Quasi-Orthogonal Space-Time Block Code with Givens Rotation for SC-FDE Transmission in Frequency Selective Fading Channels

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***Abstract*—**Conventional space-time block codes are normally designed and studied for Rayleigh flat fading channels. As Single Carrier Frequency-Domain Equalization (SC-FDE) can help to combat the Inter-Symbol Interference (ISI) caused by multipath radio channels, this paper investigates quasi-orthogonal space-time block code (QOSTBC) with Givens rotation in order to enhance the reliability of the SC-FDE transmission in the frequency selective fading channels. To use QOSTBC with Givens rotation for the SC-FDE system, the encoding is performed on the data block basis, and we derive the corresponding decoding method performing in the frequency domain at the receiver. With Givens rotation, the correlation of channel equivalent matrix is eliminated, and the decoding can be performed with linear combiner at the receiver. Such a proposed scheme can achieve full rate transmission and provide high diversity gain. Simulation results show that the BER performance of the proposed scheme is better than QOSTBC for four transmit antennas, and is better than OSTBC (orthogonal space-time block code) in the low SNR regime.

***Index Terms*—**quasi-orthogonal space-time block code; single-carrier frequency domain equalization; frequency selective fading

I. Introduction

In wireless communications, the time dispersion introduced by multipath radio channels often leads to frequency-selective fading and serious Inter-Symbol Interference (ISI) for high speed data transmissions. The Orthogonal Frequency Division Multiplexing (OFDM) and Single Carrier Frequency-Domain Equalization (SC-FDE) transmission schemes can help to combat the ISI in frequency selective fading channels. Compared with OFDM, the transmission scheme of SC-FDE has the advantages of lower PAPR and less sensitivity to frequency offset [1]. By using multiple transmit and receive antennas, space-time block codes (STBC) can establish a number of independent communication links between transmitter and receiver, and provide diversity gain. It is promising to employ STBC in the SC-FDE system to enhance the transmission reliability in frequency selective fading channels for broadband wireless communications.

Currently the research works on employing STBC for SC-FDE transmission systems are mainly focused on orthogonal space-time block codes (OSTBC). An OSTBC scheme was first proposed by Alamouti for achieving maximum diversity gain for two transmit antennas [2]. It can achieve the full rate and full diversity gain. Subsequently, Tarokh proposed OSTBC schemes to achieve full diversity for more than two transmit antennas. However, such schemes cannot achieve full rate. The SC-FDE transmission with Alamouti STBC is studied in [3]. It shows that the combination of SC-FDE with Alamouti STBC can improve the error performance about 6dB, and achieve full diversity, full rate over EDGE TU frequency selective multipath channel. However, when the number of transmit antennas is greater than 2, the complex OSTBC has highest transmission rate of 3/4 [4]. Then, quasi-orthogonal space-time block code (QOSTBC) is proposed by Jafarkhani and other researchers [5][6]. QOSTBC can achieve a full rate transmission but sacrifice some diversity gain in Rayleigh flat fading channels. When using QOSTBC in frequency selective fading channels, the non-orthogonal coding matrix of QOSTBC makes the SC-FDE decoding and equalization much more complex in the frequency domain. In [7], an improved QOSTBC for transmission over frequency selective fading channel is proposed by improving decoding and equalization at receiver, but the simulation results show that the scheme achieves full rate at the loss much of the diversity gain. Next, QOSTBC with Givens rotation was studied for flat fading channel [8]-[10]. The main use of Givens rotations in numerical linear algebra is to introduce zeros in vectors or matrices. The Givens matrix can rotate and eliminate the correlation of channel matrix, and hence the QOSTBC can be linear decoded at the receiver such that it achieves the performance of ML (Maximum Likelihood) decoding with reduced decoding complexity.

In this paper, we propose to extend QOSTBC with Givens rotation for the SC-FDE transmission in frequency selective fading channels. To use QOSTBC with Givens rotation for the SC-FDE transmission system, the encoding should be performed on the data block basis, and we derive the corresponding decoding method performing in the frequency domain at receiver. Such a proposal can realize full rate transmission and provide high diversity gain. With Givens rotation, the correlation

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of channel equivalent matrix is eliminated, and the decoding can be performed by linear combiner at the receiver. Such a proposal can achieve full rate with high diversity gain even when the number of transmit antennas is greater than 2, and it improves the BER performance of the system in such channels.

The rest of this paper is organized as follows. In Section II, we review the related work on SC-FDE transmission with OSTBC and QOSTBC. Our proposed scheme of SC-FDE transmission with QOSTBC with Givens rotation in frequency selective channels is presented in Section III. Simulation results and analysis are given in Section IV. Section V gives the conclusions.

II. RELATED WORK ON SC-FDE TRANSMISSION WITH OSTBC AND QOSTBC

The system model of SC-FDE transmission system with STBC is shown in Fig. 1. In flat fading channels without frequency domain equalization (FDE), the STBC encoding is based on the modulated symbols, and the STBC decoding is performed in time domain. On the other hand, when using for SC-FDE transmission in frequency selective fading channels, the STBC encoding should be based on the frames (i.e., blocks of modulated symbols) and the STBC decoding should be performed in frequency domain before FDE.

