Hardware Implementation of Proposed Antenna Selection Algorithm and its Performance Evaluation Using Received Signals in Field Experiment

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***Abstract*—Multiple-input multiple-output (MIMO) systems with antenna selection are practical ones that can intuitively alleviate the computational complexity at the receiver and achieve good reception performance. Channel correlation, not just carrier-to-noise ratio (CNR), has a great impact on the reception performance in MIMO channels. We propose a simple antenna selection algorithm that exploits the condition number of the channel matrix and a predetermined threshold CNR. This paper describes the hardware implementation of the proposed algorithm and its performance evaluation, which was conducted in an indoor measurement using received signals obtained in the actual mobile outdoor experiment. The results confirm that our proposed method provides good bit error rate performance by setting a threshold CNR properly.**

I. Introduction

A wireless link system that can transmit high-definition videos with high link reliability is anticipated for large-scale live broadcasts such as road races. To achieve high link reliability, we have proposed a minimum mean square error macro-diversity (MMSE-MD) reception system using many distributed remote antennas and radio-on-fiber (RoF) links and confirmed its effectiveness in field experiments on an actual road race course [1]. The prototype MMSE-MD receiver has 16 input ports and can detect orthogonal frequency division multiplexing (OFDM) signals. The receiver selects four optimum antennas from the maximum of 16 based on the carrier-to-noise ratio (CNR) after delay difference correction and combines them using the MMSE algorithm.

We have also been considering to introduce multiple-input multiple-output (MIMO) techniques into the system to achieve high transmission capacity. However, the CNR-based antenna selection method for OFDM systems is not optimal for MIMO-OFDM systems because channel correlation greatly affects the signal-detection performance at the receiver. Several antenna selection methods for MIMO systems have been proposed to alleviate the cost of multiple RF chains associated with multiple antennas [2], [3]. Most of them use the Shannon capacity and various bounds on the error rate as antenna selection criteria. Several semi-optimal antenna selection methods have also been presented in [4], [5], [6], [7]. The method in [4] uses the maximum mutual information criterion to reduce the computational complexity caused by an exhaustive search over all possible antenna subsets. However, a semi-optimal antenna selection algorithm with lower complexity and better performance is necessary in order to implement the actual hardware with limited resources.

The authors propose a simple antenna selection algorithm that exploits the condition number of the channel matrix and a predetermined threshold CNR. In the algorithm, the antenna with the largest CNR is first selected as a reference branch. Then, antennas whose CNRs exceed the predetermined threshold CNR are chosen on the basis of the condition number of the channel matrix between the reference and the others in order to avoid an exhaustive combination search. This paper also describes the hardware implementation of the proposed algorithm and its performance evaluation, which was conducted in an indoor measurement using signals received in the actual mobile outdoor experiment. In particular, the relation between the threshold CNR setting and the reception performance is explored using the empirical cumulative probability function of BER, CNR and the condition number of the channel matrix.

This paper is organized as follows: Section II describes the proposed antenna selection algorithm. Section III describes the hardware implementation of the algorithm and the prototype MMSE-MD receiver for the MIMO system. Section IV outlines a field experiment to record the received signals. Section V demonstrates the evaluation method using the acquired received signals and evaluation results. Section VI concludes this paper.

II. Antenna Selection Algorithm

A. MIMO system with antenna selection

Assume a MIMO system with N transmit and M receive antennas which are selected from all receive antennas of P.

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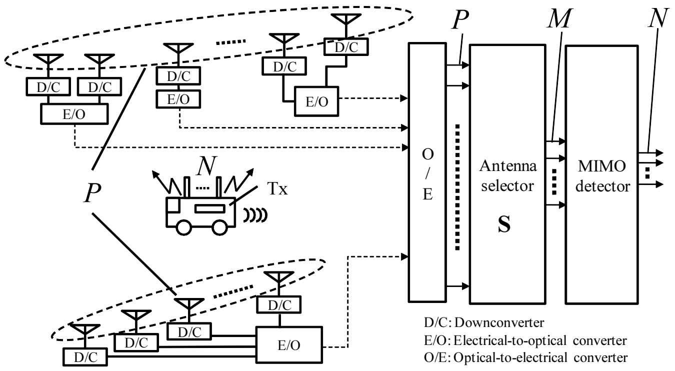

Fig. 1. MIMO system with antenna selection.

