Modified Orthogonal Space-Time Block Codes for Time-Selective Fading Channels

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Abstract — **In this paper Modified Orthogonal Space-Time Block Codes (MO-STBC) were designed as a way to improve the system performance in the presence of "*non-quasi-static*" fading channels. Loss of orthogonality in symbol decoding is mitigated by a very simple though efficient redesign of the conventional O-STBC encoding scheme. MO-STBC is proven by simulations to significantly outperform the conventional O-STBC despite having exactly the same structure, therefore complexity. Systematic construction of MO-STBC for any number of transmit antennas is also introduced. More over, the combination of MO-STBC with time-selectivity robust decoding techniques is easily implemented yielding improved robustness, also indicated by computer simulations.**

Keywords — **O-STBC, interference, transmit diversity, non-quasi-static fading**

I. Introduction

Since Space-Time Block Codes from Orthogonal Designs [1] were first analyzed under more realistic conditions as *non-quasi-static* fading channels, multi-user scenario, presence of channel estimation errors, just to mention a few, researchers were faced to new a challenge of reducing the overall system degradation caused by those non-desired though real adversities.

One of the most critical problems of this quite promising field is the loss of orthogonality in symbol decoding resultant from the application of O-STBC in a *non-quasi-static* fading channel environment. Here, the authors would like to remark that the loss of orthogonality mentioned is a consequence of interference generated exclusively by the O-STBC decoder (hereafter referred as self-interference) during the process of linear combination of the received signal vectors, thus present even in a single user environment.

This problem has been tackled by some authors and among all solutions, the most significative one [2] ensures orthogonality in symbol decoding by paying the price of loss in diversity gain.

In this paper, a not so intuitive though simple approach is given to the aforementioned problem. Instead of developing a new decoding algorithm, which would likely increase the decoder complexity, a simple but not simplistic redesign of O-STBC encoding scheme leads to a more robust (against time-selectivity) technique, baptized as MO-STBC. In addition to preserving full diversity gain in symbol decoding, MO-STBC reduces the self-interference to much lower levels when compared to conventional [4] schemes, despite having exactly the same structure and complexity.

Systematic designs for MO-STBC encoding scheme are also introduced allowing code construction for any number of transmit antennas.

Unlike [2] which is a time-selectivity robust decoding technique, MO-STBC robustly encodes the transmit symbols. Thus, both approaches are non-mutually excluding techniques, being easily combined and becoming a very attractive solution to improve the system performance in the presence of time-selective fading channels.

This paper is organized as follows. In section II a four transmit antennas MO-STBC design is presented. Analysis of the self-interference is found in section III. Systematic construction of the proposed technique is introduced in section IV. In section V, MO-STBC is combined with the robust decoder [2]. Simulations results and performance analysis can be found in section VI. Finally, in section VII, some conclusions are drawn.

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II. A four transmit antennas MO-STBC design

We start this section with the introduction of a four transmit antennas MO-STBC encoding scheme. Here $*$, $\mathcal{H}$ and T represent conjugate, Hermitian and transpose operations, respectively.

$$\mathcal{G}_{\mathcal{M}\mathbf{4}} = \begin{bmatrix} s_1 & s_2 & s_3 & s_4 \\ -s_2^* & s_1^* & -s_4^* & s_3^* \\ -s_3 & s_4 & s_1 & -s_2 \\ -s_4^* & -s_3^* & s_2^* & s_1^* \\ s_1^* & s_2^* & s_3^* & s_4^* \\ -s_2 & s_1 & -s_4 & s_3 \\ -s_3^* & s_4^* & s_1^* & -s_2^* \\ -s_4 & -s_3 & s_2 & s_1 \end{bmatrix} \quad (1)$$

Here, s_n denotes a transmit symbol from the MO-STBC block. It is clear that the structure of this complex orthogonal design is the same as the conventional one ($\mathcal{G}_\mathbf{4}$) proposed by *Tarokh et al.* [1], thus resulting in no addition of complexity. The difference lies in the position of each conjugate operation, which for the conventional scheme are located on the lower-half, while for the MO-STCB scheme, are carefully placed in a "*every-other-line*" fashion in the upper and lower-halves of the matrix.

For coherent MO-STBC the received signal model is given by

$$\mathbf{r} \quad = \quad \mathcal{G}_{\mathcal{M}\mathbf{4}}\mathbf{h}^T + \mathbf{n} \quad (2)$$

$$\mathbf{h} = \begin{bmatrix} h_{1,1} & h_{2,1} & h_{3,1} & h_{4,1} \\ h_{1,2} & h_{2,2} & h_{3,2} & h_{4,2} \\ h_{1,3} & h_{2,3} & h_{3,3} & h_{4,3} \\ h_{1,4} & h_{2,4} & h_{3,4} & h_{4,4} \\ h_{1,5} & h_{2,5} & h_{3,5} & h_{4,5} \\ h_{1,6} & h_{2,6} & h_{3,6} & h_{4,6} \\ h_{1,7} & h_{2,7} & h_{3,7} & h_{4,7} \\ h_{1,8} & h_{2,8} & h_{3,8} & h_{4,8} \end{bmatrix} \quad (3)$$

where $\mathbf{r}$ denotes the received signal vector and $\mathbf{h}$, the time-selective fading channel matrix with elements $h_{m,n}$ designating the channel value from antenna m to the receiver during the time-slot n. Also, $\mathbf{n}$ denotes the vector of the zero-mean white complex Gaussian distributed noise values with variance $\sigma_n^2/2$ per dimension.

