Abstract—In this paper, we propose a new differential space-time-frequency (DSTF) modulation for MIMO-OFDM system with four transmit-antennas and arbitrary receive-antennas, which can improve the transmission rate since it can adopt high order quadrature amplitude modulation (QAM) modulation. Our proposed DSTF scheme embeds some full diversity full rate (FDFR) quasi-orthogonal space-time codes (QOSTBC) with QAM modulation into the frequency intervals and adopts the differential modulation in both time and frequency domains. The simulation results demonstrate that the proposed DSTF scheme can improve transmission rate greatly. Compared with the conventional differential unitary space-time modulation (DUSTM), it can get better transmission performance in high transmission rate for MIMO-OFDM system.

Index Terms—Differential modulation, high transmission rate, MIMO-OFDM, space-time-frequency.

1. Introduction

In the past few years, many space-time modulation techniques for transmit diversity over the wireless channels have been studied. However, most of the space-time schemes require the knowledge of the channel state information (CSI) at the receiver. Although the CSI can be obtained by sending training symbols or pilot tones, it is difficult to estimate the CSI, especially when the channel changes rapidly. Recently, several differential space-time modulations (DSTM) have been proposed, in which the CSI is not needed to know at both transmitter and receiver. Hughes [1] has proposed a DSTM based on group codes; Tarokh and Jafarkhani [2] have proposed a DSTM by using orthogonal space-time block code (OSTBC); Hochwald and Sweldens [3] have designed a DSTF based on unitary matrices. In [4], Ganesa and Stoica have suggested a DSTM that has very low bit error rate and low complexity. But the conventional differential unitary space-time codes can not support high rate transmission because these codes are not easy to adopt high order constellations. In order to improve the transmission rate, Xia and Li [5,6] have proposed their differential space-time codes based on amplitude and phase shift keying constellations. Zhang et al. [7] have designed a rate-embedded differential space-time codes that can achieve much better bit error performance and improve the total transmission rate greatly, in which some high rate space-time codes, such as full diversity full rate (FDFR) codes, are embedded into the time intervals of the conventional differential space-time coding schemes, but it requires that the channels have to remain invariant within three consecutive transmitted matrices periods. So it is less effective in rapidly fading environments.

It is well known that quasi-orthogonal space-time block codes (QOSTBC) proposed in [8] for four transmit-antennas systems can achieve full rate and half diversity. Furthermore, a full rate and full rank quasi-orthogonal space-time block code was presented in [9]-[13], which use rotated constellations or rotation coefficient to achieve the full rate and the full rank. Although differential QOSTBCs have been studied in [14] and [15], it is difficult to implement differential QOSTBC when high order quadrature amplitude modulation (QAM) modulation is used, because their transmitted matrices are not unitary matrices. In this paper, we generalize the rate-embedded differential space-time modulation proposed in [7] for flat fading channel into MIMO-OFDM system with frequency-selective fading channel. In our scheme, some high rate and full diversity QOSTBCs with QAM modulation are mapped into the even subcarriers and the remained odd subcarriers carry the conventional differential unitary space-time codes in an OFDM symbol. And the differential processing is done within two consecutive transmitted matrices periods. Therefore it only requires the channel to remain invariant within two consecutive transmitted matrices periods. Simulation results demonstrate that our scheme can improve the overall transmission rate and the bit error performance in MIMO-OFDM system and can get a better performance in the fast time varying fading channel.

Notation: Vectors and matrices are printed in bold case letters: $(\cdot)^{\dagger}$, $(\cdot)^{H}$, $(\cdot)^{T}$, $tr\{\cdot\}$, $\|\|$ and det{\cdot} denote the conjugate, Hermitian transpose, transpose, trace, Frobenius norm, and determinant of a matrix (or vector), respectively. $I_{n}$ is the $n \times n$ identity matrix.
\section{System Model}

