Performance Comparison of MIMO Diversity Schemes in a Frequency-selective Rayleigh Fading Channel

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Abstract—**Although multi-user MIMO multiplexing is known as a powerful means to increase the sum throughput, MIMO diversity still remains as an important means to improve the bit error rate (BER) performance in a poor channel condition. Recently, we proposed selective MIMO diversity with subcarrier-wise user equipment (UE) antenna identification/selection. Selective MIMO diversity jointly uses maximal-ratio transmit diversity & frequency-domain equalization (MRTD-FDE) and minimum mean square error combining diversity & FDE (MMSECD-FDE) both at base station (BS) for OFDM downlink and SC uplink, respectively. In this paper, we compare selective MIMO diversity with two other typical MIMO diversity schemes, i.e., the space-time block-coded (STBC) diversity and the MMSE filtering combined with singular value decomposition (MMSE-SVD) based diversity. Pilot-aided channel estimation (PACE) is used for generating the transmit/receive diversity & equalization weights at BS and the transmit/receive diversity weights at UE. The uncoded average BER performance of selective MIMO diversity in a frequency-selective Rayleigh fading MIMO channel is evaluated by computer simulation and is compared with those of STBC-TD and MMSE-SVD diversity.**

Keywords—MIMO diversity; frequency-domain equalization; MIMO channel estimation; space-time block coding

I. INTRODUCTION

Recently, a lot of attention is payed to multi-user multi-input multi-output (MIMO) multiplexing which can significantly increase the sum throughput in mobile communications systems. However, MIMO diversity still remains as an important technique to improve the bit error rate (BER) performance in a poor channel condition e.g. cell-edge area [1,2]. Typical examples of MIMO diversity are the maximum ratio transmission (MRT) [3], [4] and the maximum ratio transmission and combining (MRTC) [5]. For recent mobile broadband communications, propagation channels are severely frequency-selective and hence, MIMO diversity must be jointly used with equalization techniques. Assuming time-division duplex (TDD) and by exploiting the channel reciprocity, the equalization techniques are implemented solely at the base station (BS) for downlink transmission from BS to user equipment (UE) and uplink transmission from UE to BS [6]. The authors proposed a selective MIMO diversity with subcarrier-wise UE antenna identification/selection [7]. Joint MRT diversity and frequency-domain equalization (MRTD-FDE) and joint minimum mean square error combining diversity and FDE (MMSECD-FDE) [8] are applied for OFDM downlink and SC uplink, respectively.

Among other MIMO diversity schemes may be the space-time block coded (STBC) diversity [9,10-13]. In order to apply STBC diversity to a frequency-selective fading MIMO channel, we consider STBC diversity jointly used with MRTD/MMSECD-FDE, which permits an arbitrary number of BS transmit antennas while limiting the number of UE receive antennas to up to 6 [14, 15]. However, the STBC coding rate is reduced to equal or lower than 3/4 if more than two UE receive antennas are used. Knowing that the diversity and multiplexing tradeoff exists in MIMO channels [16], another interesting MIMO diversity could be the alternative use of MIMO multiplexing. There are a number of MIMO multiplexing schemes [17,18]. In this paper, the MMSE filtering combined with singular value decomposition (MMSE-SVD) [6] based diversity is considered.

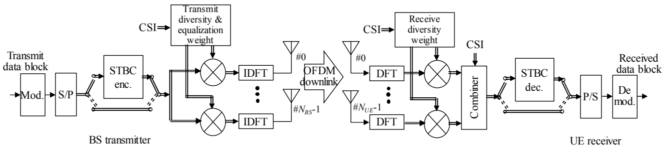
In this paper, we compare selective MIMO diversity with two other typical MIMO diversity schemes, i.e., STBC diversity and MMSE-SVD diversity, when using practical channel estimation. This paper is organized as follows. Section II briefly describes the transmission system model and the orthogonal pilot design. The selective MIMO diversity, STBC diversity and MMSE-SVD diversity are overviewed in Sect. III. In Sect. IV, their BER performances in a quasi-static frequency-selective Rayleigh fading MIMO channel are evaluated by computer simulation and compared. Finally, Sect. V offers concluding remarks.

