Field Experiments of Linearly Precoded Multi-User MIMO System at 5 GHz Band

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***Abstract*—In this paper, implementation of a multi-user MIMO experimental system is presented. Linear spatial precoding and a simple two-way channel estimation technique are adopted in the experimental system. In-lab and field transmission experiments are carried out and the performance is evaluated. The impact of channel estimation error under average channel gain discrepancy between two mobile stations is analyzed by means of computer simulation. It is shown that channel estimation error has a greater influence on the mobile station with greater average channel gain.**

I. Introduction

Multiple-input multiple-output (MIMO) is an essential part for recent wireless networks to provide high data rate through spatial multiplexing. However, mobile stations (MSs) are limited in size, power, and computational resources. Multi-user MIMO (MU-MIMO) techniques are drawing attention to achieve high spectral efficiency even when mobile stations are not equipped with multiple antennas. In MU-MIMO systems, the computational complexity of the mobile stations can be reduced with precoding at the base station (BS).

MU-MIMO systems have been studied mainly through theoretical analysis and computer simulation. However, MIMO precoding requires precise control over transmit signals of multiple BS antennas (BSAs) and there may be a variety of practical issues such as frequency offset, timing synchronization, and limited dynamic range. Implementation and experimental studies on MU-MIMO systems are of great importance to evaluate such practical issues. However, to the authors' best knowledge, few studies have been reported on implementation and transmission experiments of MU-MIMO systems [1]–[3] and they consider only indoor environments.

The authors are designing and implementing a MU-MIMO experimental platform to study techniques such as interference coordination between multiple MU-MIMO clusters in a distributed antenna system. In this paper, a single 2×2 system has been considered for basic performance evaluation and implementation of the experimental system is presented.

Real-time feedback and channel estimation are done using a simple two-way training method [4]. In this method, the MSs just send back the received training packets by amplify-and-forward relaying and downlink channel estimation is performed at the BS. Required hardware specifications for the amplify-and-forward operation in this method have been studied by means of computer simulation [5]. However, hardware implementation feasibility of this method is not studied yet.

In-lab transmission experiments are conducted using a fading emulator. Computer simulation is also carried out and the system performance is evaluated in terms of bit error rate (BER). Outdoor transmission experiments are conducted in an actual propagation environment. The impact of channel estimation error under average channel gain discrepancy between two mobile stations is analyzed by means of computer simulation.

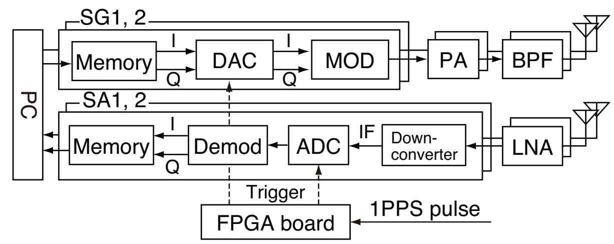

Fig. 1. Block diagram of BS equipment.

Fig. 2. BS equipment.

Fig. 3. MS equipment.

II. Experimental System

A. BS Equipment

A block diagram and a picture of the BS equipment are given in Figs. 1 and 2, respectively. Two modular RF signal generators (SGs), two modular RF signal analyzers (SAs), an FPGA board, and a modular PC are embedded in the

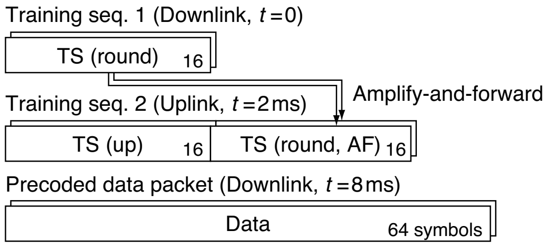

Fig. 4. Packet structure. Two training packets are used for channel estimation.

same chassis. An SG consists of a 16-bit ADC and a vector modulator. Two SGs use the same local oscillator (LO) and sample clock. An SA consists of a downconverter and a 16-bit DAC. Two SAs also use the same LO and sample clock. The received signal is translated to IF by the downconverter, and then digitized by the ADC. The digital IF signal is demodulated by the onboard digital signal processor, and the resultant baseband signal is recorded in the onboard memory. Real-time baseband signal processing is done on the modular PC by accessing the memories in SGs and SAs. For field experiments, a power amplifier ($P_{\mathrm{1dB}} = 33$ dBm, typ.), a BPF, and an omni-directional collinear antenna are connected with each SG, and a low noise amplifier (NF 1.9 dB, typ.) and an omni-directional collinear antenna with each SA.