Fig. 1 depicts the block diagram of our proposed differential space-time-frequency (DSTF) for MIMO-OFDM system with $N_r = 4$ transmit-antennas, $N_r$ receive-antennas and $N_c$ OFDM subcarriers. The channel between the $n$th transmit antenna and $m$th receive-antenna in the $t$th OFDM symbol is frequency-selective fading, which can be expressed as

\[ h_{n,m}(t) = \left[ h_{n,m(0)}(t), h_{n,m(1)}(t), \ldots, h_{n,m(L)}(t) \right]^T, \]

where $L$ is the number of multipaths. Then during the $t$th OFDM symbol, the post-FFT signal $y_n(t,k)$ at the $n$th receive-antenna on the $k$th OFDM subcarrier is given as

\[ y_n(t,k) = \sum_{n=1}^{N_c} H_{n,m}(t,k)x_n(t,k) + W_n(t,k), \]

\[ 0 \leq k \leq N_c - 1, 1 \leq m \leq N_r, 0 \leq t \]

\[ H_{n,m}(t,k) = \sum_{l=0}^{L-1} h_{n,m(l)}(t)e^{j2\pi l/N_c} \]

where $x_n(t,k)$ is the transmitted data symbol from the $n$th transmit-antenna on the $t$th OFDM symbol. And $W_n(t,k)$ is the additive white noise of complex Gaussian random variables with zero mean and variance $\sigma_n^2$.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{Block diagram of DSTF MIMO-OFDM system.}
\end{figure}

The received signals can be expressed in a matrix form as:

\[ Y(p,k) = H(p,k)X(p,k) + W(p,k), \quad 0 \leq k \leq N_c - 1 \]

where $p$ denotes the $p$th transmitted matrix period which includes 4 OFDM symbols, $X(p,k)$ is a $4 \times 4$ matrix coded by QOSTBC or unitary space-time modulation, and $W(p,k)$ is a $N_r \times N_r$ ($N_r = 4$) matrix which can be written as

\[ W(p,k) = \begin{bmatrix}
W_1(4p,k) & W_1(4p+1,k) & \cdots & W_1(4p+3,k) \\
W_2(4p,k) & W_2(4p+1,k) & \cdots & W_2(4p+3,k) \\
\vdots & \vdots & \ddots & \vdots \\
W_{N_c}(4p,k) & W_{N_c}(4p+1,k) & \cdots & W_{N_c}(4p+3,k)
\end{bmatrix}. \]

The $H(p,k)$ and $Y(p,k)$ are both $N_r \times N_r$ matrices which can be expressed respectively as

\[ H(p,k) = \begin{bmatrix}
H_{1,1}(4p,k) & H_{1,1}(4p+1,k) & \cdots & H_{1,1}(4p+3,k) \\
H_{1,2}(4p,k) & H_{1,2}(4p+1,k) & \cdots & H_{1,2}(4p+3,k) \\
\vdots & \vdots & \ddots & \vdots \\
H_{1,N_r}(4p,k) & H_{2,N_r}(4p+1,k) & \cdots & H_{N_r,N_r}(4p+3,k)
\end{bmatrix} \]

\[ Y(p,k) = \begin{bmatrix}
y_1(4p,k) & y_1(4p+1,k) & \cdots & y_1(4p+3,k) \\
y_2(4p,k) & y_2(4p+1,k) & \cdots & y_2(4p+3,k) \\
\vdots & \vdots & \ddots & \vdots \\
y_{N_r}(4p,k) & y_{N_r}(4p+1,k) & \cdots & y_{N_r}(4p+3,k)
\end{bmatrix} \]

where $0 \leq k \leq N_c - 1$ and $p \geq 0$.

\section{New Differential Space-Time-Frequency Modulation}

\subsection{Differential Modulation Encoding}

Firstly, we will briefly introduce the rate-embedded differential space-time coding scheme proposed in [7]. In this scheme, two kinds of message matrices, $U_{2p}$ and $V_{2p+1}$, are transmitted, where $U_{2p}$ can be composed of some high performance and high rate space-time codes used in the case of coherent detection and $V_{2p+1}$ is the conventional unitary message matrix with low rate information. Because this scheme is used for MIMO system, $X(p,k)$ can be replaced as $X_p$. Fig. 2 shows the encoding structure, and then this differential space-time transmission scheme can be modeled as [7]

\[ X_{2p} = X_{2p-1}U_{2p}, \quad p = 1,2,\cdots \]

\[ X_{2p+1} = X_{2p-1}V_{2p+1}, \quad p = 1,2,\cdots \]