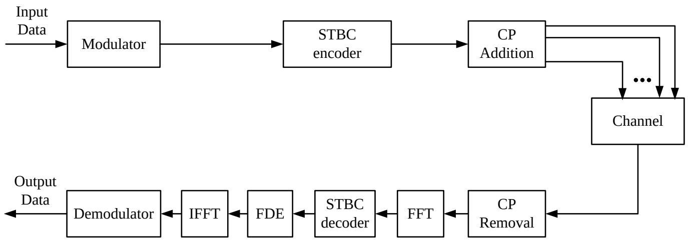

Fig. 1. System model of SC-FDE transmission with STBC

It has been studied that when using OSTBC for two antennas in the frequency selective fading channels, the SC-FDE transmission with OSTBC can achieve full diversity and full rate transmission, and the decoding of STBC and equalization in the frequency domain at SC-FDE receiver can be implemented with low complexity. Since a complex OSTBC scheme that provides full diversity and full transmission rate is not feasible for more than two antennas, the rate one transmission cannot be reached, and the system transmission rate R is less than 1 for more than two transmit antennas. Thus, 1/R bandwidth expansion is introduced for such cases. The spectral expansion caused by non-full-rate STBC is not desirable because extra bandwidth expansion is introduced in the air interface of wireless communication systems.

The channel coding matrices of OSTBC with three and four antennas designed for single-path Rayleigh flat fading channels are given in [10] as follows,

$$G_3 = \begin{bmatrix} s_1 & -s_2 & -s_3 & -s_4 & \overline{s}_1 & -\overline{s}_2 & -\overline{s}_3 & -\overline{s}_4 \\ s_2 & s_1 & s_4 & -s_3 & \overline{s}_2 & \overline{s}_1 & \overline{s}_4 & -\overline{s}_3 \\ s_3 & -s_4 & s_1 & s_2 & \overline{s}_3 & -\overline{s}_4 & \overline{s}_1 & \overline{s}_2 \end{bmatrix} \quad (1)$$

$$G_4 = \begin{bmatrix} s_1 & -s_2 & -s_3 & -s_4 & \overline{s}_1 & -\overline{s}_2 & -\overline{s}_3 & -\overline{s}_4 \\ s_2 & s_1 & s_4 & -s_3 & \overline{s}_2 & \overline{s}_1 & \overline{s}_4 & -\overline{s}_3 \\ s_3 & -s_4 & s_1 & s_2 & \overline{s}_3 & -\overline{s}_4 & \overline{s}_1 & \overline{s}_2 \\ s_4 & s_3 & -s_2 & s_1 & \overline{s}_4 & \overline{s}_3 & -\overline{s}_2 & \overline{s}_1 \end{bmatrix} \quad (2)$$

It can be seen from (1) and (2) that the transmission rate is 1/2 with three and four antennas, and the bandwidth is expanded two times. These results still hold when using them with SC-FDE for frequency selective fading channels, but there are differences in the OSTBC processing at the transmitter and receiver in SC-FDE transmission as we mentioned in the system model.

The SC-FDE transmission with QOSTBC for four transmit antennas in the frequency selective fading channel was studied in [7]. By improving Jafarkhani-proposed QOSTBC, the transmitted data blocks on the first and second antennas are orthogonal, and the transmitted data blocks on the third and fourth antennas are orthogonal. At the receiver, the transmit data blocks can be decoded in groups separately. Hence, the complexity of decoding and equalization are simplified. Though such a scheme can achieve full transmission rate, it results in lower diversity gain.

The extension of QOSTBC to be used over the frequency selective fading channels in [7] is reviewed as follows. Denote the n -th symbol of k -th transmitted data block from antenna i by $x_i^k(n)$. The encoding method for four transmit antennas are expressed as

$$\begin{array}{ll} x_1^{k+1}(n) = -\overline{x}_2^k((-n)_N) & x_2^{k+1}(n) = \overline{x}_1^k((-n)_N) \\ x_1^{k+2}(n) = x_1^k(n) & x_2^{k+2}(n) = x_2^k(n) \\ x_1^{k+3}(n) = -\overline{x}_2^k((-n)_N) & x_2^{k+3}(n) = \overline{x}_1^k((-n)_N) \\ x_3^{k+1}(n) = -\overline{x}_4^k((-n)_N) & x_4^{k+1}(n) = \overline{x}_3^k((-n)_N) \\ x_3^{k+2}(n) = -x_3^k(n) & x_4^{k+2}(n) = -x_4^k(n) \\ x_3^{k+3}(n) = \overline{x}_4^k((-n)_N) & x_4^{k+3}(n) = -\overline{x}_3^k((-n)_N) \end{array} \quad (3)$$

where $n = 0,1,..., N-1,$ N is the block length of modulated symbols; $k = 0,...,4,$ $\overline{(.)}$ and $(.)_N$ denote complex conjugation and modulo N operations, respectively. The CP (Cyclic Prefix) is added to the encoded data blocks to combat the interference between data blocks (i.e., IBI). To maintain constant total transmit power, the transmit power of each antenna is assumed to be 1/4 of single antenna. The received signals can be represented as

