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ADAPTIVE TIME-FREQUENCY SPREADING OF QUASI-ORTHOGONAL BLOCK CODES FOR MIMO-OFDM SYSTEMS

J. L. Ong and A. D. S. Jayalath

Research School of Information Sciences
and Engineering and National ICT Australia (NICTA)
Faculty of Engineering
The Australian National University
Email: {Julynn.Ong,Dhammika.Jayalath}@anu.edu.au

C. R. N. Athaudage

ARC Special Research Center for
Ultra-Broadband Information Networks (CUBIN)
Dept. of Electrical and Electronic Engineering
The University of Melbourne
Email: c.athaudage@ee.unimelb.edu.au

ABSTRACT

This paper describes a novel low complexity time-frequency spreading of orthogonal block codes for MIMO-OFDM systems in highly time and frequency selective channels. The space-time codes (STC) and space-frequency codes (SFC) proposed in literature for MIMO-OFDM systems require a quasi-static channel, where the channel is assumed to be constant over a number of OFDM time symbols or OFDM subcarriers. In orthogonal block codes (OBC) this is equal to the number of transmit antennas N_t employed. For higher order space-diversity systems with $N_t \geq 4$, it is likely that the assumption of constant channel within the OBC to be violated in fast fading channels resulting performance degradation. We propose an adaptive time-frequency spreading strategy that minimizes the decoding error rate in different types of fading channels. The adaptation technique incorporated is based on a fading interference matric, which is evaluated at the transmitter using channel fading statistics. Simulation results demonstrate the effectiveness of the proposed adaptive time-frequency spreading of OBCs.

1. INTRODUCTION

A hybrid of MIMO (Multiple-Input and Multiple-Output) and OFDM (Orthogonal Frequency Division Multiplexing) is a promising way to achieve high-bit-rate communication systems in frequency selective (broadband) fading channels [1]. Multiple antennas at the transmitter and the receiver provide spatial diversity gains, while OFDM provides simple framework for equalization at the receiver. In MIMO-OFDM systems, spatial diversity gains can be achieved by employing space-time coding (STC), space-frequency coding (SFC) or space-time-frequency coding (STFC) [2]-[3].

Jointly coding over space, time and frequency by resorting to subchannel grouping (division of a set of correlated OFDM subchannels into groups) is reported in [4]-[5]. This is termed group STF (GSTF) and preserves maximum diversity gains while simplifying code construction and decoding algorithms. However, the use of three dimensional codes still results in a receiver decoding complexity considerably higher than the simple STC or SFC. A method which distributes the elements of an orthogonal block code both in time and frequency to relax the constant channel requirements over the OBC is proposed in [6]. But this technique doesn't exploit the full diversity gains of a proper STFBC system. An orthogonal precoding scheme whereby data symbols are firstly coded in the frequency domain to obtain frequency diversity before being transmitted in a traditional STBC-OFDM system is also reported [7]. Although proven to perform better particularly at low vehicle speeds, this code also did not have an effect on reducing the number of OFDM blocks over which the channel coefficients are assumed to be constant.

A problem faced by many of the existing STC and SFC codes is that they assume constant channel coefficients over N_t OFDM blocks or subcarriers. This condition needed to be relaxed by reducing this quasi-static channel length assumption to improve system performance in fast time-varying, highly frequency-selective channels. In this paper, we combine both the STC and SFC coding for MIMO-OFDM to exploit the full spatial diversity while assuming constant channel coefficients only over $N_t/2$ OFDM blocks and subcarriers. Moreover, we propose adaptation to channel statistics (Doppler frequency and delay-spread) by switching to either STC, SFC, or STFC modes as an effective technique of minimizing the receiver error performance degradation due to highly time and/or frequency selective nature of the channel. We quantify the error performance degradation of OBC in fading channels using a *fading interference matric*, which can be used select the best (error minimizing) space-diversity transmission mode. The transmitter requires the fading statistics of the mobile wireless channel through a low-rate feedback link in the case of frequency-division duplexing (FDD).