II. TRANSMISSION SYSTEM MODEL

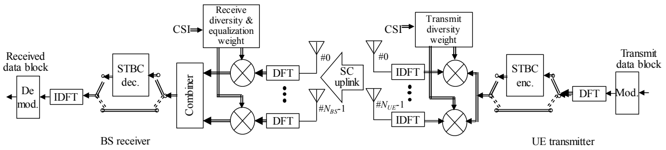
It is assumed that the number of subcarriers is N_c for both OFDM downlink and SC uplink and that BS and UE are equipped with N_{BS} and N_{UE} ($<N_{BS}$) antennas, respectively. MIMO channel estimation is necessary at both BS and UE to generate the transmit/receive diversity & equalization weights at BS and the transmit/receive diversity weights at UE prior to data transmission. Assuming TDD and by transmitting orthogonal pilots from UE antennas first and then from BS antennas (or vice versa), BS and UE can share the MIMO channel state information (CSI) without CSI feedback. An accurate MIMO channel estimation is possible by the pilot-aided channel estimation (PACE) [19,20].

Throughout the paper, discrete-time representation normalized by inverse discrete Fourier transform (IDFT) sampling period T_s is used, where $T_s = T / N_c$ with T being the IDFT block length in time.

The transmission system model of MIMO diversity is illustrated in Fig. 1. OFDM downlink and SC uplink are considered. Note that in this paper, it is assumed that SC waveform is generated by discrete Fourier transform (DFT)-spread OFDM principle. The transmit/receive diversity & equalization weights at BS and the transmit/receive diversity at UE are described in Sect. III. The TDD subframe structure considered in this paper is illustrated in Fig. 2, which consists of uplink pilot time slot (UpPTS) and downlink PTS (DwPTS), followed by 12 data time slots (DTSs) [21]. Due to TDD, the channel reciprocity can be exploited to share the MIMO CSI. During UpPTS period (slot time t=0), the orthogonal uplink pilots are transmitted from N_{UE} antennas. Then, during DwPTS period (slot time t=1), orthogonal downlink pilots are transmitted from N_{BS} antennas. By performing PACE, BS and UE share MIMO CSI to compute the transmit/receive diversity & equalization weight at BS and the receive/transmit diversity weight at UE to be used during slot time t=2~13.



(a) OFDM downlink



(b) SC uplink

Fig. 1. Simplified model of transmission system.

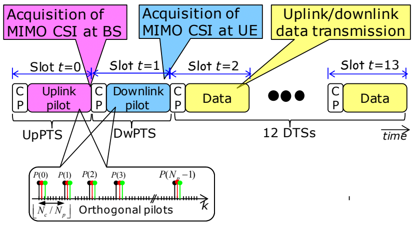


Fig. 2. TDD subframe structure.

III. MIMO DIVERSITY

Operation principles of selective MIMO diversity, STBC diversity, and MMSE-SVD diversity are described. The estimated CSI of $N_{BS} \times N_{UE}$ MIMO channel is denoted by $\{\hat{H}_{m,n}(k); k = 0 \sim N_c - 1\}$, where m (=0~N_{BS}−1) and n (=0~N_{UE}−1) represent the BS antenna index and the UE antenna index, respectively. The transmit/receive diversity & equalization weight at BS and the receive/transmit diversity weight at UE are denoted by $W_{BS,m}(k)$ and $W_{UE,n}(k)$, respectively, where k (=0~N_c−1) represents the subcarrier index.