The MO-STBC decoding scheme has also the same structure of the conventional one [4], being distinct only by the "*every-other-line*" conjugate operation fashion, which leads to a minimization of the self-interference while keeping the maximum diversity gain in symbol decoding.

$$\begin{bmatrix} h_{1,1} & h_{2,1} & h_{3,1} & h_{4,1} & & & & \\ h_{2,2}^* & -h_{1,2}^* & h_{4,2}^* & -h_{3,2}^* & & \mathbf{0} & & \\ h_{3,3} & -h_{4,3} & -h_{1,3} & h_{2,3} & & & & \\ h_{4,4}^* & h_{3,4}^* & -h_{2,4}^* & -h_{1,4}^* & & & & \\ & & & & h_{1,5} & h_{2,5} & h_{3,5} & h_{4,5} \\ & \mathbf{0} & & & h_{2,6}^* & -h_{1,6}^* & h_{4,6}^* & -h_{3,6}^* \\ & & & & h_{3,7} & -h_{4,7} & -h_{1,7} & h_{2,7} \\ & & & & h_{4,8}^* & h_{3,8}^* & -h_{2,8}^* & -h_{1,8}^* \end{bmatrix} \tag{4}$$

$$\widehat{\mathbf{S}} = \mathbf{H}_{\mathcal{M}\mathbf{4}}^{\mathcal{H}}\, \mathbf{r_1} + \mathbf{H}_{\mathcal{M}\mathbf{4}}^{\mathcal{H}}\, \mathbf{r_2} \tag{5}$$

where $\widehat{\mathbf{S}}$ is the estimate symbol vector and $\mathbf{H}_{\mathcal{M}\mathbf{4}}$ is the notation for the encoded channel matrix (4).

$$\mathbf{r_1} = [\; r_1 \quad r_2^* \quad r_3 \quad r_4^* \quad r_5 \quad r_6 \quad r_7 \quad r_8 \;]^T \tag{6}$$

$$\mathbf{r_2} = [\; r_1 \quad r_2 \quad r_3 \quad r_4 \quad r_5^* \quad r_6 \quad r_7^* \quad r_8 \;]^T \tag{7}$$

Above, $\mathbf{r_1}$ and $\mathbf{r_2}$ are, respectively, slight modifications of the received signal vector $\mathbf{r}$ with its upper and lower-halves following the same conjugation pattern as in (1).

Equation (5) yields the estimation of the transmit symbols. Thus, $\hat{s}_1$ is given by

$$\begin{aligned} \hat{s}_1 \;=\;& \Big(\sum_{t=1}^{4} |\mathbf{H}_{\mathcal{M}\mathbf{4}(\mathbf{t},\mathbf{1})}|^2 + \sum_{t=5}^{8} |\mathbf{H}_{\mathcal{M}\mathbf{4}(\mathbf{t},\mathbf{5})}|^2\Big) s_1 + \\ +\;& (\;\; s_2 h_{2,1} + s_3 h_{3,1} + s_4 h_{4,1} + n_1) h_{1,1}^* \;+ \\ +\;& (-s_2 h_{1,2}^* - s_4 h_{3,2}^* + s_3 h_{4,2}^* + n_2^*) h_{2,2} \;+ \\ +\;& (-s_3 h_{1,3} + s_4 h_{2,3} - s_2 h_{4,3} + n_3) h_{3,3}^* \;+ \\ +\;& (-s_4 h_{1,4}^* - s_3 h_{2,4}^* + s_2 h_{3,4}^* + n_4^*) h_{4,4} \;+ \\ +\;& (\;\; s_2 h_{2,5}^* + s_3 h_{3,5}^* + s_4 h_{4,5}^* + n_5^*) h_{1,5} \;+ \\ +\;& (-s_2 h_{1,6} - s_4 h_{3,6}^* + s_3 h_{4,6} + n_6) h_{2,6}^* \;+ \\ +\;& (-s_3 h_{1,7}^* + s_4 h_{2,7}^* - s_2 h_{4,7}^* + n_7^*) h_{3,7} \;+ \\ +\;& (-s_4 h_{1,8} - s_3 h_{2,8} + s_2 h_{3,8} + n_8) h_{4,8}^* \end{aligned} \tag{8}$$

It is obvious that the presence of any other symbols in the estimation of s_1 leads to a self-interference resultant from the continuous (rather than block) fluctuation characteristic of the *non-quasi-static* fading channels.

III. Self-Interference Coefficient quantification

The self-interference for MO-STBC scheme and for O-STBC can be quantified by modeling the channel as an auto-regressive process [5], therefore consecutive samples of the same channel can be related by

$$h_{m,n+x} = \alpha_x h_{m,n} + z_n \tag{9}$$

where z_n is a zero-mean complex Gaussian random variable uncorrelated to all other variables. Also, α_x is the normalized autocorrelation function of h, given by

$$\alpha_x = J_0(2\pi f d x \Delta t) \tag{10}$$

for Rayleigh fading channels, where J_0 is the Bessel function of the first kind, fd represents the maximum Doppler frequency, x is the instant difference between the channel samples and Δt represents the symbol duration.

