# On Antenna Selection for Selective MIMO Diversity

Fumiyuki ADACHI† and Amnart BOONKAJAY††
Research Organization of Electrical Communication (ROEC), Tohoku University
2-1-1 Katahira, Aoba-ku, Sendai, Miyagi, 980-8577 Japan
E-mail: †adachi@ecei.tohoku.ac.jp, ††amnart@riec.tohoku.ac.jp

***Abstract*— Single-user and single-stream multi-input multi-output (MIMO) diversity is a powerful means to improve the bit error rate (BER) performance in a poor channel condition. A large number of transmit/receive antennas can be equipped at a base station (BS) while only a few antennas at a user equipment (UE). In this paper, we consider a selective MIMO diversity. Prior to data transmission, pilot-aided channel estimation (PACE) is done for selecting a predetermined number of BS antennas and one UE antenna. We propose subcarrier-wise antenna selection and subcarrier-averaged antenna selection. It is shown by computer simulation that the subcarrier-wise antenna selection provides better BER performance than the subcarrier-averaged antenna selection in a frequency-selective channel.**

***Keywords—MIMO; diversity; channel estimation; antenna selection***

## I. INTRODUCTION

Antenna diversity [1-4] is a powerful means to improve the bit error rate (BER) performance in a poor channel condition. Basically, a large number of transmit/receive antennas can be equipped at a base station (BS) while a few antennas at a user equipment (UE). The maximal-ratio transmit diversity (MRTD) [5] and the minimum mean square error based combining diversity (MMSECD) [6] are typical examples for orthogonal frequency division multiplexing (OFDM) downlink and single-carrier (SC) uplink. All the signal processing necessary for MRTD/MMSECD is implemented at the BS side only. Since MRTD/MMSECD permits use of only single receive/transmit UE antenna, the achievable diversity gain is limited. To increase the diversity gain, we consider a selective MIMO diversity which allows to use multiple UE antennas. It should be noted that although the antenna selection is done on MIMO channel, the single-user and single-stream data transmission is carried out using MISO/SIMO diversity after antenna selection. We propose subcarrier-wise antenna selection and subcarrier-averaged antenna selection using pilot-aided channel estimation (PACE).

This paper is organized as follows. Section II describes the antenna selection methods using PACE. In Sect. III, the uncoded bit error rate (BER) performance is examined by computer simulation to compare antenna selection methods. Finally, Sect. IV offers concluding remarks and a future study.

## II. ANTENNA SELECTION

The equal number $N_c$ of subcarriers is assumed for OFDM downlink and SC uplink. BS and UE are assumed to have $N_{BS}$ antennas and $N_{UE}$ antennas, respectively. The time-division duplex (TDD), which can exploit the channel reciprocity in antenna selection, is assumed. Knowing that $N_{UE}$ is generally much smaller than $N_{BS}$, PACE is done first at BS. The subframe structure considered in this paper is illustrated in Fig.1, which consists of uplink pilot time slot (UpPTS) and downlink PTS (DwPTS) followed by 12 data time slots (DTSs) [7]. During UpPTS period (slot time $t$=0), UE transmits the uplink pilots from $N_{UE}$ antennas. After performing PACE, BS selects the best set of $N_{bs}$ ($<N_{BS}$) antennas and one UE antenna for computing the MRTD weight for OFDM downlink transmission and MMSECD weight for uplink reception, respectively. Then, during DwPTS period (slot time $t$=1), BS transmits downlink pilots from $N_{bs}$ selected antennas. The information about which UE antenna has been selected by BS is unknown to UE. By performing PACE, UE identifies the best UE antenna selected by BS. Uplink and downlink pilots are a type of frequency-division multiplexed (FDM) pilot with equally spaced pilot subcarrier mapping (see Fig. 1).

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. $N_{BS}$×$N_{UE}$ channels are assumed to be an independent and identically distributed (i.i.d.), quasi-static frequency-selective Rayleigh fading channels with the same maximum time delay $\tau_{\max}$ ($<\lfloor N_c/\max\{N_{BS}, N_{UE}\}\rfloor$). $\mathbf{N}_{BS}$ and $\mathbf{N}_{UE}$ represent a set of $N_{BS}$ BS antennas and that of $N_{UE}$ UE antennas, respectively. $\mathbf{N}_{bs}$ represents a set of $N_{bs}$ ($<N_{BS}$) selected BS antennas.