A. Selective MIMO diversity

Using the acquired CSI $\{\hat{H}_{m,n}(k); k = 0 \sim N_c - 1\}$ by PACE, BS identifies the best UE antenna $\breve{n}(k)$ at slot time t=0 as $\breve{n}(k) = \arg\max_{n=0\sim N_{UE}-1} \sum_{m=0}^{N_{BS}-1} \left|\hat{H}_{m,n}(k)\right|^2$ and UE selects the $\breve{n}(k)$ th antenna at slot time t=1, which has been identified as the best by BS. Therefore, $W_{\mathrm{UE},n}(k)$ for both OFDM downlink and SC uplink can be expressed as

$$W_{UE,n}(k) = \begin{cases} 1 & \text{if } n = \breve{n} \\ 0 & \text{otherwise} \end{cases}. \quad (2)$$

In addition, the downlink pilot can be an MRTD-FDE-precoded pilot using N_c subcarriers. In this case, the UE antenna selection can be done by comparing the instantaneous pilot received powers on N_{UE} antennas for each subcarrier.

Assuming that the UE correctly selects the $\breve{n}(k)$-th antenna, BS computes the MRTD-FDE weight $W_{BS,m}^{\mathrm{MRTD}}(k)$ for OFDM downlink transmission and the MMSECD-FDE weight $W_{BS,m}^{\mathrm{MMSECD}}(k)$ for SC uplink reception as

$$\begin{cases} W_{BS,m}^{\mathrm{MRTD}}(k) = \dfrac{\hat{H}^*_{m,\breve{n}}(k)}{\sum_{m=0}^{N_{BS}-1} \left|\hat{H}_{m,\breve{n}}(k)\right|^2} \Bigg/ \sqrt{\dfrac{1}{N_c} \sum_{k=0}^{N_c-1} \left(\sum_{m=0}^{N_{BS}-1} \left|\hat{H}_{m,\breve{n}}(k)\right|^2 \right)^{-1}} \\ \qquad \text{for OFDM downlink transmission} \\ W_{BS,m}^{\mathrm{MMSECD}}(k) = \dfrac{\hat{H}^*_{m,\breve{n}}(k)}{\sum_{m=0}^{N_{BS}-1} \left|\hat{H}_{m,\breve{n}}(k)\right|^2 + (E_s / N_0)^{-1}} \\ \qquad \text{for SC uplink reception} \end{cases}, \quad (3)$$

where E_s and N_0 respectively denote the symbol energy and the single-sided additive white Gaussian noise (AWGN) power spectrum density. It should be noted that the MRTD-FDE weight of Eq.(3) is a combination of the conventional MRTD-FDE weight [3] and 2-dimensional (antennas and subcarriers) power allocation for keeping the transmit power intact. The MRTD-FDE weight achieves a close-to-frequency-nonselective equivalent channel while maximizing the received signal-to-noise power ratio (SNR) at the UE. On the other hand, the MMSECD-FDE weight can sufficiently weaken the frequency-selectivity of the diversity combiner output at the BS.

The symbol decision rules for the OFDM downlink at UE and for the SC uplink at BS are expressed as

$$\hat{d}(k \text{ or } t') = \begin{cases} \arg\min_{d \in \mathbf{D}} \left| R(k) - \sqrt{2S}\hat{H}_e(k) d \right|, \; k = 0 \sim N_c\text{-}1 \\ \qquad \text{for OFDM downlink} \\ \arg\min_{d \in \mathbf{D}} \left| r(t') - \sqrt{2S} \left(\dfrac{1}{N_c} \sum_{k=0}^{N_c-1} \hat{H}_e(k) \right) d \right|, \; t' = 0 \sim N_c\text{-}1, \\ \qquad \text{for SC uplink} \end{cases}, \quad (4)$$

where S denotes the average transmit power, d and $\mathbf{D}$ denote the symbol candidate and a set of candidate symbols, respectively, and $\hat{H}_e(k)$ is the equivalent channel gain given as

