CODED SPACE-TIME-FREQUENCY OFDM OVER IEEE 802.11 FADING CHANNELS

N. K. Noordin, B. M. Ali and S. S. Jamuar

Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM, Serdang, Selangor

E-mail: nknordin@eng.upm.edu.my

ABSTRACT

This paper will present a 4-transmit and 1-receive (4Tx:1Rx) antenna system of coded space-time-frequency in conjunction with orthogonal frequency division multiplexing (Coded STF-OFDM). STF block code is concatenated with channel coding namely convolutional code of rate $1/2$ with length 5 to further combat channel impairment. The coded STF scheme is compared to ST-OFDM and SF-OFDM over IEEE 802.11 multipath channel at delay spread of 700 ns and 1 ms in outdoor environments. Results show that Coded STF-OFDM scheme outperforms other schemes by as much as 8 dB (against ST-OFDM) at 700 ns delay spread. The scheme also outperforms others at longer delay spread but is almost comparable to coded SF-OFDM.

Keywords: Convolutional Coding, Delay Spread, OFDM, STF Coding

1. INTRODUCTION

In recent years there has been an increasing interest of exploring spatial diversity, first proposed by Alamouti [1] in 1998, in conjunction with OFDM technique. Alamouti [1] proposed a 2 transmit and 1 receive antenna system of Space-Time Block Code (STBC) with Binary Phase Shift Keying (BPSK) modulation. This technique works well in a narrow flat fading environment where channel is static and non dispersive. Lee and Williams [2] showed that combining STBC with OFDM produces an improved system that would combat frequency selective fading especially in Multiple Input and Multiple Output (MIMO) system. Unfortunately, this technique requires that fading to be slow to ensure that channel is constant over several OFDM symbols' duration [3] (depending on the configuration of the space-time scheme). Later works (e.g. [3]-[4]) introduced space-frequency in the context of OFDM and MIMO, to fully achieve spatial and frequency diversity that would combat both fast fading and frequency-selective fading for broadband channels. Recent works explore into space-time-frequency OFDM (e.g. [5] and [6]) which attempt to exploit transmit diversity in space, time and frequency in order to achieve higher diversity gain.

Even though MIMO can provide higher capacity and gain, in order to ensure that the handset is kept light and small, spatial diversity is best applied at the transmitter (base station) that service hundreds number of users. Taking that into consideration and to fully exploit space, time, frequency diversity and coding gain. A coded space-time-frequency (STF) OFDM using 4 transmit and 1 receive (4 Tx:1 Rx) antenna was proposed. In this coded STF system channel coding was concatenated i.e. convolutional code of rate $1/2$ with length 5 with our STF block code of rate $3/4$. A lower symbol rate was adopted since full rate orthogonal codes are not achievable when the number of transmit antenna is more than 2 [7]. A quasi orthogonal code with rate equals 1 is possible to use in transmit diversity technique but with non-optimal performance [8].

Early works in space diversity involves in the constructions of various block orthogonal codes, trellis and turbo codes to be used in conjunction with space diversity scheme [8]-[9]. However 'large delay spread in frequency selective fading channels destroy the orthogonality of the received signal' [10] in frequency-selective fading and makes detection of the system more difficult. The use of space diversity in the context of OFDM transforms frequency selective fading of single carrier system into multiple flat fading channels, and the effects of large delay spread can be mitigated using OFDM cyclic prefix. Some guard band could also be introduced in between carriers to avoid inter carrier interference among the many adjacent subcarriers in OFDM system.

The outline of this paper is as follows. In Section II the motivation of using multiple antennas is explained. In Section III a conventional OFDM is briefly described. In Section IV, the coded STF in the context of OFDM is presented in detail. Section V describes the channel model used in the simulation. Section VI presents the simulation and parameters setup as well as some significant results, while section VII deals with the implementation issues. The conclusions with proposed future works is presented in Section VIII.

2. MOTIVATION

OFDM is sufficient to mitigate multipath fading because it is able to transform time-variant channel into invariant flat-fading channel and is currently being employed in broadcasting like European Digital Audio Broadcasting (DAB) and Digital Video Broadcasting (DVB) as well as Wireless Local Area Network (WLAN) system. However this technology has some drawbacks when implemented in the current IEEE 802.11 WLAN particularly in mitigating multipath fading in frequency-selective fading. The proposed multiple antenna system incorporated with space-time-frequency coding not only can take advantage of the multipath fading phenomenon but also on the diversity of the system in terms of space (antenna), time, and frequency (from OFDM subcarriers).