where $X_{2p-1}$, $X_{2p}$, and $X_{2p+1}$ represent the transmitted matrices in different time blocks $2p-1$, $2p$, and $2p+1$ respectively. In this differential scheme, the high rate transmitted matrix in each even time block is only determined by the transmitted matrix in previous time block, while those transmitted matrices in odd time blocks represent the conventional differential space-time scheme during longer transmission time blocks.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2.png}
\caption{Rate-embedded differential space-time codes.}
\end{figure}
Because the rate-embedded differential space-time codes require that the channels have to remain invariant within three consecutive transmitted matrices periods, it is less effective in rapid fading environments. In order to improve the transmission performance in rapidly fading environments, cording to the rate-embedded differential space-time modulation proposed in [7] for flat fading channel, we propose a new differential space-time-frequency modulation scheme for MIMO-OFDM system with frequency-selective fading channel. In our scheme, some high rate and full diversity QOSTBCs with QAM modulation are mapped into the even subcarriers and the remained odd subcarriers carry the conventional differential unitary space-time codes in a transmitted matrix’s block. And the differential processing is done between the two adjacent transmitted matrices periods. Therefore it only requires the channel to remain invariant within two consecutive transmitted matrices periods. Fig. 3 depicts the block diagram of the new differential space-time-frequency modulation. For MIMO-OFDM system, two kinds of message matrices, $U_{2p}$ and $V_{2p+1}$ can be replaced as $U(p,k+1)$ and $V(p,k)$, respectively. In the encoding process, we transmit the first DSTF code matrix as $X(0,k) = I_k$, $0 \leq k \leq N_c - 1$. For subsequent transmission, we encode as follows:

$$X(p,k) = X(p-1,k)V(p,k)$$

$$X(p,k+1) = X(p-1,k)U(p,k+1)$$

where $X(p,k)$ and $X(p-1,k)$ represent the transmitted matrices in different time block $p$ and $p-1$ respectively, and $k = 0, 2, \cdots, N_c - 2$. $X(p,k)$ and $X(p,k+1)$ represent the $k$th and $(k+1)$th OFDM subcarriers respectively. We suppose that the number $N_c$ of OFDM subcarriers is an even. In the new differential space-time-frequency modulation, $V(p,k)$ can adopt orthogonal or other unitary space-time codes and $U(p,k+1)$ are FDFR QOSTBCs.

![Fig. 3. Block diagram of the differential space-time-frequency modulation.](image)

### 3.2 Differential Modulation Decoding

In the decoding process, if we assume that the channel remains unchanged during two consecutive code matrices periods, then the relationship between the received data matrices and the transmitted data matrices can be given as follows:

$$Y(p-1,k) = H(p-1,k)X(p-1,k) + W(p-1,k)$$

$$Y(p,k) = H(p,k)X(p,k) + W(p,k)$$

$$Y(p,k+1) = H(p,k+1)X(p,k+1) + W(p,k+1)$$

$$H(p-1,k) = H(p,k)$$

where $k = 0, 2, \cdots, N_c - 2$. Since $H(p,k)$ and $H(p,k+1)$ are the adjacent OFDM subcarriers’ CSI, then (15) can be rewritten as

$$H(p-1,k) = H(p,k) = H(p,k+1).$$

From (10) to (16), the transmitted matrices can be estimated by the maximum likelihood estimation methods, which can be written as

$$\hat{V}(p,k) = \arg \max_{\nu \in Q_1} \text{Re}(\nu Y(p-1,k)Y(p-1,k)^{\dagger})$$

$$\hat{U}(p,k+1) = \arg \max_{\nu \in Q_2} \text{Re}(\nu Y(p,k+1)Y(p,k+1)^{\dagger})$$

where $Q_1$ and $Q_2$ denote the set of all possible code matrices of $V$ and $U$, respectively.