$$\hat{H}_e(k) = \begin{cases} \sum_{m=0}^{N_{BS}-1} W_{BS,m}^{\mathrm{MRTD}}(k)\hat{H}_{m,\breve{n}}(k) = 1 \Bigg/ \sqrt{\frac{1}{N_c}\sum_{k=0}^{N_c-1}\left(\sum_{m=0}^{N_{BS}-1}\left|\hat{H}_{m,\breve{n}}(k)\right|^2\right)^{-1}} & \text{for OFDM downlink} \\ \sum_{m=0}^{N_{BS}-1} W_{BS,m}^{\mathrm{MMSECD}}(k)H_{m,\breve{n}}(k) = \frac{\sum_{m=0}^{N_{BS}-1}\left|\hat{H}^*_{m,\breve{n}}(k)\right|^2}{\sum_{m=0}^{N_{BS}-1}\left|\hat{H}_{m,\breve{n}}(k)\right|^2 + \left(E_s/N_0\right)^{-1}} & \text{for SC uplink} \end{cases} . \quad (5)$$

Here, $R(k) = \sum_{n=0}^{N_{UE}-1} W_{UE,n}(k)R_n(k) = R_{\breve{n}}(k)$ for OFDM downlink and $\{r(t');t'=0\sim N_c-1\}$ of SC uplink is the N_c-point IDFT of $\{R(k);k=0\sim N_c-1\}$ with $R(k)$ given as $R(k) = \sum_{m=0}^{N_{BS}-1} W_{BS,m}^{\mathrm{MMSECD}}(k)R_m(k)$.

B. STBC diversity

The BS applies MRTD-FDE after STBC encoding in the case of OFDM downlink transmission and MMSECD-FDE before STBC decoding in the case of SC uplink reception. 2×2 Alamouti STBC is applied. The encoding and decoding rules are simple and expressed as [9]

$$\begin{cases} \text{Encoding rule: } \mathbf{D}(k) = \begin{bmatrix} D_0(k) & -D_1^*(k) \\ D_1(k) & D_0^*(k) \end{bmatrix} \\ \text{Decoding rule: } \begin{bmatrix} \hat{D}_0(k) \\ \hat{D}_1(k) \end{bmatrix} = \begin{bmatrix} R_{0,0}(k) + R_{1,1}^*(k) \\ R_{0,1}(k) - R_{1,0}^*(k) \end{bmatrix} \end{cases}, \quad (6)$$

where $D_0(k)$ and $D_1(k)$ are respectively the k-th frequency components in the 0th (even) and 1st (odd) data symbol blocks to be transmitted and $\hat{D}_0(k)$ and $\hat{D}_1(k)$ represents the corresponding decoded components. By using MRTD/MMSECD-FDE at BS, N_{UE}=2 antennas are allowed to be used while N_{BS} can be an arbitrary number (it is noted that by using other STBC codes, up to 6 UE antennas can be used [14,15]. $\{R_{n_{ue},q}(k); n_{ue}=0,1,\ q=0,1\}$ is the (n_{ue},q)-th element of the frequency-domain received signal matrix **R**(k) of size N_{UE}(=2)×2. Note that, for SC uplink reception at BS, **R**(k) is obtained by multiplying the received signal vector of size N_{BS}×2 by MMSECD-FDE weight matrix $\mathbf{W}_{BS}^{\mathrm{MMSECD}}(k)$ of size N_{UE}(=2)×N_{BS}.

For OFDM downlink transmission, the transmit signal matrix **S**(k) of size N_{BS}×2 is obtained by multiplying **D**(k) by MRTD-FDE weight matrix $\mathbf{W}_{BS}^{\mathrm{MRTD}}(k)$ of size N_{BS}×N_{UE} (=2). On the other hand, for SC uplink transmission, no transmit weight is applied to **S**(k) of size N_{UE}(=2)×2, i.e., **S**(k)=**D**(k). Therefore, **S**(k) can be expressed as

$$\mathbf{S}(k) = \begin{cases} \sqrt{\frac{2E_s}{T_s}}\mathbf{W}_{BS}^{\mathrm{MRTD}}(k)\mathbf{D}(k) \text{ for OFDM downlink} \\ \sqrt{\frac{2E_s}{T_s}}\mathbf{D}(k) \text{ for SC uplink} \end{cases}. \quad (7)$$