Consider a case where $h_i(t)$ $i = 1,2,...,M$ are multipath components of a channel impulse response with number of
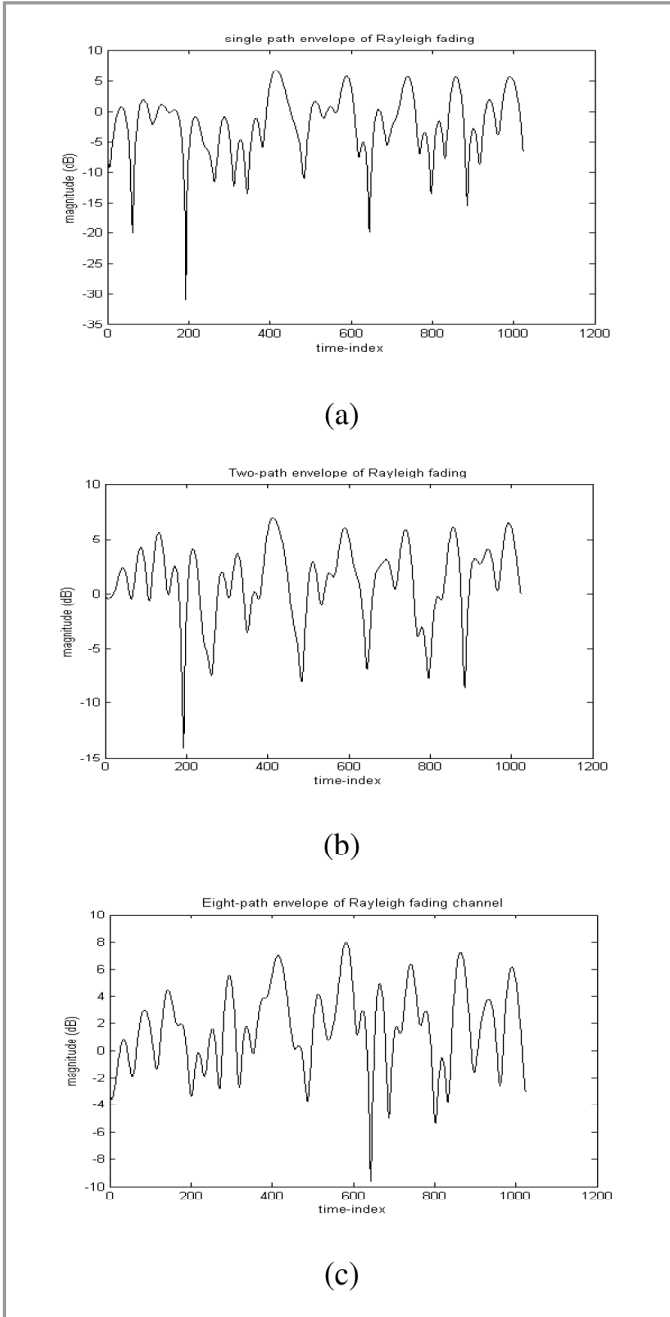
Figure 1: a) single path, b) two-path and c) resultant eight-path envelope in 8-antenna transmit diversity channel

maximum available antennas equals 8. Note that in Figure 1 deepest fade of envelope $h_1(t)$ has been reduced in the two-path envelope (Figure 1b) and further reduced in the resultant eight-path envelope channel (Figure 1c) which will then make it more reliable from a communication perspective. With this in mind, the more number of channels combined is expected hence the number of transmitted antenna, the better the resultant channel would be at the receiver. This can be translated into improved performance with increase data rate.

3. ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING

In a simple OFDM system a sequence of binary input is modulated to QAM symbols with symbol interval, T_s. The serial to parallel converter collects the serial data symbols $S^{(n)}$ into length N vector $S = [S^{(0)} S^{(1)} S^{(2)} ... S^{(n-2)} S^{(N-1)}]$, where N is the number of subcarriers in the OFDM system. This vector is then modulated by an inverse fast Fourier transform (IFFT) into an OFDM symbol sequence as follows [2]:

$$s^{(n)} = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} S^{(k)} e^{j\frac{2\pi nk}{N}}, 0 \leq n \leq N-1 \qquad (1)$$

A cyclic prefix of length P of the modulator output is added as a guard interval with resulting sequence $s^n_n = [sp^{(0)} sp^{(1)} ... sp^{(N+P-1)}]^T$. The sequence is transmitted through a frequency selective fading channel $h(n,\tau)$ of order L defined as [11],

$$h(n,\tau) \begin{cases} \neq 0 & \tau = L, \\ = 0 & \tau > L. \end{cases} \qquad (2)$$

The guard interval P is chosen such that $P \geq L$ to avoid intersymbol interference (ISI). The chosen length ensures that channel has died down before the receipt of the next sequence. The prefixed sequence $s_p^{(n)}$ convolved with h(n,τ) resulting in the received sequence, $r_p^{(n)}$ as follows:

$$r_p^{(n)} = \sum_{k=0}^{L} s_p^{(n-k)} h(n,k) + w(n), \quad 0 \leq n \leq N+P-1 \qquad (3)$$

where $w(n)$ is the additive white Gaussian noise (awgn) of the channel. Assuming the channel impulse response remains constant during the entire block interval, the time-varying response $h(n,k)$ can be replaced by the time-invariant response $h(k)$. At the receiver, the cyclic prefix is removed from the received sequence such that $r^{(n)} = r_p^{(n+P)}$, $\phi \leq n \leq N$ - 1. The OFDM demodulator perform an N-point fast Fourier transform (FFT) on the sequence to yield the demodulated output $R(n)$. Notice that with $s_p^{(n)}$ constructed as the cyclic extension of $s^{(n)}$, the sequence $r^{(n)}$ is the cyclic convolution of $s_p^{(n)}$ and $h(n)$ resulting in multiplication in the frequency domain. Therefore, the FFT output can be expressed as

$$R(n) = H(n)S^{(n)} + W(n), 0 \leq n \leq N - 1 \qquad (4)$$

where $H(n)$ is the FFT output of the channel impulse response, and $W(n)$ is the FFT output of the channel noise. Note also that OFDM with cyclic prefix transforms a frequency selective fading subchannels into N flat fading subchannels [2], [3], [6]. These flat fading subchannels provide a good platform on which space-time or space frequency or even spce-time-frequency processing techniques developed for flat fading channels can be applied.

