Robust Frequency-Domain Equalization Against Doubly Selective Fading for Single-Carrier STBC Time-Division Duplex Transmission

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Abstract— **Single-carrier (SC) space-time block coded (STBC) time-division duplex (TDD) transmission achieves a good bit-error rate (BER) performance while the channel state information (CSI) is not required at the mobile terminal (MT). However, in a high mobility environment, the channel changes within a STBC codeword and the BER performance significantly degrades due to the interference caused by the orthogonality distortion of STBC codeword. In this paper, we propose a multi-block (MB)-frequency-domain equalization (FDE) for SC-STBC-TDD transmission in a high mobility environment. The STBC codeword consists of multiple signal blocks. The proposed MB-FDE uses jointly optimized multiple FDE weight matrices, each associated with each signal block in a STBC codeword. We evaluate, by computer simulation, the BER performance when using the proposed transmit/receive MB-FDE and show that the proposed MB-FDE achieves a good BER performance in a high mobility environment.**

Keywords-component; Space-time block coding, frequency-domain equalization, single-carrier transmission

I. INTRODUCTION

The bit error rate (BER) performance of broadband single-carrier (SC) transmissions significantly degrades due to the inter-symbol interference (ISI) caused by the frequency-selective fading [1]. The minimum mean square error (MMSE) based frequency-domain equalization (FDE) can take advantage of channel frequency-selectivity and obtain large frequency diversity gain [2-4]. Space-time block coding (STBC) transmit diversity [5-10] is also an effective scheme to improve the BER performance. There are two types of STBC transmit diversity: space-time transmit diversity (STTD) [6] and space-time block coded joint transmit/receive diversity (STBC-JTRD) [7]. The STBC-JTRD requires the channel state information (CSI) at the transmitter while the STTD requires it at the receiver.

Recently, we proposed SC-STBC time-division duplex (TDD) transmission system [8], in which the frequency-domain (FD)-STTD [9] and FD-STBC-JTRD [10] are used for the uplink and downlink transmissions, respectively. Only the base station (BS) requires the CSI and the complexity problem of mobile terminal (MT) can be alleviated. Since the same frequency is used in TDD for the uplink and downlink, the CSI estimate for the uplink FD-STTD reception can be reused for the downlink FD-STBC-JTRD transmission. As a consequence, no CSI feedback is required between MT and BS.

In the next generation wireless communications, broadband data services are demanded even in a high mobility environment. When the channel varies within a STBC codeword, the BER performance significantly degrades due to the interference caused by the orthogonality distortion of the STBC codeword [11]. To remedy this performance degradation, the iterative interference cancellation was proposed [12,13]. However, the above technique requires a high computational complexity and the CSI at the receiver, and hence is not suitable for downlink FD-STBC-JTRD transmission.

Recently, we proposed the transmit multi-block (MB)-FDE for FD-STBC-JTRD [14]. The STBC-JTRD codeword consists of multiple signal blocks. The transmit MB-FDE uses multiple weight matrices, each associated with each signal block in a STBC codeword. The transmit MB-FDE weight matrices are designed so as to minimize the mean square error (MSE) between the transmit signal before STBC encoding and the received signal after STBC decoding. However, the past study for MB-FDE [14] assumed a quasi-static fading channel and did not take into account the channel variation within a STBC codeword. Therefore, the BER performance when using the previous MB-FDE [14] also degrades due to the interference caused by the orthogonality distortion of the STBC codeword in a high mobility environment.

In this paper, we propose a MB-FDE for SC-STBC TDD transmission system (uplink FD-STTD and downlink FD-STBC-JTRD) in a high mobility environment. The MB-FDE weight matrices (receive MB-FDE for uplink FD-STTD and transmit MB-FDE for downlink FD-STBC-JTRD), each associated with each signal block in a STBC codeword, are jointly optimized based on the MMSE criterion by taking into account the channel variation within a STBC codeword. We evaluate, by computer simulation, the BER performance when using the proposed MB-FDE and show that the proposed MB-FDE achieves a good BER performance in a high mobility environment.

The remainder of this paper is organized as follows. The SC-STBC TDD transmission system is introduced in Sect. II. Sect. III derives the MB-FDE weight matrices. Sect. IV discusses the computer simulation results, and Sect. V offers conclusions.

II. SC-STBC TDD TRANSMISSION SYSTEM

In this paper, we consider SC-STBC TDD transmission system. We assume that BS equips with N_{BS} antennas and MT has N_{MT} antennas, respectively. Fig. 1 illustrates the frame structure considered in this paper. Fig. 2 and 3 show the transmitter/receiver structures. In SC-STBC TDD transmission system, both channel estimation and FDE are performed at BS in order to make MT structure simple and eliminate CSI feedback. The uplink transmission frame consists of N_B STBC encoded data blocks and 2 pilot blocks and the downlink transmission frame consists of N_B STBC encoded data blocks, respectively. For uplink transmission, MT transmits the uplink transmission frame to BS. After estimating CSI at the uplink transmission frame, BS detects the uplink data signal by applying the receive MB-FDE and STBC decoding. Then, BS estimates CSI at the downlink transmission frame. After STBC encoding and the transmit MB-FDE, BS transmits the downlink transmission frame to MT.

