Multilayered Space-Frequency Block Coded OFDM Systems

Ahmed S. Ibrahim
Elect. and Comm. dept.
Faculty of Engineering
Cairo Univ., Giza, Egypt
ahmed_salah@eng.cu.edu.eg

Mohamed M. Khairy
Elect. and Comm. dept.
Faculty of Engineering
Cairo Univ., Giza, Egypt
mkhairy@eng.cu.edu.eg

A. F. Hussein
Elect. and Comm. dept.
Faculty of Engineering
Cairo Univ., Giza, Egypt
afayez@idsc.net.eg

Abstract—**In this paper, we propose a multilayered space-frequency block coded OFDM system, which is a combination of the vertical layered space-time architecture, known as V-BLAST, and the space-frequency block coded OFDM system. This system is designed to provide reliable as well as very high data rate communications over frequency-selective fading channels with low decoding complexity. Orthogonal Frequency Division Multiplexing (OFDM) is used to transform the frequency-selective fading channel into multiple flat fading sub-channels. Using four transmit and receive antennas at a data rate of 4 Bits/Sec/Hz, we achieve a diversity gain of about 4.5 dB over the conventional layered space-frequency coded OFDM structures (VBLAST-OFDM) at a bit error rate of 10^{-3}.**

***Index Terms*—multilayered, OFDM, space-frequency, V-BLAST.**

I. INTRODUCTION

SPACE-TIME coding has gained much interest due to its capability of achieving better performance using transmit diversity. Transmit diversity can achieve diversity gain by transmitting from multiple spatially separated antennas. A number of space-time coding techniques have been proposed for transmit diversity [1]-[3]. Space-time coding techniques were used to achieve lower error rates or higher data rates in narrowband systems.

Recently, there has been an increasing interest in providing high data rate services such as video conference and multimedia over wideband wireless channels. In wideband wireless channels, the symbol period becomes smaller relative to the channel delay spread, and consequently, the transmitted signals experience frequency-selective fading. Therefore, it is desirable to investigate the effect of frequency-selective fading on space-time codes performance.

A particularly promising candidate for next-generation fixed and mobile wireless systems is the combination of multiple-input multiple-output (MIMO) technology with orthogonal frequency division multiplexing (OFDM), known as MIMO-OFDM schemes. OFDM [4] is a technique for combating the effects of multi-path propagation in frequency selective fading channels. OFDM transforms the frequency selective fading channel into multiple flat fading sub-channels.

MIMO-OFDM schemes employ multiple transmit and receive antennas in an OFDM communication system. MIMO-OFDM was first presented in [5], which applied the space-time trellis codes (STTCs) [1] in frequency-selective fading channels with the aid of OFDM. Space-frequency trellis coded OFDM (SFTC-OFDM) is a joint design of coding, modulation, transmit and receiver diversity in an OFDM system to provide lower error rates. When the number of transmit antennas is fixed, the decoding complexity of SFTC-OFDM increases exponentially with the transmission rate.

For less decoding complexity, Lee *et al.* proposed space-time block coded OFDM (STBC-OFDM) [6], and space-frequency block coded OFDM (SFBC-OFDM) [7] techniques for wireless communications over frequency-selective fading channels. STBC-OFDM applies the conventional Alamouti scheme [2] on OFDM blocks instead of individual symbols, while SFBC-OFDM applies Alamouti scheme on the OFDM sub-carriers (frequency domain).

While all these kinds of MIMO-OFDM systems tend to achieve better performance without increasing the transmission rate, Giannakis *et al.* has produced layered space-time coded OFDM, denoted by VBLAST-OFDM [8] to achieve high data rates on frequency-selective fading channels through OFDM systems. Where V-BLAST, *(Vertical Bell Laboratories Layered Space-Time)* is a wireless architecture, produced by Foschini [9], capable of realizing very high bit rates using multiple transmit antennas on flat fading channels.