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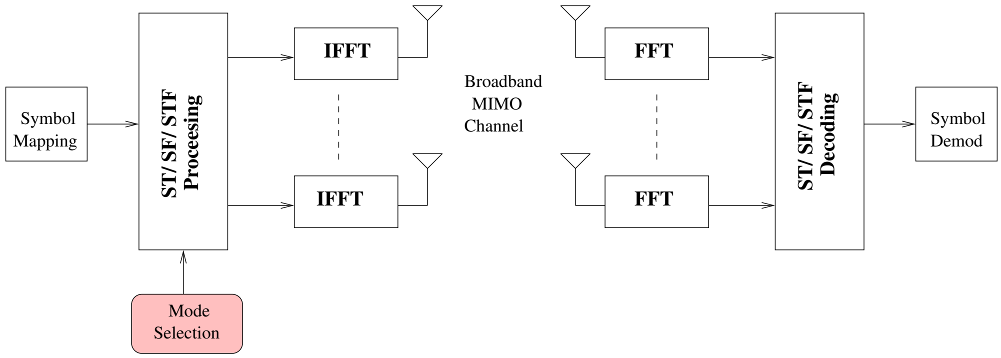

Fig. 1. Block diagram of an adaptive ST/SF/STFBC-OFDM system.

2. SYSTEM DESCRIPTION

The ST-codes (STC) assume a quasi-static channel, i.e. constant channel coefficients over N_t adjacent OFDM block intervals, while SF-codes (SFC) assume constant channel coefficients over N_t adjacent subcarriers. For $N_t > 2$, variations between the actual adjacent channel values in the time and frequency domains will be significant. This gives rise to the need for a space-time-frequency codes (STFC) which will encode across all three signal domains: space, time and frequency, while assuming constant channel coefficients over a fewer number of OFDM blocks and subcarriers. The construction of the proposed new STFC for an $N_t = 4$ transmitter system and the investigation of its performance compared to the STC and SFC are given in Sections 6 and 7. In this Section we introduce general signal and the channel model incorporated.

Let us consider a multi-antenna wireless communication with N_t transmitter antennas and N_r receiver antennas, where an N_s subcarrier OFDM system is employed. The fading channel between pth transmitter antenna and the qth receiver antenna during μth OFDM block is assumed to be frequency selective and time selective and is described by the discrete-time baseband equivalent impulse response vector $\mathbf{a}_{pq}^{\mu} = [a_{pq}^{\mu}(0) \quad \ldots a_{pq}^{\mu}(L-1)]^T$, where L is the channel order. If $x(n)_{\mu}^{p}$ is the data symbol transmitted on the nth subcarrier from the pth transmit antenna during the μth OFDM block interval, the symbols $x(n)_{\mu}^{p}, p = 1, \ldots, N_t$, $n = 0, 1, \ldots, N_s - 1$ are transmitted in parallel on N_s subcarriers and N_t transmitter antennas. Variables p, μ and n index the space time and frequency respectively.

At the receiver, each antenna receives a noisy superposition of the signals transmitted through the multiple transmitter antennas. Assuming that the ideal carrier synchronization, timing and perfect symbol-rate sampling are achieved at the receiver and the cyclic prefix is removed, the received data sample $y(n)_{q}^{\mu}$ at the qth receiver antenna can be expressed as

$$y(n)_{q}^{\mu} = \sum_{p=1}^{N_t} h_{pq}^{\mu}(n) x(n)_{\mu}^{p} + w_{\mu}^{q}(n), \quad q = 1, \ldots, N_r \quad (1)$$

where $h_{pq}^{\mu}(n)$ is the sub-channel gain from the pth transmitter antenna to the qth receiver antenna evaluated on the nth subcarrier

$$h_{pq}^{\mu}(n) = \sum_{l=0}^{L-1} a_{pq}^{\mu}(l) e^{-\sqrt{-1}\frac{2\pi}{N_s} ln} \quad (2)$$

and the additive white Gaussian noise $w_{\mu}^{q}(n)$ is a circularly symmetric zero-mean complex gaussian with variance σ_0^2. The general signal model for multi-antenna OFDM system is described by (1). The different STF-codes (STFC) employ different coding schemes to obtain the transmitted symbol $x_{\mu}^{p}(n)$ by mapping information symbols s_i.

3. CODE CONSTRUCTION

3.1. STFBC Design Considerations

Proper measures of the coherence time and the coherence bandwidth are important to design a transmission matrix mapping in time and frequency for STFC design [6]. The 50% coherence time T_c is given by $T_c = \frac{9}{16\pi f_d}$, where f_d is the maximum Doppler shift of the channel. The appropriate coherence bandwidth B_c , or the range of frequencies over which the channel response is highly correlated, is given by $B_c = \frac{1}{15\sigma_\tau}$, where σ_τ is the RMS delay-spread of the channel. Generally, STC requires that $T_c > P \times T_{\text{block}}$ where T_c is the coherence time, T_{block} is the total OFDM symbol duration including the cyclic-prefix and P is the number of rows of the orthogonal block code (OBC) design. Conversely, SFC requires that $B_c > P \times \Delta f_{\text{sub}}$, where B_c is the coherence bandwidth and P is the number of rows of the OBC design, and Δf_{sub} is the subcarrier spacing of the OFDM system.

