Adaptive Switching Technique for Space-Time/Frequency Coded OFDM Systems

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SUMMARY In this letter, a switched transmission technique is presented that can provide the orthogonal frequency division multiplexing (OFDM) systems with additional diversity gain. The space-time block coding (STBC) and space-frequency block coding (SFBC) are considered for the transmission of the OFDM signals. A proper coding scheme is selected based on the estimated normalized delay spread and normalized Doppler spread. The selection criterion is derived empirically. It is shown through computer simulations that the proposed switching technique can improve the bit error rate (BER) performance of an OFDM system when the corresponding wireless channel has some time variation of time selectivity as well as frequency selectivity.

**key words:** OFDM, space-time block code, space-frequency block code

1. Introduction

Recently, orthogonal frequency division multiplexing (OFDM) systems [1] are rapidly being combined with the multi-input multi-output (MIMO) technology [2]–[4]. Among the various MIMO transmission schemes, the space-time block coded OFDM (STBC-OFDM) [5] and space-frequency block coded OFDM (SFBC-OFDM) [6] are estimated to achieve more reliable transmission by taking advantages both of OFDM and of MIMO. The STBC-OFDM is robust in channels with high frequency selectivity, whereas SFBC-OFDM is robust against time selectivity of channels due to high mobility. Even though these two different diversity coding schemes have their own preferred channel conditions, few studies associated with the relevant switching criterion have been carried out.

This letter presents a switching criterion between the STBC-OFDM and SFBC-OFDM. For proper switching, we estimate the two major parameters, which are the normalized delay spread and normalized Doppler spread of time-frequency-selective channel, and then use them to determine the appropriate coding scheme. Computer simulation results show that the bit error rate (BER) performance can be improved by the proposed switching technique compared to the case where only one coding scheme is used all the time.

2. Space-Time/Frequency Coded OFDM

The system model considered in this letter is shown in Fig. 1. The space-time/frequency coded OFDM system employs two transmit antennas. The number of subcarriers is set to be \(N\), and the maximum multipath delay index of channel is assumed to be \(L-1\). In a time-frequency-selective channel, the received OFDM signal can be expressed as

\[
y = [y(0), \ldots, y(n), \ldots, y(N-1)]^T = H_1 x_1 + H_2 x_2 + z
\]

where \(x_r\) and \(z\) are \(N \times 1\) transmitted signal and AWGN vector, respectively, and \(H_r\) denotes the \(N \times N\) time domain channel matrix. The operator \((\cdot)^T\) is the transpose of vector or matrix. Let \(F_N\) and \(F_N^\dagger\) denote the fast Fourier transform (FFT) and inverse FFT (IFFT) matrix, respectively. Then, \(x_r = F_N^\dagger x_r\) for \(r \in \{1, 2\}\), where \(x_r\) is an \(N \times 1\) column vector consisting of \(N\) subcarrier symbols transmitted from the \(r\)-th antenna. Now, let’s use the argument \(m\) to denote the \(m\)-th OFDM symbol. Then, the \(m\)-th received OFDM symbol can be expressed in the frequency-domain by

\[
Y(m) = [Y(m;0), \ldots, Y(m;k), \ldots, Y(m;N-1)]^T = G_1(m) X_1(m) + G_2(m) X_2(m) + Z(m)
\]

where \(Y(m;k)\) is the received signal at the \(k\)-th subcarrier; \(X_r(m)\) is the \(N \times 1\) coded OFDM signal vector from \(r\)-th transmit antenna; \(Z(m)\) is \(N \times 1\) AWGN vector; and

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\( G_r(m) = F_y H_r(m) F_i^H \) is the frequency domain channel matrix. Let \( A_r(m) \) denote a diagonal matrix in which the \((k,k)\)-th element, \( A_r(m; k) \), equals the \((k,k)\)-th element of \( G_r(m) \). \( A_r(m; k) \) is the channel response of the subcarrier index \( k \) of the \( m \)-th OFDM symbol.) Then, (2) can be rewritten as

\[
Y(m) = \Lambda_1(m) X_1(m) + \Lambda_2(m) X_2(m) + W(m) \tag{3}
\]

where

\[
W(m) = [W(m;0), \ldots, W(m;k), \ldots, W(m;N-1)]^T
= Z(m) + \left[ (G_1(m) - \Lambda_1(m)) X_1(m) + (G_2(m) - \Lambda_2(m)) X_2(m) \right].
\]

Notice that \( W(m) \) contains the AWGN plus inter-carrier interference produced by the Doppler spread.