$$y^j = \sum_{i=1}^{4} H_i^j x_i^j + n^j,\ j = k, k+1, ..., k+3 \tag{4}$$

where H_i^j is a circulant matrix whose first column equals to the channel impulse response (CIR) appended by $N-L-1$ zeros (L is the time dispersion length), and it is assumed that the circulant matrix remains constant in four consecutive time slots. Since H_i^j is a circulant matrix, it has eigen-decomposition as $H_i^j = \bar{Q}\Lambda_i^j Q$, where $\overline{(.)}$ is a conjugate transpose matrix, $Q(l,k) = 1/\sqrt{N} e^{-j2\pi/Nlk}$, $0 \le l, k \le N-1$; Λ_i^j is a diagonal matrix, and $\Lambda_i^j(k,k)$ is the kth N-point DFT coefficient of the channel impulse response. Then, the N-point DFT is performed to the received signal $y^{(j)}$

$$Y^{(j)} = Qy^{(j)} = \sum_{i=1}^{4} \Lambda_i^j X_i^j + N^j \tag{5}$$

where $X_i^{(j)} = Qx_i^{(j)}, N^{(j)} = Qn^{(j)}$.

$$Y_a^k = Y^k + Y^{k+2} = 2\Lambda_1 X_1^k + 2\Lambda_2 X_2^k + N^k \tag{6}$$

$$Y_a^{k+1} = Y^{k+1} + Y^{k+3} = 2\Lambda_2 \bar{X}_1^k - 2\Lambda_1 \bar{X}_2^k + N^{k+1} \tag{7}$$

$$Y_b^k = Y^k - Y^{k+2} = 2\Lambda_3 X_3^k + 2\Lambda_4 X_4^k + N'^k \tag{8}$$

$$Y_b^{k+1} = Y^{k+1} - Y^{k+3} = 2\Lambda_4 X_3^k - 2\Lambda_3 X_4^k + N'^{k+1} \tag{9}$$

By taking the conjugate transformation to Y_a^{k+1} and Y_b^{k+1}, we get:

$$Y_a = \begin{bmatrix} Y_a^k \\ \bar{Y}_a^{k+1} \end{bmatrix} = 2\begin{bmatrix} \Lambda_1 & \Lambda_2 \\ \bar{\Lambda}_2 & -\bar{\Lambda}_1 \end{bmatrix}\begin{bmatrix} X_1^k \\ X_2^k \end{bmatrix} + \begin{bmatrix} N^k \\ \bar{N}^{k+1} \end{bmatrix} = 2\Lambda_a X_i + N', i = 1, 2 \tag{10}$$

$$Y_b = \begin{bmatrix} Y_b^k \\ \bar{Y}_b^{k+1} \end{bmatrix} = 2\begin{bmatrix} \Lambda_3 & \Lambda_4 \\ \bar{\Lambda}_4 & -\bar{\Lambda}_3 \end{bmatrix}\begin{bmatrix} X_3^k \\ X_4^k \end{bmatrix} + \begin{bmatrix} N'^k \\ \bar{N}'^{k+1} \end{bmatrix} = 2\Lambda_b X_i + N'', i = 3, 4 \tag{11}$$

where

$$\Lambda_a = \begin{bmatrix} \Lambda_1 & \Lambda_2 \\ \bar{\Lambda}_2 & -\bar{\Lambda}_1 \end{bmatrix},\ \Lambda_b = \begin{bmatrix} \Lambda_3 & \Lambda_4 \\ \bar{\Lambda}_4 & -\bar{\Lambda}_3 \end{bmatrix}$$

are orthogonal matrices, The left side of (10) and (11) can be multiplied with $\bar{\Lambda}_a$ and $\bar{\Lambda}_b$ to decouple the signals in Y_a and Y_b, and then they become

$$\tilde{Y}_a = 2\begin{bmatrix} \tilde{\Lambda}_a & 0 \\ 0 & \tilde{\Lambda}_a \end{bmatrix}\begin{bmatrix} X_1^k \\ X_2^k \end{bmatrix} + \tilde{N}' \tag{12}$$

$$\tilde{Y}_b = 2\begin{bmatrix} \tilde{\Lambda}_b & 0 \\ 0 & \tilde{\Lambda}_b \end{bmatrix}\begin{bmatrix} X_3^k \\ X_4^k \end{bmatrix} + \tilde{N}'' \tag{13}$$

where $\tilde{\Lambda}_a = |\Lambda_1|^2 + |\Lambda_2|^2$ and $\tilde{\Lambda}_b = |\Lambda_3|^2 + |\Lambda_4|^2$ are both diagonal matrices of $N \times N$. After decoding, MMSE-FDE is performed at the equalizer. The equalizer coefficients for Eq. (12) and Eq. (13) are equal to $1/(2\tilde{\Lambda}_a(i,i) + 1/SNR)$ and $1/(2\tilde{\Lambda}_b(i,i) + 1/SNR)$, respectively, where $0 \le i \le N-1, SNR = \sigma_x^2/\sigma_n^2$.