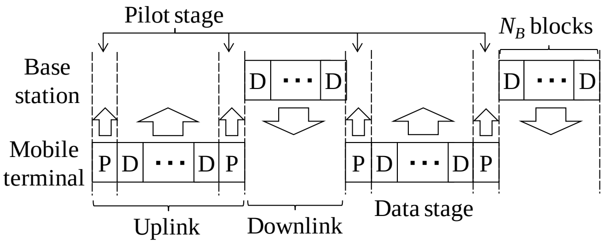
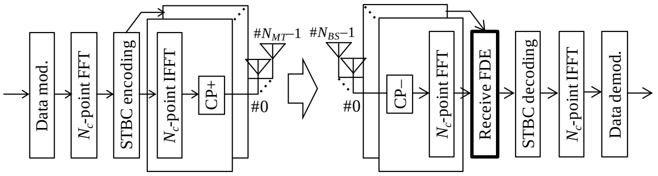
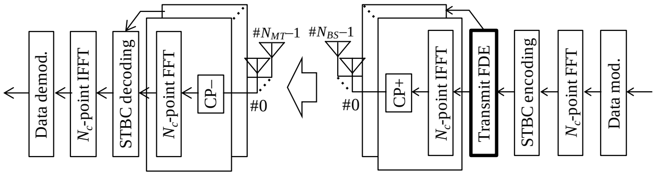


Fig. 1. Frame structure



(a) Mobile terminal (b) Base station

Fig. 2. Uplink transmitter/receiver structure



(a) Mobile terminal (b) Base station

Fig. 3. Downlink transmitter/receiver structure

A. *Uplink FD-STTD transmission*

In the uplink transmission, FD-STTD is performed. At the MT transmitter, the $J\times N_c$ data modulated symbols are divided into the a sequence of J block of N_c symbol each. The J transmit signal blocks are transformed into the frequency-domain signal by the N_c-point fast Fourier transform (FFT). A sequence of J frequency-domain signals are encoded into N_{MT} streams of Q STBC coded frequency-domain single blocks each. Denoting the frequency-domain transmit signal block as $\{D_{U,j}(k);k=0,\ldots,N_c-1,\ j=0,\ldots,J-1\}$, The STBC coded frequency-domain transmit signal block $\{X_{U,q}(n_{MT},k);k=0,\ldots,N_c\text{-}1,\ n_{MT}=0,\ldots,N_{MT}-1,\ q=0,\ldots,Q-1\}$ can be expressed as

$$\begin{pmatrix}\mathbf{X}_{U,0}^T(k)\\ \mathbf{X}_{U,1}^T(k)\end{pmatrix}=\begin{pmatrix}D_{U,0}(k) & D_{U,1}(k)\\ -D_{U,1}^*(k) & D_{U,0}^*(k)\end{pmatrix}\quad \text{... for } N_{MT}\text{=2, (1a)}$$

$$\begin{pmatrix}\mathbf{X}_{U,0}^T(k)\\ \mathbf{X}_{U,1}^T(k)\\ \mathbf{X}_{U,2}^T(k)\\ \mathbf{X}_{U,3}^T(k)\end{pmatrix}=\begin{pmatrix}D_{U,0}(k) & D_{U,1}(k) & D_{U,2}(k)\\ -D_{U,1}^*(k) & D_{U,0}^*(k) & 0\\ -D_{U,2}^*(k) & 0 & D_{U,0}^*(k)\\ 0 & D_{U,2}(k) & -D_{U,1}(k)\end{pmatrix}\quad \text{... for } N_{MT}\text{=3, (1b)}$$

$$\begin{pmatrix}\mathbf{X}_{U,0}^T(k)\\ \mathbf{X}_{U,1}^T(k)\\ \mathbf{X}_{U,2}^T(k)\\ \mathbf{X}_{U,3}^T(k)\end{pmatrix}=\begin{pmatrix}D_{U,0}(k) & D_{U,1}(k) & D_{U,2}(k) & 0\\ -D_{U,1}^*(k) & D_{U,0}^*(k) & 0 & D_{U,2}(k)\\ -D_{U,2}^*(k) & 0 & D_{U,0}^*(k) & D_{U,1}^*(k)\\ 0 & D_{U,2}(k) & -D_{U,1}(k) & D_{U,0}(k)\end{pmatrix}$$

... for N_{MT}=4, (1c)

where $\mathbf{X}_q(k)=[X_q(0,k),\ldots,X_q(N_{MT}-1,k)]^T$ is the qth STBC coded block vector. In FD-STTD, the STBC coding rate J/Q is determined by the number of the transmitter antennas, (i. e. the number of MT antennas) [9]. As understood from (1), the conjugate operations is only required and no CSI is required at the MT transmitter. The frequency-domain STBC codeword is transformed back to the time-domain STBC codeword by applying N_c-point inverse FFT (IFFT). After insertion of cyclic prefix (CP) into the beginning the each block, the STBC codeword is transmitted to BS in Q time-slot.

At the BS receiver, a super position of N_{MT} transmitted signal is received by N_{BS} antennas. After CP removal, the received signal is transformed into the frequency-domain signal by N_c-point FFT. The frequency-domain received signal, $\{R_{U,q}(n_{BS},k);\ k=0,\ldots,N_c\text{-}1,\ n_{BS}=0,\ldots,N_{BS}-1\}$ in the qth time-slot is expressed as

$$\mathbf{R}_{U,q}(k)=\sqrt{\frac{2P_t}{N_{MT}\cdot(J/Q)}}\mathbf{H}_{U,q}(k)\mathbf{X}_{U,q}(k)+\mathbf{N}_{U,q}(k),\qquad (2)$$