### 2.1 STBC-OFDM

In the STBC-OFDM system, the transmit data for each subcarrier are coded over two successive OFDM symbols. Let \( [\cdot]_k \) denote the \( k \)-th element of a vector in the bracket. Suppose that the two symbols, \( S(1) \) and \( S(2) \), are in order transmitted in the \( k \)-th subcarrier of the \( m \) and \( (m+1) \)-th OFDM symbol. Then, by STBC, we have \( [X_1(m)]_k = S(1) \), \( [X_2(m)]_k = S(2) \), \( [X_1(m+1)]_k = -S^*(2) \), and \( [X_2(m+1)]_k = S^*(1) \); and hence, the received signals of the subcarrier index \( k \) can be written as

\[
Y(m;k) = \Lambda_1(m;k) S(1) + \Lambda_2(m;k) S(2) + W(m;k),
\]

\[
Y(m+1;k) = -\Lambda_1(m+1;k) S^*(2) + \Lambda_2(m+1;k) S^*(1) + W(m+1;k).
\]

Define \( Y = [Y(m;k), Y^*(m+1;k)]^T \). Then, we have

\[
Y = \Lambda S + W \tag{4}
\]

where

\[
\begin{align*}
\Lambda &= \begin{bmatrix} \Lambda_1(m;k) & \Lambda_2(m;k) \\
\Lambda_1^*(m+1;k) & -\Lambda_2^*(m+1;k) \end{bmatrix}, \\
S &= \begin{bmatrix} S(1) \\
S(2) \end{bmatrix}, \\
W &= \begin{bmatrix} W(m;k) \\
W^*(m+1;k) \end{bmatrix}.
\end{align*}
\]

Let \( (\cdot)^H \) denote conjugate transpose of a vector or matrix. Multiplying \( \Lambda^H \) on both sides of (4), we have

\[
\hat{S} = \Lambda^H \Lambda S + \Lambda^H W
\]

where

\[
\Lambda^H \Lambda = \begin{bmatrix} \Lambda_1(m;k)^2 + |\Lambda_2(m; k+1)|^2 & \alpha \\
\beta & \Lambda_1(m+1; k)^2 + |\Lambda_2(m;k)|^2 \end{bmatrix}.
\]

The off-diagonal terms are defined as

\[
\alpha = \Lambda_1^*(m;k) \Lambda_2(m;k) - \Lambda_2(m+1;k) \Lambda_1^*(m+1;k),
\]

\[
\beta = \Lambda_1^*(m;k) \Lambda_1(m;k) - \Lambda_2(m+1;k) \Lambda_2^*(m+1;k).
\]

(5) indicates that in a static channel, \( \Lambda^H \Lambda \) becomes a diagonal matrix, so that there is no interference between \( S(1) \) and \( S(2) \). If the channel varies with time, however, \( \Lambda^H \Lambda \) is no longer a diagonal matrix, and hence, there happens mutual interference between \( S(1) \) and \( S(2) \).