III. SC-FDE Transmission with QOSTBC and Givens Rotation

To improve the performance of QOSTBC for SC-FDE transmission, we propose to extend the QOSTBC with Givens rotation for such a system. According to [10], the coding matrix and the equivalent channel matrix of three transmit antennas and four transmit antennas after Givens rotation matrix in flat fading channel are given as follows,

$$\hat{X}_4 = \begin{bmatrix} x_1 + x_3 & x_2 + x_4 & x_3 - x_1 & x_4 - x_2 \\ -\bar{x}_2 - \bar{x}_4 & \bar{x}_1 + \bar{x}_3 & \bar{x}_2 - \bar{x}_4 & \bar{x}_3 - \bar{x}_1 \\ x_3 - x_1 & x_4 - x_2 & x_1 + x_3 & x_2 + x_4 \\ \bar{x}_2 - \bar{x}_4 & \bar{x}_3 - \bar{x}_1 & -\bar{x}_2 - \bar{x}_4 & \bar{x}_1 + \bar{x}_3 \end{bmatrix}$$

$$\hat{H}_4 = \begin{bmatrix} h_1 - h_3 & h_2 - h_4 & h_1 + h_3 & h_2 + h_4 \\ \bar{h}_2 - \bar{h}_4 & \bar{h}_3 - \bar{h}_1 & \bar{h}_2 + \bar{h}_4 & -\bar{h}_1 - \bar{h}_3 \\ h_3 - h_1 & h_4 - h_2 & h_1 + h_3 & h_2 + h_4 \\ \bar{h}_4 - \bar{h}_2 & \bar{h}_1 - \bar{h}_3 & \bar{h}_2 + \bar{h}_4 & -\bar{h}_1 - \bar{h}_3 \end{bmatrix} \tag{14}$$

$$\hat{X}_3 = \begin{bmatrix} x_1 + x_3 & x_2 + x_4 & x_3 - x_1 \\ -\bar{x}_2 - \bar{x}_4 & \bar{x}_1 + \bar{x}_3 & \bar{x}_2 - \bar{x}_4 \\ x_3 - x_1 & x_4 - x_2 & x_1 + x_3 \\ \bar{x}_2 - \bar{x}_4 & \bar{x}_3 - \bar{x}_1 & -\bar{x}_2 - \bar{x}_4 \end{bmatrix}$$

$$\hat{H}_3 = \begin{bmatrix} h_1 - h_3 & h_2 & h_1 + h_3 & h_2 \\ \bar{h}_2 & \bar{h}_3 - \bar{h}_1 & \bar{h}_2 & -\bar{h}_1 - \bar{h}_3 \\ h_3 - h_1 & -h_2 & h_1 + h_3 & h_2 \\ -\bar{h}_2 & \bar{h}_1 - \bar{h}_3 & \bar{h}_2 & -\bar{h}_1 - \bar{h}_3 \end{bmatrix} \tag{15}$$

The Givens rotation is given by $G = G_1 G_2$. The matrices G_1 and G_2 are given as follows,

$$G_2 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\pi/4) & 0 & \sin(\pi/4) \\ 0 & 0 & 1 & 0 \\ 0 & -\sin(\pi/4) & 0 & \cos(\pi/4) \end{bmatrix},$$

$$G_1 = \begin{bmatrix} \cos(\pi/4) & 0 & \sin(\pi/4) & 0 \\ 0 & 1 & 0 & 0 \\ -\sin(\pi/4) & 0 & \cos(\pi/4) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{16}$$

For using Givens rotation with QOSTBC for the SC-FDE transmission in frequency-selective fading channels, we derive the encoding and decoding methods for three transmission antennas and four transmission antennas.

Fig. 2 shows the block format for SC-FDE transmission using QOSTBC with Givens rotation for four antennas at the transmitter. Fig. 3 shows our designed block diagram of SC-FDE transmission using QOSTBC with Givens rotation at the receiver .

As we have mentioned, when using STBC for SC-FDE transmission in frequency selective fading channels, the STBC encoding should be based on blocks of modulated symbols instead of symbols in flat fading channels, and the STBC decoding should be performed in frequency domain before FDE. Hence, in order to use QOSTBC and Givens rotation for the SC-FDE transmission in frequency selective fading channels, we must modify the encoding method based on block of symbols. Furthermore, the encoding scheme should lead to linear decoding in the frequency domain at receiver as Alamouti coding does in time domain. For this purpose, we must change the encoding according to the properties of DFT.

Denote the n-th symbol of k-th transmitted block from antenna i by $s_i^k(n)$. After derivation, the encoding method of four transmission antennas for QOSTBC with Givens rotation to be used in the SC-FDE transmission are expressed as