This system is shown in Fig. 1 and expressed as

$$\begin{aligned} \mathbf{y} &= \mathbf{SHx} + \mathbf{n} \\ &= \widetilde{\mathbf{H}}\mathbf{x} + \mathbf{n} \end{aligned} \tag{1}$$

where $\mathbf{H} \in \mathbb{C}^{P \times N}$ is the channel matrix, and $\mathbf{x} \in \mathbb{C}^{N \times 1}$ and $\mathbf{y} \in \mathbb{C}^{M \times 1}$ are transmitted and received signal vectors. $\mathbf{S} \in \mathbb{Z}^{M \times P}$ is the antenna selection matrix and given by

$$\mathbf{S} = [\mathbf{e}_1 \ \ \mathbf{e}_2 \ \cdots \ \mathbf{e}_M]^T \tag{2}$$

where $\mathbf{e}_m \in \mathbb{Z}^{P \times 1}$ is the unit vector whose elements are zero except for the p-th one corresponding to the selected p-th antenna, so that $\widetilde{\mathbf{H}} \in \mathbb{C}^{M \times N}$ shows the channel matrix among N transmit antennas and selected M receive antennas. The vector $\mathbf{n} \in \mathbb{C}^{M \times 1}$ is additive white Gaussian noise (AWGN).

B. Conventional Algorithms

Several antenna selection algorithms have been reported in [2], [3]. Most of them exploit the Shannon capacity $C(\widetilde{\mathbf{H}})$, as a selection criterion and exhaustively search for the best antenna subset that maximizes the criterion from possible antenna combinations. The Shannon capacity is given by

$$C(\widetilde{\mathbf{H}}) = \log_2 \det\left(\mathbf{I} + \left(\frac{\gamma}{N}\right)\widetilde{\mathbf{H}}^H \widetilde{\mathbf{H}}\right) \tag{3}$$

where $\mathbf{I}$ and γ show the identity matrix and the average signal-to-noise ratio (SNR) per receive antenna, respectively. On the other hand, a low-complexity method that computes the correlation Ξ between arbitrary row vectors $\mathbf{h}_k$ and $\mathbf{h}_l$ of the matrix $\mathbf{H}$ was proposed in [4]. The algorithm calculates each norm of the row vectors with the largest correlation and deletes the row vector with the lower norm repeatedly. Furthermore, when γ is available, another method, a modified version, selects two row vectors with the maximum mutual information $I(y_k; y_l)$ and deletes the row vector with the lower norm, where

$$I(y_k; y_l) = \log \frac{(||\mathbf{h}_k||^2 \frac{\gamma}{N} + 1)(||\mathbf{h}_l||^2 \frac{\gamma}{N} + 1)}{(||\mathbf{h}_k||^2 \frac{\gamma}{N} + 1)(||\mathbf{h}_k||^2 \frac{\gamma}{N} + 1) - \Xi^2 \frac{\gamma^2}{N^2}} \tag{4}$$

C. Proposed Algorithm

First, we investigate what parameter without the CNR has an impact on the signal-detection performance in a MIMO channel. In eq. (1), when we omit the AWGN vector $\mathbf{n}$ and consider errors of $\Delta\mathbf{H}$, $\Delta\mathbf{x}$ and $\Delta\mathbf{y}$, $\Delta\mathbf{x}$ is expressed as

$$\begin{aligned} &(\mathbf{H} + \Delta\mathbf{H})(\mathbf{x} + \Delta\mathbf{x}) = \mathbf{y} + \Delta\mathbf{y} \\ \Leftrightarrow\ &(\mathbf{H} + \Delta\mathbf{H})\Delta\mathbf{x} = \Delta\mathbf{y} - \Delta\mathbf{H}\mathbf{x} \\ \Leftrightarrow\ &\Delta\mathbf{x} = (\mathbf{H} + \Delta\mathbf{H})^{-1}(\Delta\mathbf{y} - \Delta\mathbf{H}\mathbf{x}) \\ &\quad = (\mathbf{I} + \mathbf{H}^{-1}\Delta\mathbf{H})^{-1}\mathbf{H}^{-1}(\Delta\mathbf{y} - \Delta\mathbf{H}\mathbf{x}) \end{aligned} \tag{5}$$

When the norm $|| \cdot ||$ of (5) is divided by $||\mathbf{x}||$, the following inequality is given.

