

MIMO-OFDM Transmissions Invoking Space-Time/Frequency Linear Dispersion Codes Subject to Doppler and Delay Spreads

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Abstract—Linear dispersion codes (LDC) can support arbitrary configurations of transmit and receive antennas in multi-input multi-output (MIMO) systems. In this paper, we investigate two transmit diversity applications of LDC for orthogonal frequency division multiplexing (OFDM) systems in order to achieve space-time/frequency (ST/SF) diversity gains when transmitting over time-/frequency-selective fading channels. LDC-aided ST/SF-OFDM is flexible in configuring various numbers of transmit antennas and time-slots or frequency-tones. Our results show that the ST-OFDM scheme is sensitive to exploiting diversity gains, subject to the impact of varying channel Doppler spreads; while the performance of SF-OFDM is mainly subject to delay spread. Particularly, when the transmitter employs more than two antennas, the LDC-aided ST/SF-OFDM outperforms the orthogonal block codes (e.g. Tarokh's codes) aided ST/SF-OFDM, when communicating over higher Doppler/delay spread.

I. INTRODUCTION

Multi-input multi-output (MIMO) [1] is a most attractive multi-antenna technique that has been adopted by many emerging wireless communication standards, such as IEEE 802.11n and 3GPP LTE, owing to the achievable antenna array, multiplexing, and diversity gain. In order to improve link reliability, the diversity gain enabled at transmission can be exploited by space-time coding, while the diversity gain achieved at the receiver may benefit from maximum ratio combining (MRC) [2]–[5]. These gains are obtained without increasing the transmission power by employing multiple transmit and/or receive antennas. Particularly, Hassibi's linear dispersive codes (LDC) [4], [6]–[8] allow arbitrary configurations in space-time coding for high-rate MIMO transmissions.

Meanwhile, broadband communication plays an increasingly important role in meeting the growing demand for high-speed multimedia transmissions in our daily lives. However, when the bandwidth of a signal exceeds the coherent bandwidth of the wireless channel, the small-scale fading imposed on the signal becomes frequency-selective rather than frequency-flat. Such a fading time-dispersion incurs inter-symbol interference (ISI) to the air-interface and therefore degrades the link performance [9]. Orthogonal frequency division multiplexing (OFDM) [10] is one of the transceiver techniques designed to combat ISI. When the number of subcarriers in OFDM is sufficiently larger than the number of taps, the frequency-selective channel can be decomposed

into mutually independent frequency-flat fading channels on each subcarrier with the aid of OFDM transmission. Moreover, a center length of cyclic prefix (CP) or zero-padding (ZP) should be inserted between any two adjacent OFDM blocks to mitigate inter-block interference (IBI) incurred by multipath fading [11]. As a result, each received signal can be recovered at the low-complexity single-tap equalizer without inter-carrier interference (ICI), thanks to the orthogonality between adjacent subcarriers with flat fading [12].

For transmit diversity aided MIMO systems, a simple time-reversed space-time block coding scheme [13] was proposed in the context of a broadband MIMO channel to combat ISI. Such a large time-reversal frame requires slow channel varying, which is not suitable for mobile wireless communications [9]. In [14], [15], the space-time block coding (STBC) including the LDC schemes were investigated when communicating over uncorrelated and correlated frequency-flat fading channels. With the aid of a multi-antenna employed at the transmitter, many of transmit diversity schemes have been invented to combat the frequency-selective fading incurred by the high-speed data rate and also achieve diversity gain at the same time [16]–[19]. Specifically, the space-time block coding (STBC) schemes that were used in frequency-flat fading channels may be applied to each subcarrier to achieve space-time diversity and combat channel time-dispersion [20]. In parallel, rather than exploiting the achievable diversity by crossing spatial antennas and time-slots, the alternative approach may benefit from OFDM's multi-carrier feature relying on so-called space-frequency block coding (SFBC) schemes by exploiting the diversity crossing transmit antennas and subcarriers [21]. A further combined version of the above two schemes is known as space-time-frequency block coding, which can exploit diversity in all three domains [22]–[25]. Furthermore, the authors in [25], [26] propose various LDC-aided OFDMs to achieve space-frequency diversity for the constant fading channel within a single OFDM block; while in [27] the LDC is designed to obtain diversity from the time and frequency domain rather than the spatial domain. However, to the best of our knowledge, there has not been a comprehensive investigation assessing LDC in space-time (ST) and space-frequency (SF) diversity gain impacts varying channel coherent times and bandwidths.