where $\mathbf{R}_{U,q}(k)=[R_{U,q}(0,k),\ldots,R_{U,q}(N_{BS}-1,k)]^T$ is the frequency-domain received signal vector in the qth time-slot. $\mathbf{H}_{U,q}(k)=[\mathbf{H}_{U,q}(0,k),\ldots,\mathbf{H}_{U,q}(N_{MT}-1,k)]$ with $\mathbf{H}_{U,q}(n_{MT},k)=[H_{U,q}(n_{MT},0,k),\ldots,H_{U,q}(n_{MT},N_{BS}-1,k)]^T$ is the $N_{BS}\times N_{MT}$ channel transfer function matrix in the qth time-slot. P_t denotes the transmit power. $\mathbf{N}_{U,q}(k)=[N_{U,q}(0,k),\ldots,N_{U,q}(N_{BS}-1,k)]^T$ is the noise vector and $N_{U,q}(n_{BS},k)$ is the zero mean complex valued additive white Gaussian noise (AWGN) having variance $2N_0/T_s$ with N_0 and T_s being the single-sided power spectrum density of AWGN and the symbol duration, respectively. BS performs the receive MB-FDE to the received STBC codeword. The qth received signal vector, $\hat{\mathbf{R}}_{U,q}(k)=[\hat{R}_{U,q}(0,k),\ldots,\hat{R}_{U,q}(N_{MT}-1,k)]^T$, after the receive MB-FDE is given as

$$\hat{\mathbf{R}}_{U,q}(k)=\mathbf{W}_{U,q}(k)\mathbf{R}_{U,q}(k),\qquad (3)$$

where $\mathbf{W}_{U,q}(k)=[\ \mathbf{W}_{U,q}^T(0,k),\ldots,\mathbf{W}_{U,q}^T(N_{MT}-1,k)\ ]^T$ with $\mathbf{W}_{U,q}(n_{MT},k)=[W_{U,q}(0,n_{MT},k),\ldots,W_{U,q}(N_{BS}-1,n_{MT},k)]$ is the $N_{MT}\times N_{BS}$ receive MB-FDE weight matrix for the qth STBC coded block vector. After the receive MB-FDE, The STBC decoding is performed to obtain the STBC decoded frequency-domain signal. The STBC decoded frequency-domain signal $\{\hat{D}_{U,j}(k);\, k=0,\ldots,N_c-1,\, j=0,\ldots,J-1\}$ as

$$\begin{pmatrix}\hat{D}_{U,0}(k)\\ \hat{D}_{U,1}(k)\end{pmatrix}=\begin{pmatrix}\hat{R}_{U,0}(0,k)+\hat{R}^*_{U,1}(1,k)\\ \hat{R}_{U,0}(1,k)-\hat{R}^*_{U,1}(0,k)\end{pmatrix} \quad \text{... for } N_{MT}=2, \tag{4a}$$

$$\begin{pmatrix}\hat{D}_{U,0}(k)\\ \hat{D}_{U,1}(k)\\ \hat{D}_{U,2}(k)\end{pmatrix}=\begin{pmatrix}\hat{R}_{U,0}(0,k)+\hat{R}^*_{U,1}(1,k)+\hat{R}^*_{U,2}(2,k)\\ \hat{R}_{U,0}(1,k)-\hat{R}^*_{U,1}(0,k)+\hat{R}^*_{U,3}(2,k)\\ \hat{R}_{U,0}(2,k)-\hat{R}^*_{U,2}(0.k)-\hat{R}^*_{U,3}(1,k)\end{pmatrix} \quad \text{... for } N_{MT}=3, \tag{4b}$$

$$\begin{pmatrix}\hat{D}_{U,0}(k)\\ \hat{D}_{U,1}(k)\\ \hat{D}_{U,2}(k)\end{pmatrix}=\begin{pmatrix}\hat{R}_{U,0}(0,k)+\hat{R}^*_{U,1}(1,k)+\hat{R}^*_{U,2}(2,k)+\hat{R}^*_{U,3}(3,k)\\ \hat{R}_{U,0}(1,k)-\hat{R}^*_{U,1}(0,k)-\hat{R}_{U,2}(3,k)+\hat{R}^*_{U,3}(2,k)\\ \hat{R}_{U,0}(2,k)+\hat{R}_{U,1}(3,k)-\hat{R}^*_{U,2}(0.k)-\hat{R}^*_{U,3}(1,k)\end{pmatrix} \quad \text{... for } N_{MT}=4. \tag{4c}$$

The STBC decoded frequency-domain signal is transformed back to the time-domain signal by N_c-point IFFT, and finally, the data demodulation is carried out.

B. Downlink FD-STBC-JTRD transmission

In the downlink transmission, FD-STBC-JTRD is performed. At the BS transmitter, the $J\times N_c$ data modulated symbols are divided into the a sequence of J block of N_c symbol each. The J transmit signal blocks are transformed into the frequency-domain signal by the N_c-point FFT. A sequence of J frequency-domain signals are encoded into N_{MT} streams of Q STBC coded frequency-domain single blocks each. Denoting the frequency-domain transmit signal block as $\{D_{D,j}(k);k=0,\ldots,N_c-1,\, j=0,\ldots,J-1\}$, The STBC coded frequency-domain transmit signal block $\{X_{D,q}(n_{MT},k);k=0,\ldots,N_c-1,\, n_{MT}=0,\ldots,N_{MT}-1,\, q=0,\ldots,Q-1\}$ can be expressed as

$$\begin{pmatrix}\mathbf{X}^T_{D,0}(k)\\ \mathbf{X}^T_{D,1}(k)\end{pmatrix}=\begin{pmatrix}D_{D,0}(k) & D_{D,1}(k)\\ -D^*_{D,1}(k) & D^*_{D,0}(k)\end{pmatrix} \quad \text{... for } N_{MT}=2, \tag{5a}$$

$$\begin{pmatrix}\mathbf{X}^T_{D,0}(k)\\ \mathbf{X}^T_{D,1}(k)\\ \mathbf{X}^T_{D,2}(k)\\ \mathbf{X}^T_{D,3}(k)\end{pmatrix}=\begin{pmatrix}D_{D,0}(k) & D_{D,1}(k) & D_{D,2}(k)\\ -D^*_{D,1}(k) & D^*_{D,0}(k) & 0\\ -D^*_{D,2}(k) & 0 & D^*_{D,0}(k)\\ 0 & D_{D,2}(k) & -D_{D,1}(k)\end{pmatrix} \quad \text{... for } N_{MT}=3, \tag{5b}$$