In order to quantify the total self-interference present in the estimation of s_1, let's first quantify the influence that each symbol (s_2, s_3 and s_4) has, individually, on this interference.

For normalized transmit power MO-STBC and O-STBC with non-correlated branches, the self-interference caused by the presence of s_2 on the estimation of s_1 ($\widehat{s}_1$), is respectively given by

$$\begin{aligned} I_{MO} \;=\;& s_2(h_{2,1}h_{1,1}^* - h_{2,2}h_{1,2}^* - h_{4,3}h_{3,3}^* + h_{4,4}h_{3,4}^* + \\ +\;& h_{2,5}^* h_{1,5} - h_{2,6}^* h_{1,6} - h_{4,7}^* h_{3,7} + h_{4,8}^* h_{3,8}) \end{aligned} \tag{11}$$

and

$$\begin{aligned} I_{O} \;=\;& s_2(h_{2,1}h_{1,1}^* - h_{2,2}^* h_{1,2} - h_{4,3}h_{3,3}^* + h_{4,4}^* h_{3,4} + \\ +\;& h_{2,5}^* h_{1,5} - h_{2,6}h_{1,6}^* - h_{4,7}^* h_{3,7} + h_{4,8}h_{3,8}^*). \end{aligned} \tag{12}$$

To simplify the calculation of $\sigma^2_{I_{MO}}$ we split equation (11) into smaller terms $(h_{2,1}h_{1,1}^* - h_{2,2}h_{1,2}^*) = p_1$; $(-h_{4,3}h_{3,3}^* + h_{4,4}h_{3,4}^*) = p_2$; $(h_{2,5}^* h_{1,5} - h_{2,6}^* h_{1,6}) = p_3$ and $(-h_{4,7}^* h_{3,7} + h_{4,8}^* h_{3,8}) = p_4$, where, clearly, $\sigma^2_{p_1} = \sigma^2_{p_2} = \sigma^3_{p_1} = \sigma^2_{p_4} = \frac{(1-\alpha_1^2)}{8}$. Since I_{MO} is composed by p_1, p_2, p_3 and p_4,

$$\sigma^2_{I_{MO}} = \frac{(1-\alpha_1^2)}{2}. \tag{13}$$

By using the same procedure described above, $\sigma^2_{I_O}$ can be represented as

$$\sigma^2_{I_O} = \frac{(1-\alpha_3^2)}{4} + \frac{(1-\alpha_5^2)}{4}. \tag{14}$$

Again, by repeating the same procedure to define the self-interference caused by s_3 and s_4 of both MO-STBC and O-STBC, and adding these results to the ones in equations (13) and (14), respectively, the total self-interferences ζ_{MO} and ζ_O are given by

$$\begin{aligned} \zeta_{MO} \;=\;& \frac{3(1-\alpha_1^2)}{4} + \frac{(1-\alpha_2^2)}{4} + \frac{(1-\alpha_3^2)}{4} + \\ +\;& \frac{(1-\alpha_6^2)}{4} \end{aligned} \tag{15}$$

and

$$\begin{aligned} \zeta_{O} \;=\;& \frac{(1-\alpha_1^2)}{8} + \frac{(1-\alpha_2^2)}{4} + \frac{3(1-\alpha_3^2)}{8} + \\ +\;& \frac{3(1-\alpha_5^2)}{8} + \frac{(1-\alpha_6^2)}{4} + \frac{(1-\alpha_7^2)}{8} \end{aligned} \tag{16}$$

As can be observed from equations (15) and (16), if the channel is block fading ($\alpha_x = 1$), ζ_{MO} and ζ_O converge to zero, yielding fully orthogonal symbol decoding for both MO-STBC and O-STBC, therefore the same system performance. Also, if the fading rate $fd\Delta t$ is extremely high ($\alpha_x = 0$), ζ_{MO} and ζ_O reach the same maximum value, thus yielding again the same performance for both systems. As can be concluded throughout this brief analysis, both boundary conditions ($\alpha_x = 1$ and $\alpha_x = 0$) cause MO-STBC and O-STBC to have the same performance. However, for other than these two extreme conditions ζ_{MO} is smaller than ζ_O, causing MO-STBC to outperform O-STBC, as can be verified by figure 1.

IV. Systematic MO-STBC design

In this section we unveil a simple and systematic method for construction of MO-STBC encoding schemes for an arbitrary number of transmit antennas (n_t) consisting only of matrix rearrangements. For $n_t \leqslant 8$ the code structure is identical to the one proposed by [1], except for the "*every-other-line*" fashion of the conjugation operation in the upper and lower-halves of the encoding matrix, which ensures time-selectivity robustness. In order to construct MO-STBC encoding matrices for n_t bigger than 8, the following matrix rearrangement is effectuated

