Performance Evaluation of SVD-MIMO-OFDM System with a Thinned-out Number of Precoding Weights

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***Abstract*—We are designing system parameters for manufacturing a prototype SVD-based 4×4 MIMO-OFDM system with our adaptive bit and power allocation (ABPA) algorithm. Designing the parameters at the cost of a minimum amount of feedback is important to achieve high spectral efficiency in time division duplex (TDD) systems. We constructed a performance evaluation system for the SVD-based MIMO system and evaluated the bit error rate (BER) performances when the number of precoding weights fed back was thinned out under three MIMO channel models with different delay spreads. The measurement results demonstrated that the amount of feedback can be reduced by one eighth in the model with the largest delay spread, keeping BER performance degradation.**

I. INTRODUCTION

An advanced wireless transmission system is required for 8K ultrahigh-definition television (UHDTV) live productions, such as of road races. Video materials for 8K UHDTV have extremely high video quality and need compressed data rates of more than 100 Mbps for wireless transmission. Although recently standardized wireless links [1] for the conventional 2K HDTV, which is based on space-time trellis code-multiple-input multiple-output (STTC-MIMO) [2], [3], can achieve a transmission rate of around 40 Mbps, this is still inadequate.

To achieve a higher transmission rate and link reliability, we started to develop a MIMO-orthogonal frequency division multiplexing (OFDM) system that uses singular value decomposition-based (SVD-based) precoding. We proposed a practical adaptive bit and power allocation (ABPA) algorithm suitable for fixed-rate SVD-MIMO-OFDM systems and demonstrated its effectiveness by computer simulation [4]. As a next step, we are designing system parameters for manufacturing a prototype system equipped with the ABPA algorithm. Since time division duplex (TDD) is assumed for feedback, reducing the amount of feedback without degrading transmission performance is needed to achieve high spectral efficiency. It is more reasonable and feasible to feed back the SVD precoding weight, which corresponds to the right singular matrix obtained by the SVD of the channel matrix, rather than the channel matrix itself since the wireless link we assume is a single-user MIMO system. The right singular matrix has an advantage in quantization since it is unitary. The feedback reduction method has been also studied by using the Givens rotation [5]. However, our interest is on how a large number of precoding weights fed back can be thinned out without degrading transmission performance.

In this paper, we construct a performance evaluation system for SVD-based 4×4 MIMO-OFDM equipped with our ABPA algorithm and evaluate bit error rate (BER) performances when the number of precoding weights fed back is thinned out. Three channel models (EPA, EVA, and ETU) [6] that have different delay spreads were tested. The measurement results demonstrated that the amount of feedback can be reduced by one eighth, keeping the required signal-to-noise ratio (SNR) degradation at about 1 dB at a BER of 1×10^{-3} in the ETU model with the largest delay spread of 991 ns and a maximum relative delay of 5 µs.

II. SVD-MIMO SYSTEM

A. Basis of SVD-MIMO

Let us consider a MIMO channel with N transmit and M receive antennas. Given that $\mathbf{x}$, $\mathbf{H}$, and $\mathbf{n}$ are the transmitted signal vector, the channel matrix, and the additive white Gaussian noise (AWGN) vector, respectively, the received signal vector $\mathbf{y}$ can be expressed as

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}. \tag{1}$$

The SVD of the channel matrix $\mathbf{H}$ can be written as

$$\mathbf{H} = \mathbf{U}\mathbf{\Sigma}\mathbf{V}^H \tag{2}$$

, where the left singular matrix $\mathbf{U}$ and the right singular matrix $\mathbf{V}$, which corresponds to the SVD precoding weight, are unitary, and $\mathbf{\Sigma}$ is a diagonal matrix with the singular values $\sqrt{\lambda_1}, \cdots, \sqrt{\lambda_K}$ of $\mathbf{H}$ sorted in descending order. The superscript H denotes the Hermitian transpose. Following the above, we define the matrices $\mathbf{F}$ and $\mathbf{G}$ as

$$\mathbf{F} = \mathbf{V}\mathbf{W}^{1/2} \tag{3}$$

$$\mathbf{G} = \mathbf{U}^H \tag{4}$$

$$\mathbf{W} = \mathrm{diag}[p_1, \cdots, p_K] \tag{5}$$

, where $\mathbf{W}$ is a transmit power allocation matrix whose diagonal elements p_k are the power allocated to the k-th eigenmode. When the information signal vector $\mathbf{s}$ is multiplied