4. SPATIAL DIVERSITY WITH TIME AND FREQUENCY BLOCK CODING

The simple OFDM model is extended to space-time/space-frequency/space-time-fequency (ST/SF/STF)-OFDM with N_t transmit and N_r receive antenna as shown in Figure 2. The concatenated ST/SF/STF coded symbols with channel coding consisting of convolutional coding of rate $\frac{1}{2}$ with length of 5 to further combat channel impairments. Each coded vector X_i is then inverse fast Fourier transformed (IFFT) and cyclic-

prefixed. The prefixed signals are then passed through their respective antennas. Each transmitted stream will undergo the influence of multipath fading and additive white Gaussian noise. At the receiver, cyclic prefix is removed and fast Fourier transform (FFT) is performed to recover the received symbols. These symbol is then estimated using maximum likelihood decoding or sphere decoding scheme. The symbols are then demodulated and decoded using Viterbi algorithm and the recovered bits are then compared with the transmitted bits for bit error rate (BER) measurement. Throughout the work the assumption is that channel is static during one OFDM symbol in SF-OFDM and two consecutive OFDM symbols in ST and STF-OFDM systems.

A. Space-Time-Frequency OFDM

In this scheme a 4 Tx:1 Rx antenna system of N subcarriers over 2 time slots corresponding to two consecutive OFDM symbols were employed. Figure 2 shows an STF coding that spans along 2 transmit antenna, across N-subcarriers and over 2 OFDM symbols.
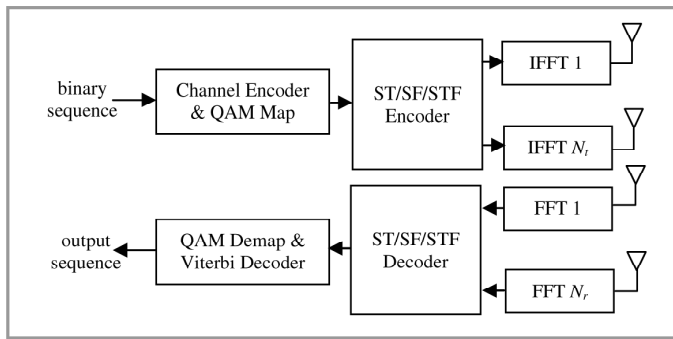

Figure 2: A simplified concatenated channel coding with ST/SF/STF-OFDM schemes
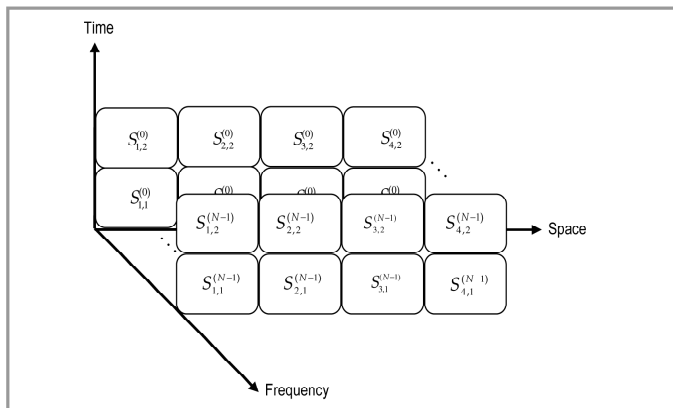

Figure 3: A 3-dimensional diagram showing STF coding across 2 OFDM symbols (N_s), with number of transmit antenna $N_t = 4$, and N subcarriers

An orthogonal transmission matrix of rate $^3/_4$ is adopted as follows [8]:

$$\mathbf{A}_4 = \begin{bmatrix} x_1 & x_2 & \dfrac{x_3}{\sqrt{2}} & \dfrac{x_3}{\sqrt{2}} \\[2mm] -x_2^* & x_1^* & \dfrac{x_3}{\sqrt{2}} & -\dfrac{x_3}{\sqrt{2}} \\[2mm] \dfrac{x_3^*}{\sqrt{2}} & \dfrac{x_3^*}{\sqrt{2}} & \dfrac{-x_1-x_1^*+x_2-x_2^*}{2} & \dfrac{-x_2-x_2^*+x_1-x_1^*}{2} \\[2mm] \dfrac{x_3^*}{\sqrt{2}} & -\dfrac{x_3^*}{\sqrt{2}} & \dfrac{x_2+x_2^*+x_1-x_1^*}{2} & \dfrac{-(x_1+x_1^*+x_2-x_2^*)}{2} \end{bmatrix}$$