$$\begin{aligned} \frac{||\Delta\mathbf{x}||}{||\mathbf{x}||} &\leq ||(\mathbf{I} + \mathbf{H}^{-1}\Delta\mathbf{H})^{-1}|| \cdot ||\mathbf{H}^{-1}|| \cdot \left(||\Delta\mathbf{H}|| + \frac{||\Delta\mathbf{y}||}{||\mathbf{x}||}\right) \\ &\leq \frac{||\mathbf{H}^{-1}||}{1 - ||\mathbf{H}^{-1}\Delta\mathbf{H}||}\left(||\Delta\mathbf{H}|| + \frac{||\mathbf{H}|| \cdot ||\Delta\mathbf{y}||}{||\mathbf{y}||}\right) \\ &\leq \frac{||\mathbf{H}|| \cdot ||\mathbf{H}^{-1}||}{1 - ||\Delta\mathbf{H}||/||\mathbf{H}||}\left(\frac{||\Delta\mathbf{H}||}{||\mathbf{H}||} + \frac{||\Delta\mathbf{y}||}{||\mathbf{y}||}\right) \end{aligned} \tag{6}$$

Furthermore, when $||\Delta\mathbf{H}|| \ll ||\mathbf{H}||$ holds, (6) is expressed as

$$\frac{||\Delta\mathbf{x}||}{||\mathbf{x}||} \leq \kappa(\mathbf{H}) \cdot \left(\frac{||\Delta\mathbf{H}||}{||\mathbf{H}||} + \frac{||\Delta\mathbf{y}||}{||\mathbf{y}||}\right) \tag{7}$$

$$\kappa(\mathbf{H}) = ||\mathbf{H}|| \cdot ||\mathbf{H}^{-1}|| \tag{8}$$

where $\kappa(\mathbf{H})$ is the condition number of the channel matrix $\mathbf{H}$ [8]. When $\kappa(\mathbf{H})$ becomes large, (7) means that the accurate signal detection of $\mathbf{x}$ becomes difficult, even if $\Delta\mathbf{H}$ and $\Delta\mathbf{y}$ remain small. Therefore, we exploit the condition number $\kappa(\mathbf{H})$ as one of the antenna selection criteria in this paper.

Next, we describe the low-complexity antenna selection method that exploits the condition number of the channel matrix and a threshold CNR. We explain the method under the assumption that the number of transmit antennas is fixed to N = 2 as in our prototype system.

(I) The receive antenna p_0 with the largest CNR is first selected as a reference antenna.

(II) The 2×2 partial channel matrix $\hat{\mathbf{H}}_p$ is generated using the p_0-th row vector $[\mathbf{h}_{p_0,1} \ \mathbf{h}_{p_0,2}]$ and the p-th ($\neq p_0$) row vector $[\mathbf{h}_{p,1} \ \mathbf{h}_{p,2}]$ of the channel matrix $\mathbf{H}$ as follows.

$$\widehat{\mathbf{H}}_p = \begin{pmatrix} \mathbf{h}_{p_0,1} & \mathbf{h}_{p_0,2} \\ \mathbf{h}_{p,1} & \mathbf{h}_{p,2} \end{pmatrix} \tag{9}$$

(III) The condition number $\kappa(\widehat{\mathbf{H}}_p)$ of the partial channel matrix is computed in accordance with the formula

$$\kappa(\widehat{\mathbf{H}}_p) = \sqrt{\frac{a + d + \sqrt{(a+d)^2 - 4(ad - bc)}}{a + d - \sqrt{(a+d)^2 - 4(ad - bc)}}} \tag{10}$$

where a, b, c and d are given by

$$\begin{aligned} a &= \mathbf{h}^*_{p_0,1}\mathbf{h}_{p_0,1} + \mathbf{h}^*_{p,1}\mathbf{h}_{p,1} \\ b &= \mathbf{h}^*_{p_0,1}\mathbf{h}_{p_0,2} + \mathbf{h}^*_{p,1}\mathbf{h}_{p,2} \\ c &= \mathbf{h}^*_{p_0,2}\mathbf{h}_{p_0,1} + \mathbf{h}^*_{p,2}\mathbf{h}_{p,1} \\ d &= \mathbf{h}^*_{p_0,2}\mathbf{h}_{p_0,2} + \mathbf{h}^*_{p,2}\mathbf{h}_{p,2} \end{aligned}$$