TABLE I
MER THRESHOLD THAT SATISFIES BER OF 1×10^{-4}

Modulation scheme	MER threshold [dB]
BPSK	9.0
QPSK	11.7
8 QAM	15.5
16 QAM	18.3
32 QAM	21.2
64 QAM	24.3
128 QAM	27.2
256 QAM	30.3
512 QAM	33.1
1024 QAM	36.2

by matrix $\mathbf{F}$ at the transmitter, the transmitted signal vector $\mathbf{x}$ is expressed as

$$\begin{aligned} \mathbf{x} &= \mathbf{Fs} \\ &= \mathbf{VW}^{1/2}\mathbf{s}. \end{aligned} \tag{6}$$

Furthermore, by taking matrix $\mathbf{G}$ to be the weight matrix at the receiver, the detected signal vector $\hat{\mathbf{s}}$ can be expressed as follows.

$$\begin{aligned} \hat{\mathbf{s}} &= \mathbf{Gy} \\ &= \mathbf{U}^H(\mathbf{Hx}+\mathbf{n}) \\ &= \mathbf{U}^H\mathbf{U}\mathbf{\Sigma}\mathbf{V}^H\mathbf{V}\mathbf{W}^{1/2}\mathbf{s}+\mathbf{U}^H\mathbf{n} \\ &= \mathbf{\Sigma}\mathbf{W}^{1/2}\mathbf{s}+\hat{\mathbf{n}} \end{aligned} \tag{7}$$

As shown in the above, the channel is virtually decomposed into K independent single-input single-output (SISO) channels.

B. Proposed Adaptive Bit and Power Allocation Algorithm

Our ABPA algorithm improves the BER performance of fixed-rate SVD-MIMO-OFDM systems by determining a combination of bit and power allocation so that each BER for every eigenmode becomes equal and the smallest. We exploit the modulation error ratio (MER), which is defined as the ratio of the average signal constellation power to the average constellation error power, as a metric in the ABPA process. Specifically, we predetermine an MER threshold that satisfies the specific BER for every modulation scheme and choose a combination of bit and power allocation that equalizes and maximizes the MER margins that correspond to the difference between the MER threshold and the MER after power allocation. The optimum combination can be uniquely determined by solving a system of simple linear equations without an exhaustive search. The detailed procedure was described in [4]. Table I, which is used in the following evaluation system, lists MER thresholds that satisfy BER = 1×10^{-4} for modulation schemes from BPSK to 1024 QAM.

III. PERFORMANCE EVALUATION

In this section, we describe a performance evaluation system constructed for SVD-based 4×4 MIMO-OFDM with our ABPA algorithm, and show the measurement results for three MIMO channel models when the number of precoding weights fed back was thinned out.

TABLE II
SPECIFICATIONS OF EVALUATION SYSTEM

MIMO configuration	4×4 MIMO-OFDM
Radio frequency band	2.3 GHz
Channel bandwidth	18 MHz
Modulation schemes	BPSK, QPSK, 8 QAM, 16 QAM, 32 QAM, 64 QAM, 128 QAM, 256 QAM, 512 QAM, 1024 QAM
FFT size	1024
Preamble length	50.06 µs
OFDM symbol length	56.33 µs
Guard interval length	6.26 µs
Number of subcarriers	860
Number of data subcarriers	844
Number of pilot subcarriers	215 per one transmit antenna