In a way to achieve both lower error rates and higher data rates on flat fading channels, Tarokh *et al.* proposed multilayered space-time trellis codes [10], which is a combination of space-time trellis codes (STTCs) and V-BLAST.

In this paper, we propose a multilayered space-frequency block coded OFDM system, denoted by VBLAST-SFBC-OFDM, which provides high data rates over frequency-selective fading channel with reliable transmission. For the sake of comparison, we will mention the multilayered space-time block coded OFDM systems, denoted by VBLAST-STBC-OFDM, which we have previously presented in [11].

The multilayered space-frequency block coded OFDM scheme partitions antennas at the transmitter into small groups, and uses individual space–frequency block coded OFDM encoders to transmit information from each group of antennas. At the receiver, each individual group is decoded by a linear processing technique that suppresses signals transmitted by other groups of antennas by treating them as interferers.

The outline of this paper is as follows. In Section II, we describe the system overview of the multilayered space-frequency block coded OFDM system, denoted by VBLAST-

SFBC-OFDM, including the frequency-selective fading channel model. In Section III, we describe the mathematical analysis of the complete VBLAST-SFBC-OFDM systems, with a mention to the encoding and decoding of each group using space-frequency block coded OFDM systems (SFBC-OFDM). For the sake of comparison, we mention encoding and decoding of each group in the multilayered space-time block coded OFDM system (VBLAST-STBC-OFDM). In Section IV, we show the simulation results for the proposed VBLAST-SFBC-OFDM system over frequency-selective fading channels. Finally, section V concludes the paper

II. SYSTEM OVERVIEW

Frequency-selective fading channels can be modeled by a tapped-delay line. For a multi-path fading channel with L different paths, the fading channel between the j^{th} transmit antenna and i^{th} receive antenna has discrete-time baseband equivalent finite impulse response (FIR) coefficients collected in the $L\times 1$ vector

$$h_{ij}=[h_{ij}^{0},h_{ij}^{1},\cdots,h_{ij}^{L-1}] \tag{1}$$

for $1\le i\le N_r, 1\le j\le N_t$, where $h_{ij}^{\,l}$'s, $l=0,1,\cdots,L-1$ are independent and identically distributed (i.i.d.), zero-mean, complex Gaussian random variables with variance $\frac{1}{2L}$ per dimension. We assume that the MIMO frequency-selective Rayleigh fading channel is constant during each OFDM block, and vary from block to another.

A high-level block diagram of a multilayered space-frequency block coded OFDM system is shown in Figure 1. We consider a baseband space-frequency block coded OFDM communication system with N OFDM sub-carriers, N_t transmit antennas, and N_r receive antennas. The total available bandwidth of the system is W Hz. It is divided into N overlapping sub-bands. The N_t transmit antennas are partitioned into q groups $G_1,G_2,\cdots,G_q$, respectively, comprising antennas $N_{t1},N_{t2},\cdots,N_{tq}$ with $N_{t1}+N_{t2}+\cdots+N_{tq}=N_t$. We will consider that the number of transmit antennas in each group is two, so that $N_{t1}=N_{t2}=\cdots=N_{tq}=2$.

At each time t, a block of information bits is encoded to generate a space-frequency codeword which consists of $N_t N$ modulated symbols. The space-frequency codeword is given by

$$S=\begin{bmatrix} S_1(0) & S_1(1) & \cdots & S_1(N-1)\\ S_2(0) & S_2(1) & \cdots & S_2(N-1)\\ \vdots & \vdots & \ddots & \vdots\\ S_{N_t}(0) & S_{N_t}(1) & \cdots & S_{N_t}(N-1)\end{bmatrix} \tag{2}$$

where $S_j(k)$ is the transmitted symbol from transmit antenna j over the k^{th} sub-carrier. Signals $S_j(0),S_j(1),\cdots,S_j(N-1)$ are modulated on N different OFDM sub-carriers and transmitted from the j^{th} antenna during one OFDM frame.