The MRTD/MMSECD-FDE weights are expressed, similarly to Eq. (3), as

$$\left\{\mathbf{W}_{BS}^{\mathrm{MRTD/MMSECD}}(k)\right\}_{m,n} = \begin{cases} \frac{\hat{H}^*_{m,n}(k)}{\sum_{m=0}^{N_{BS}-1}\sum_{n=0}^{N_{UE}-1}\left|\hat{H}_{m,n}(k)\right|^2} \Bigg/ \sqrt{\frac{1}{N_c}\sum_{k=0}^{N_c-1}\left(\sum_{m=0}^{N_{BS}-1}\sum_{n=0}^{N_{UE}-1}\left|\hat{H}_{m,n}(k)\right|^2\right)^{-1}}, & \text{MRTD for OFDM downlink} \\ \left(\sum_{n=0}^{N_{UE}-1}\sum_{m=0}^{N_{BS}-1}\left|\hat{H}_{m,n}(k)\right|^2 + \left(\frac{1}{N_{UE}}\frac{E_s}{N_0}\right)^{-1}\right)^{-1} \times \hat{H}^*_{m,n}(k), & \text{MMSECD for SC uplink} \end{cases} \quad (8)$$

with $\{\mathbf{W}\}_{m,n}$ denoting the (m,n)-th element of matrix **W**.

C. MMSE-SVD diversity

Originally, MMSE-SVD was proposed for multi-user MIMO multiplexing. By exploiting the diversity and multiplex tradeoff and letting all streams contain the same data (i.e., the single stream), the spatial diversity gain can be attained. For the OFDM downlink transmission, the BS's MMSE filter (or MMSE weight) matrix for OFDM transmission and SC uplink reception and the UE's eigenmode filter (or eigenmode weight) matrix generated by SVD are respectively expressed as [6]

$$\mathbf{W}_{BS}^{\mathrm{MMSE}}(k) = \begin{cases} \left(\mathbf{u}_{UE}^H(k)\mathbf{H}^T(k)\right)^H \times \left(\left(\mathbf{u}_{UE}^H(k)\mathbf{H}^T(k)\right)\left(\mathbf{u}_{UE}^H(k)\mathbf{H}^T(k)\right)^H + N_{UE}\left(\frac{E_s}{N_0}\right)^{-1}\right)^{-1} & \text{for OFDM downlink} \\ \left(\mathbf{H}(k)\mathbf{v}_{UE}(k)\right)^H \times \left(\left(\mathbf{H}(k)\mathbf{v}_{UE}(k)\right)\left(\mathbf{H}(k)\mathbf{v}_{UE}(k)\right)^H + \left(\frac{E_s}{N_0}\right)^{-1}\mathbf{I}_{N_{BS}}\right)^{-1} & \text{for SC uplink} \end{cases} \quad (9)$$

$$\mathbf{W}_{UE}^{\mathrm{SVD}}(k) = \begin{cases} \mathbf{u}_{UE}^H(k) & \text{for OFDM downlink} \\ \mathbf{v}_{UE}(k) & \text{for SC uplink} \end{cases}, \quad (10)$$

where **H**(k) is an N_{BS}×N_{UE} MIMO channel matrix. $\mathbf{u}_{UE}(k)$ and $\mathbf{v}_{UE}(k)$ are unitary vectors corresponding to the maximum eigenmode which are contained in $\mathbf{U}_{UE}(k)$ and $\mathbf{V}_{UE}(k)$ respectively. $\mathbf{U}_{UE}(k)$ and $\mathbf{V}_{UE}(k)$ are obtained by applying SVD to $\mathbf{H}(k)$ and $\mathbf{H}^T(k)$ as [20]

$$\begin{cases} \mathbf{H}(k) = \mathbf{U}_{UE}(k)\mathbf{\Lambda}^{1/2}(k)\mathbf{V}_{BS}^H(k) \\ \mathbf{H}^T(k) = \mathbf{U}_{BS}(k)\mathbf{\Lambda}^{1/2}(k)\mathbf{V}_{UE}^H(k) \end{cases}, \quad (11)$$

where, $\mathbf{\Lambda}(k)$ is the diagonal matrix whose diagonal element has the eigenvalue of the $\mathbf{H}(k)$.

