Combination of Space-Time Block Coding with MC-CDMA Technique for MIMO systems with two, three and four transmit antennas

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Abstract - **For future wideband wireless networks, space diversity schemes relying on multiple antennas at the receiver and/or at the transmitter are very attractive to combat fadings and improve the transmission performance. In this paper, Multi-Carrier Code Division Multiple Access (MC-CDMA) technique combined with several Space-Time Block Codes (STBC) is analyzed in the case of N_t transmit antennas and N_r receive antennas to provide a diversity order of N_tN_r for a 2 bps/Hz spectral efficiency. A general method to decode STBC from orthogonal designs associated with MC-CDMA is proposed. Two Single-user Detection techniques, Zero Forcing (ZF) and Minimum Mean Square Error (MMSE), are studied and compared in the downlink synchronous case over frequency selective Rayleigh channels.**

I. INTRODUCTION

Recently, Space-Time Block Coding (STBC), relying on multiple-antenna transmissions and appropriate linear signal processing in the receiver was proposed in order to improve performance [1][2] by providing optimal spatial diversity.

On the other hand, Multi-Carrier Code Division Multiple Access (MC-CDMA) [3], based on a serial concatenation of direct sequence spreading with Orthogonal Frequency Division Multiplex (OFDM), offers flexibility, robustness and very high spectral efficiency for wireless transmissions [4]. Thus, MC-CDMA is nowadays a very promising multiple access scheme, especially for the downlink of the future wideband wireless networks [5].

For multiple antenna transmissions, MC-CDMA systems was combined with Alamouti's STBC for $N_t = 2$ transmit antennas and $N_r = 1$ receive antennas in [6] and for $N_t = 2$ transmit antennas and $N_r = 2$ receive antennas in [7].

For Single Input Single Output (SISO) MC-CDMA, Single-user Detection (SD) techniques was demonstrated to be a good trade-off between complexity and performance specially when associated with a powerful channel coding [5]. For Multiple Input Multiple Output (MIMO) MC-CDMA and in the case of $N_t = 2$ transmit antennas and $N_r = 2$ receive antennas, Minimum Mean Square Error (MMSE) SD offers the best results among the main SD schemes [7].

In this paper, we compare different STBC MC-CDMA schemes which offer a 2 bps/Hz spectrum efficiency with N_t = 2, 3 or 4 and N_r = 1 or 2 jointly with QPSK or 16QAM constellations. We propose a general formulation to decode STBC from orthogonal designs [1][2]. Moreover, two MIMO SD techniques, respectively called Zero Forcing (ZF) and MMSE, are studied and compared in the downlink synchronous case. We assume a frequency non-selective Rayleigh channel per subcarrier and decorrelated fadings in the space and frequency domains leading to asymptotical performance.

First, a system description is given for the transmitter and the receiver. Then, a general method to decode STBC from orthogonal designs associated with MC-CDMA is worked out on a matrix-based approach. In the following, we describe the chosen SD techniques (ZF and MMSE). Finally, simulations results of the different STBC offering a spectral efficiency of 2 bps/Hz are given for ZF and MMSE equalization SD techniques for a MC-CDMA system at full load without channel coding.

II. SYSTEM DESCRIPTION

A general configuration for multiple antenna STBC MC-CDMA system including both transmitter and receiver part is shown in Figure 1 and Figure 2 in the downlink case.

A. Transmitter part

The multiuser matrix is denoted $\mathbf{x} = [\mathbf{x_1} \ldots \mathbf{x_n} \ldots \mathbf{x_N}]$ and includes the information of all the users, where $\mathbf{x_n} = [x_{1,n} \ldots x_{j,n} \ldots x_{N_u,n}]^T$ is a vector of length N_u, where N_u is the number of users, N is the number of transmitted symbol vectors, and $[.]^T$ denotes the transpose operation.