$$\begin{pmatrix}\mathbf{X}^T_{D,0}(k)\\ \mathbf{X}^T_{D,1}(k)\\ \mathbf{X}^T_{D,2}(k)\\ \mathbf{X}^T_{D,3}(k)\end{pmatrix}=\begin{pmatrix}D_{D,0}(k) & D_{D,1}(k) & D_{D,2}(k) & 0\\ -D^*_{D,1}(k) & D^*_{D,0}(k) & 0 & D_{D,2}(k)\\ -D^*_{D,2}(k) & 0 & D^*_{D,0}(k) & D^*_{D,1}(k)\\ 0 & D_{D,2}(k) & -D_{D,1}(k) & D_{D,0}(k)\end{pmatrix} \quad \text{... for } N_{MT}=4, \tag{5c}$$

where $\mathbf{X}_{D,q}(k)=[X_{D,q}(0,k),\ldots,X_{D,q}(N_{MT}-1,k)]^T$ is the qth STBC coded block vector. In FD-STBC-JTRD, the STBC coding rate J/Q is determined by the number of the receiver antennas, (i. e. the number of MT antennas) [10]. After STBC encoding, the transmit MB-FDE is performed. The qth transmit signal vector, $\hat{\mathbf{X}}_{D,q}(k)=[\hat{X}_{D,q}(0,k),\ldots,\hat{X}_{D,q}(N_{BS}-1,k)]^T$, after the transmit MB-FDE is given as

$$\hat{\mathbf{X}}_{D,q}(k)=A_{N_{MT}}\mathbf{W}_{D,q}(k)\mathbf{X}_{D,q}(k), \tag{6}$$

where $\mathbf{W}_{D,q}(k)=[\mathbf{W}_{D,q}(0,k),\ldots,\mathbf{W}_{D,q}(N_{MT}-1,k)]$ with $\mathbf{W}_{D,q}(n_{MT},k)=[W_{D,q}(0,n_{MT},k),\ldots,W_{D,q}(N_{BS}-1,n_{MT},k)]^T$ is the $N_{BS}\times N_{MT}$ transmit MB-FDE weight matrix for the qth STBC coded block vector. $A_{N_{MT}}$ is the power normalization factor to keep average transmit power constant given as

$$A_{N_{MT}}=\frac{1}{\sqrt{\frac{1}{N_c}\frac{1}{Q}\sum_{q=0}^{Q-1}\sum_{n_{MT}=0}^{N_{MT}-1}\sum_{k=0}^{N_c-1}\left\|\mathbf{W}_{D,q}(n_{MT},k)\right\|^2}}\,. \tag{7}$$

The frequency-domain STBC codeword after the transmit MB-FDE is transformed back to the time-domain STBC codeword by applying N_c-point IFFT. After insertion of CP into the beginning the each block, the STBC codeword is transmitted to the receiver in Q time-slot.

At the MT receiver, a super position of N_{BS} transmitted signal is received by N_{MT} antennas. After CP removal, the received signal is transformed into the frequency-domain signal by N_c-point FFT. The frequency-domain received signal, $\{R_{D,q}(n_{MT},k);\, k=0,\ldots,N_c-1,\, n_{MT}=0,\ldots,N_{MT}-1\}$ in the qth time-slot is expressed as

$$\mathbf{R}_{D,q}(k)=\sqrt{2P_t}\mathbf{H}_{D,q}(k)\hat{\mathbf{X}}_{D,q}(k)+\mathbf{N}_{D,q}(k), \tag{8}$$

where $\mathbf{R}_{D,q}(k)=[R_{D,q}(0,k),\ldots,R_{D,q}(N_{MT}-1,k)]^T$ is the frequency-domain received signal vector in the qth time-slot. $\mathbf{H}_{D,q}(k)=\left[\mathbf{H}^T_{D,q}(0,k),\ \cdots,\ \mathbf{H}^T_{D,q}(N_{MT}-1,k)\right]^T$ with $\mathbf{H}_{D,q}(n_{MT},k)=[H_{D,q}(n_{MT},0,k),\ldots,H_{D,q}(n_{MT},N_{BS}-1,k)]$ is the $N_{MT}\times N_{BS}$ channel transfer function ,matrix in the qth time-slot. $\mathbf{N}_{D,q}(k)=[N_{D,q}(0,k),\ldots,N_{D,q}(N_{MT}-1,k)]^T$ is the noise vector and $n_{D,q}(n_{MT},k)$ is the AWGN having variance $2N_0/T_s$. The STBC decoding is performed to obtain the STBC decoded frequency-domain signal. The STBC decoded frequency-domain signal $\{\hat{D}_{D,j}(k);\, k=0,\ldots,N_c-1,\, j=0,\ldots,J-1\}$ as

$$\begin{pmatrix}\hat{D}_{D,0}(k)\\ \hat{D}_{D,1}(k)\end{pmatrix}=\begin{pmatrix}R_{D,0}(0,k)+R^*_{D,1}(1,k)\\ R_{D,0}(1,k)-R^*_{D,1}(0,k)\end{pmatrix} \quad \text{… for } N_{MT}=2, \tag{9a}$$

$$\begin{pmatrix}\hat{D}_{D,0}(k)\\ \hat{D}_{D,1}(k)\\ \hat{D}_{D,2}(k)\end{pmatrix}=\begin{pmatrix}R_{D,0}(0,k)+R^*_{D,1}(1,k)+R^*_{D,2}(2,k)\\ R_{D,0}(1,k)-R^*_{D,1}(0,k)+R^*_{D,3}(2,k)\\ R_{D,0}(2,k)-R^*_{D,2}(0.k)-R^*_{D,3}(1,k)\end{pmatrix} \quad \text{… for } N_{MT}=3, \tag{9b}$$