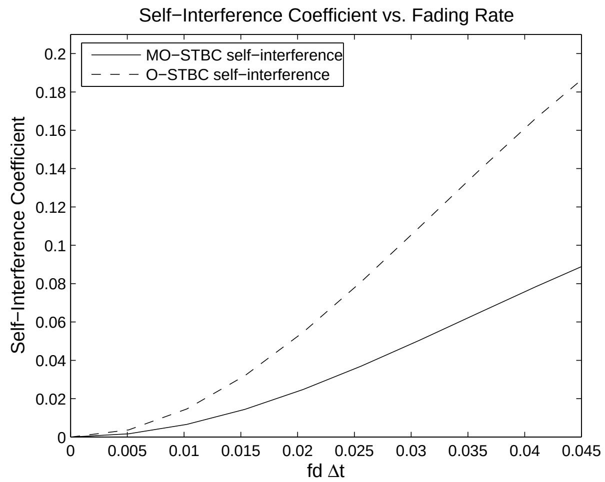

Figure 1: Self-interference coefficient for different fading rates of a four transmit antennas system

$$\mathcal{G}_{\mathcal{M}\mathbf{2n_t}} = \begin{bmatrix} \mathcal{G}_{\mathcal{M}\mathbf{n_t}} & \mathcal{G}'_{\mathcal{M}\mathbf{n_t}} \\ {\mathcal{G}'_{\mathcal{M}\mathbf{n_t}}}^* & {\mathcal{G}_{\mathcal{M}\mathbf{n_t}}}^* \\ \mathcal{G}_{\mathcal{M}\mathbf{n_t}} & -\mathcal{G}'_{\mathcal{M}\mathbf{n_t}} \\ {\mathcal{G}'_{\mathcal{M}\mathbf{n_t}}}^* & -{\mathcal{G}_{\mathcal{M}\mathbf{n_t}}}^* \end{bmatrix} \tag{17}$$

where $\mathcal{G}'_{\mathcal{M}\mathbf{n_t}}$ denotes $\mathcal{G}_{\mathcal{M}\mathbf{n_t}}$ with a set of different symbols. By applying this simple rearrangement of MO-STBC codes, orthogonality can be achieved at any coding size, therefore providing full diversity gain while reducing the self-interference. As an example, to construct $\mathcal{G}_{\mathcal{M}\mathbf{16}}$ we start with the mother matrix $\mathcal{G}_{\mathcal{M}\mathbf{8}}$ given by (18) and follow the rearrangement introduced in (17). If bigger MO-STBC encoding matrices are to be created, the repetition of (17) will yield the desired size (dimension). Moreover, by deleting columns of higher dimensional MO-STBC designs, encoding matrices for n_t different from a power of two can be obtained.

$$\mathcal{G}_{\mathcal{M}\mathbf{8}}=\begin{bmatrix} s_1 & s_2 & s_3 & s_4 & s_5 & s_6 & s_7 & s_8 \\ -s_2^* & s_1^* & s_4^* & -s_3^* & s_6^* & -s_5^* & -s_8^* & s_7^* \\ -s_3 & -s_4 & s_1 & s_2 & s_7 & s_8 & -s_5 & -s_6 \\ -s_4^* & s_3^* & -s_2^* & s_1^* & s_8^* & -s_7^* & s_6^* & -s_5^* \\ -s_5 & -s_6 & -s_7 & -s_8 & s_1 & s_2 & s_3 & s_4 \\ -s_6^* & s_5^* & -s_8^* & s_7^* & -s_2^* & s_1^* & -s_4^* & s_3^* \\ -s_7 & s_8 & s_5 & -s_6 & -s_3 & s_4 & s_1 & -s_2 \\ -s_8^* & -s_7^* & s_6^* & s_5^* & -s_4^* & -s_3^* & s_2^* & s_1^* \\ s_1^* & s_2^* & s_3^* & s_4^* & s_5^* & s_6^* & s_7^* & s_8^* \\ -s_2 & s_1 & s_4 & -s_3 & s_6 & -s_5 & -s_8 & s_7 \\ -s_3^* & -s_4^* & s_1^* & s_2^* & s_7^* & s_8^* & -s_5^* & -s_6^* \\ -s_4 & s_3 & -s_2 & s_1 & s_8 & -s_7 & s_6 & -s_5 \\ -s_5^* & -s_6^* & -s_7^* & -s_8^* & s_1^* & s_2^* & s_3^* & s_4^* \\ -s_6 & s_5 & -s_8 & s_7 & -s_2 & s_1 & -s_4 & s_3 \\ -s_7^* & s_8^* & s_5^* & -s_6^* & -s_3^* & s_4^* & s_1^* & -s_2^* \\ -s_8 & -s_7 & s_6 & s_5 & -s_4 & -s_3 & s_2 & s_1 \end{bmatrix} \tag{18}$$

The rate of the full-diversity, self-interference reduced and complex MO-STBC can be found in Table 1, where n_t is a power of two.

TABLE 1: RATES FOR MO-STBC SCHEME

n_t	transmit epochs	symbols	rate
3 to 4	8	4	1/2
5 to 8	16	8	1/2
9 to 16	64	16	1/4
$\frac{n_t}{2}+1$ to n_t	$(n_t/2)^2$	n_t	$4/n_t$

It can be noticed that the more transmit antennas n_t, the smaller the coding rate of the proposed design. This behavior is also observed on the design presented in [7].

