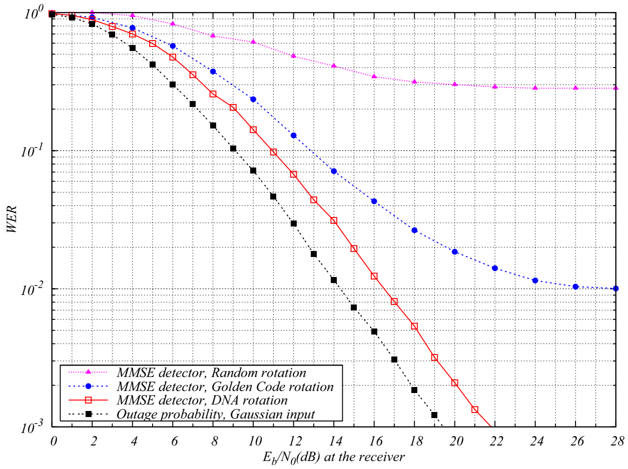

Fig. 4. ST-BICM with linear detectors, $n_t = 2$, $n_r = 1$, $N = 1024$.

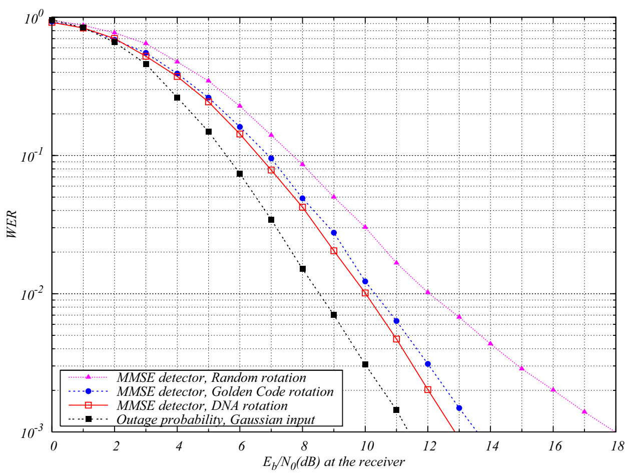

Fig. 5. ST-BICM with linear detectors, $n_t = n_r = 2$, $N = 1024$.

[14] J. Liu, J. Zhang, and K.M. Wong, "On the design of minimum BER linear space-time block codes for MIMO systems equipped with MMSE receivers," *IEEE Trans. Signal Process.*, vol. 54, no. 8, pp. 3147–3158, Aug. 2006.

[15] E.N. Onggosanusi, A.G. Dabak, T. Schmidl, and T. Muharemovic, "Capacity analysis of frequency-selective MIMO channels with sub-optimal detectors," *IEEE Int. Conf. Acoustics, Speech, Sig. Proc. (ICASSP)*, 2002.

[16] L.H. Ozarow, S. Shamai, and A.D. Wyner, "Information theoretic considerations for cellular mobile radio," *IEEE Trans. Vehic. Tech.*, vol. 43, no. 2, pp. 359–378, Feb. 1994.

[17] G.S. Rajan and B.S. Rajan, "MMSE optimal algebraic space-time codes," *IEEE Trans. Wireless Comm.*, submitted, `http://arxiv.org/abs/cs/0702008`.

[18] M. Rupp, C. Mecklenbräuker, and G. Gritsch, "High diversity with simple space time block-codes and linear receivers," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, 2003.

[19] P. Salvo Rossi and R.R. Müller, "Joint twofold-iterative channel estimation and multiuser detection for MIMO-OFDM systems," *IEEE Trans. Wireless Comm.*, vol. 7, no. 11, pp. 4719–4729, Oct. 2008.

[20] I.E. Telatar, "Capacity of multi-antenna Gaussian channels," *Europ. Trans. Comm.*, vol. 10, no. 6, pp. 585–596, Jun. 1999.

[21] M. Tuchler, R. Koetter, and A.C. Singer, "Turbo equalization: principles and new results," *IEEE Trans. Comm.*, vol. 50, no. 5, pp. 754–767, May 2002.

[22] S. Verdu, *Multiuser detection*, Cambridge University Press, 1998.

[23] X. Wang and V.H. Poor, "Iterative (turbo) soft interference cancellation and decoding for coded CDMA," *IEEE Trans. Comm.*, vol. 47, no. 7, pp. 1046–1061, Jul. 1999.