In the case of N_t = 2, 3 or 4 transmit antennas, the STBC $\mathcal{G}_2$, $\mathcal{G}_3$, $\mathcal{G}_4$ are respectively used [2]. In the multiuser case, the coded sequences are defined by:

$$\mathcal{G}_2^{\mathbf{x}} = \begin{bmatrix} \mathbf{x_1} & -\mathbf{x_2^*} \\ \mathbf{x_2} & \mathbf{x_1^*} \end{bmatrix}$$

$$\mathcal{G}_3^{\mathbf{x}} = \begin{bmatrix} \mathbf{x_1} & -\mathbf{x_2} & -\mathbf{x_3} & -\mathbf{x_4} & \mathbf{x_1^*} & -\mathbf{x_2^*} & -\mathbf{x_3^*} & -\mathbf{x_4^*} \\ \mathbf{x_2} & \mathbf{x_1} & \mathbf{x_4} & -\mathbf{x_3} & \mathbf{x_2^*} & \mathbf{x_1^*} & \mathbf{x_4^*} & -\mathbf{x_3^*} \\ \mathbf{x_3} & -\mathbf{x_4} & \mathbf{x_1} & \mathbf{x_2} & \mathbf{x_3^*} & -\mathbf{x_4^*} & \mathbf{x_1^*} & \mathbf{x_2^*} \end{bmatrix}$$

$$\mathcal{G}_4^{\mathbf{x}} = \begin{bmatrix} \mathbf{x_1} & -\mathbf{x_2} & -\mathbf{x_3} & -\mathbf{x_4} & \mathbf{x_1^*} & -\mathbf{x_2^*} & -\mathbf{x_3^*} & -\mathbf{x_4^*} \\ \mathbf{x_2} & \mathbf{x_1} & \mathbf{x_4} & -\mathbf{x_3} & \mathbf{x_2^*} & \mathbf{x_1^*} & \mathbf{x_4^*} & -\mathbf{x_3^*} \\ \mathbf{x_3} & -\mathbf{x_4} & \mathbf{x_1} & \mathbf{x_2} & \mathbf{x_3^*} & -\mathbf{x_4^*} & \mathbf{x_1^*} & \mathbf{x_2^*} \\ \mathbf{x_4} & \mathbf{x_3} & -\mathbf{x_2} & \mathbf{x_1} & \mathbf{x_4^*} & \mathbf{x_3^*} & -\mathbf{x_2^*} & \mathbf{x_1^*} \end{bmatrix}$$

where $[.]^*$ denotes the complex conjugate operation.

Since L time slots are used to transmit N symbols, the rate R of the code is defined by $R = N/L$. Hence, the rate of $\mathcal{G}_2$ is one and the rate of $\mathcal{G}_3$ and $\mathcal{G}_4$ is 1/2. As we compare different schemes offering a 2 bps/Hz spectral efficiency, the $\mathcal{G}_2$ STBC will be associated with QPSK while $\mathcal{G}_3$ and $\mathcal{G}_4$ with 16QAM. The l^{th} column of $\mathcal{G}_{N_t}^{\mathbf{x}}$ represents the transmitted symbols at