V. Combination with receive robust techniques

In this section we combine MO-STBC schemes, due to its intrinsic transmit robustness, with a receive robust technique. This combination apparently would not yield any improvement in performance since the Linear Maximum Likelihood Decoder [2] is a zero-forcing technique which would cancel all the self-interference minimized by the MO-STBC in the presence of time-selective fading channels. As described though not analyzed in [2], this decoder exchange its diversity gain in order to keep orthogonality in symbol decoding. However, throughout the application of MO-STBC, diversity gain loss (exchange) is reduced in the same way as self-interference is minimized for conventional decoders, thus improving the effectiveness of the Linear Maximum Likelihood Decoder.

$$\begin{aligned} \widehat{s}_{1,\tilde{2}} &= s_1h_{1,1}h_{1,2}^*+(\ s_2h_{2,1}+s_3h_{3,1}+s_4h_{4,1}+n_1)h_{1,2}^*+ \\ &+ s_1h_{2,2}^*h_{2,1}+(-s_2h_{1,2}^*-s_4h_{3,2}^*+s_3h_{4,2}^*+n_2^*)h_{2,1}+ \\ &+ s_1h_{3,3}h_{3,4}^*+(-s_3h_{1,3}+s_4h_{2,3}-s_2h_{4,3}+n_3)h_{3,4}^*+ \\ &+ s_1h_{4,4}^*h_{4,3}+(-s_4h_{1,4}^*-s_3h_{2,4}^*+s_2h_{3,4}^*+n_4^*)h_{4,3}+ \\ &+ s_1h_{1,5}^*h_{1,6}+(\ s_2h_{2,5}^*+s_3h_{3,5}^*+s_4h_{4,5}^*+n_5^*)h_{1,6}+ \\ &+ s_1h_{2,6}h_{2,5}^*+(-s_2h_{1,6}-s_4h_{3,6}+s_3h_{4,6}+n_6)h_{2,5}^*+ \\ &+ s_1h_{3,7}^*h_{3,8}+(-s_3h_{1,7}^*+s_4h_{2,7}^*-s_2h_{4,7}^*+n_7^*)h_{3,8}+ \\ &+ s_1h_{4,8}h_{4,7}^*+(-s_4h_{1,8}-s_3h_{2,8}+s_2h_{3,8}+n_8)h_{4,7}^* \end{aligned} \tag{19}$$

$$\begin{aligned} \widehat{s}_{1,\tilde{3}} &= s_1h_{1,1}h_{1,7}^*+(\ s_2h_{2,1}+s_3h_{3,1}+s_4h_{4,1}+n_1)h_{1,7}^*+ \\ &+ s_1h_{2,2}^*h_{2,8}+(-s_2h_{1,2}^*-s_4h_{3,2}^*+s_3h_{4,2}^*+n_2^*)h_{2,8}+ \\ &+ s_1h_{3,3}h_{3,5}^*+(-s_3h_{1,3}+s_4h_{2,3}-s_2h_{4,3}+n_3)h_{3,5}^*+ \\ &+ s_1h_{4,4}^*h_{4,6}+(-s_4h_{1,4}^*-s_3h_{2,4}^*+s_2h_{3,4}^*+n_4^*)h_{4,6}+ \\ &+ s_1h_{1,5}^*h_{1,3}+(\ s_2h_{2,5}^*+s_3h_{3,5}^*+s_4h_{4,5}^*+n_5^*)h_{1,3}+ \\ &+ s_1h_{2,6}h_{2,4}^*+(-s_2h_{1,6}-s_4h_{3,6}+s_3h_{4,6}+n_6)h_{2,4}^*+ \\ &+ s_1h_{3,7}^*h_{3,1}+(-s_3h_{1,7}^*+s_4h_{2,7}^*-s_2h_{4,7}^*+n_7^*)h_{3,1}+ \\ &+ s_1h_{4,8}h_{4,2}^*+(-s_4h_{1,8}-s_3h_{2,8}+s_2h_{3,8}+n_8)h_{4,2}^* \end{aligned} \tag{20}$$

$$\begin{aligned} \widehat{s}_{1,\tilde{4}} &= s_1h_{1,1}h_{1,4}^*+(\ s_2h_{2,1}+s_3h_{3,1}+s_4h_{4,1}+n_1)h_{1,4}^*+ \\ &+ s_1h_{2,2}^*h_{2,3}+(-s_2h_{1,2}^*-s_4h_{3,2}^*+s_3h_{4,2}^*+n_2^*)h_{2,3}+ \\ &+ s_1h_{3,3}h_{3,2}^*+(-s_3h_{1,3}+s_4h_{2,3}-s_2h_{4,3}+n_3)h_{3,2}^*+ \\ &+ s_1h_{4,4}^*h_{4,1}+(-s_4h_{1,4}^*-s_3h_{2,4}^*+s_2h_{3,4}^*+n_4^*)h_{4,1}+ \\ &+ s_1h_{1,5}^*h_{1,8}+(\ s_2h_{2,5}^*+s_3h_{3,5}^*+s_4h_{4,5}^*+n_5^*)h_{1,8}+ \\ &+ s_1h_{2,6}h_{2,7}^*+(-s_2h_{1,6}-s_4h_{3,6}+s_3h_{4,6}+n_6)h_{2,7}^*+ \\ &+ s_1h_{3,7}^*h_{3,6}+(-s_3h_{1,7}^*+s_4h_{2,7}^*-s_2h_{4,7}^*+n_7^*)h_{3,6}+ \\ &+ s_1h_{4,8}h_{4,5}^*+(-s_4h_{1,8}-s_3h_{2,8}+s_2h_{3,8}+n_8)h_{4,5}^* \end{aligned} \tag{21}$$