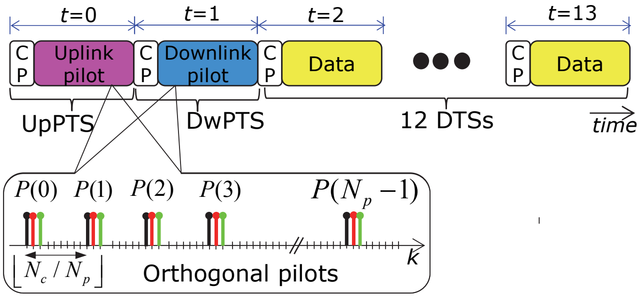


Fig. 1. Subframe structure.

### A. *Orthogonal pilot construction*

Orthogonal pilots $\{p_g(\nu); \nu = 0 \sim N_c - 1, g = 0 \sim \lfloor N_c/N_p \rfloor - 1\}$ are constructed by $N_c$-point IDFT using the Zadoff-Chu sequence [8] of $N_p$-symbol length, $\{P(\omega); \omega = 0 \sim N_p - 1\}$ with $|P(\omega)| = 1$. Filling zeros at subcarrier indices $\{k \neq g + \omega \cdot \lfloor N_c/N_p \rfloor; \omega = 0 \sim N_p - 1\}$ in $N_c$-point IDFT, $p_g(\nu)$ can be written as

$$\begin{cases} p_g(\nu)=\dfrac{1}{\sqrt{N_c}}\displaystyle\sum_{k=0}^{N_c-1}\sqrt{2S}P_g(k)\exp\left(j2\pi\frac{k}{N_c}\nu\right) \\ P_g(k)=\begin{cases}P(\omega) & \text{if } k=g+\omega\cdot\lfloor N_c/N_p\rfloor;\ \omega=0\sim N_p-1\\ 0 & \text{otherwise}\end{cases}\end{cases}, \quad (1)$$

where $\lfloor a \rfloor$ denotes an integer greater than or equal to $a$. The length $N_p$ of Zadoff-Chu sequence should satisfy the condition $\tau_{\max} < N_p \le \lfloor N_c/\max\{N_{BS}, N_{UE}\}\rfloor$ . $\lfloor N_c/N_p \rfloor$ pilots constructed in the above are orthogonal to each other. Different pilots are chosen for transmitting simultaneously from UE antennas or BS antennas. It should be noted that each subcarrier of any pilot has the same power of $(S/N_c)\cdot N_p < S$, where $S$ represents the average power of data signals to be transmitted at slot time $t$=2~13.

### *B. BS antenna selection and MRTD/MMSECD weights computation at slot time t=0*

UE transmits the $N_{UE}$ pilots $\{p_{n=g}(\nu); n=0\sim N_{UE}-1\}$ simultaneously from $N_{UE}$ antennas during the UpPTS period (slot time $t$=0). Without loss of generality, $N_{UE}$ pilots are chosen in the ascending order of index $g$ in Eq. (1). BS transforms the pilot received on the $m(\in \mathbf{N}_{BS})$ th antenna into the frequency-domain received pilot by performing $N_c$-point DFT and picks up components at frequencies $\{k=n+\omega\cdot\lfloor N_c/N_p\rfloor; \omega=0\sim N_p-1\}$ for each of $N_{UE}$ antennas. Since we are assuming that the maximum time delay is $\tau_{\max} < \lfloor N_c/\max\{N_{BS}, N_{UE}\}\rfloor$ , the delay-time domain windowing technique [9,10] can be used to obtain the channel gain estimates $\{\hat{H}_{m,n}(k,t=0); k=0\sim N_c-1\}$. Using the channel gain estimates, BS selects the best set of $N_{bs}$ (<$N_{BS}$) BS antennas and one UE antenna.