The context of this paper is *"What happens if the above conditions can not be satisfied due the fast-fading nature of the channel?"*. We have investigated the performance degradation in OBC decoding due to fast-fading and show that adaptive spreading of the OBC in time and frequency directions can provide an overall performance benefit.

3.2. Transmission Matrix Design

The design of a 4 transmitter transmission matrix (OBC) is slightly different to the conventional Alamouti code developed for the 2 transmitter case. This is because it has been proved that full-rate complex orthogonal codes do not exist for $N_t > 2$ [8]. As such, 3 alternative transmit diversity schemes (OBC design) are reported in the literature:

- Fully orthogonal $\frac{1}{2}$ rate or $\frac{3}{4}$ rate coding schemes at the expense of the coding rate [8].
- Quasi-orthogonal full rate coding schemes proposed for 4 transmit antennas, at the expense of orthogonality [9].
- Walsh-Hadamard transformation schemes applied to two Alamouti codes resulting in rate 1 orthogonal codes, but at a reduced diversity order [10].

For simplicity, in this work we have used the quasi-orthogonal full-rate coding scheme [9] which most closely resembles the twin transmitter transmission matrix proposed by Alamouti. Since these codes are not fully orthogonal, the performance of these codes may be inferior to that of the lower rate, fully orthogonal codes. In practice, the requirements of the communications system being developed would determine which alternative would best be employed. Lets define the sub-code matrices $\mathbf{A}$ and $\mathbf{B}$ as

$$\mathbf{A} = \begin{bmatrix} s_0 & s_1 \\ -s_1^* & s_0^* \end{bmatrix} \text{ and } \mathbf{B} = \begin{bmatrix} s_2 & s_3 \\ -s_3^* & s_2^* \end{bmatrix}. \quad (3)$$

The 4 transmitter transmission matrix (QOBC) $\mathbf{C}$ is then formed as

$$\mathbf{C} = \begin{bmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{B} & \mathbf{A} \end{bmatrix}. \quad (4)$$

We thus have

$$\mathbf{C} = \begin{bmatrix} s_0 & s_1 & s_2 & s_3 \\ -s_1^* & s_0^* & -s_3^* & s_2^* \\ s_2 & s_3 & s_0 & s_1 \\ -s_3^* & s_2^* & -s_1^* & s_0^* \end{bmatrix}. \quad (5)$$

The quasi-orthogonality of the code can seen as few of the non-diagonals terms of $\mathbf{C}^{\mathcal{H}}\mathbf{C}$ are non-zero, where $(.)^{\mathcal{H}}$ is the conjugate-transpose of a matrix.

$$\mathbf{C}^{\mathcal{H}}\mathbf{C} = \sum_{i=0}^{3} |s_i|^2 \mathbf{I} + \mathbf{N} \quad (6)$$

where, $\mathbf{I}$ is a unit matrix of size 4×4, and the non-orthogonality matrix $\mathbf{N}$ is given by

$$\mathbf{N} = 2\Re[s_0 s_2^* + s_1 s_3^*] \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}. \quad (7)$$

The above non-orthogonality matrix $\mathbf{N}$ indicates that only interferences are between symbols s_0, s_2 and s_1, s_3.

4. DECODING PERFORMANCE OF QOBC

4.1. Slow Fading (Quasi-Static) Channel

In the slow fading channel case, the channel values can be considered to be constant over the length of the QOBC. Here the QOBC length can be either in the time-domain or the frequency-domain depending on the implementation, i.e. STBC or SFBC. Let the quasi-static channel vector to be given by $\mathbf{h} = [h_0 \quad h_1 \quad h_2 \quad h_3]^T$, then the received signal vector $\mathbf{r}' = [r_0 \quad r_1 \quad r_2 \quad r_3]^T$ for the transmitted QOBC $\mathbf{C}$ by a single receive antenna can be given as

$$\mathbf{r}' = \mathbf{C}\mathbf{h} + \mathbf{w}' \quad (8)$$

where, $\mathbf{w}'$ is a AWGN noise vector. Alternatively, by swapping the elements between $\mathbf{C}$ and $\mathbf{h}$ in (8) the modified received signal $\mathbf{r} = [r_0 \quad r_1^* \quad r_2 \quad r_3^*]^T$ can be given as