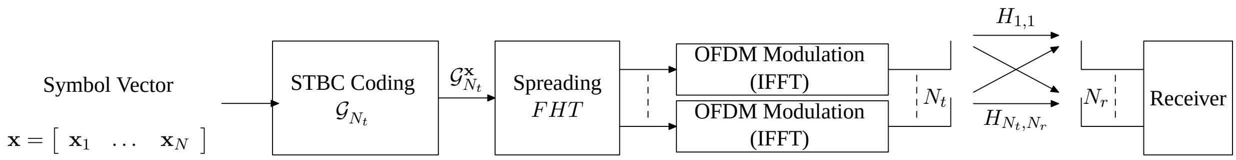

Fig. 1. MC-CDMA Transmitter using STBC

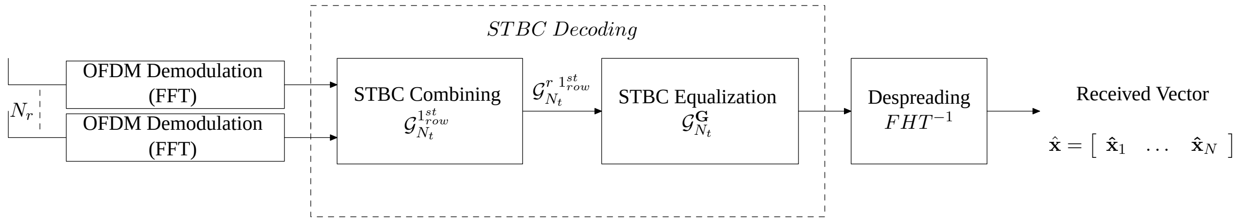

Fig. 2. MC-CDMA Receiver using STBC

time slot l while the t^{th} row of $\mathcal{G}^{\mathbf{x}}_{N_t}$ represents the transmitted symbols from the antenna t. We can note for $\mathcal{G}^{\mathbf{x}}_3$ and $\mathcal{G}^{\mathbf{x}}_4$, the four last columns are the complex conjugate of the four first columns and the three first lines of $\mathcal{G}^{\mathbf{x}}_4$ corresponds to $\mathcal{G}^{\mathbf{x}}_3$.

After STBC coding, the multiuser coded sequence $\mathcal{G}^{\mathbf{x}}_{N_t}$ is spread using, for instance, a Fast Hadamard Transform FHT over each STBC coded symbol as with classical MC-CDMA.

We consider that the length of the spreading sequences is equal to L_c. These spreading codes are orthogonal. Here we assume $L_c \leq N_c$, where N_c is the number of subcarriers of the Orthogonal Frequency Division Multiplex (OFDM).

The signals of the N_u users are assumed to be transmitted with the same power. In the case of the synchronous downlink, the different data-modulated spreading codes of the N_u users are added. Then, the Multi-Carrier modulation is easily performed by an Inverse Fast Fourier Transform (IFFT). We can note that the FHT could have been performed before STBC scheme with a penalty in terms of complexity.

B. *Receiver part*

Since STBC is carried out on L adjacent OFDM symbols, the receiver has to deal with L successive symbols as a whole. Then, for this study, frequency non-selective Rayleigh fading per subcarrier and time invariance during L symbols are assumed to permit the recombination of symbols.

Moreover, we consider uncorrelated channels from each transmit antenna t to each receive antenna r. Based on these assumptions and considering ideal time and frequency interleaving, the complex channel fading coefficients are considered independent between each subcarrier k.

Hence, the theoretical channel response, for the k^{th} subcarrier, from transmit antenna t to receive antenna r can be estimated by $h_{tr,k} = \rho_{tr,k} e^{i\theta_{tr,k}}$.

This modelization has the advantage of giving the asymptotical performance of the system, since optimal spatial and frequency diversity is obtained.

In the SISO case, the signal received for the L_c subcarriers at the antenna r, after the inverse OFDM operation and deinterleaving, is equal to :

$$\mathbf{r} = \mathbf{H}\mathbf{C}\mathbf{x} + \mathbf{n} \tag{1}$$

where $\mathbf{r} = [r_1 \ldots r_k \ldots r_{L_c}]^T$ is the vector of the L_c received signals,

$\mathbf{H}$ is a diagonal matrix with L_c elements, each element of the diagonal standing for the frequency channel response h_k of each subcarrier,

$\mathbf{C} = [\mathbf{c}_1 \mathbf{c}_2 \ldots \mathbf{c}_{N_u}]$ is the $L_c \times N_u$ matrix of user's spreading codes,

$\mathbf{x} = [x_1 \ldots x_j \ldots x_{N_u}]^T$ is the vector of the data symbols transmitted to the N_u users,

and $\mathbf{n} = [n_1 \ldots n_k \ldots n_{L_c}]^T$ is the Additive White Gaussian Noise (AWGN) vector.

In the MIMO case, when STBC is used, the signal received during L adjacent OFDM symbols is equal to:

$$\mathcal{R}_r = \mathcal{H}_r \mathcal{C} \mathcal{G}^{\mathbf{x}}_{N_t} + \mathcal{N}_r \tag{2}$$

where $\mathcal{R}_r = [\mathbf{r}_{1r} \ldots \mathbf{r}_{lr} \ldots \mathbf{r}_{Lr}]$ is a $N_t L_c \times L$ matrix of the L received signals $\mathbf{r}_{lr}$ at the r^{th} antenna, with $\mathbf{r}_{lr}$ is the vector of the L_c subcarriers received at time l,

$\mathcal{H}_r = \text{diag}(\mathbf{H}_{1r} \ldots \mathbf{H}_{tr} \ldots \mathbf{H}_{N_t r})$ is the diagonal channel matrix of length $N_t L_c \times N_t L_c$ where $\mathbf{H}_{tr}$ is a $L_c \times L_c$ diagonal matrix with $h_{tr,k}$ the k^{th} element,