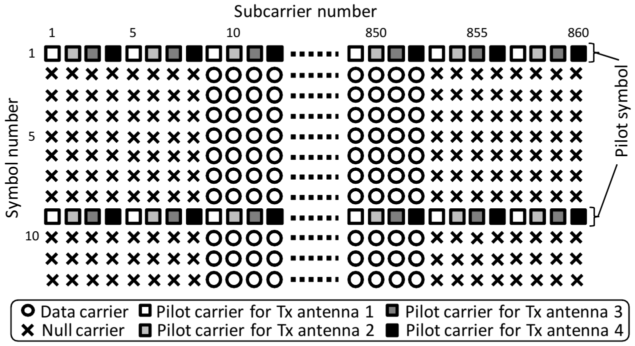

Fig. 1. OFDM subcarrier allocation

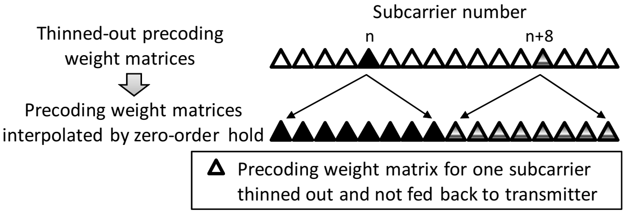

Fig. 2. Thinning out and interpolation of precoding weight matrices

A. Specification of Evaluation System

Table II shows the major specification of the evaluation system. The system can adaptively change from rank-1 transmission to full rank transmission, i.e. rank 4, depending on the instantaneous MIMO channel. The total allocated bits per carrier symbol was assumed to be 10. Therefore, in the case of rank-1 transmission, 1024 QAM was applied on each subcarrier. In the case of rank-3 transmission, if the information bits of 5, 3, and 2 were allocated for the first, second, and third eigenmodes, respectively, 32 QAM, 8 QAM, and QPSK were performed in the eigenmodes. The same modulation scheme was assumed to be applied to all subcarriers with the same symbol and eigenmode. The OFDM subcarrier allocation originally designed for the system is shown in Fig. 1. Pilot carriers for each transmit antenna are allocated for every four subcarriers in the pilot symbols inserted for every eight symbols. Data carriers are not allocated in the eight subcarriers at both ends of the signal spectrum to avoid performance degradation due to the cut-off characteristics of band-path filters and the channel estimation error.