$$\begin{aligned}
&s_1^k(n) = x_1^k(n) + x_3^k(n)\\
&s_1^{k+1}(n) = -\bar{x}_2^k((-n)_N) - \bar{x}_4^k((-n)_N)\\
&s_1^{k+2}(n) = -x_3^k(n) - x_1^k(n)\\
&s_1^{k+3}(n) = \bar{x}_2^k((-n)_N) - \bar{x}_4^k((-n)_N)\\
&s_2^k(n) = x_2^k(n) + x_4^k(n)\\
&s_2^{k+1}(n) = \bar{x}_1^k((-n)_N) + \bar{x}_3^k((-n)_N)\\
&s_2^{k+2}(n) = x_4^k(n) - x_2^k(n)\\
&s_2^{k+3}(n) = \bar{x}_3^k((-n)_N) - \bar{x}_1^k((-n)_N)\\
&s_3^k(n) = x_3^k(n) - x_1^k(n)\\
&s_3^{k+1}(n) = \bar{x}_2^k((-n)_N) - \bar{x}_4^k((-n)_N)\\
&s_3^{k+2}(n) = x_1^k(n) + x_3^k(n)\\
&s_3^{k+3}(n) = -\bar{x}_2^k((-n)_N) - \bar{x}_4^k((-n)_N)\\
&s_4^k(n) = x_4^k(n) - x_2^k(n)\\
&s_4^{k+1}(n) = \bar{x}_3^k((-n)_N) - \bar{x}_1^k((-n)_N)\\
&s_4^{k+2}(n) = x_2^k(n) + x_4^k(n)\\
&s_4^{k+3}(n) = \bar{x}_1^k((-n)_N) + \bar{x}_3^k((-n)_N)
\end{aligned} \tag{17}$$

During the derivation of (17), the encoding of the first antenna for $n = 0,1,\cdots,N-1$ is as follows,

$$\begin{aligned}
&s_1^k(n) = x_1^k(n) + x_3^k(n)\\
&s_1^{k+1}(n) = -\bar{x}_2^k((-n)_N) - \bar{x}_4^k((-n)_N)\\
&s_1^{k+2}(n) = -x_3^k(n) - x_1^k(n)\\
&s_1^{k+3}(n) = \bar{x}_2^k((-n)_N) - \bar{x}_4^k((-n)_N)
\end{aligned} \tag{18}$$

After the DFT transform, the signals in frequency domain for $n = 0,1,\cdots,N-1$ become

$$\begin{aligned}
&S_1^k(m) = X_1^k(m) + X_3^k(m)\\
&S_1^{k+1}(m) = -\bar{X}_2^k(m) - \bar{X}_4^k(m)\\
&S_1^{k+2}(m) = -X_3^k(m) - X_1^k(m)\\
&S_1^{k+3}(m) = \bar{X}_2^k(m) - \bar{X}_4^k(m)
\end{aligned} \tag{19}$$

The blocks of symbol of other antennas at the transmitter take the similar steps. By DFT transform, the receiver signals are decoded in the frequency domain. Compared with the symbols-based decoding scheme for flat fading channels in [10], it can be found that one block of symbols in the frequency domain here corresponds to one symbol in [10] at receiver. Therefore, the decoding scheme based on symbols in [10] can be applied to our proposed scheme, though it is based on block of symbols.

Similarly, the encoding method of three transmission antennas for QOSTBC with Givens rotation to be used in the SC-FDE transmission can be derived as

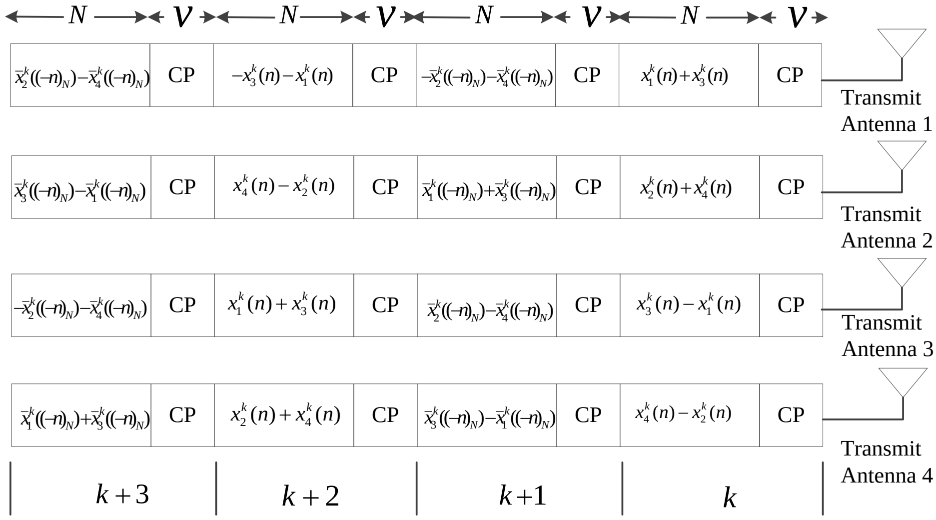

Fig. 2. Block format of SC-FDE transmission using QOSTBC with Givens rotation for 4 antennas at transmitter