$$\mathbf{r} = \mathbf{H}\mathbf{s} + \mathbf{w} \quad (9)$$

where, $\mathbf{s}$ is the symbol vector contained in the QOBC given by $\mathbf{s} = [s_0 \quad s_1 \quad s_2 \quad s_3]^T$, and $\mathbf{H}$ is the channel matrix given by

$$\mathbf{H} = \begin{bmatrix} h_0 & h_1 & h_0 & h_3 \\ h_1^* & -h_0^* & h_3^* & -h_2^* \\ h_2 & h_3 & h_0 & h_1 \\ h_3^* & -h_2^* & h_1^* & -h_0^* \end{bmatrix} \quad (10)$$

The equalized (channel equalization) received vector is given by

$$\begin{aligned} \tilde{\mathbf{r}} &= \mathbf{H}^{\mathcal{H}}\mathbf{r} \\ &= \left(\sum_{i=0}^{3} |h_i|^2 \mathbf{I} + \tilde{\mathbf{N}}) \right) \mathbf{s} + \tilde{\mathbf{w}} \end{aligned} \quad (11)$$

where, $\tilde{\mathbf{w}} = \mathbf{H}^{\mathcal{H}}\mathbf{w}$, and $\tilde{\mathbf{N}}$ is given by

$$\tilde{\mathbf{N}} = 2\Re[h_0 h_2^* + h_1 h_3^*] \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}. \quad (12)$$

The symbol interference in (11) can be further removed by appropriate design of a MMSE type decoder [9].

4.2. Fast Fading Channel

In the fast fading channel case the four spatial channels h_0, h_1, h_2, and h_3 vary within the QOBC length, thus the fading channel matrix $\mathbf{H}_f$ takes the form

$$\mathbf{H}_f = \begin{bmatrix} h_0 & h_0+\delta h_{01} & h_0+\delta h_{02} & h_0+\delta h_{03} \\ h_1 & h_1+\delta h_{11} & h_1+\delta h_{12} & h_1+\delta h_{13} \\ h_2 & h_2+\delta h_{21} & h_2+\delta h_{22} & h_2+\delta h_{23} \\ h_3 & h_3+\delta h_{31} & h_3+\delta h_{32} & h_3+\delta h_{33} \end{bmatrix} \tag{13}$$

where, different rows of $\mathbf{H}_f$ provide the variation of spacial channel values in time-domain or a frequency-domain, i.e. δh_{ij} gives the variation of the ith spatial channel at the jth location (j=1, 2, 3) within the block-code. Assuming only one receiver antenna ($N_r = 1$), the received signal $\mathbf{r}'$ for the transmitted QOBC matrix $\mathbf{C}$ can be given as

$$\begin{aligned} \mathbf{r}' &= \operatorname{diag}\{\mathbf{CH}_f\} + \mathbf{w}' \\ &= \mathbf{Ch} + \operatorname{diag}\{\mathbf{C}\boldsymbol{\Delta}_f\} + \mathbf{w}' \end{aligned} \tag{14}$$

where, $\boldsymbol{\Delta}_f$ is the incremental channel variation matrix given by

$$\boldsymbol{\Delta}_f = \begin{bmatrix} 0 & \delta h_{01} & \delta h_{02} & \delta h_{03} \\ 0 & \delta h_{11} & \delta h_{12} & \delta h_{13} \\ 0 & \delta h_{21} & \delta h_{22} & \delta h_{23} \\ 0 & \delta h_{31} & \delta h_{32} & \delta h_{33} \end{bmatrix} \tag{15}$$

By swapping the elements between $\mathbf{C}$ and $\mathbf{h}$ and also between $\mathbf{C}$ and $\boldsymbol{\Delta}_f$ the modified received signal vector $\mathbf{r} = [r_0 \quad r_1^* \quad r_2 \quad r_3^*]^T$ can be expressed as

$$\mathbf{r} = \mathbf{Hs} + \tilde{\boldsymbol{\Delta}}_f\mathbf{s} + \mathbf{w} \tag{16}$$

where the modified incremental channel variation matrix $\tilde{\boldsymbol{\Delta}}_f$ is given by

$$\tilde{\boldsymbol{\Delta}}_f = \begin{bmatrix} 0 & 0 & 0 & 0 \\ \delta h_{11}^* & -\delta h_{01}^* & \delta h_{31}^* & -\delta h_{21}^* \\ \delta h_{22} & \delta h_{32} & \delta h_{02} & \delta h_{12} \\ \delta h_{33}^* & -\delta h_{23}^* & \delta h_{13}^* & -\delta h_{03}^* \end{bmatrix} \tag{17}$$