At the receiver, the output of the OFDM demodulator for the k^{th} OFDM sub-carrier, $k=0,1,\cdots N-1$ at receive antenna i, $i=1,2,\cdots N_r$, is given by

$$R_i(k)=\sqrt{E_s}\sum_{j=1}^{N_t}H_{i,j}(k)S_j(k)+n_i(k) \tag{3}$$

where E_s is the average symbol energy, $H_{i,j}(k)$ is the channel frequency response for the path from the j^{th} transmit antenna, to the i^{th} receive antenna, on the k^{th} OFDM sub-channel, and $n_i(k)$ is the OFDM demodulation output for the noise sample at the i^{th} receive antenna and the k^{th} sub-channel with power spectral density $N_0/2$ per dimension.

Therefore,

$$\begin{pmatrix} R_1(k)\\ R_2(k)\\ \vdots\\ R_{N_r}(k)\end{pmatrix}=\sqrt{E_s}\begin{bmatrix} H_{1,1}(k) & H_{1,2}(k) & \cdots & H_{1,N_t}(k)\\ H_{2,1}(k) & H_{2,2}(k) & \cdots & H_{2,N_t}(k)\\ \vdots & \vdots & \ddots & \vdots\\ H_{N_r,1}(k) & H_{N_r,2}(k) & \cdots & H_{N_r,N_t}(k)\end{bmatrix}\begin{pmatrix} S_1(k)\\ S_2(k)\\ \vdots\\ S_{N_t}(k)\end{pmatrix}+\begin{pmatrix} n_1(k)\\ n_2(k)\\ \vdots\\ n_{N_r}(k)\end{pmatrix} \tag{4}$$

which may be written as

$$R(k)=\sqrt{E_s}H(k).S(k)+n(k),\ k=0,1,\cdots N-1 \tag{5}$$

To decode each group, the Null Space algorithm, presented in [10], is used to suppress the interference from the other groups. We use this method to cancel the interference on each sub-carrier.

III. MULTILAYERED SPACE-FREQUENCY BLOCK CODED OFDM SYSTEMS

In this section, the mathematical analysis of the proposed multilayered space-frequency block coded OFDM system including group interference suppression algorithm is presented. Following, the encoding and decoding of each group using space-frequency block coded OFDM schemes is described.