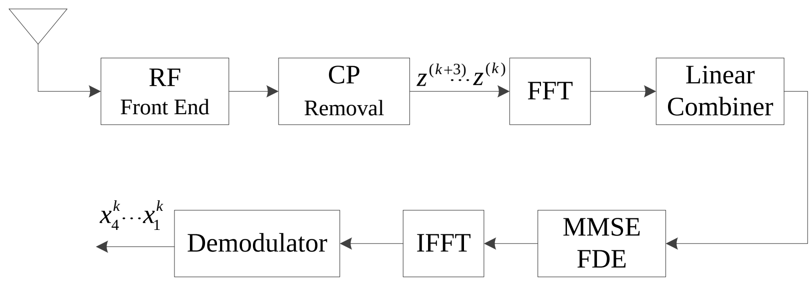

Fig. 3. Block diagram of SC-FDE transmission using QOSTBC with Givens rotation at receiver

$$
\begin{aligned}
s_1^k(n) &= x_1^k(n) + x_3^k(n) \\
s_1^{k+1}(n) &= -\bar{x}_2^k((-n)_N) - \bar{x}_4^k((-n)_N) \\
s_1^{k+2}(n) &= -x_3^k(n) - x_1^k(n) \\
s_1^{k+3}(n) &= \bar{x}_2^k((-n)_N) - \bar{x}_4^k((-n)_N) \\
s_2^k(n) &= x_2^k(n) + x_4^k(n) \\
s_2^{k+1}(n) &= \bar{x}_1^k((-n)_N) + \bar{x}_3^k((-n)_N) \\
s_2^{k+2}(n) &= x_4^k(n) - x_2^k(n) \\
s_2^{k+3}(n) &= \bar{x}_3^k((-n)_N) - \bar{x}_1^k((-n)_N) \\
s_3^k(n) &= x_3^k(n) - x_1^k(n) \\
s_3^{k+1}(n) &= \bar{x}_2^k((-n)_N) - \bar{x}_4^k((-n)_N) \\
s_3^{k+2}(n) &= x_1^k(n) + x_3^k(n) \\
s_3^{k+3}(n) &= -\bar{x}_2^k((-n)_N) - \bar{x}_4^k((-n)_N)
\end{aligned}
\tag{20}
$$

To maintain constant total transmit power, the transmit power of each antenna is assumed to be 1/4 for four transmitting antennas and 1/3 for three transmitting antennas of single antenna. The received signals for four transmitting antennas can be expressed as

$$z^j = \sum_{i=1}^{4} H_i^j s_i^j + n^j,\ j = k, k+1, ..., k+3 \tag{21}$$

For three transmission antennas, the receiver signal is expressed as

$$z^j = \sum_{i=1}^{3} H_i^j s_i^j + n^j,\ j = k, k+1, ..., k+3 \tag{22}$$

where H_i^j is a cyclic channel matrix.

Then, by using eigen-decomposition of H_i^j, applying the DFT to z^j, and taking conjugation of the receive data block of the second slot and the fourth slot, we obtain the data at four transmission antennas as

$$
\begin{aligned}
Z &= \begin{bmatrix} Z^{(k)} & Z^{(k+1)} & Z^{(k+2)} & Z^{(k+3)} \end{bmatrix}^T \\
&= \begin{bmatrix} \Lambda_1 - \Lambda_3 & \Lambda_2 - \Lambda_4 & \Lambda_3 + \Lambda_1 & \Lambda_4 + \Lambda_2 \\ \bar{\Lambda}_2 - \bar{\Lambda}_4 & \bar{\Lambda}_3 - \bar{\Lambda}_1 & \bar{\Lambda}_2 + \bar{\Lambda}_4 & -\bar{\Lambda}_1 - \bar{\Lambda}_3 \\ \Lambda_3 - \Lambda_1 & \Lambda_4 - \Lambda_2 & \Lambda_1 + \Lambda_3 & \Lambda_4 + \Lambda_2 \\ \bar{\Lambda}_4 - \bar{\Lambda}_2 & \bar{\Lambda}_1 - \bar{\Lambda}_3 & \bar{\Lambda}_2 + \bar{\Lambda}_4 & -\bar{\Lambda}_1 - \bar{\Lambda}_3 \end{bmatrix} \begin{bmatrix} X_1^{(k)} \\ X_2^{(k)} \\ X_3^{(k)} \\ X_4^{(k)} \end{bmatrix} + \\
&\quad \begin{bmatrix} N^{(k)} & N^{(k+1)} & N^{(k+2)} & N^{(k+3)} \end{bmatrix}^T = \hat{\Lambda} X + N
\end{aligned}
\tag{23}
$$

and obtain the data at three transmission antennas as

$$
\begin{aligned}
Z &= \begin{bmatrix} Z^{(k)} & Z^{(k+1)} & Z^{(k+2)} & Z^{(k+3)} \end{bmatrix}^T \\
&= \begin{bmatrix} \Lambda_1 - \Lambda_3 & \Lambda_2 & \Lambda_3 + \Lambda_1 & \Lambda_2 \\ \bar{\Lambda}_2 & \bar{\Lambda}_3 - \bar{\Lambda}_1 & \bar{\Lambda}_2 & -\bar{\Lambda}_1 - \bar{\Lambda}_3 \\ \Lambda_3 - \Lambda_1 & -\Lambda_2 & \Lambda_1 + \Lambda_3 & \Lambda_2 \\ -\bar{\Lambda}_2 & \bar{\Lambda}_1 - \bar{\Lambda}_3 & \bar{\Lambda}_2 & -\bar{\Lambda}_1 - \bar{\Lambda}_3 \end{bmatrix} \begin{bmatrix} X_1^{(k)} \\ X_2^{(k)} \\ X_3^{(k)} \\ X_4^{(k)} \end{bmatrix} + \\
&\quad \begin{bmatrix} N^{(k)} & N^{(k+1)} & N^{(k+2)} & N^{(k+3)} \end{bmatrix}^T = \hat{\Lambda} X + N
\end{aligned}
\tag{24}
$$