The transmit signal matrix $\mathbf{S}(k)$ for OFDM downlink and SC uplink are expressed as

$$\mathbf{S}(k)=\begin{cases}\sqrt{\frac{2E_s}{T_s}}\mathbf{W}_{BS}^{\mathrm{MMSE}}(k)D(k) \text{ for OFDM downlink}\\ \sqrt{\frac{2E_s}{T_s}}\mathbf{W}_{BS}^{\mathrm{SVD}}(k)D(k) \text{ for SC uplink}\end{cases}. \tag{12}$$

The k-th frequency component after diversity combining, , $\hat{D}(k)$, can be obtained as

$$\hat{D}(k)=\begin{cases}\mathbf{W}_{UE}^{\mathrm{SVD}}(k)\mathbf{R}(k) \text{ for OFDM downlink}\\ \mathbf{W}_{BS}^{\mathrm{MMSE}}(k)\mathbf{R}(k) \text{ for SC uplink}\end{cases}. \tag{13}$$

IV. COMPUTER SIMULATION

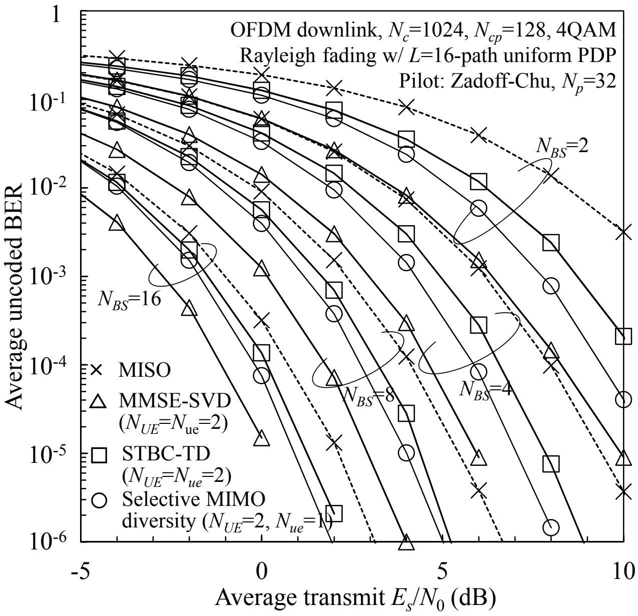
The average uncoded BER performances of three MIMO diversity schemes in OFDM downlink and SC uplink are evaluated by computer simulation. The computer simulation parameters are summarized in Table 1. It is assumed that BS and UE are equipped with N_{BS}=4~16 antennas and N_{UE}=2 antennas, respectively. $N_{BS}\times N_{UE}$ channels are assumed to be independent and identically distributed (i.i.d.) quasi-static frequency-selective Raleigh fading channels having L-path uniform power delay profile (PDP) with $\tau_{\max}=L-1$, where L=1 or 16 in this paper. The number of subcarriers (equal to IDFT/DFT size) is N_c=1024 and the CP length is N_{cp}=128. The Zadoff-Chu sequence [22] of N_p-symbol length is employed as the pilot symbol sequence, where N_p=32 is used. 4QAM data modulation is assumed. Prior to data transmission, PACE using delay-time domain windowing technique [23,24] is carried out for computing the transmit/receive diversity & equalization weight at BS and the receive/transmit diversity weight at UE.