Our proposed subcarrier-wise antenna selection and subcarrier-averaged antenna selection are written as

$$\{\{m\},\breve{n}\}=\begin{cases}\displaystyle\max_{\substack{m\in\mathbf{N}_{bs}\\ n\in\mathbf{N}_{UE}}}\sum_m\left(\left|\hat{H}_{m,n}(k,t=0)\right|^2\right)\\ \text{for subcarrier-wise selection}\\ \displaystyle\max_{\substack{m\in\mathbf{N}_{bs}\\ n\in\mathbf{N}_{UE}}}\sum_m\left(\sum_{k=0\sim N_c-1}\left|\hat{H}_{m,n}(k,t=0)\right|^2\right)\\ \text{for subcarrier-averaged selection}\end{cases}. \quad (2)$$

For the sake of brevity, the index $k$ has been omitted from $m(k)$ and $\breve{n}(k)$ for the subcarrier-wise selection method in Eq. (2). Hereafter, the above representation is used unless otherwise stated.

BS computes the MRTD weight $W_m^{MRTD}(k)$ for OFDM downlink transmission and the MMSECD weight $W_m^{MMSECD}(k)$ for SC uplink reception. They are given as

$$W_m^{MRTD}(k)=\frac{\left(\dfrac{\hat{H}^*_{m,\breve{n}}(k,t=0)}{\sum_{m\in\mathbf{N}_{bs}}\left|\hat{H}_{m,\breve{n}}(k,t=0)\right|^2}\right)}{\sqrt{\dfrac{1}{N_c}\displaystyle\sum_{k=0}^{N_c-1}\left(\sum_{m\in\mathbf{N}_{bs}}\left|\hat{H}_{m,\breve{n}}(k,t=0)\right|^2\right)^{-1}}}$$

for OFDM downlink transmission (3)

$$W_m^{MMSECD}(k)=\frac{\hat{H}^*_{m,\breve{n}}(k,t=0)}{\displaystyle\sum_{m\in\mathbf{N}_{bs}}\left|\hat{H}_{m,\breve{n}}(k,t=0)\right|^2+(E_s/N_0)^{-1}}$$

for SC uplink reception, (4)

where $E_s$ represents the transmit data signal energy given by $E_s=S\cdot(T/N_c)$ and $N_0$ denotes the single-sided power spectrum density of zero-mean complexed-valued additive white Gaussian noise (AWGN).

The MRTD weight of Eq. (3) maximizes the received signal-to-noise power ratio (SNR) and achieves the frequency-nonselective equivalent channel seen at the UE receiver while keeping the transmit power intact (i.e., always equal to $S$). On the other hand, the MMSECD weight of Eq. (4) sufficiently weakens the frequency-selectivity of the equivalent channel seen at the BS receiver (the equivalent channel will be discussed in Sect. III).

### *C. UE antenna selection and equivalent OFDM downlink channel gain computation at slot time t=1*

MBS transmits the $N_{bs}$ pilots $\{p_{g=m}(\nu); m=0\sim N_{bs}-1\}$ simultaneously from selected $N_{bs}$ antennas during the DwPTS period (slot time $t$=1). Similar to the uplink PACE using the delay-time domain windowing technique [9,10] performed at BS, UE obtains the channel gain estimates $\{\hat{H}_{m,n}(k,t=1); k=0\sim N_c-1, m\in\mathbf{N}_{bs}, n\in\mathbf{N}_{UE}\}$ and identifies the $\breve{n}$ th antenna, which has been selected by BS, as follows.

$$\breve{n}=\begin{cases}\displaystyle\max_{n\in\mathbf{N}_{UE}}\sum_{m\in\mathbf{N}_{bs}}\left(\left|\hat{H}_{m,n}(k,t=1)\right|^2\right)\\ \text{for subcarrier-wise selection}\\ \displaystyle\max_{n\in\mathbf{N}_{UE}}\sum_m\left(\sum_{k=0\sim N_c-1}\left|\hat{H}_{m,n}(k;t=1)\right|^2\right)\\ \text{for subcarrier-averaged selection}\end{cases}. \quad (5)$$

Since the uplink and downlink channels are reciprocal due to TDD, the probability of false identification of UE antenna can be negligibly small (this was confirmed by a preliminary computer simulation). The subcarrier-averaged antenna selection requires IDFT/DFT for each of $N_{BS}$ and $N_{UE}$ antennas and hence, is more complex.