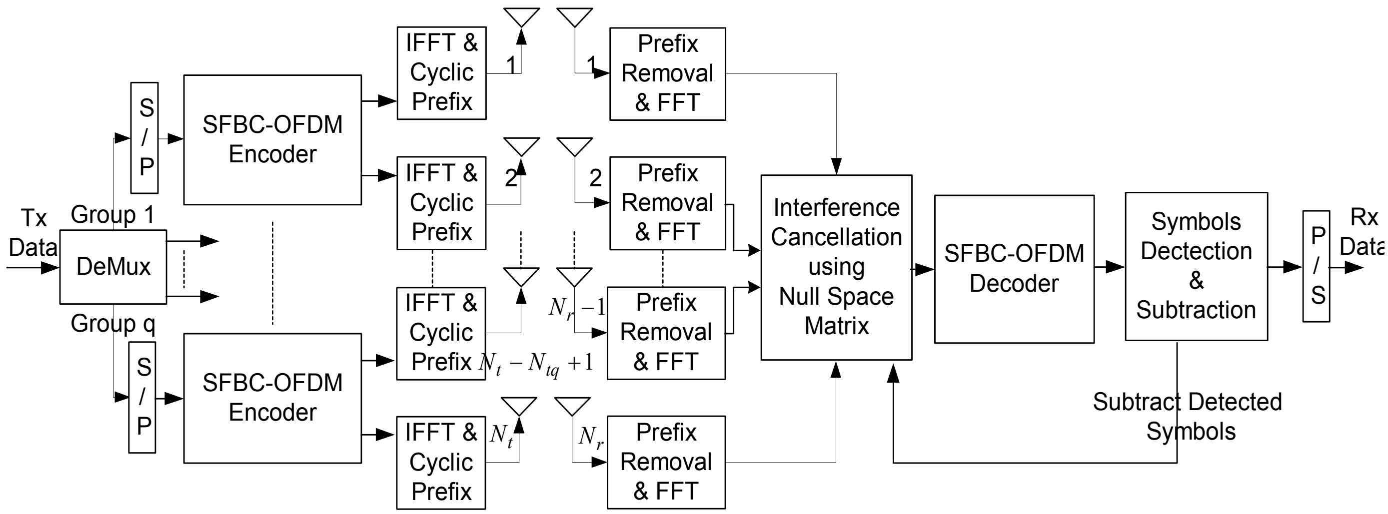

Figure 1 Block diagram of multilayered space-frequency block coded OFDM system (VBLAST-SFBC-OFDM).

We apply the algorithm of group interference suppression [10] on each sub-carrier. To describe the group interference suppression method, we consider the first group, with N_{t1} transmit antennas, as the desired group, and the other groups as interferers. Therefore, there are $N_t - N_{t1}$ interfering signals.

We assume that there are $N_r \geq N_t - N_{t1} + 1$ receive antennas and that the receiver has ideal channel state information (CSI) about the channel matrix H

Let the matrix

$$G_{N_{t1}}(k) = \begin{bmatrix} H_{1,N_{t1}+1}(k) & H_{1,N_{t1}+2}(k) & \cdots & H_{1,N_t}(k) \\ H_{2,N_{t1}+1}(k) & H_{2,N_{t1}+2}(k) & \cdots & H_{2,N_t}(k) \\ \vdots & \vdots & \ddots & \vdots \\ H_{N_r,N_{t1}+1}(k) & H_{N_r,N_{t1}+2}(k) & \cdots & H_{N_r,N_t}(k) \end{bmatrix}_{N_r \times (N_t - N_{t1})} \quad (6)$$

Therefore, the null space matrix of $G_{N_{t1}}(k)$ is $N_{N_{t1}}(k)$, which satisfies

$$N_{N_{t1}}(k).G_{N_{t1}}(k) = [0]_{(N_r - N_t + N_{t1}) \times (N_t - N_{t1})} \quad (7)$$

Multiplying both sides of equation (5) by $N_{N_{t1}}$, we get

$$N_{N_{t1}}(k).R(k) = \sqrt{E_s}\, N_{N_{t1}}(k).H(k).S(k) + N_{N_{t1}}(k).n(k) \quad (8)$$

Let

$$H_{N_{t1}}(k) = \begin{bmatrix} H_{1,1}(k) & H_{1,2}(k) & \cdots & H_{1,N_{t1}}(k) \\ H_{2,1}(k) & H_{2,2}(k) & \cdots & H_{2,N_{t1}}(k) \\ \vdots & \vdots & \ddots & \vdots \\ H_{N_r,1}(k) & H_{N_r,2}(k) & \cdots & H_{N_r,N_{t1}}(k) \end{bmatrix}_{N_r \times N_{t1}} \quad (9)$$

Therefore, $H(k)$ can be written as

$$H(k) = \left(H_{N_{t1}}(k) \;\vdots\; G_{N_{t1}}(k) \right) \quad (10)$$

Also, the transmitted vector is divided as

$$S(k) = \begin{pmatrix} S_{N_{t1}}(k) \\ \cdots\cdots\cdots \\ S_{N_t - N_{t1}}(k) \end{pmatrix} \quad (11)$$

where $S_{N_{t1}}(k)$ is an $N_{t1} \times 1$ vector, which is the symbols of the first group on the k^{th} sub-carrier.