In this scheme the channel coded data symbol vector $\mathbf{S}$ is divided into three vectors of length $N/3$, $\mathbf{X}_1$, $\mathbf{X}_2$, and $\mathbf{X}_3$ as follows,

$$\mathbf{X}_1 = [S^{(0)} \ S^{(3)} \ \cdots \ S^{(N-6)} \ S^{(N-3)}]^T$$
$$\mathbf{X}_2 = [S^{(1)} \ S^{(4)} \ \cdots \ S^{(N-5)} \ S^{(N-2)}]^T \qquad (6)$$
$$\mathbf{X}_3 = [S^{(2)} \ S^{(5)} \ \cdots \ S^{(N-4)} \ S^{(N-1)}]^T$$

The vector $\mathbf{S}$ was converted with the STF encoder into eight data symbol vectors as shown in Table 1. The details of each $\mathbf{S}_{i,t}$ transmitted from antenna i at time t is shown in Equation (7).

Table 1: The notation for the transmitted signals at the four transmit antennas

	Transmitter 1	Transmitter 2	Transmitter 3	Transmitter 4
t1	$S_{1,1}$	$S_{2,1}$	$S_{3,1}$	$S_{4,1}$
t2	$S_{1,2}$	$S_{2,2}$	$S_{3,2}$	$S_{4,2}$

$$\mathbf{S}_{1,1} = [S^{(0)} \ \frac{S^{(2)*}}{\sqrt{2}} \ S^{(3)} \ \frac{S^{(5)*}}{\sqrt{2}} \ \cdots \ S^{(N-3)} \ \frac{S^{(N-1)*}}{\sqrt{2}}]^T$$

$$\mathbf{S}_{2,1} = [S^{(1)} \ \frac{S^{(2)*}}{\sqrt{2}} \ S^{(4)} \ \frac{S^{(5)*}}{\sqrt{2}} \ \cdots \ S^{(N-2)} \ \frac{S^{(N-1)*}}{\sqrt{2}}]^T$$

$$\mathbf{S}_{3,1} = [\frac{S^{(2)}}{\sqrt{2}} \ \frac{-S^{(0)}-S^{(0)*}+S^{(1)}-S^{(1)*}}{2} \ \frac{S^{(5)}}{\sqrt{2}} \ \frac{-S^{(3)}-S^{(3)*}+S^{(4)}-S^{(4)*}}{2}$$
$$\cdots \ \frac{S^{(N-1)}}{\sqrt{2}} \ \frac{-S^{(N-3)}-S^{(N-3)*}+S^{(N-2)}-S^{(N-2)*}}{2}]^T$$

$$\mathbf{S}_{4,1} = [\frac{S^{(2)}}{\sqrt{2}} \ \frac{-S^{(1)}-S^{(1)*}+S^{(0)}-S^{(0)*}}{2} \ \frac{S^{(5)}}{\sqrt{2}} \ \frac{-S^{(4)}-S^{(4)*}+S^{(3)}-S^{(3)*}}{2}$$
$$\cdots \ \frac{S^{(N-1)}}{\sqrt{2}} \ \frac{-S^{(N-2)}-S^{(N-2)*}+S^{(N-3)}-S^{(N-3)*}}{2}]^T$$

$$\mathbf{S}_{1,2} = [-S^{(1)*} \ \frac{S^{(2)*}}{\sqrt{2}} \ -S^{(4)*} \ \frac{S^{(5)*}}{\sqrt{2}} \ \cdots \ -S^{(N-2)*} \ \frac{S^{(N-1)*}}{\sqrt{2}}]^T$$

$$\mathbf{S}_{2,2} = [S^{(0)*} \ -\frac{S^{(2)*}}{\sqrt{2}} \ S^{(3)*} \ -\frac{S^{(5)*}}{\sqrt{2}} \ \cdots \ S^{(N-3)*} \ -\frac{S^{(N-1)*}}{\sqrt{2}}]^T$$

$$\mathbf{S}_{3,2} = [\frac{S^{(2)}}{\sqrt{2}} \ \frac{S^{(1)}+S^{(1)*}+S^{(0)}-S^{(0)*}}{2} \ \frac{S^{(5)}}{\sqrt{2}} \ \frac{+S^{(4)}+S^{(4)*}+S^{(3)}-S^{(3)*}}{2}$$
$$\cdots \ \frac{S^{(N-1)}}{\sqrt{2}} \ \frac{S^{(N-2)}+S^{(N-2)*}+S^{(N-3)}-S^{(N-3)*}}{2}]^T$$

$$\mathbf{S}_{4,2} = [-\frac{S^{(2)}}{\sqrt{2}} \ -\frac{S^{(0)}+S^{(0)*}+S^{(1)}-S^{(1)*}}{2} \ -\frac{S^{(5)}}{\sqrt{2}} \ -\frac{S^{(3)}+S^{(3)*}+S^{(4)}-S^{(4)*}}{2}$$
$$\cdots \ -\frac{S^{(N-1)}}{\sqrt{2}} \ -\frac{S^{(N-3)}+S^{(N-3)*}+S^{(N-2)}-S^{(N-2)*}}{2}]^T$$