## III. MIMO DIVERSITY TRANSMISSION AND RECEPTION

BS uses the MRTD weight $W_m^{MRTD}(k)$ of Eq. (3) and the MMSECD weight of Eq. (4) for OFDM downlink transmission and SC uplink reception, respectively, during slot time $t$=2~13.

### A. OFDM downlink

BS transforms an $N_c$-symbol data block $\{d(\nu,t);\nu = 0 \sim N_c - 1\}$ with $E[|d(\nu,t)|^2] = 1$ to be transmitted into the frequency-domain signal $\{d(k,t);k = 0 \sim N_c - 1\}$ and then, multiplies $d(k,t)$ by $W_m^{MRTD}(k)$. The resultant frequency-domain signal $\left\{\sqrt{2S}W_m^{MRTD}(k)d(k,t);k = 0 \sim N_c - 1\right\}$ to be transmitted from the $m$th BS antenna is transformed back to the time-domain OFDM signal by $N_c$-point IDFT. The resultant time-domain signals are transmitted from $N_{bs}$ antennas.

UE transforms the OFDM signals received on $N_{UE}$ antennas by $N_c$-point DFT into the frequency-domain signals. Then, for each $k(= 0 \sim N_c - 1)$, UE selects the frequency component $R_{\breve{n}}(k,t)$ received on the $\breve{n}(k)$th antenna. The antenna selection output $\{R(k,t);n = 0 \sim N_c - 1\}$ can be written as

$$R(k,t) = \sqrt{2S}H_e(k,t)d(k,t) + N_{\breve{n}}(k,t), \tag{6}$$

where $H_e(k,t)$ and $N_{\breve{n}}(k,t)$ are the equivalent channel gain and the noise, respectively. $H_e(k,t)$ is given as

$$H_e(k,t) = \sum_{m\in\mathbf{N}_{bs}} W_m^{MRTD}(k)H_{m,\breve{n}}(k,t)\cdot \tag{7}$$

The symbol decision rule is expressed as

$$\hat{d}(k,t) = \min_{d\in\mathbf{D}}\left|R(k,t) - \sqrt{2S}\hat{H}_e(k,t)d\right|,\quad k = 0 \sim N_c - 1, \tag{8}$$

where $d$ and $\mathbf{D}$ denote the symbol candidate and a set of candidate symbols, respectively. Since $H_e(k,t)$ is unknown to UE, it has been replaced with its estimate $\hat{H}_e(k,t)$, which is computed as follows.

$$\begin{aligned}\hat{H}_e(k,t) &= \sum_{m\in\mathbf{N}_{bs}} W_m^{MRTD}(k)\hat{H}_{m,\breve{n}}(k,t=1)\\ &= \frac{\left(\dfrac{\sum_{m\in\mathbf{N}_{bs}}\hat{H}^*_{m,\breve{n}}(k,t=1)\hat{H}_{m,\breve{n}}(k,t=1)}{\sum_{m\in\mathbf{N}_{bs}}\left|\hat{H}_{m,\breve{n}}(k,t=1)\right|^2}\right)}{\sqrt{\dfrac{1}{N_c}\sum_{k=0}^{N_c-1}\left(\sum_{m\in\mathbf{N}_{bs}}\left|\hat{H}_{m,\breve{n}}(k,t=1)\right|^2\right)^{-1}}}.\end{aligned} \tag{9}$$

Note that $\hat{H}_{m,\breve{n}}(k,t=0)$ in $W_m^{MRTD}(k)$ of Eq. (3) is unknown to UE and hence, it has been replaced with $\hat{H}_{m,\breve{n}}(k,t=1)$. Furthermore, it should be noted that $\breve{n}$ is a function of $k$ for the subcarrier-wise antenna selection.

### B. SC uplink

UE transforms an $N_c$-symbol data block $\{d(\nu,t);\nu = 0 \sim N_c - 1\}$ to be transmitted into the frequency-domain signal $\{D(k,t);k = 0 \sim N_c - 1\}$ by $N_c$-point DFT. Then, $\{D(k,t);k = 0 \sim N_c - 1\}$ are mapped to $N_{UE}$ antennas according to the antenna selection $\{\breve{n};k = 0 \sim N_c - 1\}$. The frequency-domain signal $\left\{\sqrt{2S}D_n(k,t);k = 0 \sim N_c - 1\right\}$ to be transmitted from the $n$th UE antenna is transformed back to the time-domain SC signals by $N_c$-point IDFT, where $D_n(k,t) = D(k,t)$ if $n = \breve{n}(k)$, $D_n(k,t) = 0$ otherwise. The resultant time-domain signals are transmitted from $N_{UE}$ antennas (note that the same antenna is selected for all $k$ in the subcarrier-averaged antenna selection).