TABLE I. COMPUTER SIMULATION PARAMETERS

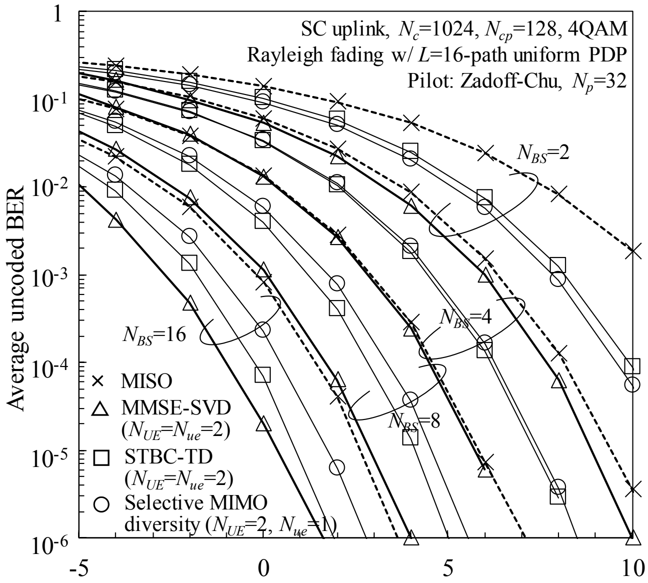
Subframe structure (14 slots)	No. of subcarriers	N_c=1024
	CP length	N_{cp}=128 samples
	Uplink/downlink pilots	Zadoff-Chu
	Data (12 slots)	4QAM
Fading channel	Type of fading	Quasi-static frequency-selective Rayleigh
	PDP	L-path uniform
	Maximum delay time	$\tau_{\max}=L$-1
Selective MIMO diversity	No of BS antennas	N_{BS}=4, 8, and 16
	No of UE antennas	N_{UE}=2

A. BER performance

The simulated average uncoded BER performances achievable with MIMO diversity schemes in a quasi-static L=16-path frequency-selective Rayleigh fading MIMO channel (the maximum Doppler frequency f_D=0) is plotted in Fig. 3 for various values of N_{BS}. For comparison, the average uncoded BER performance achievable with MISO/SIMO diversity (N_{UE}=1 always) is also plotted. The transmit power loss due to CP insertion, which is 0.51dB, is taken into account in the BER performance evaluation. It can be seen from the figure that three MIMO diversity schemes are superior to MISO/SIMO diversity. MMSE-SVD diversity is seen the best and is similar to the BER performance of $2N_{BS}\times 1$ MISO diversity.



(a) OFDM downlink



(b) SC uplink

Fig. 3. Average uncoded BER performance when L=16 (a freqeuncy-selective Rayleigh fading MIMO channel).

B. Computational complexity

Computational complexity for transceivers of three MIMO diversity techniques per subframe is estimated by counting the number of real-valued multiplication operations. Note that the complexity of MMSE-SVD diversity depends on the channel gain and is different for a different subcarrier in a frequency-selective fading MIMO channels. Therefore, its complexity is the averaged one. It can be shown that for SC uplink transmission with N_{BS}=8 and N_{UE}=2, selective MIMO diversity requires almost the same complexity as STBC-TD while it provides slightly better BER performance. On the other hand, although MMSE-SVD provides the best BER performance than others, it requires 5.3 times higher complexity at the BS and 3.5 times higher complexity at the UE, respectively, compared to selective MIMO diversity. The reason is that it requires the complex matrix inversion and SVD operations for weights calculation.

As a summary, it is worth to notice that MMSE-SVD achieves the best BER performance but at the cost of computational complexity, while selective MIMO diversity and STBC diversity achieve slightly worse BER performance but with much less computational complexity.

V. CONCLUSION

In this paper, selective MIMO diversity was compared with space-time block-coded (STBC) diversity and MMSE-SVD diversity in terms of uncoded average BER performance in a quasi-static Rayleigh fading MIMO channel. Pilot-aided channel estimation (PACE) was assumed to design transmit/receive diversity & equalization weights at BS and transmit/receive diversity weights at UE. The BER performance comparison in a quasi-static Rayleigh fading MIMO channel showed that the simple selective MIMO diversity provides comparable performance to STBC diversity while MMSE-SVD diversity provides the best BER performance among three diversity schemes. It should be noted that MMSE-SVD demands a high computational complexity, selective MIMO diversity is promising in practical mobile communications systems.

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