$$(7)$$

Now let $\mathbf{H}_1$, $\mathbf{H}_2$, $\mathbf{H}_3$ and $\mathbf{H}_4$ be 4 diagonal matrices whose diagonal elements are the FFTs of the channel impulse responses from the four transmit antennas, respectively. Assuming that the channel responses are constant over the two OFDM symbols, the demodulated signal vectors in the corresponding time slots are given by

$$\mathbf{Y}_1 = \mathbf{H}_1\mathbf{S}_{1,1} + \mathbf{H}_2\mathbf{S}_{2,1} + \mathbf{H}_3\mathbf{S}_{3,1} + \mathbf{H}_4\mathbf{S}_{4,1} + \mathbf{G}_1 \qquad (8)$$
$$\mathbf{Y}_2 = \mathbf{H}_1\mathbf{S}_{1,2} + \mathbf{H}_2\mathbf{S}_{2,2} + \mathbf{H}_3\mathbf{S}_{3,2} + \mathbf{H}_4\mathbf{S}_{4,2} + \mathbf{G}_2$$

where $\mathbf{G}_t$ represents the additive white Gaussian noise (awgn) at time t equals 1 and 2, respectively.

If $\mathbf{Y}_{i,e}$ and $\mathbf{Y}_{i,o}$ as the even and odd subcarrier of $\mathbf{Y}_i$, respectively (8) can be rewritten as follows [6],

$$\mathbf{Y}_{1,e} = \mathbf{H}_{1,1,e}\mathbf{S}_{1,1,e} + \mathbf{H}_{2,1,e}\mathbf{S}_{2,1,e} + \mathbf{H}_{3,1,e}\mathbf{S}_{3,1,e} + \mathbf{H}_{4,1,e}\mathbf{S}_{4,1,e} + \mathbf{G}_{1,e}$$

$$\mathbf{Y}_{1,o} = \mathbf{H}_{1,1,o}\mathbf{S}_{1,1,o} + \mathbf{H}_{2,1,o}\mathbf{S}_{2,1,o} + \mathbf{H}_{3,1,o}\mathbf{S}_{3,1,o} + \mathbf{H}_{4,1,o}\mathbf{S}_{4,1,o} + \mathbf{G}_{1,o}$$

$$\mathbf{Y}_{2,e} = \mathbf{H}_{1,2,e}\mathbf{S}_{1,2,e} + \mathbf{H}_{2,2,e}\mathbf{S}_{2,2,e} + \mathbf{H}_{3,2,e}\mathbf{S}_{3,2,e} + \mathbf{H}_{4,2,e}\mathbf{S}_{4,2,e} + \mathbf{G}_{2,e}$$

$$\mathbf{Y}_{2,o} = \mathbf{H}_{1,2,o}\mathbf{S}_{1,2,o} + \mathbf{H}_{2,2,o}\mathbf{S}_{2,2,o} + \mathbf{H}_{3,2,o}\mathbf{S}_{3,2,o} + \mathbf{H}_{4,2,o}\mathbf{S}_{4,2,o} + \mathbf{G}_{2,o} \quad (9)$$

where $\mathbf{H}_{i,t,e/o}$ denotes the channel response of the even/odd subcarrier of the t-th time slot fom the i-th antenna, and $\mathbf{S}_{i,t,e/t}$ is the data symbol vectors transmitted on the even/odd sucarrier of the t-th time slot fom the i-th antenna. Equation (9) can be expanded by plugging in Equations (6) and (7) to yield

$$\mathbf{Y}_{1,e} = \mathbf{H}_{1,1,e}\mathbf{X}_1 + \mathbf{H}_{2,1,e}\mathbf{X}_2 + \mathbf{H}_{3,1,e}\frac{\mathbf{X}_3}{\sqrt{2}} + \mathbf{H}_{4,1,e}\frac{\mathbf{X}_3}{\sqrt{2}} + \mathbf{W}_{1,e}$$

$$\mathbf{Y}_{1,o} = \mathbf{H}_{1,1,o}\frac{\mathbf{X}_3^*}{\sqrt{2}} + \mathbf{H}_{2,1,o}\frac{\mathbf{X}_3^*}{\sqrt{2}} + \mathbf{H}_{3,1,o}\frac{-\mathbf{X}_1 - \mathbf{X}_1^* + \mathbf{X}_2 - \mathbf{X}_2^*}{2}$$
$$+ \mathbf{H}_{4,1,o}\frac{-\mathbf{X}_2 - \mathbf{X}_2^* + \mathbf{X}_1 - \mathbf{X}_1^*}{2} + \mathbf{W}_{1,o}$$

$$\mathbf{Y}_{2,e} = -\mathbf{H}_{1,2,e}\mathbf{X}_2^* + \mathbf{H}_{2,2,e}\mathbf{X}_1^* + \mathbf{H}_{3,2,e}\frac{\mathbf{X}_3}{\sqrt{2}} + \mathbf{H}_{4,2,e}(-\frac{\mathbf{X}_3}{\sqrt{2}}) + \mathbf{W}_{2,e}$$