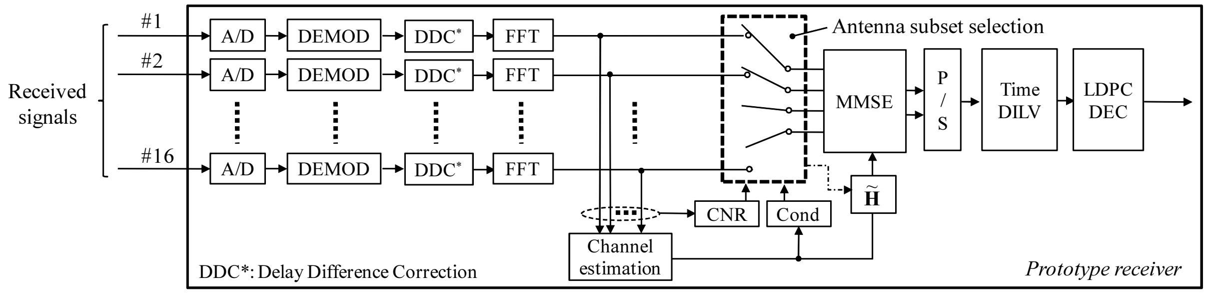

Fig. 2. Structure of prototype receiver with antenna selection.

(IV) The receive antennas with smaller $\kappa(\widehat{\mathbf{H}}_p)$ are selected in turn until the number of selected antennas reaches M, under the condition that CNR of each antenna exceeds a predetermined threshold CNR $\gamma_{\rm th}$.
(V) If the number of selected antennas in (IV) does not reach M, antennas with smaller $\kappa(\widehat{\mathbf{H}}_p)$ are chosen from the remainder in turn until the antenna subset becomes complete.

In what follows, we present the hardware implementation of the algorithm and its evaluation and discuss the impact of the threshold CNR setting of $\gamma_{\rm th}$ on the performance in detail.

III. Hardware Implementation

Fig. 2 is a schematic diagram of the structure of the prototype receiver with the proposed antenna selection algorithm, and Table 1 lists the system parameters. The signals are assumed to be OFDM ones based on the wireless link standard in [9]. The receiver has P = 16 input ports, and the signal processing until the fast Fourier transform (FFT) is performed independently for every antenna input. The channel is estimated by 108 pilot carriers inserted beforehand in the channel estimation block, and the condition number of the channel matrix is calculated at the cond block with the algorithm described in the previous section. On the other hand, the CNR is computed from the ratio of the power of the pilot carriers and 64 null ones. For performance comparison, the antenna subset selection block selects M = 4 antennas for the MMSE detection using one of three antenna selection methods: the "CNR-base" method, in which the selection criterion is based on only the CNR; the "Cond-base" method, where the condition number is the selection criterion; or the "Cond/CNR-base" method, which corresponds to the "Cond-base" method with the threshold CNR setting. The receiver can change the antenna subset every eight OFDM symbols, which corresponds to about 450 µs. A low-density parity-check (LDPC) decoder, the code length and code rate of which are 13056 bits and 1/2, respectively, is implemented in the system. Time interleaving whose length corresponds to about 75 ms is also implemented. The system can record the resulting data, such as the BER, CNR, and condition numbers, once every second.

IV. Field Experiment

We conducted a field experiment at the Nagano marathon course to acquire the received intermediate frequency (IF) signals into high-speed and large-capacity hard disks and evaluate the performance of the prototype receiver in an indoor measurement. Fig. 3 shows a map of the test course and antenna setup on the rooftop of a vehicle [mobile station (MS)] and tower [base station (BS)]. The radio frequency, output power, and number of substreams of the transmitter were 779 MHz, 5 W /antenna, and 2, respectively. QPSK modulation was used in the test. The vehicle traveled at a speed 40 km/h along the straight course shown in Fig. 3. The test course was located in an urban area where the propagation environment between the MS and BS was non line-of-sight (NLOS). The transmitted signals were received by eight Yagi antennas (four of which are shown in Fig. 3), which have 5, 8, or 11 elements and were positioned on the BS at a height of 50 m. Four of them were positioned with horizontal polarization; the other four with vertical polarization. All received signals of the eight antennas were converted into the 20-MHz-band IF signals by downconverters and recorded continuously into hard disks at a sampling rate of about 80 MHz with 14-bit resolution. The recording time was about 130 seconds while the MS moved from A to B in Fig. 3.