BS transforms the SC signal received on its $m$th antenna by an $N_c$-point DFT into the frequency-domain signal $\{R_m(k,t);k = 0 \sim N_c - 1\}$. MMSECD is performed as

$$R(k,t) = \sum_{m\in\mathbf{N}_{bs}} W_m^{MMSECD}(k)R_m(k,t)\cdot \tag{10}$$

For carrying out the symbol decision, the time-domain received signal $\{r(\nu,t);\nu = 0 \sim N_c - 1\}$ is obtained by applying $N_c$-point IDFT to $\{R(k,t);k = 0 \sim N_c - 1\}$. $R(k,t)$ can be written as

$$R(k,t) = \sqrt{2S}H_e(k,t)D(k,t) + \sum_{m\in\mathbf{N}_{bs}} W_m^{MMSECD}(k)N_m(k,t)\cdot \tag{11}$$

In the above, $H_e(k,t) = \sum_{m\in\mathbf{N}_{bs}} W_m^{MMSECD}(k)H_{m,\breve{n}}(k,t)$ is the equivalent channel gain. However, it is unknown to BS. Therefore, it is replaced with its estimate $\hat{H}_e(k,t)$. The symbol decision rule is expressed as

$$\hat{d}(\nu,t) = \min_{d\in\mathbf{D}}\left|r(\nu,t) - \sqrt{2S}\left(\frac{1}{N_c}\sum_{k=0}^{N_c-1}\hat{H}_e(k,t)\right)d\right|, \nu = 0 \sim N_c - 1, \tag{12}$$

where $\hat{H}_e(k,t)$ can be computed by using $W_m^{MMSECD}(k)$ of Eq. (4) and $\hat{H}_{m,\breve{n}}(k,t=0)$ as

$$\begin{aligned}\hat{H}_e(k,t) &= \sum_{m\in\mathbf{N}_{bs}} W_m^{MMSECD}(k)H_{m,\breve{n}}(k,t=0)\\ &= \frac{\sum_{m\in\mathbf{N}_{bs}}\left|\hat{H}_{m,\breve{n}}(k,t=0)\right|^2}{\sum_{m\in\mathbf{N}_{bs}}\left|\hat{H}_{m,\breve{n}}(k,t=0)\right|^2 + \left(E_s/N_0\right)^{-1}}.\end{aligned} \tag{13}$$

## IV. COMPUTER SIMULATION

The average uncoded BER performances of OFDM downlink and SC uplink with selected MIMO diversity are evaluated by computer simulation. The computer simulation parameters are summarized in Table 1.

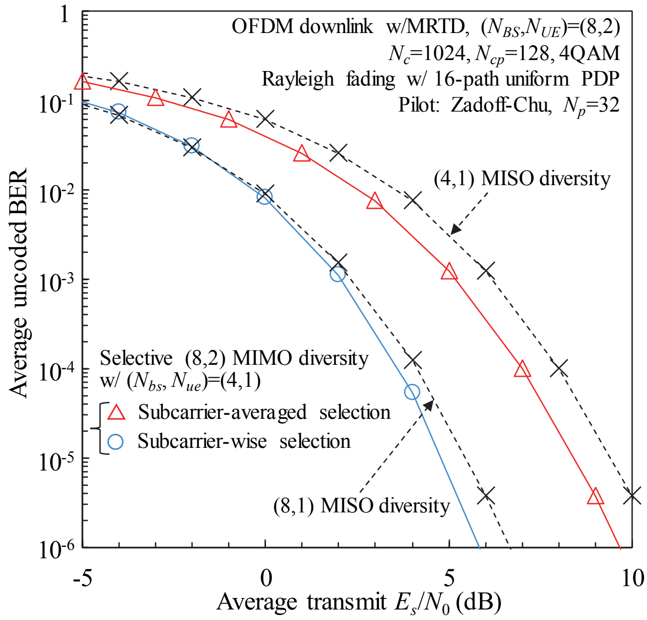
TABLE I. COMPUTER SIMULATION PARAMETERS

| | | |
|---|---|---|
| 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 | 16-path block Rayleigh assuming Jakes model |
| | Power delay profile | Uniform |
| | Maximum delay time | $\tau_{max}$=16 |
| Selective MIMO diversity | No of BS antennas | $N_{BS}$=8 |
| | No of UE antennas | $N_{UE}$=2 |