where the channel equivalent matrix $\hat{\Lambda}$ becomes an orthogonal matrix. Then, we can multiply the left side of Eq.(23) and Eq.(24) by $\hat{\Lambda}$ to decouple the four signals as

$$\tilde{Z} = \begin{bmatrix} \tilde{Z}^{(k)} \\ \tilde{Z}^{(k+1)} \\ \tilde{Z}^{(k+2)} \\ \tilde{Z}^{(k+3)} \end{bmatrix} = \hat{\Lambda}^h Z = \begin{bmatrix} \alpha - \beta & 0 & 0 & 0 \\ 0 & \alpha - \beta & 0 & 0 \\ 0 & 0 & \alpha + \beta & 0 \\ 0 & 0 & 0 & \alpha + \beta \end{bmatrix} \begin{bmatrix} X_1^k \\ X_2^k \\ X_3^k \\ X_4^k \end{bmatrix} + \tilde{N} \tag{25}$$

where $\alpha - \beta$ and $\alpha + \beta$ are diagonal matrices.

For four transmit antennas,

$$
\begin{aligned}
A &= \alpha - \beta = 2\left(\sum_{i=1}^{4} |\Lambda_i|^2 - (\Lambda_1 \bar{\Lambda}_2 + \Lambda_2 \bar{\Lambda}_4 + \bar{\Lambda}_1 \Lambda_3 + \bar{\Lambda}_2 \Lambda_4) \right), \\
B &= \alpha + \beta = 2\left(\sum_{i=1}^{4} |\Lambda_i|^2 + (\Lambda_1 \bar{\Lambda}_2 + \Lambda_2 \bar{\Lambda}_4 + \bar{\Lambda}_1 \Lambda_3 + \bar{\Lambda}_2 \Lambda_4) \right)
\end{aligned}
\tag{26}
$$

For three transmit antennas,

$$
\begin{aligned}
A &= \alpha - \beta = 2\left(\sum_{i=1}^{3} |\Lambda_i|^2 - (\bar{\Lambda}_1 \Lambda_3 + \Lambda_1 \bar{\Lambda}_3) \right), \\
B &= \alpha + \beta = 2\left(\sum_{i=1}^{3} |\Lambda_i|^2 + (\bar{\Lambda}_1 \Lambda_3 + \Lambda_1 \bar{\Lambda}_3) \right)
\end{aligned}
\tag{27}
$$

Thus, the STBC decoding can be performed with a linear combiner with our proposed scheme. After the STBC decoding, the output data blocks are separated from each other, and MMSE (Minimum Mean Square Error) FDE can be performed on them separately as well. Actually, it can be easily shown that the *i*th coefficient of the MMSE-FDE for $\tilde{Z}^{(k)}$ and $\tilde{Z}^{(k+1)}$ is $1/(A(i,i) + 1/SNR)$, and the *i*th coefficient of the MMSE-FDE for $\tilde{Z}^{(k+3)}$ and $\tilde{Z}^{(k+4)}$ is $1/(B(i,i) + 1/SNR)$, where $SNR = \sigma_x^2 / \sigma_n^2$.

IV. Simulation and Analysis

In this section, we investigate the performance of the proposed SC-FDE transmission scheme by computer simulation. The symbol duration is set to 100 ns, and one data block contains 128 symbols. The BPSK modulation is used for the conventional QOSTBC scheme in [7] with four transmission antennas, and used for QOSTBC with Givens rotation for three and four transmission antennas. QPSK is used for half rate OSTBC with three and four transmission antennas. Hence, the spectrum efficiency for all compared cases after modulation and encoding is 1 bit/s/Hz. In addition, ideal synchronization and channel estimation at receiver are assumed. The parameters of the simulated frequency selective fading channel are given in Table I.

Table I: Frequency Selective fading Channel Parameters

Number of paths	Propagation delay(ns)	Path to power(dB)
0	0	0
1	200	-2
2	300	-6
3	400	-20

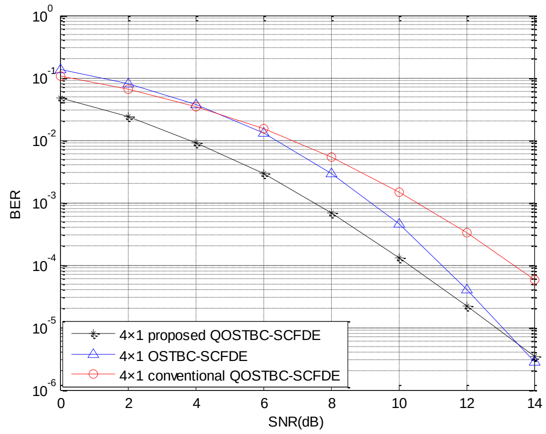

Fig. 4. BER performance of proposed and conventional schemes for SC-FDE system with 4×1 antennas