Therefore,

$$N_{N_{t1}}(k).R(k) = \sqrt{E_s}\, N_{N_{t1}}(k).H_{N_{t1}}(k) S_{N_{t1}}(k) + N_{N_{t1}}(k).n(k) \quad (12)$$

Or,

$$\tilde{R}(k) = \sqrt{E_s}\, \tilde{H}(k).S_{N_{t1}}(k) + \tilde{n}(k), \; k = 0,1,\cdots N-1 \quad (13)$$

where

$$\tilde{R}(k) = N_{N_{t1}}(k).R(k), \; \tilde{H}(k) = N_{N_{t1}}(k).H_{N_{t1}}(k), \\ \tilde{n}(k) = N_{N_{t1}}(k).n(k) \quad (14)$$

Now the interference from the other groups have been suppressed, and a simple equation now relates the output to the input of the first group only. We will use space-frequency block coded OFDM [7], to decode the symbols of the first group. After decoding them, we subtract their effect from the received vectors which will be used for decoding the next group, and so on.

We continue this section by describing the encoding and decoding of each group using space-frequency block coded OFDM (SFBC-OFDM) proposed by Lee *et al.* in [7].

In SFBC-OFDM, the data symbol vector $S = \left(S(0) \;\; S(1) \cdots S(N-1) \right)$ is coded into two vectors S_1 and S_2 by the space-frequency encoder block as

$$S_1 = \left(S(0) \quad -S^*(1) \cdots\cdots S(N-2) \quad -S^*(N-1) \right) \\ S_2 = \left(S(1) \quad S^*(0) \cdots\cdots S(N-1) \quad S^*(N-2) \right) \quad (15)$$

S_1 is transmitted from the first transmitter, while S_2 is transmitted simultaneously from the second transmitter.

The operations of the space-frequency encoder and decoder can be best described in terms of even and odd component vectors. Let S^e and S^o be two length *N/2* vectors denoting the even and odd component vectors of *S*. Therefore,

$$\begin{aligned} S^e &= \left(S(0)\ \ S(2) \cdots S(N-2) \right) \\ S^o &= \left(S(1)\ \ S(3) \cdots S(N-1) \right) \end{aligned} \tag{16}$$

Similarly, S_1^e, S_1^o, S_2^e, and S_2^o denote the even and odd component vectors of S_1 and S_2, respectively. Equation (15) can then be expressed in terms of the even and odd component vectors as

$$\begin{aligned} S_1^e &= S^e \ , \qquad & S_1^o &= -S^{o*} \\ S_2^e &= S^o \ , \qquad & S_2^o &= S^{e*} \end{aligned} \tag{17}$$

Let *R(k)* represents the demodulated symbol, after the OFDM demodulator, on the k^{th} sub-carrier, $k = 0,1,\cdots N-1$.

$$R(k) = H_{11}(k).S_1(k) + H_{12}(k).S_2(k) + n(k) \tag{18}$$

where $H_{ij}(k)$ is the channel frequency response from transmit antenna *j* to receive antenna *i*, on the k^{th} sub-carrier.

Let $R^e(k)$ and $R^o(k)$ represent the even and odd components of *R(k)*. Thus, $R^e(k)$ and $R^o(k)$, $k = 0,1,\cdots N/2-1$, can be represented as

$$R^e(k) = H_{11}^e(k).S_1^e(k) + H_{12}^e(k).S_2^e(k) + n^e(k) \tag{19}$$

$$R^o(k) = H_{11}^o(k).S_1^o(k) + H_{12}^o(k).S_2^o(k) + n^o(k) \tag{20}$$

where $n^e(k)$ and $n^o(k)$ represent the even and odd components, respectively, of the demodulated noise vector. Substituting equation (17) into equations (19) and (20), we get

$$R^e(k) = H_{11}^e(k).S^e(k) + H_{12}^e(k).S^o(k) + n^e(k) \tag{21}$$

$$R^o(k) = -H_{11}^o(k).S^{o*}(k) + H_{12}^o(k).S^{e*}(k) + n^o(k) \tag{22}$$

From equations (21) and (22), we conclude that SFBC-OFDM can be represented by the transmission matrix