$$\begin{aligned} \widehat{s}_{1,\tilde{2}} &= s_1h_{1,1}h_{1,6}^*+(\ s_2h_{2,1}+s_3h_{3,1}+s_4h_{4,1}+n_1)h_{1,6}^*+ \\ &+ s_1h_{2,2}h_{2,5}^*+(-s_2h_{1,2}-s_4h_{3,2}+s_3h_{4,2}+n_2)h_{2,5}^*+ \\ &+ s_1h_{3,3}h_{3,8}^*+(-s_3h_{1,3}+s_4h_{2,3}-s_2h_{4,3}+n_3)h_{3,8}^*+ \\ &+ s_1h_{4,4}h_{4,7}^*+(-s_4h_{1,4}-s_3h_{2,4}+s_2h_{3,4}+n_4)h_{4,7}^*+ \\ &+ s_1h_{1,5}^*h_{1,2}+(\ s_2h_{2,5}^*+s_3h_{3,5}^*+s_4h_{4,5}^*+n_5^*)h_{1,2}+ \\ &+ s_1h_{2,6}^*h_{2,1}+(-s_2h_{1,6}^*-s_4h_{3,6}^*+s_3h_{4,6}^*+n_6^*)h_{2,1}+ \\ &+ s_1h_{3,7}^*h_{3,4}+(-s_3h_{1,7}^*+s_4h_{2,7}^*-s_2h_{4,7}^*+n_7^*)h_{3,4}+ \\ &+ s_1h_{4,8}^*h_{4,3}+(-s_4h_{1,8}^*-s_3h_{2,8}^*+s_2h_{3,8}^*+n_8^*)h_{4,3} \end{aligned} \tag{22}$$

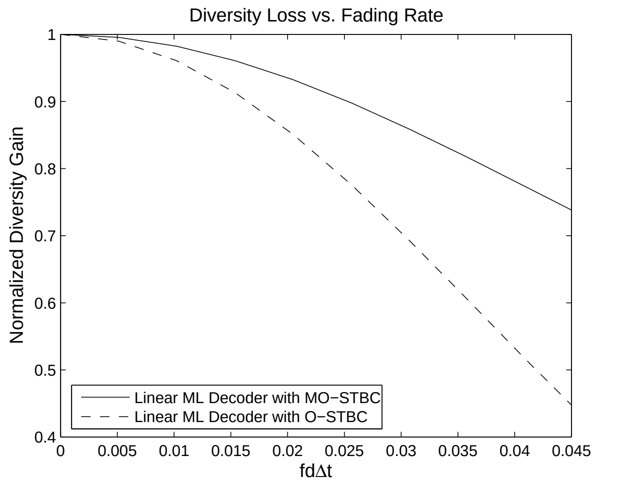

Figure 2: Normalized diversity gain loss for different fading rates of a MO-STBC and O-STBC encoded four transmit antennas system with the Linear Maximum Likelihood Decoder

$$\begin{aligned}
\widehat{s}_{1,\tilde{3}} &= s_1h_{1,1}h^*_{1,7}+(\ \ s_2h_{2,1}+s_3h_{3,1}+s_4h_{4,1}+n_1)h^*_{1,7}+\\
&+ s_1h_{2,2}h^*_{2,8}+(-s_2h_{1,2}-s_4h_{3,2}+s_3h_{4,2}+n_2)h^*_{2,8}+\\
&+ s_1h_{3,3}h^*_{3,5}+(-s_3h_{1,3}+s_4h_{2,3}-s_2h_{4,3}+n_3)h^*_{3,5}+\\
&+ s_1h_{4,4}h^*_{4,6}+(-s_4h_{1,4}-s_3h_{2,4}+s_2h_{3,4}+n_4)h^*_{4,6}+\\
&+ s_1h^*_{1,5}h_{1,3}+(\ \ s_2h^*_{2,5}+s_3h^*_{3,5}+s_4h^*_{4,5}+n^*_5)h_{1,3}+\\
&+ s_1h^*_{2,6}h_{2,4}+(-s_2h^*_{1,6}-s_4h^*_{3,6}+s_3h^*_{4,6}+n^*_6)h_{2,4}+\\
&+ s_1h^*_{3,7}h_{3,1}+(-s_3h^*_{1,7}+s_4h^*_{2,7}-s_2h^*_{4,7}+n^*_7)h_{3,1}+\\
&+ s_1h^*_{4,8}h_{4,2}+(-s_4h^*_{1,8}-s_3h^*_{2,8}+s_2h^*_{3,8}+n^*_8)h_{4,2} \qquad (23)
\end{aligned}$$