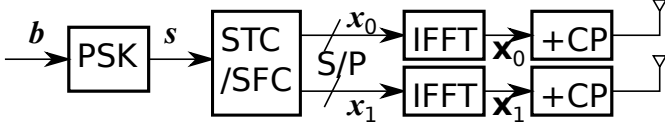


Fig. 1. Transmitter block diagram for transmit diversity aided OFDM

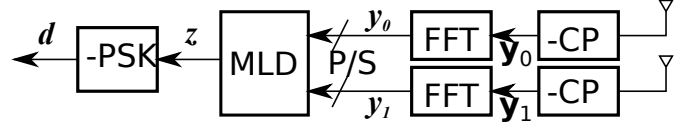


Fig. 2. Receiver block diagram for transmit diversity aided OFDM

In this paper, we investigate transmit diversity for the OFDM system by invoking LDC to take into account the trade-off between ST and SF diversities. Our contributions are highlighted as follows:

- We unify the analysing structure of transmit diversity aided block codes in order to compare LDC with the corresponding Alamouti's code and Tarokh's code [2], [3] in diverse MIMO configurations.
- The LDC, Alamouti's and Tarokh's codes are applied to OFDM in both the ST and SF approaches.
- Our results show that when the channel is constant within the coherent time/bandwidth, the ST-OFDM or SF-OFDM is capable of achieving full diversity gain in space-time or space-frequency domains, respectively.
- We quantify the performance impact with varying Doppler spreads. Results show that the ST-OFDM scheme is sensitive to exploit diversity gains subject to the effect upon varying channel Doppler spreads.
- In parallel, we examine the performance impacts owing to varying numbers of paths in terms of delay spread. As a result, the performance of SF-OFDM is mainly subject to delay spreads.
- Compared to fixed orthogonal block codes, the LDC-aided ST/SF-OFDM is flexible to configure various numbers of transmit antennas and time-slots or frequency-tones.
- When a transmitter employs more than two antennas, the performance of LDC-aided OFDM schemes is less impacted by channel Doppler/delay spreads, as compared with orthogonal block codes.

The rest of this paper is structured as follows. We firstly elaborate on the transceiver system model of MIMO-OFDM in Section II. The ST- and SF-oriented OFDM schemes that achieve transmit diversity will be studied in Section III in both the Alamouti's and a LDC cases. We will present the simulation results in Section IV, followed by closing remarks in Section V.

II. SYSTEM MODEL

A. Transmitted Signal

The multi-antenna aided OFDM transmitter is shown in Fig. 1. Specifically, the N_b -length binary source data bit stream $\mathbf{b} = [b_0^T, b_1^T, \dots, b_{N_b-1}^T]^T$ is fed into the \mathcal{M} -ary Gray labeled phase-shift keying (PSK) mapper transmitting \mathcal{Q} bits per symbol, where we have $N_s = N_b/\mathcal{Q}$ and $\mathcal{M} = 2^{\mathcal{Q}}$. Moreover, the N_s -length modulated symbol sequence $\mathbf{s} = [s_0, s_1, \dots, s_{N_s-1}]^T$ is inputted into the transmit diversity module \mathcal{C} , which maps the symbols into N_{Tx} antennas

and N_T time-slots or N_C subcarriers in terms of ST/SF coding, which will be further detailed in Section III. The n_{Tx} -th output ST/SF module containing the U -symbol block $\mathbf{x}_{n_{Tx}} = [x_{n_{Tx},0}, x_{n_{Tx},1}, \dots, x_{n_{Tx},(U-1)}]^T$ to be transmitted via the antenna n_{Tx} is then converted from serial-to-parallel (S/P) corresponding to U orthogonal subcarriers in the F-domain. These U -symbols in $\mathbf{x}_{n_{Tx}}$ are transformed by U -point inverse discrete Fourier transform (IDFT) operation matrix \mathcal{F}_U^H [28] into T-domain at the t -th time-slot for $t = 0, 1, \dots, T-1$, expressed by

$$\mathbf{x}_{n_{Tx}}[t] = \mathcal{F}_U^H \mathbf{x}_{n_{Tx}}[t] = [x_{n_{Tx},0}[t], x_{n_{Tx},1}[t], \dots, x_{n_{Tx},(U-1)}[t]]^T, \quad (1)$$

The CP is inserted at the beginning of $\mathbf{x}_{n_{Tx}}[t]$ by copying the last L_{CP} elements of the $\mathbf{x}_{n_{Tx}}[t]$, which results in the $(U+L_{CP})$ -element transmitted OFDM symbol block $\tilde{\mathbf{x}}_{n_{Tx}}[t]$ at the t -th time-slot via the n_{Tx} -th antenna.