$\mathcal{C} = \mathbf{I} \otimes \mathbf{C}$ of length $N_t L_c \times N_t N_u$,

$\mathcal{G}^{\mathbf{x}}_{N_t}$ is the $N_t N_u \times L$ matrix of multiuser coded sequences,

$\mathcal{N}_r$ is $N_t L_c \times L$ matrix of the L noise vector $\mathbf{n}_{lr}$, with $\mathbf{n}_{lr}$ is the vector of the N_c noise terms at time l.

The STBC decoding and equalization, detailed in the next part, are then performed before the despreading function.

C. STBC Decoding and MC-CDMA Equalization

The first step of STBC decoding consists in applying to the received matrix $\mathcal{R}_r$ the first row of the STBC scheme $\mathcal{G}_{N_t}$ used at the transmitter in order to obtain the vector $\mathcal{G}_{N_t}^{\mathbf{r}1^{\text{st}}\text{row}}$ with $N_t = 2, 3$ or 4. For instance, with $N_t = 2$, we have:

$$\mathcal{G}_2^{\mathbf{r}1^{\text{st}}\text{row}} = \begin{bmatrix} \mathbf{r}_{1r} \\ -\mathbf{r}_{2r}^* \end{bmatrix} \tag{3}$$

This process should be performed on each receive antenna $r = 1 \dots N_r$.

During the second step, the $NN_u \times LL_c$ equalization matrix $\mathcal{G}_{N_t}^{\mathbf{G}_r}$ is obtained for each receive antenna by applying to the equalization coefficients matrices $\mathbf{G}_{tr}$ the STBC scheme $\mathcal{G}_{N_t}$ used at the transmitter.

$\mathbf{G}_{tr}$ is a diagonal matrix containing the SD equalization coefficients $g_{tr,k}$, for the channel tr ($t \in \{1,2,3,4\}, r \in \{1,2\}$).

We can consider that the equalization coefficients matrices $\mathbf{G}_{tr} = \tilde{\mathbf{H}}_{tr}^{\dagger} = \tilde{\mathbf{H}}_{tr}^{*}$,

where $[.]^{\dagger}$ denotes the transpose conjugate operation,

$\tilde{\mathbf{H}}_{tr}^{*}$ is the conjugate diagonal matrix of the normalized channel coefficient $\tilde{h}_{tr}$ as defined in Table I for each of the L_c subcarriers.

When $N = N_t$, i.e. when the N symbols or their replicas are transmitted in the same time as for $\mathcal{G}_2^{\mathbf{x}}$ and $\mathcal{G}_4^{\mathbf{x}}$, we can write :

$$\mathcal{G}_2^{\mathbf{G}_r} = \begin{bmatrix} \mathbf{G}_{1r} & -\mathbf{G}_{2r}^* \\ \mathbf{G}_{2r} & \mathbf{G}_{1r}^* \end{bmatrix}$$

$$\mathcal{G}_4^{\mathbf{G}_r} = \begin{bmatrix} \mathbf{G}_{1r} & -\mathbf{G}_{2r} & -\mathbf{G}_{3r} & -\mathbf{G}_{4r} & \mathbf{G}_{1r}^* & -\mathbf{G}_{2r}^* & -\mathbf{G}_{3r}^* & -\mathbf{G}_{4r}^* \\ \mathbf{G}_{2r} & \mathbf{G}_{1r} & \mathbf{G}_{4r} & -\mathbf{G}_{3r} & \mathbf{G}_{2r}^* & \mathbf{G}_{1r}^* & \mathbf{G}_{4r}^* & -\mathbf{G}_{3r}^* \\ \mathbf{G}_{3r} & -\mathbf{G}_{4r} & \mathbf{G}_{1r} & \mathbf{G}_{2r} & \mathbf{G}_{3r}^* & -\mathbf{G}_{4r}^* & \mathbf{G}_{1r}^* & \mathbf{G}_{2r}^* \\ \mathbf{G}_{4r} & \mathbf{G}_{3r} & -\mathbf{G}_{2r} & \mathbf{G}_{1r} & \mathbf{G}_{4r}^* & \mathbf{G}_{3r}^* & -\mathbf{G}_{2r}^* & \mathbf{G}_{1r}^* \end{bmatrix}$$