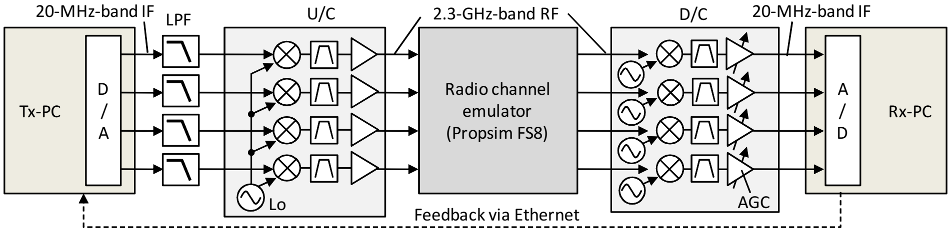

Fig. 3. Configuration of SVD-based 4×4 MIMO-OFDM evaluation system

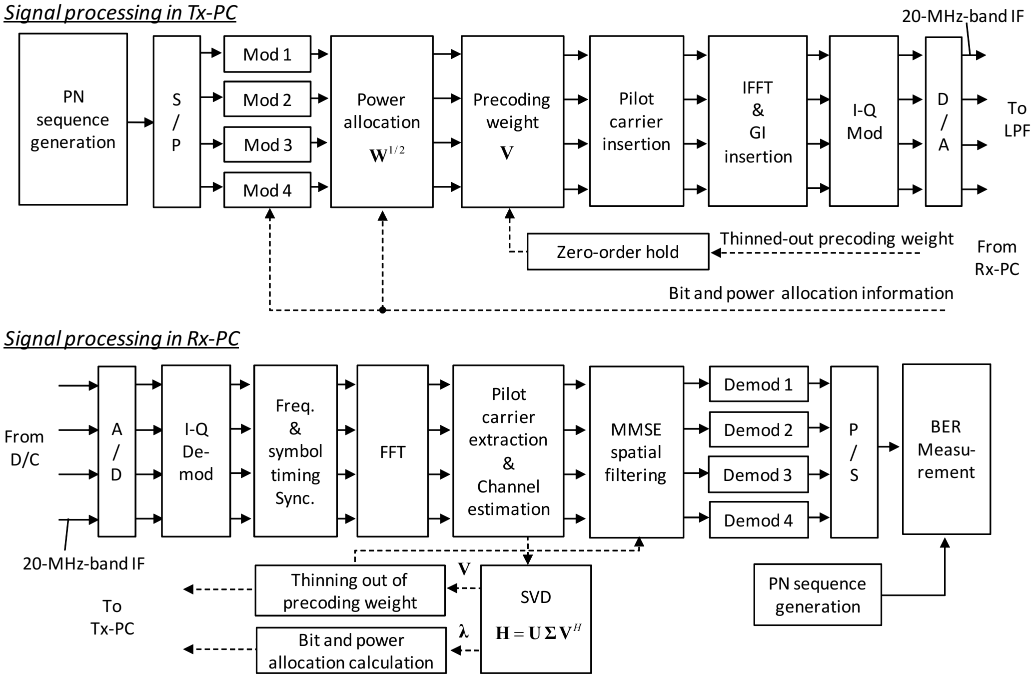

Fig. 4. Block diagram of signal processing done by MATLAB software

Figure 2 shows an example of the thinning out of the number of precoding weight matrices at the receiver and interpolation at the transmitter. All of the 4×4 precoding weight matrices for 860 subcarriers could be obtained at the receiver. In this figure, the precoding weight matrices fed back were extracted for every eight subcarriers, and the others were thinned out. The thinned-out precoding weight matrices were interpolated by zero-order hold at the transmitter.

B. Configuration of Evaluation System

Figure 3 shows the configuration of the evaluation system. The transmitted signals are generated by using the MATLAB software on a PC for the transmitter (Tx-PC), output as 20-MHz-band intermediate frequency (IF) signals through four digital-to-analog (D/A) converters, and input into an upconverter (U/C), which converts the IF signals to 2.3-GHz-band radio frequency (RF) signals. The 2.3-GHz-band RF signals are input into a radio channel emulator, travel through frequency-selective 4×4 MIMO fading channels, and are output into a downconverter (D/C). The RF signals are independently converted to 20-MHz-band IF signals in the D/C with independent automatic gain control (AGC) amplifiers and local oscillators. The IF signals are digitized by four analog-to-digital (A/D) converters at a sampling rate of around 80 MHz and demodulated by the MATLAB software on a PC for receiver (Rx-PC). The SVD precoding weight matrices calculated in Rx-PC are fed back to Tx-PC via Ethernet.

Figure 4 shows a block diagram of the signal processing done by the MATLAB software in Tx-PC and Rx-PC. Frequency and symbol timing synchronizations are performed for every piece of captured data. A minimum mean square error (MMSE) spatial filter is used at the receiver instead of the matrix $\mathbf{G}$ defined in equation (4), considering the occurrence of the inter-eigenmode interference. In this system, MERs converted from eigenvalues are used in the ABPA process.

C. BER Performance Measurement

Three channel models of EPA, EVA and ETU, which are defined in [6], were emulated in the radio channel emulator. Table III shows the specifications of the above channel models. A low spatial correlation was assumed in all models. The radio channel emulator has pause and step functions that can temporarily stop the time-varying fading and run the emulation until the next impulse response. We exploited these functions

TABLE III
EMULATED 4×4 MIMO CHANNEL MODELS

Channel model	Number of paths	Delay spread	Maximum delay
EPA	7	45 ns	410 ns
EVA	9	357 ns	2.51 μs
ETU	9	991 ns	5 μs