$$G = \begin{bmatrix} S^e & -S^{o*} \\ S^o & S^{e*} \end{bmatrix} \tag{23}$$

Assuming that ideal channel state information is available at the receiver, the decision variables are constructed by combining $R^e(k)$, $R^o(k)$, and the channel frequency response. $\hat{S}^e(k)$ and $\hat{S}^o(k)$, $k = 0,1,\cdots N/2-1$, are calculated by the following equations

$$\hat{S}^e(k) = H_{11}^{e\,*}(k).R^e(k) + H_{12}^o(k).R^{o*}(k) \tag{24}$$

$$\hat{S}^o(k) = H_{12}^{e\,*}(k).R^e(k) - H_{11}^o(k).R^{o*}(k) \tag{25}$$

Assuming the complex channel gains between adjacent sub-carriers are approximately constant, such as

$$H_{11}^e(k) = H_{11}^o(k) \ , \qquad H_{12}^e(k) = H_{12}^o(k) \tag{26}$$

Therefore,

$$\hat{S}^e(k) = \left(\left| H_{11}^e \right|^2 + \left| H_{12}^e \right|^2 \right) S^e(k) + H_{11}^{e\,*}(k).n^e(k) + H_{12}^o(k).n^{o*}(k) \tag{27}$$

$$\hat{S}^o(k) = \left(\left| H_{11}^e \right|^2 + \left| H_{12}^e \right|^2 \right) S^o(k) + H_{12}^{e\,*}(k).n^e(k) - H_{11}^o(k).n^{o*}(k) \tag{28}$$

where $\hat{S}^e(k)$ and $\hat{S}^o(k)$, $k = 0,1,\cdots N/2-1$, are combined together to construct $\hat{S}(k)$, $k = 0,1,\cdots N-1$. $\hat{S}(k)$ is sent to the maximum likelihood decoder, to decide the most probable sent vectors *S*.

That is why we denote this scheme by space-frequency, as each transmitted symbol is encoded on two consecutive sub-carriers, instead of two consecutive OFDM frames as in STBC-OFDM. In SFBC-OFDM, the encoding is done over one OFDM frame.

In the next sub-section, we will review the multilayered space-time block coded OFDM systems, denoted by VBLAST-STBC-OFDM, which have been proposed in [11].

A. Multilayered Space-Time Block Coded OFDM Systems

In this scheme the group suppression algorithm will be the same as explained earlier in VBLAST-SFBC-OFDM. The encoding and decoding of each group will be done using space-time block coded OFDM systems [6]. The main characteristic of this scheme is that diversity is done in time rather than in frequency. Diversity is achieved by applying Alamouti's scheme on OFDM frames instead of individual symbols.

Encoding of each group is done by STBC-OFDM encoder [6]. Space-time block encoder takes each pair of input vectors together and applies the Alamouti scheme on them. The length of each vector is *N*, which is the number of OFDM sub-carriers. For each pair of two successive data symbol vectors, if S_o is the first block data symbol vector and S_e is the second block vector, they are defined as

$$S_o = \left(S(0), S(1), \cdots, S(N-1) \right) \tag{29}$$

$$S_e = \left(S(N), S(N+1), \cdots, S(2N-1) \right) \tag{30}$$

For the first transmitter, S_o is transmitted during the first time slot followed by $-S_e{}^*$ in the second time slot. For the second transmitter, S_e is transmitted first followed by $S_o{}^*$.