TABLE 1. Prototype system parameters.

Diversity branch	N = 2, M = 16, P = 4 (selected antennas)
Input frequency	20.45 MHz
Signal bandwidth	17.2 MHz
Data modulation	QPSK-OFDM, 16 QAM-OFDM
Number of sub-carriers	857
Symbol duration	56.33 µs
Data rate	11.93 Mbps (QPSK), 23.859 Mbps (16 QAM)
Signal detection	MMSE
LDPC code length	13056 bits (code rate = 1/2)
LDPC decoding	UMP-BP (iteration number = 25 max.)
Time interleaving	75 ms
Antenna selection	CNR-base, Cond-base, Cond/CNR-base
Antenna switching cycle	eight-symbol duration (= 450 µs)

V. Performance Evaluation in Indoor Test

Fig. 4 shows the configuration of the evaluation system. The received IF signals were recorded into the hard disks and played back repeatedly to evaluate the reception performance of the prototype system with various parameters. As shown in Fig. 4, additional noise (AWGN), which is generated by a software program, can be added to the original received signals to control the average CNR. We prepared three kinds of

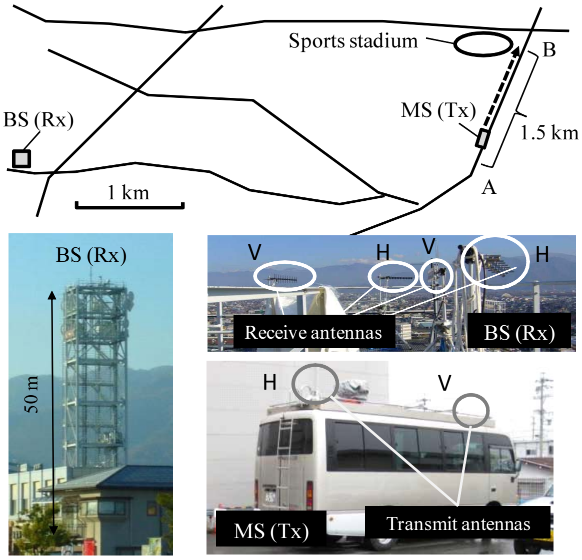

Fig. 3. Map of test course and antenna setup on rooftop at BS and MS.

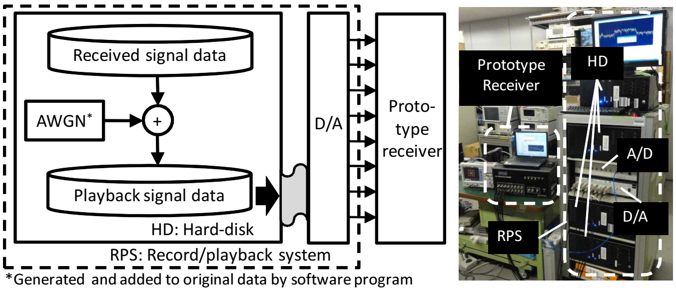

Fig. 4. Configuration of evaluation system.

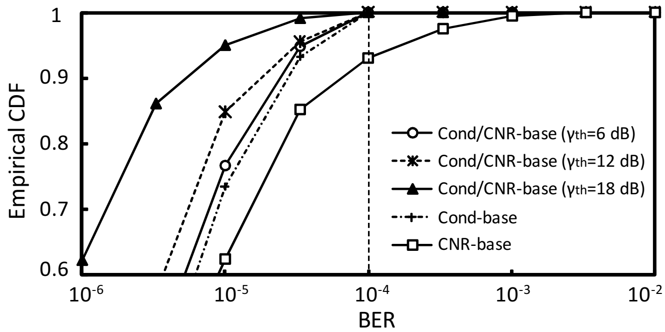

Fig. 5. BER performance of each selection method (Eval-data1, ite=1).

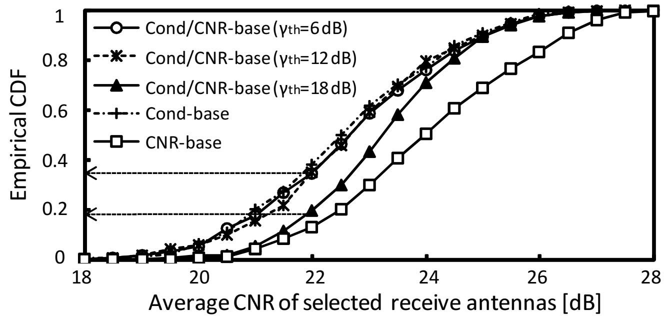

Fig. 6. Cumulative distribution of average CNR (Eval-data1).