B. Signal Representation at the BS Receiver

The multi-antenna aided OFDM receiver is shown in Fig. 2. By satisfying the channel order $L < L_{CP}$, after removing the CP at the receiver, the equivalent U -element T-domain signal block received at the t -th time-slot may be expressed as:

$$\mathbf{y}_{n_{Rx}}[t] = \sum_{n_{Tx}=0}^{N_{Tx}-1} \mathbf{H}_{n_{Rx},n_{Tx}} \mathbf{x}_{n_{Tx}}[t] + \mathbf{n}_{n_{Rx}}[t], \quad (2)$$

where $\mathbf{H}_{n_{Rx},n_{Tx}}$ denotes the $U \times U$ -element T-domain circulant matrix [28] holding the channel impulse response (CIR) between transmit and receive antennas n_{Tx} and n_{Rx} . In Eq. (2), $\mathbf{n}_{n_{Rx}}$ is the noise imposed at the n_{Rx} -th receiver antenna, each element of which has a power of $\mathcal{N}_u = \sigma_u^2$.

Hence, after the U -point discrete Fourier transform (DFT) transforming the signal $\mathbf{y}_{n_{Rx}}$ into the F-domain, we have the equivalent symbol block given by

$$\mathbf{y}_{n_{Rx}}[t] = \mathcal{F}_U \mathbf{y}_{n_{Rx}}[t] = \sum_{n_{Tx}=0}^{N_{Tx}-1} \mathbf{H}_{n_{Rx},n_{Tx}}[t] \mathbf{x}_{n_{Tx}}[t] + \mathbf{n}_{n_{Rx}}[t]. \quad (3)$$

Since we have $\mathbf{H}_{n_{Rx},n_{Tx}} = \mathcal{F}_U^H \mathbf{H}_{n_{Rx},n_{Tx}} \mathcal{F}_U$ according to [28], the $\mathbf{H}_{n_{Rx},n_{Tx}}$ in Eq. (3) is a diagonal matrix with entries $h_{u,u}$ ($u = 0, 1, \dots, U-1$) representing the corresponding F-domain channel transfer function on U subcarriers, leading to a low-complexity one-tap channel equalization method. In Eq. (3), we have $\mathbf{n}_{n_{Rx}} = \mathcal{F}_U \mathbf{n}_{n_{Rx}}$ with $\mathcal{N}_u = \sigma_u^2$.

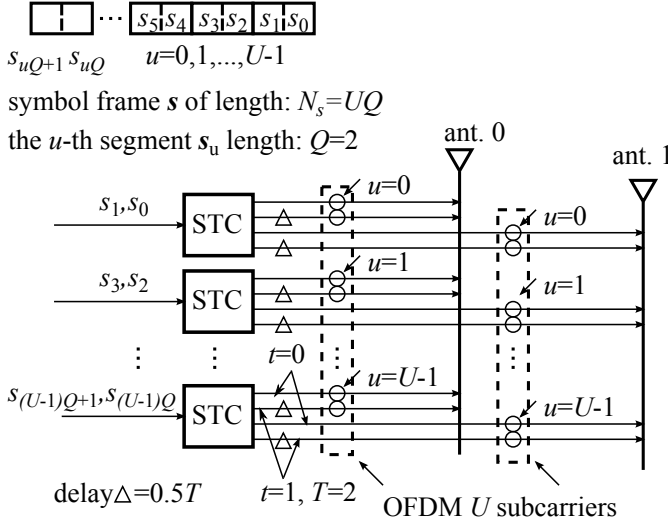


Fig. 3. Schematic diagram of space-time coded OFDM

Furthermore, we reshape Eq. (3) into an N_{Rx} -length multi-antenna received symbol vector for the u -th subcarrier at time-slot t expressed by

$$\tilde{\mathbf{y}}_u[t] = \tilde{\mathbf{H}}_u[t] \tilde{\mathbf{x}}_u[t] + \tilde{\mathbf{n}}_u[t], \quad (4)$$

where $\tilde{\mathbf{H}}_u[t]$ is a $(N_{\text{Rx}} \times N_{\text{Tx}})$ -size MIMO-channel matrix at time-slot t , in which the $(n_{\text{Rx}}, n_{\text{Tx}})$ -th entry denotes the F-domain coefficients of $\mathbf{H}_{n_{\text{Rx}}, n_{\text{Tx}}}$ on the u -th subcarrier; $\tilde{\mathbf{x}}_u[t] = [\mathbf{x}_{0,u}[t], \mathbf{x}_{1,u}[t], \dots, \mathbf{x}_{(N_{\text{Tx}}-1),u}[t]]^T$ is N_{Tx} -antenna transmitted symbol vector in the F-domain before IDFT at time-slot t . Additionally, $\tilde{\mathbf{n}}_u[t] = [\mathbf{n}_{0,u}[t], \mathbf{n}_{1,u}[t], \dots, \mathbf{n}_{(N_{\text{Tx}}-1),u}[t]]^T$ is N_{Rx} -antenna noise component added at receiver.

III. TRANSMIT DIVERSITY AIDED MIMO-OFDM SCHEMES

In this section, we elaborate two transmit diversity aided OFDM schemes, namely ST coded OFDM and SF coded OFDM, respectively.