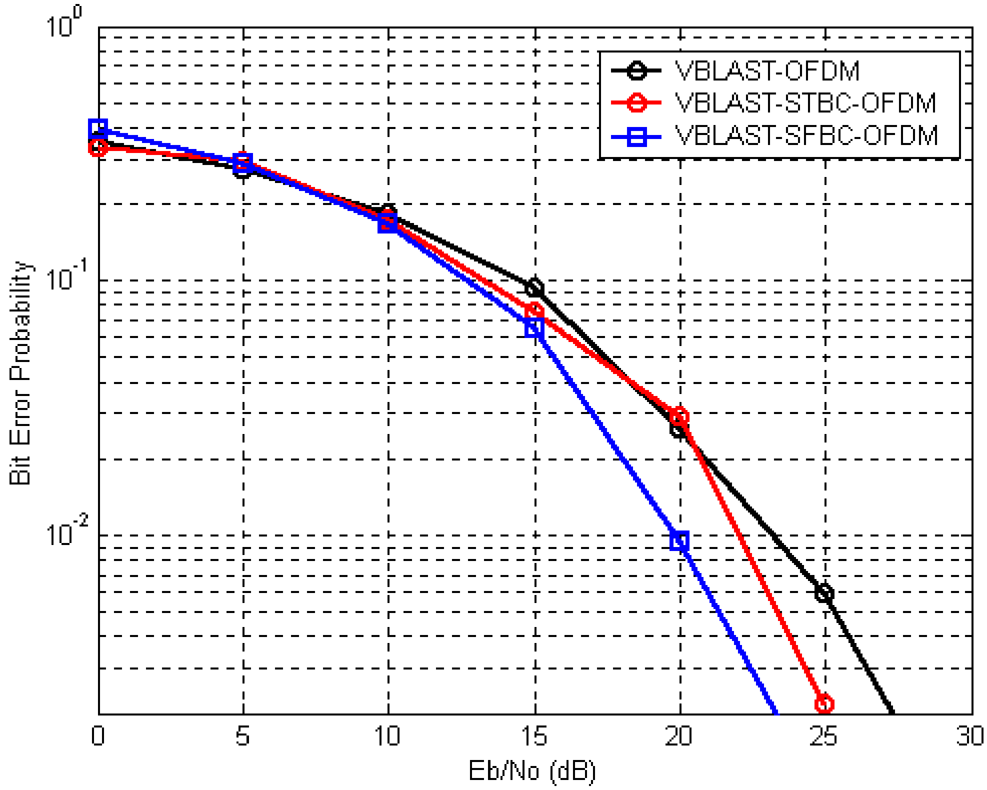

Figure 2 VBLAST-STBC-OFDM and VBLAST-SFBC-OFDM, N=256 sub-carriers, N_t=N_r=4 antennas

The equivalent space-time block code transmission matrix is given by

$$G = \begin{bmatrix} S_o & -S_e^* \\ S_e & S_o^* \end{bmatrix} \tag{31}$$

Therefore, entries of the transmission matrix are the OFDM symbol vectors S_o, S_e, and their complex conjugates.

We assume that the channel responses are constant during the two time slots. Let $R_1(k)$ and $R_2(k)$ represent the demodulated symbols, after the OFDM demodulator, on the k^{th} sub-carrier at the first and second time slot, respectively. $R_1(k)$ and $R_2(k)$, $k = 0,1,\cdots N-1$,can be represented as

$$R_1(k) = H_{11}(k).S_o(k) + H_{12}(k).S_e(k) + n_1(k) \tag{32}$$

$$R_2(k) = -H_{11}(k).S_e^*(k) + H_{12}(k).S_o^*(k) + n_2(k) \tag{33}$$

Assuming that ideal Channel State Information (CSI) is available at the receiver, the decision variables are constructed by combining $R_1(k)$, $R_2(k)$, and the channel frequency response. $\hat{S}_o(k)$ and $\hat{S}_e(k)$ are calculated by the following equations

$$\hat{S}_o(k) = H_{11}^*(k).R_1(k) + H_{12}(k).R_2^*(k) \tag{34}$$

$$\hat{S}_e(k) = H_{12}^*(k).R_1(k) - H_{11}(k).R_2^*(k) \tag{35}$$

Substituting equations (32) and (33) into equations (34) and (35), we get

$$\hat{S}_o(k) = \left(|H_{11}|^2 + |H_{12}|^2\right) S_o(k) + H_{11}^*(k).n_1(k) + H_{12}(k).n_2^*(k) \tag{36}$$

$$\hat{S}_e(k) = \left(|H_{11}|^2 + |H_{12}|^2\right) S_e(k) + H_{12}^*(k).n_1(k) - H_{11}(k).n_2^*(k) \tag{37}$$

which are then sent to the maximum likelihood decoder, to decide the most probable sent vectors S_o and S_e.