### 2.2 SFBC-OFDM

In the SFBC-OFDM system, each transmit data are spatially coded over two adjacent subcarriers. It is assumed that the two adjacent subcarriers exhibit the same channel response. Suppose that the two symbols, \( S(1) \) and \( S(2) \), are in order transmitted in the \( k \) and \( k+1 \) th subcarrier of the \( m \)-th OFDM symbol. Then, by SFBC, we have \( [X_1(m)]_k = S(1) \), \( [X_2(m)]_k = S(2) \), \( [X_1(m)]_{k+1} = -S^*(2) \), and \( [X_2(m)]_{k+1} = S^*(1) \); and hence, the received signals of the subcarrier indices, \( k \) and \( k+1 \), are can be written as

\[
Y(m;k) = \Lambda_1(m;k) S(1) + \Lambda_2(m;k) S(2) + W(m;k),
\]

\[
Y(m;k+1) = -\Lambda_1(m+1;k) S^*(2) + \Lambda_2(m+1;k) S^*(1) + W(m+1;k).
\]

These equations can be expressed as a simplified form:

\[
Y = [Y(m;k), Y^*(m+1;k)]^T = \Lambda S + W \tag{6}
\]

where

\[
\Lambda = \begin{bmatrix} \Lambda_1(m;k) & \Lambda_2(m;k) \\
-\Lambda_2^*(m+1;k) & \Lambda_1^*(m+1;k) \end{bmatrix}, \\
S = \begin{bmatrix} S(1) \\
S(2) \end{bmatrix}, \\
W = \begin{bmatrix} W(m;k) \\
W^*(m+1;k) \end{bmatrix}.
\]

Multiplying \( \Lambda^H \) on the both sides of (6),

\[
\hat{S} = \Lambda^H \Lambda S + \Lambda^H W
\]

where

\[
\Lambda^H \Lambda = \begin{bmatrix} |\Lambda_1(m;k)|^2 + |\Lambda_2(m; k+1)|^2 & \zeta \\
\eta & |\Lambda_1(m+1; k)|^2 + |\Lambda_2(m;k)|^2 \end{bmatrix}.
\]

\[
\zeta = \Lambda_1^*(m;k) \Lambda_2(m;k) - \Lambda_2(m+1;k) \Lambda_1^*(m+1;k),
\]

\[
\eta = \Lambda_2^*(m;k) \Lambda_1(m;k) - \Lambda_1(m+1;k) \Lambda_2^*(m+1;k).
\]

Note that \( \Lambda^H \Lambda \) is a diagonal matrix when \( \Lambda_r(m; k) = \Lambda_r(m+1; k+1) \) is met for \( r \in [1, 2] \). However, if the equality is not hold, \( \Lambda^H \Lambda \) is no longer a diagonal matrix, and in this case, some mutual interference between \( S(1) \) and \( S(2) \) exists. This indicates that the performance of the SFBC worsens as the frequency selectivity of the channel becomes higher.

### 3. Proposed Switching Technique

In this section, a switching transmission technique using the channel condition is presented. In the proposed scheme, the normalized Doppler spread and normalized delay spread, which characterize the given channel, are estimated from the channel state information at the receiver, and then they are used for the selection between the STBC-OFDM and
SFBC-OFDM. The selected mode is transmitted by one bit feedback toward the transmitter.

The normalized delay spread associated with the frequency selectivity can be obtained from the power delay profile as follows. When the power for the multipath delay $\tau_l$ is denoted by $P_l$, the RMS delay spread is expressed as

$$\tau_{\text{rms}} = \sqrt{\frac{\sum_{l=0}^{L-1} (\tau_l - \tau_{\text{mean}})^2 P_l}{\sum_{l=0}^{L-1} P_l}}$$

where

$$\tau_{\text{mean}} = \frac{\sum_{l=0}^{L-1} \tau_l P_l}{\sum_{l=0}^{L-1} P_l}$$

is the average delay spread. Let

$$\mathbf{h}(m) = [h(m;0), \cdots, h(m;l), \cdots, h(m;L-1)]^T$$

denote the channel impulse response for $m$-th OFDM symbol, and $h(m;l)$ is the estimated channel response of the $l$-th tap. Then, we have $P_l = |h(m;l)|^2$. The normalized delay spread is defined as

$$\bar{\tau}_{\text{norm}} = \frac{\tau_{\text{rms}}}{T_u/N}$$

where $T_u$ is the useful OFDM symbol period excluding the guard interval.