A. Space-Time Coded OFDM

In order to achieve the space- and time-diversity, the OFDM may be ST-encoded in a subcarrier-by-subcarrier basis as shown in Fig. 3. Specifically, a N_s -length symbol frame \mathbf{s} is divided into U segments, and the u -th segment for $u = 0, 1, \dots, U-1$ contains Q symbols in \mathbf{s}_u for the input of ST encoder. The encoder employs specific ST algorithms procuding the ouput frame for the n_{Tx} -th antenna having $T > 1$ consecutive OFDM blocks $\mathbf{x}_{n_{\text{Tx}}}[t]$ over time-slots $t = 0, 1, \dots, T-1$ in F-domain. For instance, the Alamouti's g2 ST [2] encoded OFDM blocks for $N_{\text{Tx}} = 2$, $Q = 2$ and $T = 2$ may be expressed as

$$\begin{cases} \mathbf{x}_{n_{\text{Tx}}=0}[t=0] = [s_0, s_2, \dots, s_{2U-2}]^T, \\ \mathbf{x}_{n_{\text{Tx}}=1}[t=0] = [s_1, s_3, \dots, s_{2U-1}]^T, \\ \mathbf{x}_{n_{\text{Tx}}=0}[t=1] = -\mathbf{x}_{n_{\text{Tx}}=1}^*[0], \\ \mathbf{x}_{n_{\text{Tx}}=1}[t=1] = \mathbf{x}_{n_{\text{Tx}}=0}^*[0], \end{cases} \quad (5)$$

where the u -th element in symbol vector $\mathbf{x}_{n_{\text{Tx}}}[t]$ is conveyed onto u -th subcarriers at time-slot t and emitted via antenna n_{Tx} . Alternatively, when the Tarokh's g4 ST [3] code is invoked in OFDM for $N_{\text{Tx}} = 4$, $Q = 4$ and $T = 8$, we have:

$$\begin{cases} \mathbf{x}_0[0] = [s_0, s_4, \dots, s_{4U-4}]^T, \\ \mathbf{x}_1[0] = [s_1, s_5, \dots, s_{4U-3}]^T, \\ \mathbf{x}_2[0] = [s_2, s_6, \dots, s_{4U-2}]^T, \\ \mathbf{x}_3[0] = [s_3, s_7, \dots, s_{4U-1}]^T, \end{cases} \quad \begin{cases} \mathbf{x}_0[1] = -\mathbf{x}_1[0], \\ \mathbf{x}_1[1] = -\mathbf{x}_0[0], \\ \mathbf{x}_2[1] = -\mathbf{x}_3[0], \\ \mathbf{x}_3[1] = \mathbf{x}_2[0], \end{cases}$$

$$\begin{cases} \mathbf{x}_0[2] = -\mathbf{x}_2[0], \\ \mathbf{x}_1[2] = \mathbf{x}_3[0], \\ \mathbf{x}_2[2] = \mathbf{x}_0[0], \\ \mathbf{x}_3[2] = -\mathbf{x}_1[0], \end{cases} \quad \begin{cases} \mathbf{x}_0[3] = -\mathbf{x}_3[0], \\ \mathbf{x}_1[3] = -\mathbf{x}_2[0], \\ \mathbf{x}_2[3] = \mathbf{x}_1[0], \\ \mathbf{x}_3[3] = \mathbf{x}_0[0], \end{cases} \quad \begin{cases} \mathbf{x}_0[4] = \mathbf{x}_0^*[0], \\ \mathbf{x}_1[4] = \mathbf{x}_1^*[0], \\ \mathbf{x}_2[4] = \mathbf{x}_2^*[0], \\ \mathbf{x}_3[4] = \mathbf{x}_3^*[0], \end{cases}$$

$$\begin{cases} \mathbf{x}_0[5] = \mathbf{x}_0^*[1], \\ \mathbf{x}_1[5] = \mathbf{x}_1^*[1], \\ \mathbf{x}_2[5] = \mathbf{x}_2^*[1], \\ \mathbf{x}_3[5] = \mathbf{x}_3^*[1], \end{cases} \quad \begin{cases} \mathbf{x}_0[6] = \mathbf{x}_0^*[2], \\ \mathbf{x}_1[6] = \mathbf{x}_1^*[2], \\ \mathbf{x}_2[6] = \mathbf{x}_2^*[2], \\ \mathbf{x}_3[6] = \mathbf{x}_3^*[2], \end{cases} \quad \begin{cases} \mathbf{x}_0[7] = \mathbf{x}_0^*[3], \\ \mathbf{x}_1[7] = \mathbf{x}_1^*[3], \\ \mathbf{x}_2[7] = \mathbf{x}_2^*[3], \\ \mathbf{x}_3[7] = \mathbf{x}_3^*[3]. \end{cases} \quad (6)$$