$$\begin{aligned}
\widehat{s}_{1,\tilde{4}} &= s_1h_{1,1}h^*_{1,8}+(\ \ s_2h_{2,1}+s_3h_{3,1}+s_4h_{4,1}+n_1)h^*_{1,8}+\\
&+ s_1h_{2,2}h^*_{2,7}+(-s_2h_{1,2}-s_4h_{3,2}+s_3h_{4,2}+n_2)h^*_{2,7}+\\
&+ s_1h_{3,3}h^*_{3,6}+(-s_3h_{1,3}+s_4h_{2,3}-s_2h_{4,3}+n_3)h^*_{3,6}+\\
&+ s_1h_{4,4}h^*_{4,5}+(-s_4h_{1,4}-s_3h_{2,4}+s_2h_{3,4}+n_4)h^*_{4,5}+\\
&+ s_1h^*_{1,5}h_{1,4}+(\ \ s_2h^*_{2,5}+s_3h^*_{3,5}+s_4h^*_{4,5}+n^*_5)h_{1,4}+\\
&+ s_1h^*_{2,6}h_{2,3}+(-s_2h^*_{1,6}-s_4h^*_{3,6}+s_3h^*_{4,6}+n^*_6)h_{2,3}+\\
&+ s_1h^*_{3,7}h_{3,2}+(-s_3h^*_{1,7}+s_4h^*_{2,7}-s_2h^*_{4,7}+n^*_7)h_{3,2}+\\
&+ s_1h^*_{4,8}h_{4,1}+(-s_4h^*_{1,8}-s_3h^*_{2,8}+s_2h^*_{3,8}+n^*_8)h_{4,1} \qquad (24)
\end{aligned}$$

Equations (19), (20) and (21) represent the estimated symbol, say $\hat{s}_1$, after one step of the Linear Maximum Likelihood decoder [2] when combined with the MO-STBC, while equations (22), (23) and (24), when combined with O-STBC. Here $\widehat{s}_{p,\tilde{q}}$ represents the estimation of s_p, orthogonal to s_q.

Since the first step of [2] is the one responsible for the diversity gain loss, we quantify the loss for each equation individually and then average it. The procedure to calculate it is similar to the one used in section III, thus it will be omitted. However, one can easily verify that the channel samples multiplying s_1 are more autocorrelated for the MO-STBC than for the O-STBC case. Thus MO-STBC will yield higher diversity gain since the diversity loss is only dependent on the autocorrelation (separation) between the channel samples. The result is shown in figure 2, where it can be readily seen that MO-STBC minimizes the diversity gain loss for all fading rates considered.

VI. Simulation and Results

In this paper the MO-STBC is analyzed under a frequency flat time-selective fading, which is the channel characteristic of subcarriers of the promising Space-Time Block Coded OFDM systems. All simulations in this paper followed the Jakes model to generate channels with variable fading rate ($fd\Delta t$). In addition to this, the time selectivity here considered is of a channel whose value is constant during one symbol transmission interval, but slightly changes between adjacent symbols [2] [3]. Moreover, the channel is estimated based on the Adaptive Frame-based Interpolation Method proposed by [3].

From figure 3 it can be noticed that the use of MO-STBC as the encoding scheme of a four transmit antennas system mitigates the loss of orthogonality in symbol decoding (minimizing the self-interference), thus improving the system's performance when in the presence of a time-selective fading channel. It can also be noticed from this figure that for low fading rate scenarios, MO-STBC performance is close to the one of ideal block fading case.

Figure 4 shows that for scenarios where the self-interference is naturally bigger, such as of systems employing numerous transmit antennas or when higher fading rates are experienced, MO-STBC significantly improves the performance when compared to O-STBC proposed in [1]. For a 10^{-3} bit error rate MO-STBC yields an improvement of about 4dB in a eight transmit antennas system with $fd\Delta t$ of 0.0051. However, if compared to the block fading case the performance degradation is significative, thus suggesting the need of combining MO-STBC with a time-selectivity robust decoding technique.

The results presented in figure 5 are of a system with four transmit antennas experiencing a higher fading rate. It can be seen that although significantly outperforming conventional O-STBC, MO-STBC also reaches an error floor due to the reduced though existent self-interference. When the Linear Maximum Likelihood Decoder [2] is used, the full diversity gain provided by O-STBC and MO-STBC is exchanged by orthogonality (canceling of self-interference), thus never reaching an error floor. Diversity gain loss can be noticed by a reduction of the steepness of the bit error rate curve, when compared to the block fading case. When combining MO-STBC with the receive robust technique [2] the diversity loss is minimized to a level where the performance degradation is less than 0.5dB for a bit error rate of 10^{-3}. In addition to this, the aforementioned combination outperforms the robust decoder with O-STBC encoding of about 1dB for the same previously considered bit error rate. Thus, for the high fading rate being considered, a system employing MO-STBC with the robust decoder would yield almost the block fading performance while the others would have performance degradations of different degrees.

Figure 6 emphasizes the diversity loss minimization provided by MO-STBC when combined with the robust decoder in high fading rate scenarios. This combination yields almost 6dB improvement for a 10^{-2} bit error rate. Also, from this figure it can be seen that due to the robust decoder intrinsic diversity loss, the O-STBC with robust decoder system is outperformed by the full diversity (though with self-interference) pure MO-STBC system until a signal-to-noise ratio of 11dB. This value reduces to 6dB when the robust decoder is using MO-STBC as the encoding scheme.