The choice of $\mathcal{G}_2^{\mathbf{G}_r}$ to recover $\mathcal{G}_2^{\mathbf{x}}$ is now explained. In order to recover for example the symbol $\mathbf{x_1}$ transmitted through the 2 channels, the signal $\mathbf{r}_{1r}$ received at time $l = 1$ has to be equalized by $\mathbf{G}_{1r}$ given that $\mathbf{x}_1$ was transmitted at time slot $l = 1$ from the antenna $t = 1$ while $-\mathbf{r}_{2r}^*$ received at time slot $l = 2$ has to be equalized by $-\mathbf{G}_{2r}^*$ given that $\mathbf{x}_1^*$ was transmitted at time $l = 2$ from the antenna $t = 2$.

However when $N > N_t$, i.e. when the N symbols or their replicas are not all transmitted in the same time as for $\mathcal{G}_3^{\mathbf{G}_r}$ where four symbols are transmitted from three antennas, we can not apply $\mathcal{G}_3$ on the equalization coefficients matrices $\mathbf{G}_{tr}$.

$$\mathcal{G}_3^{\mathbf{G}_r} = \begin{bmatrix} \mathbf{G}_{1r} & -\mathbf{G}_{2r} & -\mathbf{G}_{3r} & 0 & \mathbf{G}_{1r}^* & -\mathbf{G}_{2r}^* & -\mathbf{G}_{3r}^* & 0 \\ \mathbf{G}_{2r} & \mathbf{G}_{1r} & 0 & -\mathbf{G}_{3r} & \mathbf{G}_{2r}^* & \mathbf{G}_{1r}^* & 0 & -\mathbf{G}_{3r}^* \\ \mathbf{G}_{3r} & 0 & \mathbf{G}_{1r} & \mathbf{G}_{2r} & \mathbf{G}_{3r}^* & 0 & \mathbf{G}_{1r}^* & \mathbf{G}_{2r}^* \\ 0 & \mathbf{G}_{3r} & -\mathbf{G}_{2r} & \mathbf{G}_{1r} & 0 & \mathbf{G}_{3r}^* & -\mathbf{G}_{2r}^* & \mathbf{G}_{1r}^* \end{bmatrix}$$

In this case, when the symbol $\mathbf{x}_n$ was not transmitted at time slot l, 0 is present at the n^{th} row and l^{th} column of $\mathcal{G}_3^{\mathbf{G}_r}$.

	ZF	MMSE
SISO $\boldsymbol{g}_k$	$h_k^*/\lvert h_k\rvert^2$	$h_k^*/[\lvert h_k\rvert^2 + \frac{1}{\gamma_k}]$
MIMO $\boldsymbol{g}_{tr,k}$	$h_{tr,k}^*/[\sum_{t=1}^{N_t}\sum_{r=1}^{N_r}\lvert h_{tr,k}\rvert^2]$	$h_{tr,k}^*/[\sum_{t=1}^{N_t}\sum_{r=1}^{N_r}\lvert h_{tr,k}\rvert^2 + \frac{1}{\gamma_{r,k}}]$

TABLE I

ZF AND MMSE SD COEFFICIENTS FOR THE k^{th} SUBCARRIER IN THE SISO AND MIMO CASES

The final step consists in performing the equalization process for each receive antenna r.

Thus, to recover the N vectors $\mathbf{x}_n$ of length N_u,

$\mathcal{G}_{N_t}^{\mathbf{G}_r}$ is multiplied by $\mathcal{G}_{N_t}^{\mathbf{r}1^{\text{st}}\text{row}}$ in order to equalize the received signals and to combine them.