The normalized Doppler spread, defined by

$$f_{\text{norm}} = f_{\text{max}} T_u$$

where $f_{\text{max}}$ is the maximum Doppler spread and $1/T_u$ represents the subcarrier interval, is estimated as follows. Given the channel responses $h(m;l) | m = 0, 1, \ldots, M-1|$ where $h(m;l) = 0$ for $m < 0$ or $m \geq M$, the power spectral density of the $l$-th tap is defined by $S(\omega;l) = E[|H(\omega;l)|^2]$, where

$$H(\omega;l) = \sum_{m=-\infty}^{\infty} h(m;l)e^{-j2\pi m \omega}$$

(8)

and $\omega \in [-\pi, \pi]$ is the angular shift during one OFDM symbol period including the guard interval. Note that the sampled version of $H(\omega;l)$, at discrete points of $w = 2\pi v/N_p$ for integers $v$ and $N_p \geq M$, can be evaluated by

$$H(v;l) = \sum_{m=0}^{M-1} h(m;l)e^{-j2\pi m v/N_p}.$$  

(9)

The OFDM symbol period is written by $T_{\text{sym}} = (N + N_{GI})T_u/N$, where $N$ and $N_{GI}$ are the FFT size and the guard interval, respectively. Because the angular shift of $\omega$ for $T_{\text{sym}}$ seconds indicates that the angular frequency equals $\omega/T_{\text{sym}}$, $\omega = 2\pi v/N_p$ indicates that the frequency is given by

$$\frac{v}{N_p T_{\text{sym}}} = \frac{v N}{N_p(N + N_{GI})T_u}.$$
value becomes the switching boundary, which can be approximated by the use of the first order polynomial fitting. Then, the switching criterion can be expressed as

$$
\tau_{\text{norm}} \overset{\text{STBC}}{\geq} A_{\text{fnorm}} + B \quad (11)
$$

where

$$
A = (0.92 - 0.04 \log_2 N)(N + N_{\text{GI}}),
$$
$$
B = -0.03 + 0.005(N - 48).
$$

A and B were empirically estimated by computer simulations for various FFT sizes from 32 to 512. (11) means that if the normalized delay spread is greater than $A_{\text{fnorm}} + B$, STBC-OFDM can attain lower BER than SFBC-OFDM, and vice versa.

4. Simulation Results

The effectiveness of the proposed switching technique was examined through computer simulations. The simulation parameters were as follows: all subcarriers of the OFDM symbols were QPSK modulated; the FFT size was $N = 64$; the Guard interval $N_{\text{GI}} = 16$; and the system bandwidth $N/T_u$ was 500 kHz. The 2-ray Rayleigh fading channel was employed. Both rays had the same average power and were generated by Jakes' model. The normalized Doppler spread was a uniformly distributed from 0 to 0.06, and the normalized delay spread was randomly selected from {1, 2, 3}. The maximum delay index was determined from {2, 4, 6}. Since the maximum delay index is smaller than $N_{\text{GI}}$, the system performance does not degrade due to the variation of the delay spread. The perfect channel state information was assumed throughout the simulations. The switching mode determined after the channel estimation at every two OFDM symbol duration, and a feedback delay of two OFDM symbol duration is considered.

Figure 4 shows the advantage of the proposed switching scheme over conventional schemes in terms of BERs. At the BER of $3 \times 10^{-3}$, the proposed technique exhibited SNR gains of 2 dB and 3.5 dB over the pure STBC-OFDM and SFBC-OFDM, respectively. Since the off-diagonal terms in (5) and (7) become non-zero in time-frequency-selective channels, some error floor occurred for all BER curves in Fig. 4. The proposed technique also lowered the error floor level.

5. Conclusion

A switching technique was presented that selects an appropriate transmission scheme between the STBC-OFDM and SFBC-OFDM based on the estimated channel parameters: normalized Doppler frequency and normalized delay spread. In particular, a switching criterion was derived empirically. As shown in the simulation results, an improvement of BER performance was observed by the proposed switching scheme, which proves the effectiveness of the proposed technique.

References