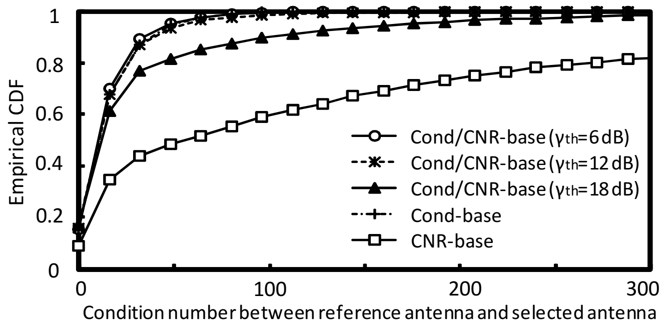

Fig. 7. Cumulative distribution of condition number (Eval-data1).

playback data: The original received signals (Eval-data1); the received signals with additional noise, which deteriorates the average CNR 6 dB compared to Eval-data1 (Eval-data2); and the received signals with additional noise, which deteriorates the average CNR 12 dB compared to Eval-data1 (Eval-data3). Figs. 5, 6, and 7 respectively show the empirical cumulative distribution function (CDF) of the BER for Eval-data1 after LDPC decoding, the average CNR of the selected four receive antennas, and the condition numbers between the reference antenna and the other selected antennas. To observe the BER performance of around 1×10^{-4}, which is a criterion that achieves error-free transmission after an outer decoder, the iteration number of the LDPC decoder was fixed to one in the measurement, although it can be set to a maximum of 25. As shown in Fig. 6, the average CNR of the antennas selected by "CNR-base" is the highest of all. Nevertheless, Fig. 5 shows that the BER performance of "CNR-base" is the worst among the methods. This is because, as shown in Fig. 7, the condition numbers between the reference antenna and the other selected antennas for "CNR-base" becomes considerably high. On the other hand, the BER performance of "Cond-base" in Fig. 5 is worse than that of "Cond/CNR-base". This is because, as shown in Fig. 6, the average CNR of the antennas selected by "Cond-base" is the smallest, although the condition numbers of "Cond-base" are the smallest of all in Fig. 7. "Cond/CNR-base ($\gamma_{\rm th}$=18 dB)", which has a threshold CNR of 18 dB, shows the best BER performance (less than 1×10^{-4}), although the performance is the same as that of "Cond/CNR-base ($\gamma_{\rm th}$=6 and 12 dB)" (more than 1×10^{-4}). As shown in Fig. 6, the CDF of the average CNR less than 22 dB is 18 % in "Cond/CNR-base ($\gamma_{\rm th}$=18 dB)", whereas it is around 35 % in "Cond-base" and "Cond/CNR-base ($\gamma_{\rm th}$=6 and 12 dB)". This means that "Cond/CNR-base ($\gamma_{\rm th}$=18 dB)" was successful in properly excluding receive antennas with lower CNRs from the candidates and improving the BER performance.

Figs. 8 and 9 respectively show the empirical CDF of the BER for Eval-data2 and the average CNR of the selected four receive antennas. The iteration number of the LDPC decoder was fixed to two in this measurement. The BER performance of "Cond/CNR-base ($\gamma_{\rm th}$=18 dB)" degrades, and "Cond/CNR-base ($\gamma_{\rm th}$=12 dB)" shows the best BER performance instead (less than BER of 1×10^{-4}). Fig. 9 shows that the antennas

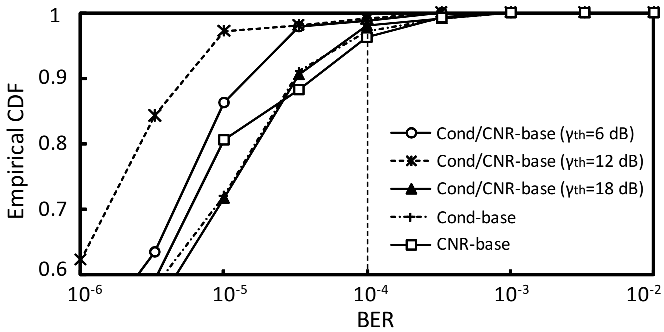

Fig. 8. BER performance of each selection method (Eval-data2, ite=2).