Finally, the signals resulting from the N_r receive antennas are the simple addition of the signals combined from each antenna. After equalization and combination, the received signal $\mathcal{Y} = \left[\mathbf{y}_1^T \dots \mathbf{y}_n^T \dots \mathbf{y}_N^T\right]^T$ is equal to :

$$\mathcal{Y} = \sum_{r=1}^{N_r} \mathcal{G}_{N_t}^{\mathbf{G}_r} \mathcal{G}_{N_t}^{\mathbf{r}1^{\text{st}}\text{row}} = \sum_{r=1}^{N_r} [\mathcal{G}_{N_t}^{\mathbf{G}_r} \mathcal{H}_r \mathcal{C} \mathcal{G}_{N_t}^{\mathbf{x}} + \mathcal{G}_{N_t}^{\mathbf{G}_r} \mathcal{N}_r]$$

For instance, with a 2 antenna STBC, we have:

$$\mathcal{Y} = [\mathbf{y}_1^T \ \mathbf{y}_2^T]^T = \sum_{r=1}^{N_r} \mathcal{G}_2^{\mathbf{G}_r} \mathcal{G}_2^{\mathbf{r}1^{\text{st}}\text{row}}$$

$$\begin{bmatrix} \mathbf{y}_1 \\ \mathbf{y}_2 \end{bmatrix} = \sum_{r=1}^{N_r} \begin{bmatrix} \mathbf{G}_{1r}\mathbf{r}_{1r} + \mathbf{G}_{2r}^*\mathbf{r}_{2r}^* \\ \mathbf{G}_{2r}\mathbf{r}_{1r} - \mathbf{G}_{1r}^*\mathbf{r}_{2r}^* \end{bmatrix} \tag{4}$$

For the k^{th} subcarrier, we can write :

$$\begin{bmatrix} y_{1,k} \\ y_{2,k} \end{bmatrix} = \sum_{r=1}^{N_r} \begin{bmatrix} g_{1r,k} r_{1r,k} + g_{2r,k}^* r_{2r,k}^* \\ g_{2r,k} r_{1r,k} - g_{1r,k}^* r_{2r,k}^* \end{bmatrix} \tag{5}$$

The final step consists in executing the despreading by applying the inverse FHT to the vector $\mathcal{Y}$ in order to detect the N symbols $x_{j,n}$ transmitted by the user j.

III. SIMULATION RESULTS

To fight Multiple Access Interference (MAI), either Single-user Detection (SD) techniques or more complex Multi-user Detection (MD) techniques may be used. For SISO MC-CDMA systems, ZF and MMSE SD schemes were demonstrated to offer a good trade-off between performance and complexity specially when associated to a powerful turbo-code [5].

Simulations are carried out to confirm the previous results in SISO case, to study SD performance in the MIMO case and to compare different STBC MC-CDMA schemes which offer a 2 bps/Hz spectrum efficiency with N_t = 2, 3 or 4 and N_r

= 1 or 2 jointly with QPSK or 16QAM constellations at full load without channel coding.

Thus, the number of active users ($N_u = 64$) is equal to the length of the spreading code ($L_c = 64$) and to the number of subcarriers ($N_c = 64$).

Results are compared in terms of BER performance versus E_b/N_0.

The different subcarriers are supposed to be multiplied by independent non-selective Rayleigh fading perfectly estimated. It is assumed that all the users' signals are received with the same mean power.

The total transmitted power is equal to P whatever the number N_t of transmit antennas.

Table I gives the ZF and MMSE SD coefficients in the SISO and MIMO cases.

Table II presents the rate STBC and constellations of the considered STBC MC-CDMA systems.

In this table, 1×1 stands for a SISO system while $\mathcal{G}_{N_t} \times N_r$ stands for a STBC scheme with N_t transmit antennas and N_r receive antennas.

$\mathcal{G}_{N_t} \times N_r$	**Rate**	**Constellation**
$1 \times 1, \mathcal{G}_2 \times 1, \mathcal{G}_2 \times 2$	1	QPSK
$\mathcal{G}_3 \times 1, \mathcal{G}_4 \times 1$	$\frac{1}{2}$	16QAM

TABLE II

RATE STBC AND CONSTELLATIONS OF THE CONSIDERED STBC MC-CDMA SYSTEMS

Figure 3 confirms results of a MC-CDMA SISO system with QPSK modulation, i.e. MMSE outperforms ZF. A 8 dB gain is obtained at BER=10^{-3}. In fact, unlike ZF SD, MMSE SD avoids an excessive noise amplification for low signal to noise ratios.

For Multiple Input Single Output (MISO) systems with $N_t = 2$ transmit antennas, MMSE outperforms ZF of only 1 dB at the same BER when STBC with Alamouti code are implemented. This result shows that when applying ZF technique on different diversity branches, the enhancement of the noise is averaged and the ZF performance approaches MMSE ones.