$$\begin{pmatrix}\hat{D}_{D,0}(k)\\ \hat{D}_{D,1}(k)\\ \hat{D}_{D,2}(k)\end{pmatrix}=\begin{pmatrix}R_{D,0}(0,k)+R^*_{D,1}(1,k)+R^*_{D,2}(2,k)+R^*_{D,3}(3,k)\\ R_{D,0}(1,k)-R^*_{D,1}(0,k)-R_{D,2}(3,k)+R^*_{D,3}(2,k)\\ R_{D,0}(2,k)+R_{D,1}(3,k)-R^*_{D,2}(0.k)-R^*_{D,3}(1,k)\end{pmatrix} \quad \text{… for } N_{MT}=4. \tag{9c}$$

As understood from (9), addition/subtraction and conjugate operations are only required and no CSI is required at the MT receiver. The STBC decoded frequency-domain signal is transformed back to the time-domain signal by N_c-point IFFT, and finally, the data demodulation is carried out.

III. MB-FDE FOR HIGH MIBOLITY ENVIRONMENT

In this paper, we derive the transmit/receive MB-FDE weights for a high mobility environment. The MB-FDE weights are jointly optimized based on the MMSE criterion by taking into account the channel variation within a STBC codeword (i.e., $\mathbf{H}_{U,0}(k)\neq\cdots\neq\mathbf{H}_{U,Q-1}(k)$ and

$\mathbf{H}_{D,0}(k) \neq \cdots \neq \mathbf{H}_{D,Q-1}(k)$). Since the transmit FDE alters the transmitted signal spectrum shape, the signal-to-noise power ratio (SNR) is unproportional to the MSE. Therefore, we derive the transmit MB-FDE which minimizes the relative downlink MSE and the receive MB-FDE which minimizes the uplink MSE, respectively. The downlink and uplink relative MSEs, e_D and e_U, are respectively given as

$$\begin{cases} e_D = \displaystyle\sum_{j=0}^{J-1}\sum_{k=0}^{N_c-1} E\left[\left|\frac{D_{D,j}(k) - \sqrt{2P_t}A_{N_{MT}}\hat{D}_{D,j}(k)}{\sqrt{2P_t}A_{N_{MT}}\sqrt{E\left[\left|D_{D,j}(k)\right|^2\right]}}\right|^2\right] \\ e_U = \displaystyle\sum_{j=0}^{J-1}\sum_{k=0}^{N_c-1} E\left[\left|D_{U,j}(k) - \sqrt{\frac{2P_t}{N_{MT}\cdot(J/Q)}}\hat{D}_{U,j}(k)\right|^2\right] \end{cases}. \quad (10)$$

Below, we derive the transmit/receive MB-FDE weights when N_{MT}=2. The transmit/receive MB-FDE weights when N_{MT}=3,4 can be also derived similar to when N_{MT}=2. However, it is skipped in this paper due to page limitation.

A. *Derivation of the transmit MB-FDE*

From (5), (6), (7), (8) and (9), e_D can be rewritten as

$$\begin{aligned} e_D = &\sum_{k=0}^{N_c-1}\left\{\begin{array}{l} \left|\mathbf{H}_{D,0}(0,k)\mathbf{W}_{D,0}(0,k) + \mathbf{W}_{D,1}^H(1,k)\mathbf{H}_{D,1}^H(1,k) - 1\right|^2 \\ + \left|\mathbf{H}_{D,0}(1,k)\mathbf{W}_{D,0}(1,k) + \mathbf{W}_{D,1}^H(0,k)\mathbf{H}_{D,1}^H(0,k) - 1\right|^2 \end{array}\right\} \\ &+ \sum_{k=0}^{N_c-1}\left\{\begin{array}{l} \left|\mathbf{H}_{D,0}(0,k)\mathbf{W}_{D,0}(1,k) - \mathbf{W}_{D,1}^H(0,k)\mathbf{H}_{D,1}^H(1,k)\right|^2 \\ + \left|\mathbf{H}_{D,0}(1,k)\mathbf{W}_{D,0}(0,k) - \mathbf{W}_{D,1}^H(1,k)\mathbf{H}_{D,1}^H(0,k)\right|^2 \end{array}\right\}. \\ &+ N_{MT}\left(\frac{J}{Q}\right)\left(\frac{P_t}{N}\right)^{-1}\sum_{q=0}^{Q-1}\sum_{n_{MT}=0}^{N_{MT}-1}\sum_{k=0}^{N_c-1}\left\|\mathbf{W}_{D,q}(n_{MT},k)\right\|^2 \end{aligned} \quad (11)$$

The first term is the contribution of the residual ISI after MB-FDE due to the channel frequency-selectivity and the second term is the contribution of the residual interference after STBC due to the orthogonality distortion in the STBC codeword. The transmit MB-FDE weights are jointly optimized so as to minimize the relative downlink MSE given as

$$\left\{\begin{array}{l} \mathbf{W}_{D,0}(0,k), \mathbf{W}_{D,0}(1,k) \\ , \mathbf{W}_{D,1}(0,k), \mathbf{W}_{D,1}(1,k) \end{array}\right\} = \arg\min e_D . \quad (12)$$