The equalized received signal vector becomes

$$\begin{aligned} \tilde{\mathbf{r}} &= \mathbf{H}^{\mathcal{H}}\mathbf{r} \\ &= \left(\sum_{i=0}^{3} |h_i|^2\mathbf{I} + \tilde{\mathbf{N}}\right)\mathbf{s} + \mathbf{H}^{\mathcal{H}}\tilde{\boldsymbol{\Delta}}_f\mathbf{s} + \tilde{\mathbf{w}} \end{aligned} \tag{18}$$

In (18), the term $\tilde{\mathbf{N}}\mathbf{s}$ indicates the interference due to the non-orthogonality of the QOBC, while the term $\mathbf{H}^{\mathcal{H}}\tilde{\boldsymbol{\Delta}}_f\mathbf{s}$ indicates the interference due the fading channel, i.e. channel variation within the QOBC. If the channel variation within QOBC is minimal the elements of the matrix $\tilde{\boldsymbol{\Delta}}_f$ become negligibly small, e.g. for a quasi-static channel $\tilde{\boldsymbol{\Delta}}_f = \mathbf{0}$.

5. ANALYSIS OF FADING INTERFERENCE

This section provides a way of quantifying the fading interference that effects the error performance of QOBC in fast fading channels. Specifically, we relate the fading interference to time and frequency domain channel correlation functions.

A single-valued fading interference (FI) $\mathcal{I}_f$ is defines as the sum of the powers of the elements of the matrix $\tilde{\boldsymbol{\Delta}}_f$. Thus

$$\begin{aligned} \mathcal{I}_f &= E\left\{tr\left(\tilde{\boldsymbol{\Delta}}_f\tilde{\boldsymbol{\Delta}}_f^{\mathcal{H}}\right)\right\} \\ &= \sum_{i=0}^{3}\sum_{j=1}^{3} E\left\{|\delta h_{ij}|^2\right\} \end{aligned} \tag{19}$$

where, $E\{.\}$ denotes the expected value of a random variable, and $tr(.)$ denotes the trace of a matrix. Also we have

$$\begin{aligned} |\delta h_{ij}|^2 &= \delta h_{ij}\delta h_{ij}^* \\ &= [(h_i+\delta h_{ij}) - h_i]\,[(h_i+\delta h_{ij}) - h_i]^* \\ &= |h_i|^2 + |h_i+\delta h_{ij}|^2 - h_i(h_i+\delta h_{ij})^* \\ &\quad -h_i^*(h_i+\delta h_{ij}) \end{aligned} \tag{20}$$

Therefore, the power of δh_{ij} becomes

$$E\left\{|\delta h_{ij}|^2\right\} = 2\,[1 - \Re\{R(j)\}] \tag{21}$$

where, $E\left\{|h_i|^2\right\} = E\left\{|h_i+\delta h_{ij}|^2\right\} = 1$ for unit power channels. And by definition the channel correlation function in time or frequency domain is given by

$$R(j) = E\left\{h_i(h_i+\delta h_{ij})^*\right\}. \tag{22}$$

By substituting (21) in (19) the fading interference (FI) for time-domain coding (STBC) can be obtained as

$$\mathcal{I}_f^{ST} = 8\left(3 - \sum_{j=1}^{3}\Re\{R_t(j)\}\right) \tag{23}$$

where, $R_t(j)$ is the time-domain channel correlation function. Similarly, the fading interference (FI) for frequency-domain domain coding (SFBC) can be obtained as

$$\mathcal{I}_f^{SF} = 8\left(3 - \sum_{j=1}^{3}\Re\{R_f(j)\}\right) \tag{24}$$

where, $R_f(j)$ is the frequency-domain channel correlation function.