Furthermore, the LDC encoded OFDM block for the n_{Tx} -th antenna on the u -th subcarrier at time-slot $t = 0, 1, \dots, T-1$ before IFFT operation is given by

$$\mathbf{x}_{n_{\text{Tx}}}[t] = [\mathbf{B}_{n_{\text{Tx}}} \mathbf{s}_0]_t, [\mathbf{B}_{n_{\text{Tx}}} \mathbf{s}_1]_t, \dots, [\mathbf{B}_{n_{\text{Tx}}} \mathbf{s}_{U-1}]_t]^T, \quad (7)$$

where $\mathbf{B}_{n_{\text{Tx}}}$ is the linear dispersion matrix defined in [6] of n_{Tx} -th antenna and

$\mathbf{s}_u = [s_{uQ}, s_{uQ+1}, \dots, s_{(u+1)Q-1}]^T$ is the u -th input symbol segment having a length of Q for $u = 0, 1, \dots, U-1$. Then, by using Eq. (1), the ST-OFDM symbols may be transmitted.

The detection of ST-OFDM receiver is also operated by subcarrier-by-subcarrier basis. After the signal transformed into F-domain by Eq. (4), we consider on the symbol blocks over all T time-slots, having an equivalent F-domain signal expression as

$$\mathbf{y}_u = \mathbf{H}_u \mathbf{x}_u + \mathbf{n}_u, \quad (8)$$

where each component vector \mathbf{y}_u , \mathbf{x}_u and \mathbf{n}_u may be expressed by $\mathbf{a}_u = [\tilde{\mathbf{a}}_u^T[0], \tilde{\mathbf{a}}_u^T[1], \dots, \tilde{\mathbf{a}}_u^T[T-1]]^T$; while the channel component matrix is given by $\mathbf{H}_u = [\tilde{\mathbf{H}}_u^T[0], \tilde{\mathbf{H}}_u^T[1], \dots, \tilde{\mathbf{H}}_u^T[T-1]]^T$.

B. Space-Frequency Coded OFDM

As shown in Fig. 4, another method to exploit the diversity in both space and frequency is to invoke SF coding in OFDM system [21]. Specifically, each consecutive Q elements of frame \mathbf{s} are SF-encoded having N_{Tx} output blocks, each of which is conveyed into $M \leq U$ subcarriers within a single time-slot, i.e. $t = 0, T = 1$. Hence, each OFDM block requires $N = U/M$ -set consecutive Q -symbol inputs in order to crossing U subcarriers. For example, the Alamouti's g2 style SF-encoded OFDM blocks for $N_{\text{Tx}} = 2$, $Q = 2$ and $M = 2$ may be expressed as

$$\begin{cases} \mathbf{x}_{n_{\text{Tx}}=0}[t=0] = [s_0, -s_1^*, s_2, -s_3^*, \dots, s_{U-2}, -s_{U-1}^*]^T, \\ \mathbf{x}_{n_{\text{Tx}}=1}[t=0] = [s_1, s_0^*, s_3, s_2^*, \dots, s_{U-1}, s_{U-2}^*]^T, \end{cases} \quad (9)$$

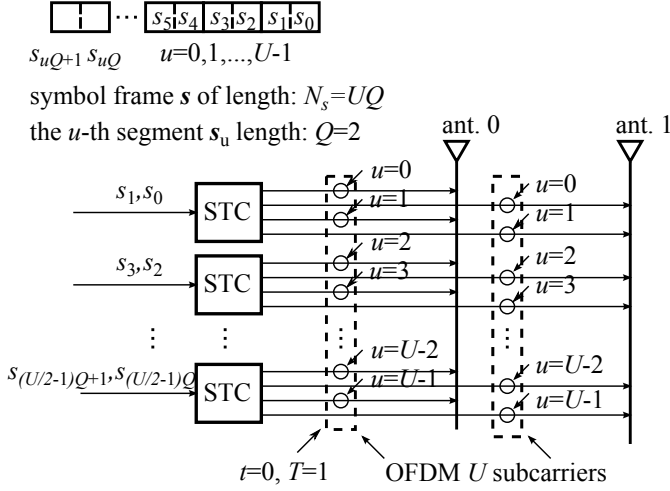


Fig. 4. Schematic diagram of space-frequency coded OFDM

where the u -th element in symbol vector $\mathbf{x}_{n_{\text{Tx}}}[t]$ is conveyed onto u -th subcarriers at time-slot t and emitted via antenna n_{Tx} . When the Tarokh's g4 based SF code with $N_{\text{Tx}} = 4$, $Q = 4$ and $M = 8$ is employed in OFDM, we have:

$$\begin{cases} \mathbf{x}_0[0] = [s_0, -s_1, -s_2, -s_3, s_0^*, -s_1^*, -s_2^*, -s_3^*, \dots, \\ \quad s_{U-4}^*, -s_{U-3}^*, -s_{U-2}^*, -s_{U-1}^*]^T, \\ \mathbf{x}_1[0] = [s_1, -s_0, -s_3, -s_2, s_1^*, -s_0^*, -s_3^*, -s_2^*, \dots, \\ \quad s_{U-3}^*, s_{U-4}^*, s_{U-1}^*, -s_{U-2}^*]^T, \\ \mathbf{x}_2[0] = [s_2, -s_3, -s_0, -s_1, s_2^*, -s_3^*, -s_0^*, -s_1^*, \dots, \\ \quad s_{U-2}^*, -s_{U-1}^*, s_{U-4}^*, s_{U-3}^*]^T, \\ \mathbf{x}_3[0] = [s_3, -s_2, -s_1, -s_0, s_3^*, -s_2^*, -s_1^*, -s_0^*, \dots, \\ \quad s_{U-1}^*, s_{U-2}^*, -s_{U-3}^*, s_{U-4}^*]^T, \end{cases} \quad (10)$$

Moreover, the LDC encoded OFDM block for the n_{Tx} -th antenna on the u -th subcarrier at time-slot $t = 0$ (before IFFT operation) is given by

$$\mathbf{x}_{n_{\text{Tx}}}[t = 0] = [\mathbf{B}_{n_{\text{Tx}}} \mathbf{s}_0]^T, [\mathbf{B}_{n_{\text{Tx}}} \mathbf{s}_1]^T, \dots, [\mathbf{B}_{n_{\text{Tx}}} \mathbf{s}_{N-1}]^T]^T, \quad (11)$$

where $\mathbf{s}_u = [s_{uQ}, s_{uQ+1}, \dots, s_{(u+1)Q-1}]^T$ is the u -th input symbol segment having a length of Q for $u = 0, 1, \dots, U-1$. Consequently, by using Eq. (1), the SF-OFDM symbols can be formed.

At the receiver side, the detection of SF-OFDM operates in subcarrier group-by-group basis. Unlike the Section III-A, after the signal transformed into F-domain by Eq. (4), the symbol blocks for the n -th subcarrier group which cross over subcarriers from nM to $(n+1)M-1$ for $n = 0, 1, \dots, N-1$ at time-slot $t = 0$ can be expressed by

$$\mathbf{y}_n[0] = \mathbf{H}_n[0] \mathbf{x}_n[0] + \mathbf{n}_n[0], \quad (12)$$

where each component vector $\mathbf{y}_n[0]$, $\mathbf{x}_n[0]$ and $\mathbf{n}_n[0]$ can be expressed by

$$\mathbf{a}_n[0] = [\check{\mathbf{a}}_{nM}^T[0], \check{\mathbf{a}}_{nM+1}^T[0], \dots, \check{\mathbf{a}}_{(n+1)M-1}^T[0]]^T; \text{ while the channel component matrix is given by } \mathbf{H}_n[0] = [\check{\mathbf{H}}_{nM}^T[0], \check{\mathbf{H}}_{nM+1}^T[0], \dots, \check{\mathbf{H}}_{(n+1)M-1}^T[0]]^T.$$

TABLE I
SIMULATION PARAMETERS

Channel model	time/frequency-selective time-correlated Rayleigh fading
Bits per symbol	$Q = 1$
Normalized Doppler frequency	$f_{\text{ND}} = 0.01, \dots, 0.1$
No. of CIR paths	$L = 1, 2, 4, 8, 16$
No. of subcarriers	$U = 128$
No. of transmitter antennas	$N_{\text{Tx}} = 2, 4$
No. of receiver antennas	$N_{\text{Rx}} = 1$
No. of time-slots per code	$T = 2, 4, 8$
No. of frequency-tone per code	$M = 2, 4, 8$
No. of symbols per code	$Q = 2, 4$

C. Maximum-Likelihood Detection

Based on Eqs. (8) and (12), the equivalent F-domain system model for detection can be represented by [1]

$$\bar{\mathbf{y}} = \bar{\mathbf{H}} \mathbf{\Xi} \mathbf{s}_n + \bar{\mathbf{n}}_n, \quad (13)$$

where¹ $\bar{\mathbf{y}} = \text{vec}(\mathbf{y})$, $\bar{\mathbf{H}} = \mathbf{I} \otimes \mathbf{H}$ is an equivalent channel matrix with a size of $(N_{\text{Rx}}T \times N_{\text{Tx}}T)$ -element for ST-OFDM and $(N_{\text{Rx}}M \times N_{\text{Tx}}M)$ -element for SF-OFDM. Most importantly, $\mathbf{\Xi}$ is referred to as the dispersion character matrix (DCM) [1], defined by $\mathbf{\Xi} = [\text{vec}(\mathbf{B}_0)], \text{vec}(\mathbf{B}_1)], \dots, \text{vec}(\mathbf{B}_{Q-1})]$. $\mathbf{s}_n = [s_0, s_1, \dots, s_{Q-1}]^T$ is the n -th segment of transmit signal frame \mathbf{s} in Eq. (1). Additionally, $\bar{\mathbf{n}}_n = \text{vec}(\mathbf{n}_n)$.