By solving $\partial e/\partial\mathbf{W}_{D,0}(0,k) = 0, \ldots, \partial e/\partial\mathbf{W}_{D,Q-1}(N_{MT}-1,k) = 0$, the MMSE transmit MB-FDE weights are obtained as

$$\begin{cases} \mathbf{W}_{D,0}(0,k) = \dfrac{\mathbf{H}_{D,0}^H(0,k) - \mathbf{H}_{D,0}^H(1,k)\left(\tilde{H}_{D,2}(k)/\tilde{H}_{D,1}(k)\right)}{\tilde{H}_{D,0}(k) - \left(\left|\tilde{H}_{D,2}(k)\right|^2/\tilde{H}_{D,1}(k)\right)} \\ \mathbf{W}_{D,0}(1,k) = \dfrac{\mathbf{H}_{D,0}^H(1,k) - \mathbf{H}_{D,0}^H(0,k)\left(\tilde{H}_{D,3}(k)/\tilde{H}_{D,0}(k)\right)}{\tilde{H}_{D,1}(k) - \left(\left|\tilde{H}_{D,3}(k)\right|^2/\tilde{H}_{D,0}(k)\right)} \\ \mathbf{W}_{D,1}(0,k) = \dfrac{\mathbf{H}_{D,1}^H(0,k) - \mathbf{H}_{D,1}^H(1,k)\left(\tilde{H}_{D,3}^*(k)/\tilde{H}_{D,0}(k)\right)}{\tilde{H}_{D,1}(k) - \left(\left|\tilde{H}_{D,3}(k)\right|^2/\tilde{H}_{D,0}(k)\right)} \\ \mathbf{W}_{D,1}(1,k) = \dfrac{\mathbf{H}_{D,1}^H(1,k) - \mathbf{H}_{D,1}^H(0,k)\left(\tilde{H}_{D,2}^*(k)/\tilde{H}_{D,1}(k)\right)}{\tilde{H}_{D,0}(k) - \left(\left|\tilde{H}_{D,2}(k)\right|^2/\tilde{H}_{D,1}(k)\right)} \end{cases}, \quad (13)$$

where

$$\begin{cases} \tilde{H}_{D,0}(k) = \left\|\mathbf{H}_{D,0}(0,k)\right\|^2 + \left\|\mathbf{H}_{D,1}(1,k)\right\|^2 + N_{MT}\left(\dfrac{J}{Q}\right)\left(\dfrac{P_t}{N}\right)^{-1} \\ \tilde{H}_{D,1}(k) = \left\|\mathbf{H}_{D,0}(1,k)\right\|^2 + \left\|\mathbf{H}_{D,1}(0,k)\right\|^2 + N_{MT}\left(\dfrac{J}{Q}\right)\left(\dfrac{P_t}{N}\right)^{-1} \\ \tilde{H}_{D,2}(k) = \mathbf{H}_{D,0}(0,k)\mathbf{H}_{D,0}^H(1,k) - \mathbf{H}_{D,1}(0,k)\mathbf{H}_{D,1}^H(1,k) \\ \tilde{H}_{D,3}(k) = \mathbf{H}_{D,0}(1,k)\mathbf{H}_{D,0}^H(0,k) - \mathbf{H}_{D,1}(1,k)\mathbf{H}_{D,1}^H(0,k) \end{cases}, \quad (14)$$

and N=N_0/T_s is the noise power. The second terms in denominator and numerator in (13) contribute to suppress the interference caused by the orthogonality distortion of the STBC codeword. When the channel variation within a STBC codeword is sufficiently slow ($\mathbf{H}_{D,0}(k) \approx, \ldots, \approx \mathbf{H}_{D,Q-1}(k)$), (13) corresponds to the MB-FDE weights designed based on the assumption of quasi-static fading [14].

B. *Derivation of the receive MB-FDE*

From (1), (2), (3), and (4), e_U given as (10) can be rewritten as

$$\begin{aligned} e_U = &\sum_{k=0}^{N_c-1}\left\{\begin{array}{l} \left|\mathbf{W}_{U,0}(0,k)\mathbf{H}_{U,0}(0,k) + \mathbf{H}_{U,1}^H(1,k)\mathbf{W}_{U,1}^H(1,k) - 1\right|^2 \\ + \left|\mathbf{W}_{U,0}(1,k)\mathbf{H}_{U,0}(1,k) + \mathbf{H}_{U,1}^H(0,k)\mathbf{W}_{U,1}^H(0,k) - 1\right|^2 \end{array}\right\} \\ &+ \sum_{k=0}^{N_c-1}\left\{\begin{array}{l} \left|\mathbf{W}_{U,0}(0,k)\mathbf{H}_{U,0}(1,k) - \mathbf{H}_{U,1}^H(0,k)\mathbf{W}_{U,1}^H(1,k)\right|^2 \\ + \left|\mathbf{W}_{U,0}(1,k)\mathbf{H}_{U,0}(0,k) - \mathbf{H}_{U,1}^H(1,k)\mathbf{W}_{U,1}^H(0,k)\right|^2 \end{array}\right\}. \\ &+ N_{MT}\left(\frac{J}{Q}\right)\left(\frac{P_t}{N}\right)^{-1}\sum_{q=0}^{Q-1}\sum_{n_{MT}=0}^{N_{MT}-1}\sum_{k=0}^{N_c-1}\left\|\mathbf{W}_{U,q}(n_{MT},k)\right\|^2 \end{aligned} \quad (15)$$

The receive MB-FDE weights for uplink are jointly optimized so as to minimize the uplink MSE given as

$$\left\{\begin{array}{l} \mathbf{W}_{U,0}(0,k), \mathbf{W}_{U,0}(1,k) \\ , \mathbf{W}_{U,1}(0,k), \mathbf{W}_{U,1}(1,k) \end{array}\right\} = \arg\min e_U . \quad (16)$$