### 3.3 Transmission Rate and Performance Analysis

Since our proposed scheme allows that the conventional unitary space-time code and FDFR QOSTBC can be differentially transmitted simultaneously, the total transmission rate is greatly improved as

$$R = \frac{R_U + R_V}{2}$$

where $R_V$ denotes the transmission rate of the unitary space-time code and $R_U$ is the transmission rate of the QOSTBC. Because the high order QAM modulation can be adopted in QOSTBC, it is capable of enhancing the total transmission rate $R$. The total bit error rate $P_e$ can be expressed as

$$P_e = \frac{R_U P_U + R_V P_V}{R_U + R_V}$$

where $P_U$ and $P_V$ denote the bit error rate of the unitary space-time code and the QOSTBC respectively. Compared with the conventional differential unitary code, the QOSTBC can adopt the lower order constellations for the same transmission rate. Therefore, our scheme can get a better performance.
performance than the conventional differential unitary space-time modulation (DUSTM).

4. Simulation Results

In this section, we provide simulation results to compare the performance of our proposed scheme and other differential schemes for MIMO-OFDM system over frequency selective fading channel. In these simulations, we assume that the number of OFDM subcarriers is 1024 and one frame is composed by 120 OFDM symbols. And all the propagation channels between pairs of the transmit-antennas and receive-antennas have the same number of propagation paths, i.e. $L = 8$, and each path has the normalized average power $1/L$.

Fig. 4 shows the performance of the proposed differential modulation and the conventional coherent and differential space-time modulation for MIMO-OFDM system in the slow time varying fading channels with a transmission rate of 3 bit/s/Hz. In our scheme, we adopt 3/4 rate orthogonal space-time code for $(p, k)$ with 16PSK modulation, and the embedded code $U(p, k + 1)$ is a full rate full diversity quasi-orthogonal space-time code proposed in [13] with 8PSK modulation. The conventional coherent and differential space-time modulation adopts 3/4 rate orthogonal space-time code with 16PSK modulation. And the maximum-likelihood (ML) algorithm is used in the decoding. From Fig. 4, we can see that the proposed scheme can get 0.7 dB gain over conventional DUSTM.

![Fig. 4. Performance comparison for slow time varying fading channel at rate 3 bit/s/Hz.](image1)

In Fig. 5, we adopt 3/4 rate orthogonal space-time code for $(p, k)$ which uses 16PSK modulation, and the embedded code $U(p, k + 1)$ is a full rate full diversity quasi-orthogonal space-time code which uses 32-QAM modulation and rotation constellation $^{[11]}$. So the transmission rate is 4 bit/s/Hz. The conventional coherent and differential space-time modulation also adopts 3/4 rate orthogonal space-time code which uses 32-PSK modulation, and then we can get a 3.75 bit/s/Hz transmission rate. The maximum-likelihood (ML) algorithm is used in the decoding. From Fig. 5, we can see that the proposed scheme can get 5 dB gain over conventional differential space-time modulation at $10^{-6}$ bit error ratio.

![Fig. 5. Performance comparison for slow time varying fading channel at rate 4 bit/s/Hz.](image2)

In Fig. 6 and Fig. 7, the set of the proposed DSTFM and orthogonal DUSTM are same as the set of the Fig. 4 and Fig. 5, respectively. The rate-embedded STBC proposed in $^{[7]}$ is used for MIMO-OFDM system. Fig. 6 and Fig. 7 show the performance of the three modulations in a fast time varying fading channel, whose Dopper frequency $f_d T$ is chosen to satisfy $f_d T = 0.005$, where $T$ denotes the period of one OFDM time block. We can see that the proposed differential modulation can get a better performance than the rate-embedded STBC in the fast time varying fading channel. Because the rate-embedded STBC requires that the channels have to remain invariant within three consecutive code matrices periods.

![Fig. 6. Performance comparison for fast time varying fading channel ($f_d T = 0.005$) at rate 3 bit/s/Hz.](image3)
5. Conclusions

We have presented a new high rate differential space-time-frequency scheme for MIMO-OFDM with four transmit-antennas and arbitrary receive-antennas, where neither the transmitter nor the receiver knows the CSI. Our proposed differential modulation can get a better performance than the rate-embedded STBC\(^\text{[7]}\) in the fast time varying fading channel and the conventional differential unitary space-time modulation in high transmission rate for MIMO-OFDM system. In order to improve the transmission rate, we will study that conventional unitary matrix \(\mathbf{V}(p,k)\) adopts QOSTBC on the future.

References


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