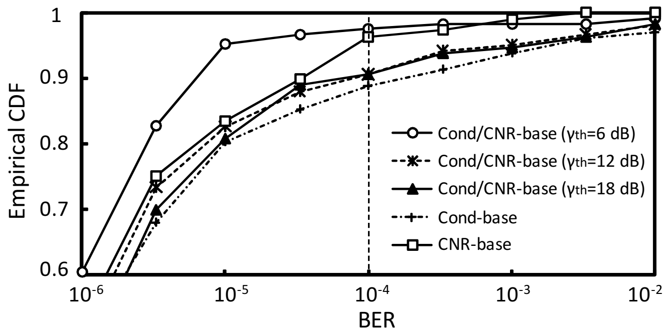

Fig. 10. BER performance of each selection method (Eval-data3, ite=25).

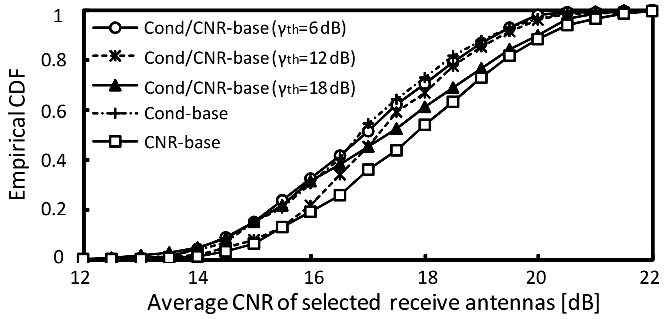

Fig. 9. Cumulative distribution of average CNR (Eval-data2).

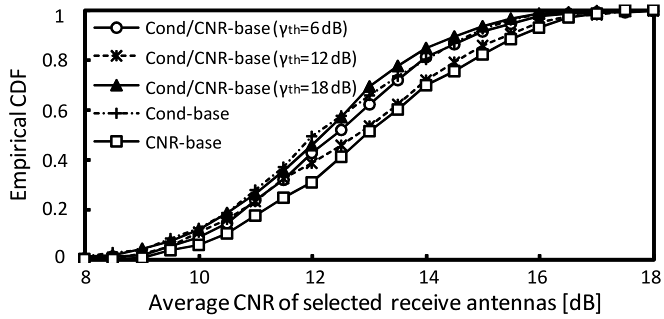

Fig. 11. Cumulative distribution of average CNR (Eval-data3).

selected by "Cond/CNR-base ($\gamma_{\rm th}$=18 dB)" have both higher and lower CNRs. This is because antennas with a higher CNR were selected regardless of the condition number and antennas with a lower CNR were selected in accordance with only the condition number.

Figs. 10 and 11 show the empirical CDF for Eval-data3, which has the lowest average CNR of all. The iteration number of the LDPC decoder was fixed to the maximum of 25 in this measurement. In this case, the BER performance of "Cond/CNR-base ($\gamma_{\rm th}$=12 dB)" and "Cond/CNR-base ($\gamma_{\rm th}$=18 dB)" degrades, becoming close to that of "Cond-base", and "Cond/CNR-base ($\gamma_{\rm th}$=6 dB)" shows the best BER performance. As shown in Fig. 11, "Cond/CNR-base ($\gamma_{\rm th}$=18 dB)" is almost the same as "Cond-base" in the CDF of the average CNR because of the considerably high threshold CNR setting.

Consequently, a high threshold CNR setting may deteriorate the reception performance in MIMO channels with a lower average CNR, whereas it can improve the reception performance when the average CNR becomes high. On the other hand, a lower threshold CNR setting may deteriorate the reception performance in MIMO channels with a high average CNR, whereas it can improve the reception performance when the average CNR becomes low.

VI. Conclusions

This paper described our proposed antenna selection algorithm, its hardware implementation and performance evaluation, which was conducted in an indoor measurement using signals received in the actual mobile outdoor experiment. The relation between the threshold CNR setting and the reception performance was explored using the empirical cumulative probability function of the BER, the CNR, and the condition number of the channel matrix. Our proposed method was confirmed to be able to improve the reception performance in MIMO channels, although an optimum threshold CNR setting differs depending on the average CNR.

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