This result is confirmed in Figure 4 for $N_t = 3$ and 4 transmit antennas where $\mathcal{G}_3 \times 1$ and $\mathcal{G}_4 \times 1$ ZF lead exactly to the same performance than respectively $\mathcal{G}_3 \times 1$ and $\mathcal{G}_4 \times 1$ MMSE detectors.

The same phenomenon is observed in the MIMO case with Alamouti $\mathcal{G}_2 \times 2$ systems, where ZF and MMSE SD detectors lead to very close performance.

Moreover, for the same 2 bps/Hz spectral efficiency, $\mathcal{G}_2 \times 2$ system outperforms the $\mathcal{G}_3 \times 1$ and $\mathcal{G}_4 \times 1$ systems.

The performance of systems including Tarokh codes are worse mainly due to the use of 16QAM modulation for a spectral efficiency of 2 bps/Hz.

However, MMSE SD has the drawback of generating at the output of the equalizer a signal level which depends on the subcarrier signal to noise ratio.

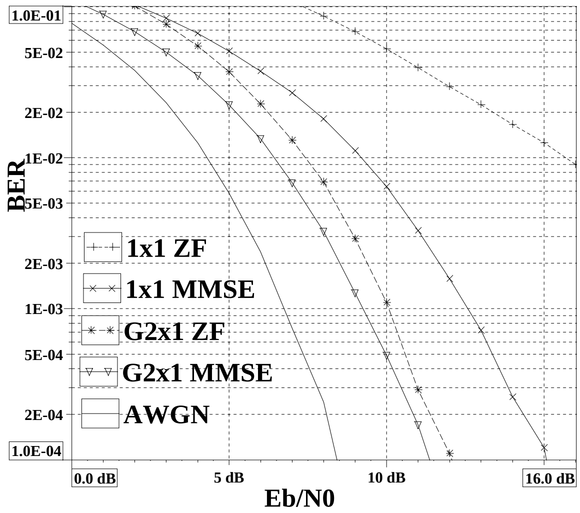

Fig. 3. MMSE and ZF SD performance over Rayleigh channel for SISO and Alamouti MISO MC-CDMA systems.

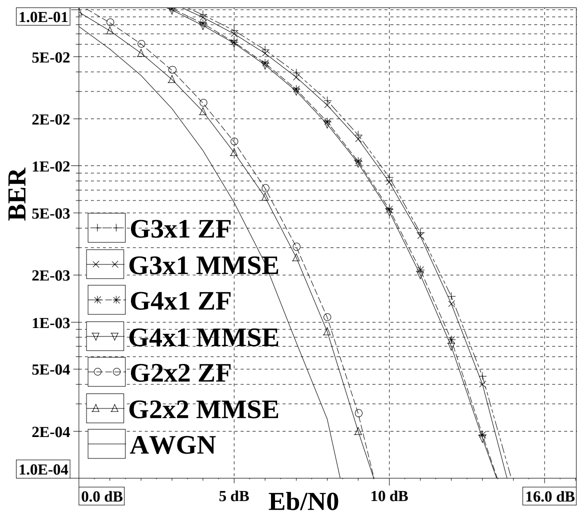

Fig. 4. Single-user MMSE and ZF SD performance over Rayleigh channel for STBC MC-CDMA systems offering a 2 bps/Hz spectrum efficiency

Then, for high order modulations as 16QAM, it is necessary to compensate for this level shift before the threshold detector whereas with ZF equalizer, this compensation is not necessary.

IV. CONCLUSION

In the synchronous case of a multiuser MC-CDMA system operating over frequency selective Rayleigh channel, it is shown that using STBC to exploit transmit diversity leads to major performance improvement. These results have confirmed the potential of MC-CDMA MMSE and ZF SD techniques which mitigate the effect of the Multi Access Interference (MAI) when using STBC.

Besides, the space diversity gain obtained with ZF SD technique reaches the space diversity gain of MMSE SD technique when using more transmit or more receive antennas with appropriate STBC. In the near future, complementary results with channel coding will be obtained over correlated MIMO channels for different loads and non perfect channel estimation.

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