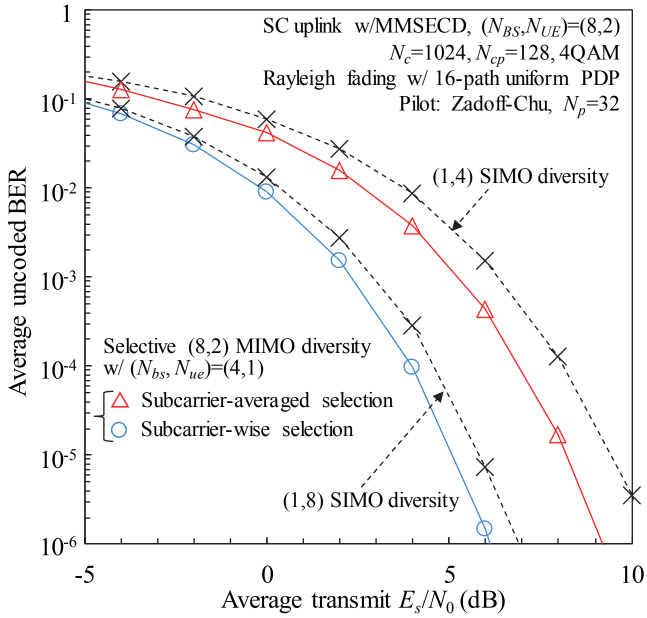
It is assumed that BS and UE are equipped with $N_{BS}$=8 antennas and $N_{UE}$=2 antennas, respectively. $N_{BS}\times N_{UE}$ channels are assumed to be i.i.d. quasi-static frequency-selective Raleigh fading channels having 16-path uniform power delay profile (PDP) with $\tau_{max}$ =16. The number of subcarriers (equal to IDFT/DFT size) is $N_c$=1024 and the cyclic prefix (CP) length is $N_{cp}$=128. According to our proposed antenna selection methods, the best set of $N_{bs}$=4 BS antennas and one UE antenna is selected, by PACE using delay-time domain windowing technique, from $N_{BS}$=8 antennas and $N_{UE}$=2 antennas prior to data transmission (hereafter called selective (8,2) MIMO diversity). The Zadoff-Chu sequence [8] of $N_p$ =32-symbol length is employed as the pilot symbol sequence $\{P(\omega);\omega=0\sim N_p-1\}$ . $N_p$ =32 satisfies the condition $\tau_{max} < N_p \le \lfloor N_c / \max\{N_{BS}, N_{UE}\} \rfloor$. The perfect knowledge of received $E_s/N_0$ is assumed for computing the MMSECD weights of Eq. (4). 4QAM data modulation is assumed.

The average uncoded BER performances achievable with two antenna selection methods in a frequency-selective Rayleigh fading channel are compared in Fig. 2. The transmit power loss due to CP insertion, which is 0.51dB was taken into account in the BER performance evaluation. For comparison, the average uncoded BER performance achievable with MISO/SIMO diversity ($N_{BS}$=4~8, $N_{UE}$=1) is also plotted. It is clearly seen from the figure that the subcarrier-wise antenna selection provides significantly better BER performance than the subcarrier-averaged antenna selection. Selective (8,2) MIMO diversity using the subcarrier-wise antenna selection provides better performance than (8,1) MISO/(1,8) SIMO diversity without antenna selection although they use the same diversity scheme, i.e., (4,1) MRTD for OFDM downlink and (1,4) MMSECD for SC uplink. It is worthwhile to notice that the OFDM downlink with MRTD and SC uplink with MMSECD provide similar BER performance.