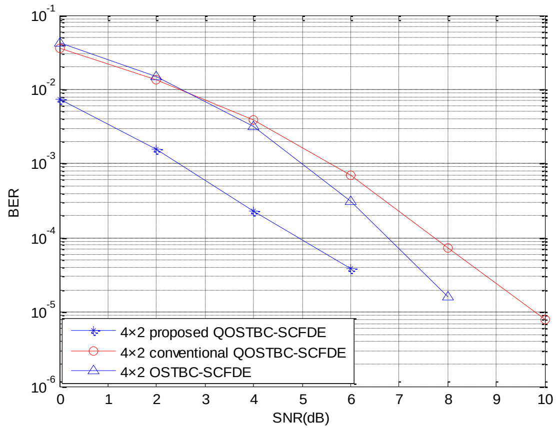

Fig. 5. BER performance of proposed and conventional schemes for SC-FDE system with 4×2 antennas

Fig. 4 show the BER performance of SC-FDE system with four transmit antennas and one receiving antenna, and Fig. 5 show the BER performance of SC-FDE system with four transmit antennas and two receiving antennas. It can be seen that the BER performance of QOSTBC with Givens rotation has significant improvement compared with the conventional QOSTBC scheme in [7] in frequency selective fading channel. From Figure 4, it is seen that the BER performance improves nearly 4dB when BER is equal to 10^{-4} comparing with QOSTBC. The BER performance is better than OSTBC until the SNR is 13dB. Note that the QOSTBC with Givens rotation can achieve rate one transmission, and OSTBC can only reach 1/2 rate.

The reasons that our proposed scheme is better than the conventional QOSTBC in [7] are analyzed as follows. For four transmit antennas in [7], the received signals are processed with (6),(7),(8),(9), and then can be divided into two groups with (10) and (11). The two signals in each group can be decoded separately according to the method similar to the Alamouti decoding. It decodes the received signals in groups and is not jointly decoded for all the received signals in four slots from four transmit antennas. The method proposed in this paper eliminates the correlation of channel equivalent matrix through the Givens rotation in the transmitter, and the received signals in four slots from four transmit antennas can be jointly decoded all together in the receiver. Hence, it has higher diversity gain than the conventional QOSTBC scheme in [7].

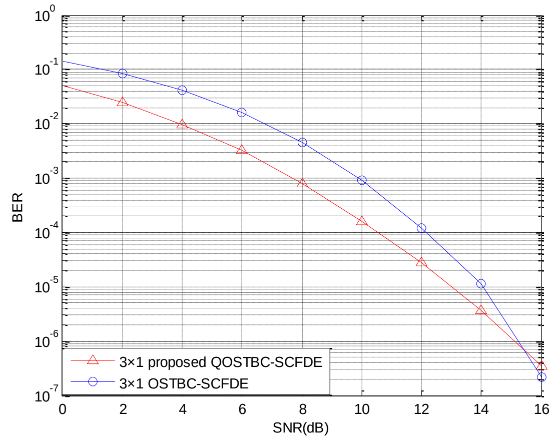

Fig. 6. BER performance of proposed and conventional schemes for SC-FDE system with 3×1 antennas

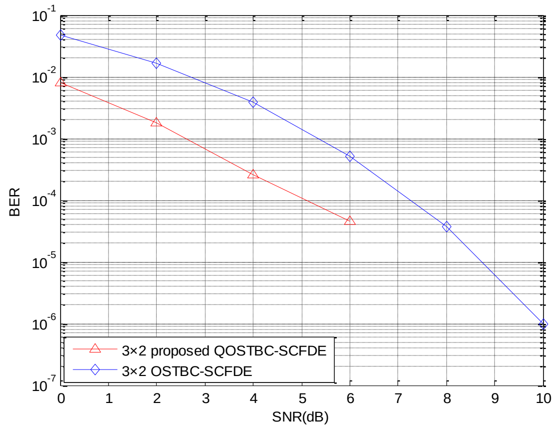

Fig. 7. BER performance of proposed and conventional schemes for SC-FDE system with 3×2 antennas

Fig. 6 show the BER performance of SC-FDE system with three transmit antennas and one receiving antenna, and Fig. 7 show the BER performance of SC-FDE system with three transmit antennas and two receiving antennas. From Fig. 6, it is seen that the BER performance improves nearly 2dB when BER is equal to 10^{-4} comparing with OSTBC, and the BER performance is better than OSTBC until the SNR is 15dB.

V. CONCLUSIONS

The conventional QOSTBC achieves full-rate transmission at the expense of lower diversity gain. The QOSTBC with Givens rotation can eliminate the correlation of channel matrix, and the QOSTBC can then be linearly decoded at the receiver. It can provide full rate transmission with high diversity gain by achieving the performance of ML decoding with reduced decoding complexity. To be used with SC-FDE transmission in frequency-selective fading channels, the encoding and decoding methods of QOSTBC with Givens rotation are designed based on block of symbols in this paper. The simplified decoding of QOSTBC can work in concert with frequency domain equalization at the receiver. The simulation results show that the BER performance of our proposed scheme is improved for more than two transmit antennas. The work in this paper helps to promote the multi-antenna STBC applications in the engineering practice.

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