6. THE PROPOSED STFBC CODE

Let the QOBC given in (5) represented as

$$\mathbf{C} = [\mathbf{a} \quad \mathbf{b} \quad \mathbf{c} \quad \mathbf{d}] \tag{25}$$

where, $\mathbf{a}$, $\mathbf{b}$, $\mathbf{c}$, and $\mathbf{d}$ are the columns of the QOBC matrix given by

$$\mathbf{a} = \begin{bmatrix} s_0 \\ -s_1^* \\ s_2 \\ -s_3^* \end{bmatrix} \mathbf{b} = \begin{bmatrix} s_1 \\ s_0^* \\ s_3 \\ s_2^* \end{bmatrix} \mathbf{c} = \begin{bmatrix} s_2 \\ -s_3^* \\ s_0 \\ -s_1^* \end{bmatrix} \mathbf{d} = \begin{bmatrix} s_3 \\ s_2^* \\ s_1 \\ s_0^* \end{bmatrix}$$

In STBC, the vectors $\mathbf{a}$, $\mathbf{b}$, $\mathbf{c}$, and $\mathbf{d}$ are transmitted in consecutive time slots in the same subcarrier as shown in Fig. 2(a). Alternatively, in SFBC, the vectors $\mathbf{a}$, $\mathbf{b}$, $\mathbf{c}$, and $\mathbf{d}$ are transmitted in consecutive subcarries in the same time slot as shown in Fig. 2(b). However, if we transmit vectors $\mathbf{a}$ and $\mathbf{b}$ at time $t = 1$ over two consecutive subcarriers, and vectors $\mathbf{c}$ and $\mathbf{d}$ at time $t = 2$ over the same two consecutive subcarriers, that forms a STFBC. Here we are effectively transmitting an equivalent 4 transmitter STBC/SFBC-OFDM code, but instead of using 4 adjacent time intervals as in the STBC-OFDM case, or 4 adjacent subcarriers as in the SFBC-OFDM case, we are only using 2 adjacent time intervals and subcarriers in this new STFBC code. The decoding of the QOBC is the same irrespective of whether it is used as STBC, SFBC, or STFBC. The proposed STFBC assumes constant channel coefficient only over 2 time intervals/subcarriers. This leads to a method of breaking down systems employing a large number of transmitters which assume constant channel coefficients over N_t time periods/subcarriers to a system that assumes that the channel is quasi-static only over half the number of transmitters employed, or $N_t/2$ time periods/subcarriers. This can have a significant impact on the BER performance of the system in fast fading channels as demonstrated later.

From (19) and (21), the fading interference (FI) for the proposed STFBC becomes

$$\begin{aligned} \mathcal{I}_f^{STF} &= 8\left(1 - \Re\{R_t(1)\} - \Re\{R_f(1)\}\right) \\ &\quad -8\left(\Re\{R_t(1)R_f(1)\}\right) \end{aligned} \quad (26)$$

It should be noted that the proposed STFBC (time-frequency spreading of the QOBC) does not provide any frequency diversity. However, it provides a better error performance compared to STBC or SFBC when the channel is fading fast in time and frequency domains. Also STFBC provides a good operating mode for adaptive time and frequency spreading of QOBC as described in the next section.

6.1. Adaptive Time and Frequency Spreading

Mobile wireless channels are characterized by both time-selective and frequency-selective fading. In this context, we propose to spread the QOBC in time or/and frequency depending on the channel status. The channel status can be categorized into the 3 scenarios given below.

S-1 If $T_c > P \times T_{\text{block}}$ irrespective of B_c STBC is used [Fig. 2(a)].

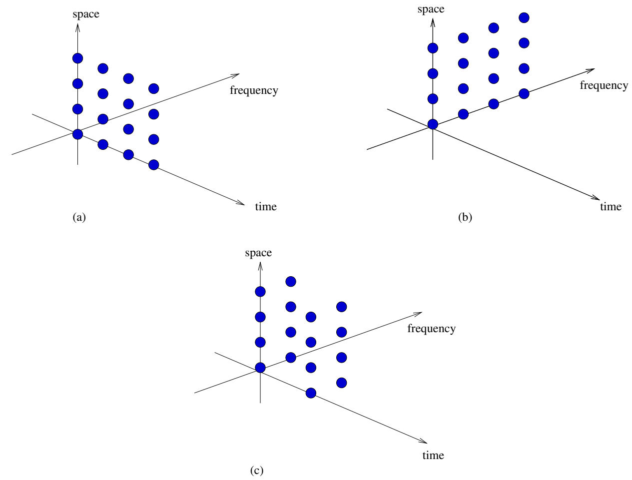

Fig. 2. Placement of 4×4 QOBC in a MIMO-OFDM system: (a) Time-domain spreading (STBC) (b) Frequency-domain spreading (SFBC), and (c) Time and frequency domain spreading (STFBC).