Therefore, we obtain the estimated symbol vector $\hat{\mathbf{s}}_n$ by maximum likelihood (ML) detection expressed as [1]:

$$\hat{\mathbf{s}} = \arg\{\min(\|\bar{\mathbf{y}} - \bar{\mathbf{H}} \mathbf{\Xi} \mathbf{a}\|^2)\}, \quad (14)$$

where \mathbf{a} denotes all possible combinations of the Q transmitted symbols in \mathbf{s}_n .

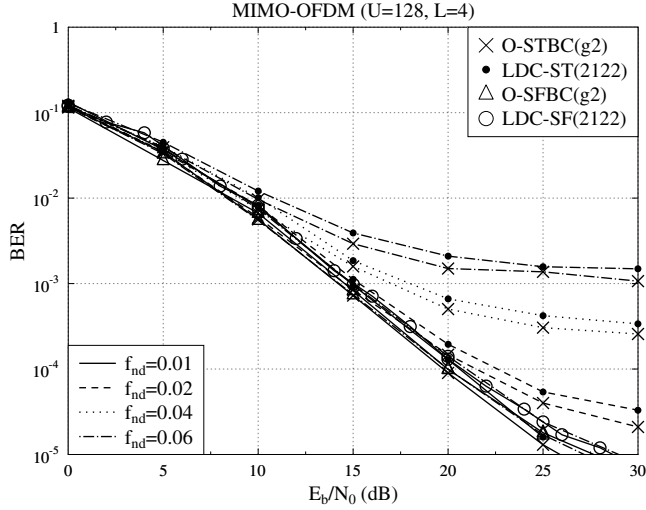
IV. SIMULATION RESULTS AND DISCUSSIONS

In this section, we evaluate the performance achieved by the varying sets of simulation parameters, which are summarized in Table I.

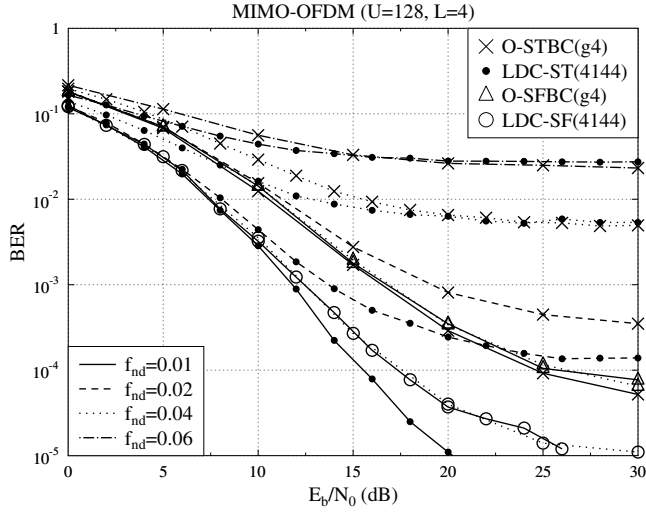
The bit error ratio (BER) performance results of ST and SF-oriented OFDM invoking LDC (2122)² or LDC (4144) upon varying the number of normalized Doppler frequency f_{ND} are shown in Fig. 5(a) and Fig. 5(b), respectively. Both LDC (2122) aided ST-OFDM having $N_{\text{Tx}} = T = Q = 2$ and LDC (4144) aided ST-OFDM associated with $N_{\text{Tx}} = 4$, $T = 4$, $Q = 4$ achieve the best performance for $f_{\text{ND}} = 0.01$ when $L = 4$. At the same time the performance degrades when f_{ND} increases up to 0.06. This means the channel becomes even more time-selective with the duration of whole ST-OFDM symbol period for $T = 2$ and 4. By contrast, the performance of orthogonal STBC (g4) aided OFDM for $N_{\text{Tx}} = 4$, $T = 8$, $Q = 4$ is decreased when $L = 4$, due to doubling the time slots for transmitting in comparison to the LDC (4144), upon varying the f_{ND} from 0.01 to 0.06.

¹We define the $\text{vec}(\cdot)$ operation as the vertical stacking of the columns of an arbitrary matrix. \mathbf{I} is a identity matrix with size of $(T \times T)$ or $(M \times M)$. \otimes is a Kronecker product operator.

²We denote that LDC $(N_{\text{Tx}}, N_{\text{Rx}}, T, Q)$ and $(N_{\text{Tx}}, N_{\text{Rx}}, M, Q)$ for ST or SF-encoded OFDM, respectively.