$$\mathbf{Y}_{2,o} = \mathbf{H}_{1,2,o}\frac{\mathbf{X}_3^*}{\sqrt{2}} + \mathbf{H}_{2,2,o}(-\frac{\mathbf{X}_3^*}{\sqrt{2}}) + \mathbf{H}_{3,2,o}\frac{\mathbf{X}_2 + \mathbf{X}_2^* + \mathbf{X}_1 - \mathbf{X}_1^*}{2}$$
$$+ \mathbf{H}_{4,2,o}\frac{-(\mathbf{X}_1 + \mathbf{X}_1^* + \mathbf{X}_2 - \mathbf{X}_2^*)}{2} + \mathbf{W}_{2,o}$$

$$(10)$$

Assuming perfect channel knowledge at the receiver with constant channel gains within the block, the STF decoder constructs the decision estimate vector $\mathbf{X}_k$, $k = 1,2,3$ as follows [6] to yield the estimated outputs.

$$\hat{\mathbf{X}}_1 = \mathbf{Y}_{1,e}\mathbf{H}_1^* + \mathbf{Y}_{2,e}^*\mathbf{H}_2 + \frac{(\mathbf{Y}_{2,o} - \mathbf{Y}_{1,o-})(\mathbf{H}_3^* - \mathbf{H}_4^*)}{2} - \frac{(\mathbf{Y}_{1,o} + \mathbf{Y}_{2,o})^*(\mathbf{H}_3 + \mathbf{H}_4)}{2}$$

$$\hat{\mathbf{X}}_2 = \mathbf{Y}_{1,e}\mathbf{H}_2^* - \mathbf{Y}_{2,e}^*\mathbf{H}_1 + \frac{(\mathbf{Y}_{2,o} + \mathbf{Y}_{1,o-})(\mathbf{H}_3^* - \mathbf{H}_4^*)}{2} + \frac{(-\mathbf{Y}_{1,o} + \mathbf{Y}_{2,o})^*(\mathbf{H}_3 + \mathbf{H}_4)}{2}$$

$$\hat{\mathbf{X}}_3 = \frac{(\mathbf{Y}_{1,e} + \mathbf{Y}_{2,e}\mathbf{H}_3^*)}{\sqrt{2}} + \frac{(\mathbf{Y}_{1,e} - \mathbf{Y}_{2,e}\mathbf{H}_4^*)}{\sqrt{2}} + \frac{(\mathbf{Y}_{1,o}^*(\mathbf{H}_1 + \mathbf{H}_2)}{\sqrt{2}} + \frac{(\mathbf{Y}_{2,o}^*(\mathbf{H}_1 - \mathbf{H}_2)}{\sqrt{2}}$$

$$(11)$$

A. Code Rate

Consider that $\mathbf{X}$ has been generated by N_M QAM symbols in the block vector $\mathbf{S} = [S(0) \; S(1) \; ... \; S(N_M\text{-}1)]^T$. Transmitting N_M symbols using N subcarriers occupying N_s OFDM symbols, yield an STF code rate of

$$R_{STF-OFDM} = \frac{N_M}{N_S N} \quad (12)$$

However since the symbol rate is $^3/_4$ then (12) becomes,

$$R_{STF-OFDM} = 0.75\frac{N_M}{N_S N} \quad (13)$$

Accounting for CP with length P and constellation size, B (4-QAM corresponding to 2 bits/symbol), our transmission rate becomes,

$$R_{STF-OFDM} = 0.75\frac{N_M}{N_S(N+P)\log_2|B|}\text{bps/Hz} \quad (14)$$

5. CHANNEL MODEL

To measure the delay and fading caused by multipath, Naftali channel model [12] of IEEE 802.11 system was chosen. Using this model the channel impulse response of complex samples using random uniformly distributed phase and Rayleigh distributed magnitude were composed. According to [12] the Naftali channel model can be described by,

$$h_k = N(0,\frac{\sigma_k^2}{2}) + jN(0,\frac{\sigma_k^2}{2}) \quad (15)$$

$$\sigma_k^2 = \sigma_0^2\exp(-kT_s/T_{rms})$$
$$\sigma_0^2 = 1 - \exp(-T_s/T_{rms}) \quad (16)$$

where $N(0,\frac{\sigma_k^2}{2})$ is zero mean Gaussian random variable with variance $\frac{\sigma_k^2}{2}$, which can be produced by generating an $N(0,1)$ Gaussian random number and multiplying it by $\frac{\sigma_k^2}{\sqrt{2}}$, and

$\sigma_0^2 = 1 - \exp(-T_s/T_{rms})$ is chosen so that the condition $\sum_{k=0}^{k\max}\sigma_k^2 = 1$