Similar to the transmit MB-FDE, the MMSE receive MB-FDE weights are derived as

$$\begin{cases} \mathbf{W}_{U,0}(0,k) = \dfrac{\mathbf{H}_{U,0}^H(0,k) - \mathbf{H}_{U,0}^H(1,k)\left(\tilde{H}_{U,2}(k)/\tilde{H}_{U,1}(k)\right)}{\tilde{H}_{U,0}(k) - \left(\left|\tilde{H}_{U,2}(k)\right|^2/\tilde{H}_{U,1}(k)\right)} \\ \mathbf{W}_{U,0}(1,k) = \dfrac{\mathbf{H}_{U,0}^H(1,k) - \mathbf{H}_{U,0}^H(0,k)\left(\tilde{H}_{U,3}(k)/\tilde{H}_{U,0}(k)\right)}{\tilde{H}_{U,1}(k) - \left(\left|\tilde{H}_{D,3}(k)\right|^2/\tilde{H}_{U,0}(k)\right)} \\ \mathbf{W}_{U,1}(0,k) = \dfrac{\mathbf{H}_{U,1}^H(0,k) - \mathbf{H}_{U,1}^H(1,k)\left(\tilde{H}_{U,3}^*(k)/\tilde{H}_{U,0}(k)\right)}{\tilde{H}_{U,1}(k) - \left(\left|\tilde{H}_{U,3}(k)\right|^2/\tilde{H}_{U,0}(k)\right)} \\ \mathbf{W}_{U,1}(1,k) = \dfrac{\mathbf{H}_{U,1}^H(1,k) - \mathbf{H}_{U,1}^H(0,k)\left(\tilde{H}_{U,2}^*(k)/\tilde{H}_{U,1}(k)\right)}{\tilde{H}_{U,0}(k) - \left(\left|\tilde{H}_{U,2}(k)\right|^2/\tilde{H}_{U,1}(k)\right)} \end{cases}, \quad (17)$$

where

$$\begin{cases} \tilde{H}_{U,0}(k) = \left\|\mathbf{H}_{U,0}(0,k)\right\|^2 + \left\|\mathbf{H}_{U,1}(1,k)\right\|^2 + N_{MT}\left(\dfrac{J}{Q}\right)\left(\dfrac{P_t}{N}\right)^{-1} \\ \tilde{H}_{U,1}(k) = \left\|\mathbf{H}_{U,0}(1,k)\right\|^2 + \left\|\mathbf{H}_{U,1}(0,k)\right\|^2 + N_{MT}\left(\dfrac{J}{Q}\right)\left(\dfrac{P_t}{N}\right)^{-1} \\ \tilde{H}_{U,2}(k) = \mathbf{H}_{U,0}(0,k)\mathbf{H}_{U,0}^H(1,k) - \mathbf{H}_{U,1}(0,k)\mathbf{H}_{U,1}^H(1,k) \\ \tilde{H}_{U,3}(k) = \mathbf{H}_{U,0}(1,k)\mathbf{H}_{U,0}^H(0,k) - \mathbf{H}_{U,1}(1,k)\mathbf{H}_{U,1}^H(0,k) \end{cases}. \quad (18)$$

IV. COMPUTER SIMULATION

We evaluate, by the computer simulation, the BER performance when using the proposed transmit/receive MB-FDE. We consider QPSK data modulation. FFT block size N_c and CP length N_g are set to N_c=128 symbols and N_g=16 samples, respectively. The number of BS antennas N_{BS} is set to N_{BS}=2 as an example. The channel is assumed to be a time and frequency-selective fading channel having symbol spaced L=16 path uniform power delay profile. In this paper, we assume perfect CSI can be obtained at BS.

A. BER performance

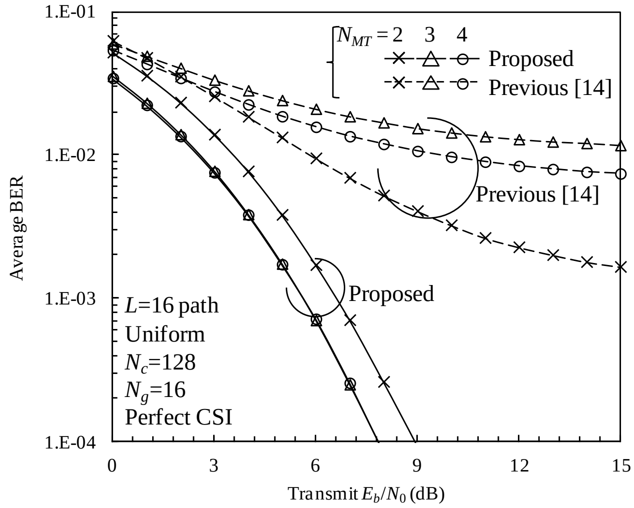
Fig. 4 shows the BER performance when using the proposed transmit/receive MB-FDE as a function of transmit signal energy per bit-to-AWGN power spectrum density ratio E_b/N_0. The normalized maximum Doppler frequency f_DT_s is assumed to be f_DT_s=8×10^{-4}. For the comparison, the performance when using the MB-FDE designed based on the assumption of quasi-static fading [14] (below, we call it as the previously proposed MB-FDE) is also plotted in Fig. 4. It is seen from Fig. 4 that the performance when using the previous MB-FDE has BER error floor. This is because the previous MB-FDE assumes a quasi-static fading channel, and hence, the BER performance degrades due to the interference caused by the orthogonality distortion of the STBC codeword. Furthermore, when N_{MT}=3,4, the performance degradation become larger than when N_{MT}=2. This is because, when N_{MT}=3,4, the length of STBC codeword is twice longer than when N_{MT}=2 and the interference caused by the orthogonality distortion of the STBC codeword become larger. It is also seen from Fig. 4 that the proposed MB-FDE can significantly improve the BER performance compared to the previous MB-FDE. This is because the proposed MB-FDE weights are jointly optimized by taking account into the channel variation within a STBC codeword, and as consequence, it can mitigate the interference caused by the orthogonality distortion of the STBC codeword. When the transmit E_b/N_0=6dB and the number of the MT antennas N_{MT}=3, the proposed MB-FDE can achieve about 1/40 times (1/20 times) lower BER than the previous MB-FDE for uplink (downlink) transmission.