S-2 If the $B_c > P \times \Delta f_{\text{sub}}$ and $T_c < P \times T_{\text{block}}$ then SFBC is used [Fig. 2(b)].

S-3 If $T_c < P \times T_{\text{block}}$ and $B_c < P \times \Delta f_{\text{sub}}$ then STFBC is used [Fig. 2(c)].

The above means that the same QOBC of size $P \times P$ is arranged in three configurations (STBC, SFBC and STFBC) depending on the channel condition. In highly frequency and time selective channels the block code is spread both over time and frequency. This scheme can be applied to any higher order block code. In order to realize this adaptive time-frequency spreading of the QOBC transmitter requires to know the mode switching information. Thus the receiver should be equipped with a channel statistics estimator (B_c and T_c estimators) and based on the mode selection criteria should provide the switching information to the transmitter through a feedback channel. As the channel statistics are normally slowly varying parameters the data rate requirement in the feedback channel is minimal.

7. NUMERICAL RESULTS

In this section, we provide the fading interference (FI) and BER performances of STBC, SFBC, and STFBC codes in three different channels in a 4 transmitter spatial diversity system. The different channels are selected to demonstrate the effectiveness of the adaptive time-frequency spreading of block codes suggested in this paper. The different wireless environments and the system parameters are shown in Table I. Note that *low-time*-selective (LTS) and *high-time*-selective (HTS) channels are characterized by vehicle speeds

Table 1. System and channel parameters

Parameter	HTS/LFS	LTS/HFS	HTS/HFS
No. of subcarrier (N_s)	512	512	512
Modulation	QPSK	QPSK	QPSK
No. of receivers (N_r)	1	1	1
No. of transmitters (N_t)	4	4	4
Vehicle speed (km/hr)	200	60	200
Channel length (L)	1	5	5

of 60 km/hr and 200 km/hr, respectively. The *low-frequency*-selective (LFS) and *high-frequency*-selective (HFS) channels are characterized by channel lengths (number of delay-taps) of 1 and 5, respectively. The RF carrier frequency is 5 GHz and the sampling rate is 20 MHz.

7.1. Fading Interference (IF)

The time-domain channel correlation function $R_t(j)$ depends on the Doppler frequency f_d of the channel and is given by

$$R_t(j) = J_0(2\pi j F_d) \tag{27}$$

where, $F_d = f_d T_{\text{block}}$ is the normalized Doppler frequency, normalized by the OFDM symbol rate $1/T_{\text{block}}$. The $J_0(.)$ is the zeroth-order Bessel function of the first kind. For a channel with L number of sample-spaced multipaths the frequency-domain channel correlation function $R_f(j)$ is given by

$$R_f(j) = \sum_{l=0}^{L-1} E\{|a_l|^2\} \exp\left(\sqrt{-1}\frac{2\pi}{N_s} jl\right) \tag{28}$$

where, a_l is the complex-amplitude of the lth multipath component. The total number of OFDM subcarriers is denoted by N_s. Using the above (27) and (28) the fading interference (FI) values given in (23), (24), and (26) can be calculated for the three channel conditions. These are given in Table II. The FI values in Table II are indicative of the high SNR performance of each type of spreading scheme (ST, SF, and STF) in the three different channels. For each channel the minimum FI value is shown in bold text which indicates the best spreading scheme. The BER performance results given in the next section verify the importance of FI in determining the performance of different spreading schemes.

Table 2. Fading Interference in Different Channels

FI	HTS/LFS	LTS/HFS	HTS/HFS
$\mathcal{I}_f^{ST}$	0.6464	**0.0584**	0.6464
$\mathcal{I}_f^{SF}$	**0.0000**	0.7960	0.7960
$\mathcal{I}_f^{STF}$	0.0928	0.1232	**0.2077**

7.2. Bit Error Performance

In Fig. 3, the BER performances of STBC, SFBC, and STFBC codes for HTS/LFS (high-time-selective and low-frequency-selective) channel are given. As can be seen, STBC is performing worse showing a high error floor which can be attributed to the high fading interference (FI) in HTS case. The SFBC is performing best as there is no FI in the LFS case. The STFBC achieves a closer performance to SFBC except for high SNR values.