IV. Simulation Results

We provide simulation results for the multilayered space-frequency and space-time block coded OFDM schemes mentioned above. In these simulations, the available bandwidth is 1 MHz and 256 sub-carriers are used for OFDM modulation. This corresponds to OFDM frame duration of 256 μs. We model the channel corresponding to each pair of transmit and receive antennas by a two-ray equal power delay profile, where the delay spread between the two rays is 5μs. Therefore, a cyclic prefix of 5 μs duration is added to each frame to combat the effect of ISI.

In Figure 2, the performance of the VBLAST-SFBC-OFDM and VBLAST-STBC-OFDM schemes using four transmit and four receive antennas is shown. It can be shown that at bit error rate of 10^{-3}, the VBLAST-STBC-OFDM scheme has a diversity gain of about 2.5 dB over the conventional VBLAST-OFDM, and the VBLAST-SFBC-OFDM scheme has a diversity gain of about 4.5 dB over the conventional VBLAST-OFDM.

V. Conclusion

We have proposed multilayered space-frequency and space-time coding schemes for OFDM systems, which achieve higher data rates with reliable transmission. OFDM was used to transform the frequency-selective fading channel into multiple flat fading channels. Simulations showed a great improvement in the bit error rate for the proposed schemes over other MIMO OFDM schemes.

References

[1] V. Tarokh, N. Seshadri, and A. R. Calderbank, "Space-time codes for high data rate wireless communications: Performance criteria and code construction," IEEE Trans. Inform. Theory, vol. 44, pp. 744–765, Mar. 1998.

[2] S. M. Alamouti, "A simple transmitter diversity scheme for wireless communications," IEEE J. Select. Areas Comm., vol. 16, no. 8, pp. 1451-1458, Oct. 1998.

[3] V. Tarokh, H. Jafarkhani, and A. R. Calderbank, "Space-time block codes from orthogonal designs," IEEE Trans. Inform. Theory, vol. 45, pp. 1456–1467, July 1999.

[4] L. J. Cimini, Jr., "Analysis and simulation of a digital mobile channel using orthogonal frequency division multiplexing," IEEE Trans. Comm., vol. COM-33, no. 7, pp. 665–675,July 1985.

[5] D. Agrawal, V. Tarokh, A. Naguib, and N. Seshadri, "Space-time coded OFDM for high data-rate wireless communication over wideband channels," in Proc. Vehicular Technology Conf., Ottawa, ON, Canada, May 18–21, 1998, pp. 2232–2236.

[6] K. F. Lee and D. B. Williams, "A space-time coded transmitter diversity technique for frequency selective fading channels," in Proc. IEEE Sensor Array and Multichannel Signal Processing Workshop, Cambridge, MA, March 2000, pp. 149-152.

[7] K. F. Lee and D. B. Williams, "A Space-frequency transmitter diversity technique for OFDM systems," in Proc. IEEE GLOBECOM, San Francisco, CA, , pp. 1473-1477,Nov. 2000.

[8] Yan Xin and Georgios B. Giannakis, "High-rate space–time layered OFDM," IEEE Comm. Letters, vol. 6, no. 5, May 2002.

[9] P. W. Wolnainsky, G. J. Foschini, G. D. Golden, and R. A. Valenzuela, "V-BLAST: An architecture for achieving very high data rates over the rich-scattering wireless channel," in Proc. ISSSE-98, Pisa, Italy.

[10] V. Tarokh, A. Naguib, N. Seshadri, and A. R. Calderbank, "Combined array processing and space–time coding," IEEE Trans. Inform. Theory, vol. 45, no. 45, pp. 1121–1128, May 1999.

[11] Ahmed S. Ibrahim, and Mohamed M. Khairy, "Multilayered space-time block codes for OFDM systems," to be published.