VII. Conclusions

We have proposed a new scheme, baptized as MO-STBC, which improves significantly the robustness against time-selectivity though having exactly the same complexity as the conventional O-STBC. In addition to this, we have shown that for high fading rate scenarios or for a higher number of transmit antennas system, the combination of MO-STBC with a robust decoding technique yields improved performance, thus being a very attractive solution for transmit diversity systems when in the presence of time-selective fading channels. Also,

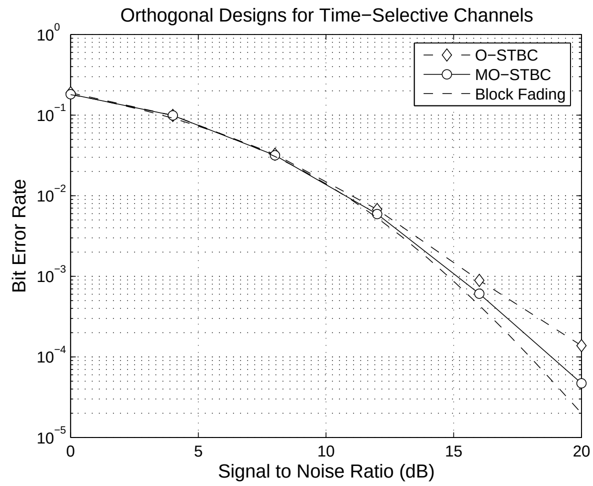

Figure 3: BER for $fd\Delta t = 0.0051$ of a four transmit antennas system in noise (snr = 15dB, 8-PSK Modulation)

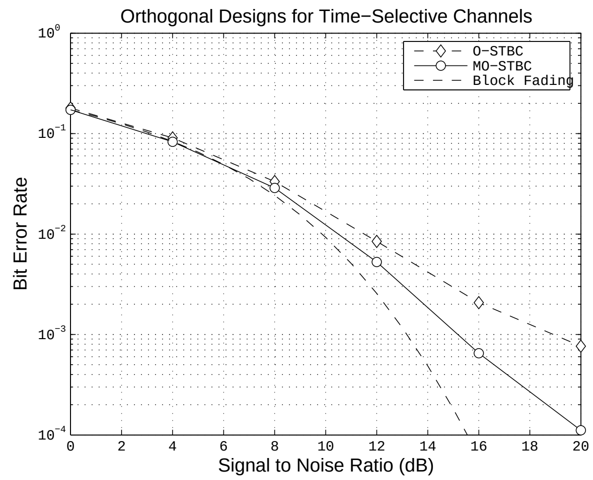

Figure 4: BER for $fd\Delta t = 0.0051$ of a eight transmit antennas system in noise (snr = 15dB, 8-PSK Modulation)

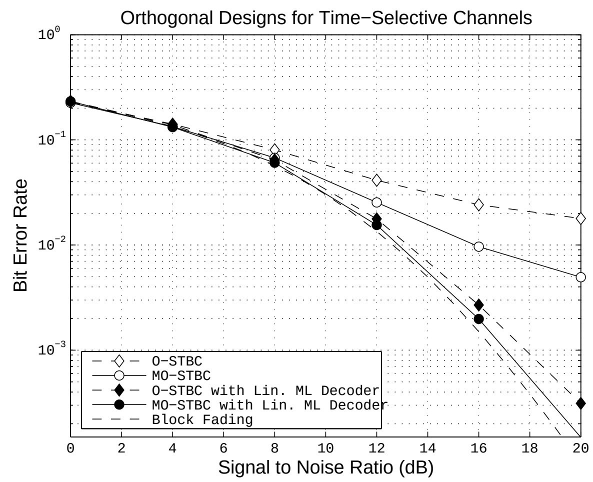

Figure 5: BER for $fd\Delta t = 0.0153$ of a four transmit antennas system in noise (snr = 15dB, 16-QAM Modulation)

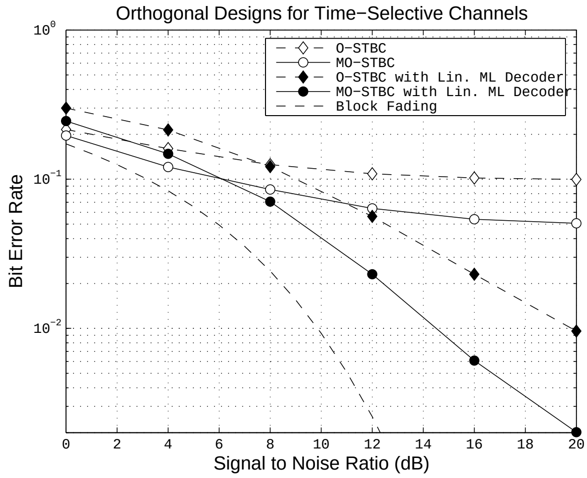

Figure 6: BER for $fd\Delta t = 0.0255$ of a eight transmit antennas system in noise (snr = 15dB, 8-PSK Modulation)

as a result of the efforts to generalize MO-STBC scheme to any number of transmit antennas, we have found a simple method of creating orthogonal matrices from the manipulation of a quasi-orthogonal one.

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