is satisfied to ensure the same average received power. T_s represents the sampling period, and T_{rms} represents the delay spread of the channel. The number of samples to be taken in the impulse response should ensure sufficient decay of impulse response tail so that to avoid inter symbol interference. For 11 MHz sampling rate, $T_s = 1/f_{sample} \approx 91$ ns. For a delay spread of $T_{rms} = 200$ ns, we have $k_{max} = 10$ x $200/90 \approx 23$. The corresponding channel model with the chosen values is shown in Figure 4.
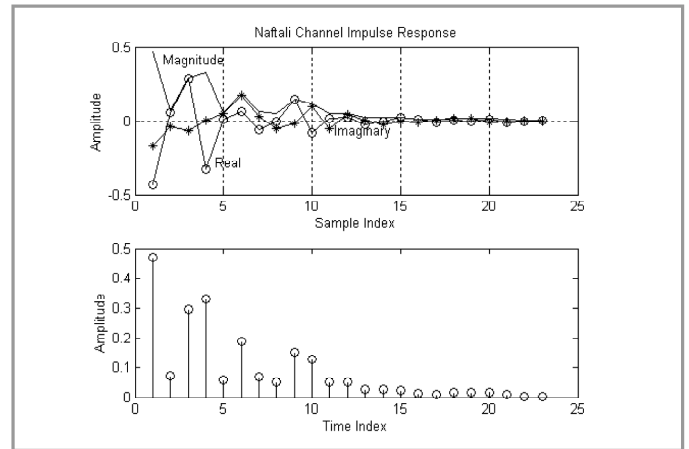

Figure 4: Channel impulse response of Naftali IEEE 802.11 channel model

6. SYSTEM PARAMETERS SETUP AND SIMULATION RESULTS

Our simulation is performed based on the following system parameters shown in Table 1. Unlike [9] larger number of subcarriers were used to fully exploit the advantage of multicarrier OFDM. The performance of each scheme was measured, namely the ST, SF, and STF-OFDM

Table 2: System parameters set up

Parameter	Value	Remarks
Operating frequency, f_c	5.25 Ghz	-
Number of subcarriers, N	1024	$N \times \Delta f \le BW$
Delay spread	700 ns (indoor) 1μs (outdoor)	
Bit rate	200 Mbps	Very high data rate
Broadband bandwidth, BW	200 MHz	Broadband
OFDM subcarrier spacing, Δf	195.3125 kHz	*BW/N*
OFDM symbol duration, T_{OFDM}	5.12 μs	$1/\Delta f$
Cylic prefix, T_{CP}	1.28 μs	At least 25% of T_{OFDM}
Constellation	4-QAM	-
FFT-points	1024	Higher number of FFT-points may be used for oversampling purposes

in indoor delay spread of 700 ns as well as in outdoor channel of 1 μs.

Beside the abovementioned parameters, other simulation parameters are as shown in Table 2 with remarks explaining how they are chosen. Note that to
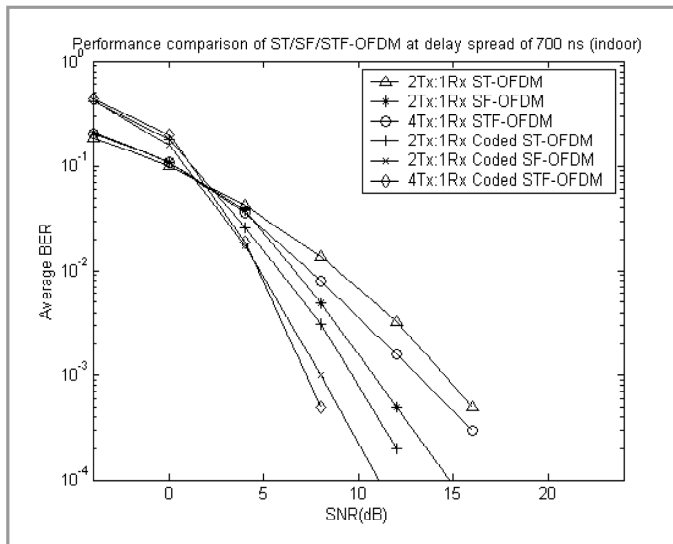

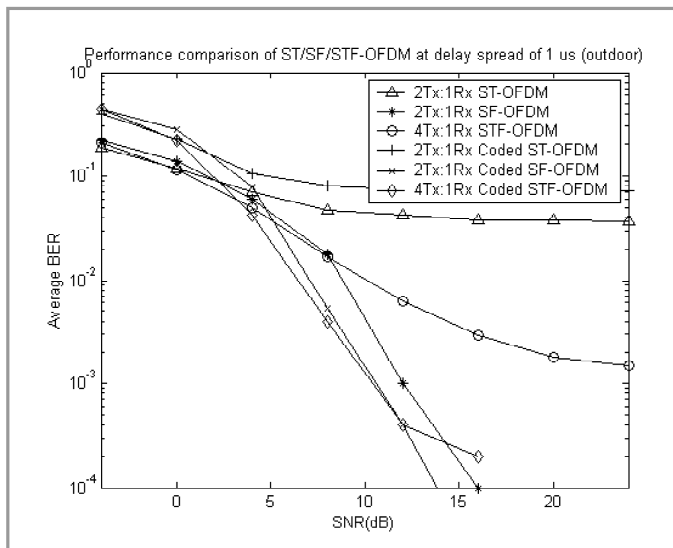**Figure 5: Performance comparisons of ST/SF/STF-OFDM at 700 ns delay spread**

Figure 6: Performance comparisons of ST/SF/STF-OFDM at a delay spread of 1 μs over outdoor environmet

achieve a very high speed data rate of 200 Mbps, we would require 1024 bits per OFDM symbol (200Mbps x 5.12μs). Since 4-QAM constellation of 2 bits/QAM-symbol/subcarrier were chosen, at least 512 subcarriers were required. Higher number of subcarriers may be chosen for oversampling, folding, or training purposes. Choosing N = 1024 and with Δf = 195.3125 kHz, total bandwidth used is exactly 200 MHz.