(a) $N_t = 2$

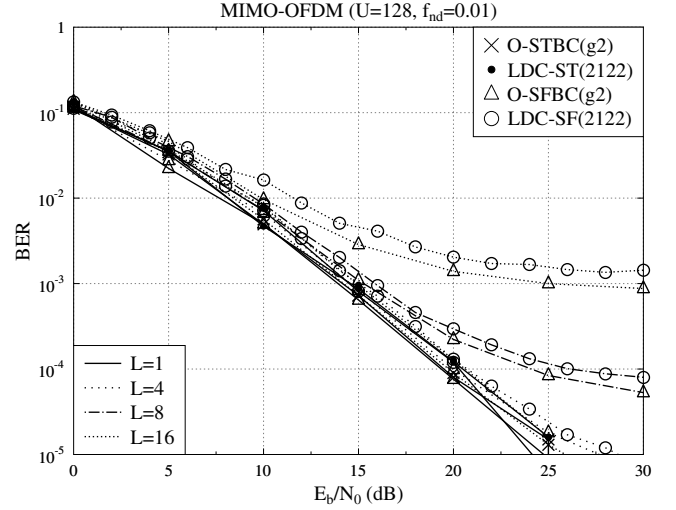


(b) $N_t = 4$

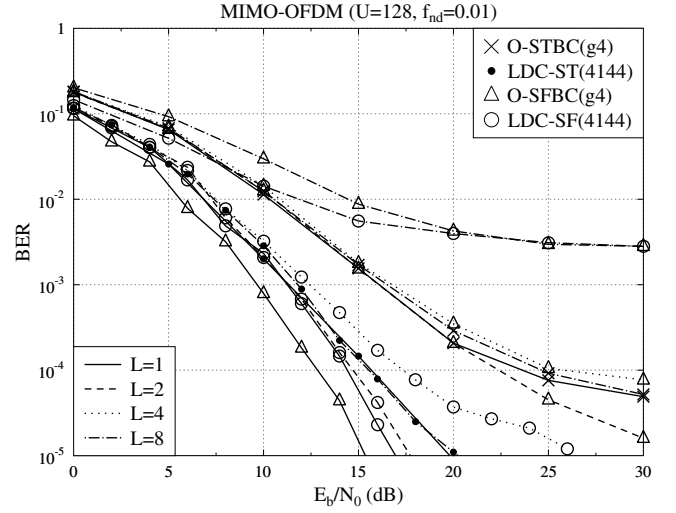
Fig. 5. BER performance of MIMO-OFDM experiencing time-selective fading in terms of varying Doppler spread.

Meanwhile, Fig. 5 also demonstrate that both the LDC and orthogonal code aided SF-OFDM are capable of achieving a constant performance in low delay spreads with the number of CIR taps $L = 4$ without the impact of increasing f_{ND} .

Furthermore, the performance of ST- and SF-OFDM invoking LDC (2122,4144) upon varying L is shown in Fig. 6. As seen in this figure, the performance of SF-OFDM is not impacted by the varying delay spreads for a given $f_{ND} = 0.01$. However, SF-OFDM benefits frequency-diversity for neighboring M subcarriers having correlated fading coefficients associated with low frequency-selectivity with $L = 1, 2, 4$ for $N_{Tx} = 2$ and with $L = 1, 2$ for $N_{Tx} = 4$. Note that, the performance degrades when increasing L . Particularly, LDC (4144) aided SF-OFDM having $M = 4$ outperforms orthogonal SFBC (g4) aided OFDM with $M = 8$ when communicating over the frequency-selective fading channel of $L = 2, 4$.



(a) $N_t = 2$



(b) $N_t = 4$

Fig. 6. BER performance of MIMO-OFDM experiencing frequency-selective fading in terms of varying delay spread (multipath).

V. CONCLUSIONS

In this contribution, we investigated ST- and SF-diversity oriented OFDM systems invoking LDC, in order to study the advantages and disadvantages of transmit diversity based MIMO transmission over time-/frequency-selective fading channels. Our results demonstrate that when the channel is constant within the coherent time/bandwidth, ST- or SF-OFDM is capable of achieving full diversity gain in ST or SF domains. The ST-OFDM scheme is sensitive to exploiting diversity gains subject to the impact of varying channel Doppler spreads; while the performance of SF-OFDM is mainly subject to delay spread. Moreover, compared with the orthogonal STBC/SFBC (g4), the LDC-aided ST/SF-OFDM is flexible in configuring various numbers of transmit antenna and time-slots or frequency-tones. When the transmitter employs more than two antennas, the performance of LDC-aided ST/SF-OFDM

schemes is less impacted by channel Doppler/delay spreads, as compared with orthogonal block codes.

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