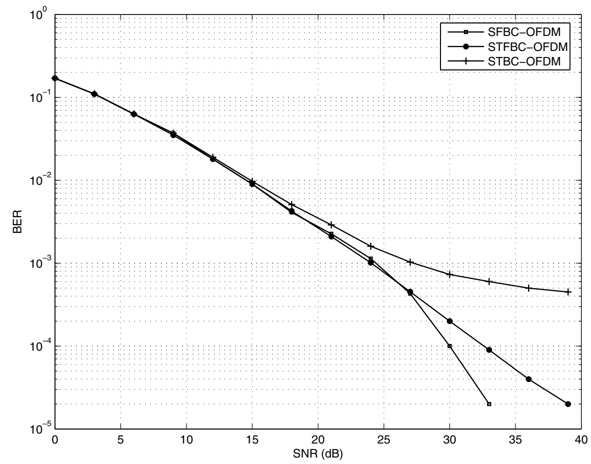

Fig. 3. Performance of SFBC, STBC and SFTBC in a high-time-selective (HTS) and low-frequency-selective (LFS) channel.

In Fig. 4, the BER performances of STBC, SFBC, and STFBC codes for LTS/HFS (low-time-selective and high-frequency-selective) channel are given. Here the performance of SFBC degrades significantly due to the HFS condition, while STBC performing the best. The performance of STFBC is close to that of STBC but still suffers form a higher IF due to the HFS condition.

In Fig. 5, the BER performances of STBC, SFBC, and STFBC codes for HTS/HFS (high-time-selective and high-frequency-selective) channel are given. Here the STFBC performances the best, while STBC providing the next best performance. The performance of SFBC is the worse due to the high FI in HFS condition.

The performances shown in Fig. 3, Fig. 4, and Fig. 5 indicates that an overall performance benefit can be achieved if the QOBC is adaptively spread in time and frequency according to the channel fading characteristics, i.e. the best error performance indicated in each of the figures (Fig. 3, Fig. 4, and Fig. 5) can be achieved, irrespective of the channel condition.

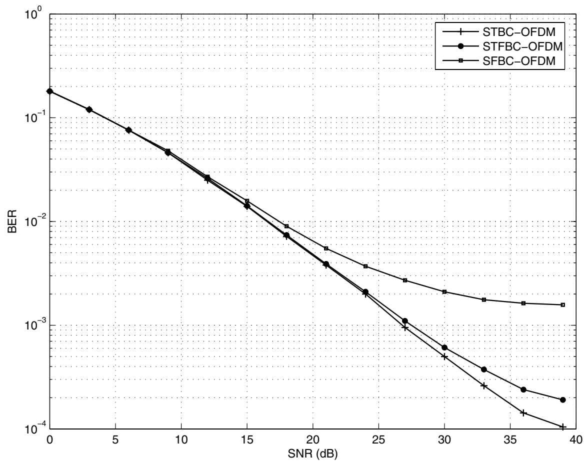

Fig. 4. Performance of SFBC, STBC and STFBC in a high-frequency-selective (HFS) and low-time-selective (LTS) channel.

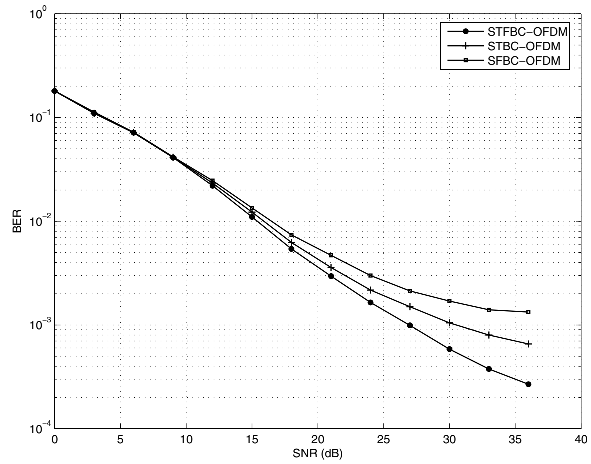

Fig. 5. Performance of STBC, SFBC and STFBC in a high-time-selective (HTS) and high-frequency-selective (HFS) channel.

8. CONCLUSIONS

In this paper, an adaptive time-frequency spreading strategy of orthogonal block codes (OBC) for MIMO-OFDM systems was presented. The fading characteristics of the wireless channel in time and frequency domains makes the adaptive spreading an effective technique of minimizing the decoding error rate. Also, by defining the fading interference (FI) term as a function of channel's time and frequency domain correlation characteristics, it is shown that either STBC, SFBC, and STFBC has a performance advantage for a given channel with particular time and frequency domain fading rates. Simulation results verify the effectiveness of the proposed adaptive time-frequency spreading strategy.

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