A. Simulation Results and Discussion

The ST, SF and STF–OFDM were simulated and their performances were compared in terms of BER of the received signals. Figures 5 and 6 show performance comparison of the schemes (coded and uncoded) in terms of BER versus SNR at 700 ns and 1 μs delay spread over outdoor environments. The employment of channel coding with ST/SF/STF-OFDM can improves system performance significantly. Results also show that with symbol duration T_{OFDM} = 5.12μs can only improves performance at tolerable delay spread of about 1.28μs (25% of T_{OFDM}), and performance deteriorates for ST (both coded and uncoded) and for uncoded STF-OFDM in outdoor environment. However coded STF outperforms other schemes by as much as 8 dB (against ST-OFDM) at both delay spreads. Notice that to achieve a BER of 10^{-3} at 700 ns delay spread environments, coded STF-OFDM requires only 7 dB of SNR, a gain of about 1 dB compared to Coded SF-OFDM and 3 dB to Coded ST-OFDM.

The diversity gain (shown by the slope of the curve), which is supposed to be 4 for our STF scheme is not easily differentiated from the other two schemes (and their hybrids) since it has been compensated by the low symbol rate transmitted (3/4 symbols/Hz). Notice also that coded SF-OFDM is more stable in both environments while STF-OFDM becomes unstable at higher SNR in 1 μs delay spread channel, exhibiting similar characteristics to ST-OFDM.

7. IMPLEMENTATION ISSUES

A multiple antenna system is not easy to implement. However with the advent of semiconductor and software defined radios, the implementation of multiple antenna system employing STF coding may be feasible in the future. Many parts of STF-OFDM system can be made reprogrammable and reconfigurable especially in the signal processing area. Intel is working towards such a system (with space-time OFDM) to produce a chip for WiMAX communications that may use up to 4 transmit antennas. The proposed coded STF-OFDM which forms part of a modem in a transmission system can be implemented on Field Programmable Gate Array (FPGA) by converting the algorithm to a VHDL model for fabrication.

8. CONCLUSIONS

A 4 Tx:1 Rx coded STF-OFDM over IEEE 802.11 fading channels was described and simulated. Results show that coded STF-OFDM outperforms other schemes in by as much as 8 dB gain over ST-OFDM at 700 ns delay spread channel. Currently investigation are carried out on the feasibility of employing adaptive spatial diversity in which the transmission of SF, ST or STF-OFDM scheme depends on channel condition fed back to the transmitter. ■

REFERENCES

[1] Alamouti, S. M., "A simple transmit diversity technique for wireless communications," *IEEE Journal on Selected Areas in Comm.*, Vol.16, No.8, pp. 1451-1458, 1998.

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

[3] L. Lihua, T. Xiaofeng, Z. Ping, H. Haas, " A practical space-frequency block coded OFDM scheme for fast fading broadband channel," *PIMRC 2002*, pp. 212-216.

[4] X. Ma, H. Kobayashi, and S. C. Schwartz, "An EM-based channel estimation algorithm for space-time and space-frequency block coded OFDM," *Proc.IEEE Intl Conf. on Acoustic, Speech, and Signal Procssing,* ICASSP 2003, vol. 4. pp. 389-392.

[5] Z. Liu, Y. Xin and G. B. Giannakis, "Space-time-frequency coded OFDM over frequency-selective fading channels," *IEEE Transac tions on Signal Processing,* vol. 50, no. 10, Oct. 2002, pp. 2465-2476.

[6] K. F. Lee and D. B. Williams, "A space-frequency transmitter diversity technique for OFDM systems," *IEEE GLOBECOM 2000, vol. 3,* pp. 1473-1477, San Francisco, USA, Nov 2000.

[7] O. Tirkkonen, A. Hottinen, "Complex space-time block codes for four tx," *GLOBECOM 2000*, pp. 1005-1009.

[8] V. Tarokh, N. Shesadri, and A.R. Calderbank, "Space-time codes for high data rate wireless communication: performance criterion and code construction," *IEEE Trans on Information Theory*, vol. 44, no.2, March 1998, pp. 744-765.

[9] 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.

[10] E. Biglieri, G. Taricco and A. Tulino, "Recent results on coding for multiple-antenna transmission systems," *IEEE 6th Intl Symposium on Spread Spectrum Techniques and Applications,* vol.1 , 6-8 Sep 2000, pp. 177-121.

[11] Y. Akaiwa, *Introduction to Digita Mobile Communication*,(Ed. J.G. Proakis), John Wiley and Sons Inc. 1997, p.108.

[12] W.Y.Chen, *Home Networking Basis – Transmission environments and Wired/Wireless Protocols,* Prentice Hall, New Jersay, 2004, pp. 470-490.

PROFILE

Dr N.K. Noordin
Faculty of Engineering,
University Putra Malaysia,
43400 UPM Serdang,
Selangor Darul Ehsan