B. Impact of the normalized maximum Doppler frequency

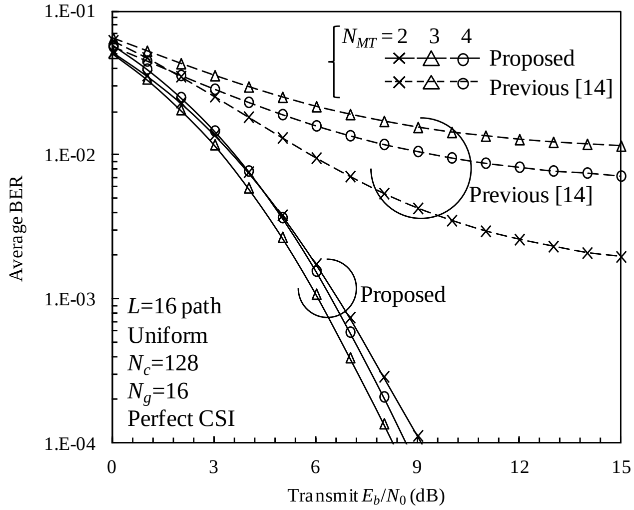
Fig.5 plots the BER performance when using the proposed MB- FDE as a function of the normalized maximum Doppler frequency f_DT_s. The transmit E_b/N_0 is set to 6dB. For comparison, the performance of the previous MB-FDE is also plotted in Fig 5. It is seen form Fig. 5 that the proposed MB-FDE is more robust to channel time-selectivity than the previous MB-FDE. This is because the proposed MB-FDE can mitigate the interference caused by the orthogonality distortion of the STBC codeword and obtain high spatial diversity gain. When required BER is BER=10^{-3} and the number of MT antenna N_{MT}=2 (N_{MT}=3,4), the proposed MB-FDE can tolerate f_DT_s=8×10^{-4} (f_DT_s=1×10^{-3}) and can tolerate about 3 (8) times higher Doppler frequency than the previous MB-FDE. Assuming 20MHz signal bandwidth at the carrier frequency 5GHz, the normalized maximum Doppler frequency f_DT_s=1×10^{-3} corresponds to a travelling speed of 432km/h. Therefore, SC-STBC TDD transmission system combined with the proposed MB-FDE achieves a good BER performance even in a high mobility environment.

V. CONCLUSION

In this paper, we proposed a transmit/receive MB-FDE for SC-STBC-TDD transmission in a high mobility environment. It was shown by the computer simulation that the proposed MB-FDE suppress the interference caused by the orhtogonality distortion of STBC codeword and tolerates about 8 times higher Doppler frequency than the MB-FDE designed based on the assumption of quasi-static fading when N_{MT}=4. In this paper, we assumed the perfect CSI. The channel estimation for SC-STBC TDD transmission is left as our future work. Performance comparison of our proposed transmit/receive MB-FDE to other techniques, e.g. iterative interference cancellation [12,13], is also left as our future study.

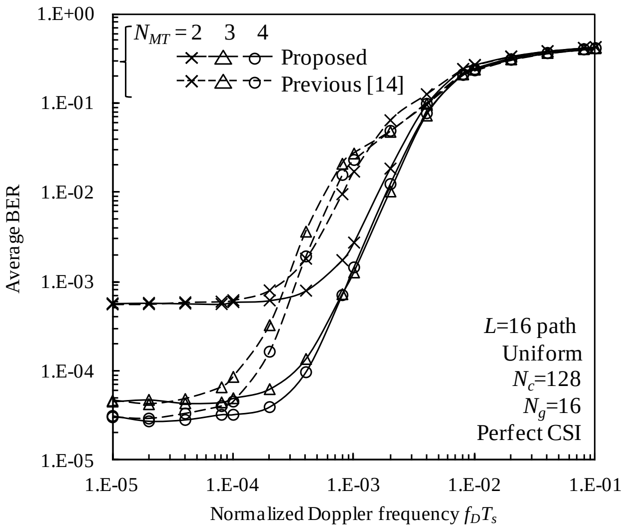


(a) Uplink

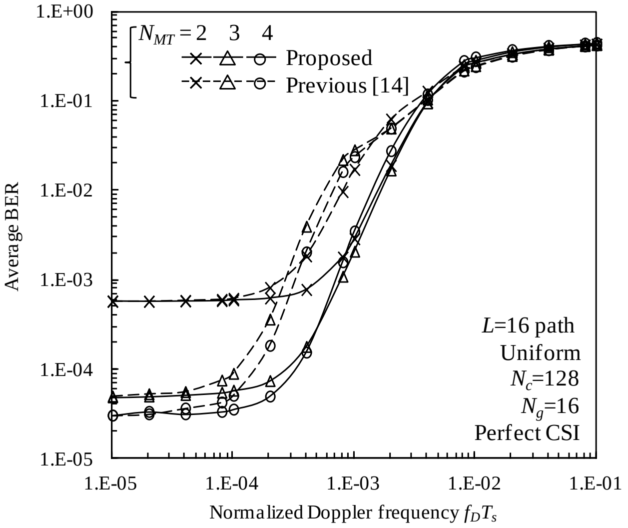


(b) Downlink

Fig. 4. BER performance



(a) Uplink



(b) Downlink

Fig. 5. Impact of Normalized Doppler frequency

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