Full (8,2) MIMO diversity is expected to provide the best performance; however, an application of space-time block coded transmit diversity (STBCTD) scheme [11] is required. Performance comparison between selective (8,2) MIMO diversity and full (8,2) MIMO STBCTD is left as our future study.



(a) OFDM downlink w/ MRTD



(b) SC uplink w/ MMSECD

Fig. 2. Average uncoded BER perfornace.

## V. CONCLUSION

In this paper, the subcarrier-wise antenna selection and the subcarrier-averaged antenna selection were proposed for selective MIMO diversity. Assuming $(N_{BS},N_{UE})$=(8,2) and $(N_{bs},N_{ue})$=(4,1), the computer simulatio, confirmed that the former selection method provides much better BER performance compared to the latter. It was shown that selective (8,2) MIMO diversity using subcarrier-wise antenna selection provides better performance than (8,1) MISO/(1,8) SIMO diversity. Meanwhile, full (8,2) MIMO diversity provides the best performance, but an application of space-time block coded transmit diversity (STBCTD) scheme [11] is required.

Performance comparison between selective (8,2) MIMO diversity and full (8,2) MIMO STBCD is left as our future study.

In the computer simulation, the quasi-static frequency-selective Rayleigh fading was assumed (i.e., a very low mobility environment). In a high mobility environment, the channels changes over the data transmission period and therefore, the PACE based antenna selection prior to the data transmission may degrade the achievable BER performance. Improving the BER performance in a high mobility environment is left as our important future study.

## ACKNOWLEDGMENT

This paper includes a part of results of "The research and development project for realization of the fifth-generation mobile communications system" commissioned to Tohoku University by The Ministry of Internal Affairs and Communications (MIC), Japan.

## REFERENCES

[1] W. C. Jakes, Jr. (Ed.), *Microwave mobile communications*, Wiley, New York, 1974.

[2] D. Tse and P. Viswanath, *Fundamental of wireless communication*, Cambridge University Press, 2005.

[3] B. Clercks and C. Oestges, *MIMO wireless networks: channels, tecniques and standatds for multi-antenna, multi-user and multi-cell systems*, Academic Press, 2013.

[4] F. Adachi, A. Boonkajay, Y. Seki, T. Saito, S. Kumagai, and H. Miyazaki, "Cooperative distributed antenna transmission for 5G mobile communications network," IEICE Trans. Commun., Vol.E100-B, No.8, pp. 1190-1204, Aug. 2017.

[5] J. K. Cavers, "Single-user and multiuser adaptive maximal ratio transmission for Rayleigh channels," IEEE Trans. Vehi. Technol., Vol. 49, No.6, pp. 2043-2050, Nov. 2000.

[6] F. Adachi, H. Tomeba, and Kazuki Takeda, "Introduction of frequency-domain signal processing to broadband single-carrier transmissions in a wireless channel," IEICE Trans. Commun., Vol.E92-B, No.09, pp. 2789-2808, Sep. 2009.

[7] F. Adachi, A. Boonkajay, Y. Seki, and T. Saito, "MIMO channel estimation for time-division duplex distributed antenna cooperative transmission," Proc. The 13th International Wireless Communications and Mobile Computing Conference (IWCMC 2017), Valencia, Spain, 26-30 June, 2017.

[8] D. C. Chu, "Polyphase codes with good periodic correlation properties," IEEE Trans. Inf. Theory, Vol. 8, No. 4, pp. 531-532, July 1972.

[9] J. J. van de Beek, O. Edfors, M. Sandell, S. K. Wilson, and P. O. Borjesson, "On channel estimation in OFDM systems," Proc. IEEE Veh. Technol. Conf. (VTC1995), Chicago, USA, Vol. 2, pp. 815-819, Jul. 1995.

[10] T. Fujimori, K. Takeda, K. Ozaki, A. Nakajima, and F. Adachi, "Channel estimation using cyclic delay pilot for SC-MIMO multiplexing," IEICE Trans. Commun., Vol.E91-B, No.09, pp. 2925-2932, Sep. 2008.

[11] S. M. Alamouti, "A simple transmit diversity technique for wireless communications," IEEE J. Sel. Areas Commun., Vol. 16, No. 8, pp. 1451–1458, Oct. 1998.