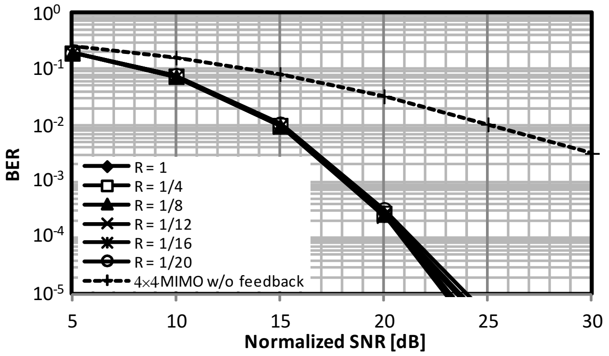

Fig. 5. BER performance in Extended Pedestrian A (EPA) model

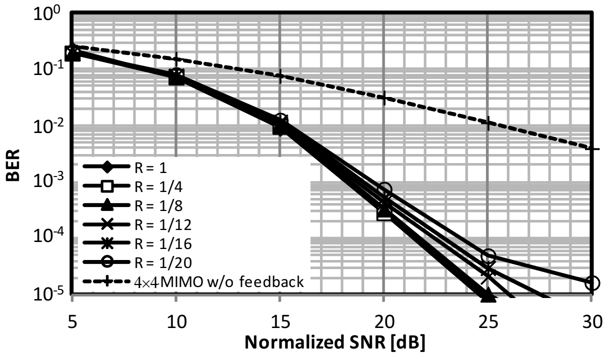

Fig. 6. BER performance in Extended Vehicular A (EVA) model

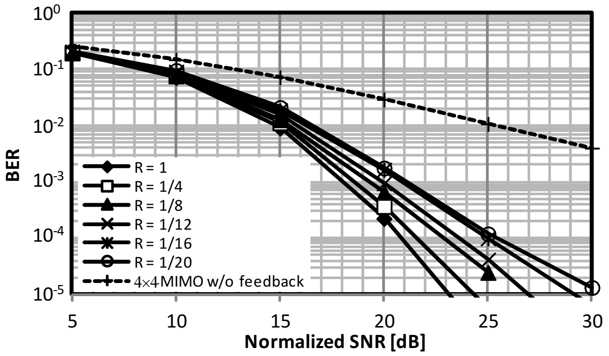

Fig. 7. BER performance in Extended Typical Urban (ETU) model

to manually generate quasi-static fading channels. Specifically, they were generated by keeping the channel state during transmission and feedback processes and proceeding to the next impulse response for the next measurement.

Figure 5 shows the BER performances for the EPA model. The parameter R corresponds to the thinning-out rate. In the case of $R = 1$, all precoding weight matrices of the 860 subcarriers were fed back to Tx-PC. In the case of $R = 1/8$, the precoding weight matrices of 108 subcarriers were fed back to the transmitter. The BER performance of the simplex 4×4 MIMO-OFDM system without feedback is also shown for reference as a broken line. The simplex system multiplexed four spatial streams with a fixed bit and power allocation and detected the signals by using the MMSE spatial filter. The total number of allocated bits per carrier symbol was assumed to be 10 for fair comparison. The SVD-based MIMO-OFDM systems were confirmed to greatly outperform the simplex system. The SVD-based MIMO-OFDM systems with different thinning-out rates had almost the same BER performances for the EPA model. When we evaluated the required SNR at BER=1×10^{-3}, the performance degradation of $R = 1/20$ was less than 0.5 dB compared with that of $R = 1$. Figure 6 shows the BER performances for the EVA model. The performance degradations of $R = 1/20$ and $R = 1/8$ were about 1.3 dB and 0.2 dB, respectively, compared with that of $R = 1$. Finally, Fig. 7 shows the BER performances for the ETU model with a largest delay spread and a maximum relative delay of 991 ns and 5 μs, respectively. Taking into account that the guard interval length of the system is 6.26 μs, the delay spread and the maximum relative delay were relatively large in the propagation channels we assume. In this model, the BER performance of $R = 1/20$ deteriorated by 3 dB compared with that of $R = 1$. In comparison, the BER performance degradation of $R = 1/8$ stayed at about 1 dB.

IV. CONCLUSION

We constructed a performance evaluation system for SVD-based 4×4 MIMO-OFDM equipped with our ABPA algorithm. We evaluated the BER performance when some precoding weights were deleted to reduce the amount of feedback. Three channel models that have different delay spreads were tested. The measurement results demonstrated that the amount of feedback can be reduced by one eighth, keeping the required SNR degradation of about 1 dB at a BER of 1×10^{-3}, even in the ETU model, which has a largest delay spread of 991 ns and the maximum relative delay of 5 μs.

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