A trigger generator is implemented on the FPGA to control timing of transmission and reception. 1 PPS pulse and 10 MHz reference signal are used so that timing and frequency synchronization between the BS and MSs can be established. 1 PPS pulse is supplied from an external GPS receiver, and trigger signals for SGs and SAs can be synchronized with the 1 PPS pulse. 10 MHz frequency reference signal is also supplied from the GPS receiver.

B. MS Equipment

An MS equipment is shown in Fig. 3. A Universal Software Radio Peripheral (USRP) is used to transmit and receive signals. A USRP consists of a motherboard and a daughterboard. The daughterboard works as an RF front end which performs frequency translation between RF and IF. The motherboard performs A/D and D/A conversion and (de)modulation between baseband and IF. A PC is connected via a Gigabit Ethernet cable and baseband signal processing is done on the PC. A BPF and an antenna are connected to the RF input/output terminal of the USRP. As the source of 1 PPS pulse and 10 MHz reference signal, a GPS receiver is embedded in each USRP.

C. Packet Structure

For downlink channel estimation, a simple two-way channel training method [4], [5] is adopted. With this method, computational complexity of the MS can be reduced because channel estimation is performed at the BS.

Fig. 4 shows the packet structure in a frame. First, the BS transmits the training sequences (TSs) for round-trip channel estimation at the time $t = 0$. The TSs from the BSAs are orthogonal sequences and are transmitted at the same time and frequency. Each MS sends back the received round-trip TS by amplify-and-forward relaying along with another TS for uplink estimation at $t = 2$ ms. Both of the two TSs have 16 symbols. The BS estimates downlink channel using the two TSs, and then transmits 64-symbol-long precoded data packet at $t = 8$ ms.

TABLE I
EXPERIMENTAL PARAMETERS

System Parameters	Values
Number of BSAs	2
Number of MSs	2
Carrier frequency	5.11 GHz
Symbol rate	97.7 ksps
Modulation	QPSK
Filter	Root roll-off Nyquist (roll-off factor $= 0.4$)
BS parameters	**Values**
Downlink channel estimation	Two-way estimation
Round-trip and uplink channel estimation	Least squares
MIMO precoding	Linear precoding (ZF)
ADC/DAC resolution	16 bit
CPU of embedded PC	Core i7 1.73 GHz
MS parameters	**Values**
Model	Ettus USRP N210
Daughterboard	XCVR2450
ADC/DAC resolution	14/16 bit
CPU of control PC	Core 2 Duo 2.4 GHz

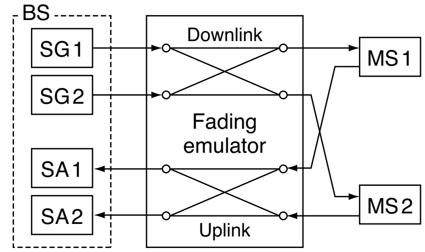

Fig. 5. Experimental setup for in-lab experiments. SGs and SAs of the BS equipment are directly connected with the fading emulator.

III. In-lab Experiments

A. Experimental Setup

As the first setup, 2×2 MU-MIMO transmission experiments with zero-forcing linear precoding are conducted. Table I shows the parameters for the experiments. Fig. 5 shows the experimental setup for the in-lab experiments. In-lab experiments are conducted using a fading emulator. Eight independent and identically distributed Rayleigh fading channels, four for 2×2 downlink and four for 2×2 uplink, are emulated.

For in-lab experiments, common 1 PPS pulse and common 10 MHz reference signal are available from a function generator and a rubidium oscillator, respectively. In this section, these common signals are first used for basic performance evaluation. Then signals from individual GPS receivers are used and the performance is compared.

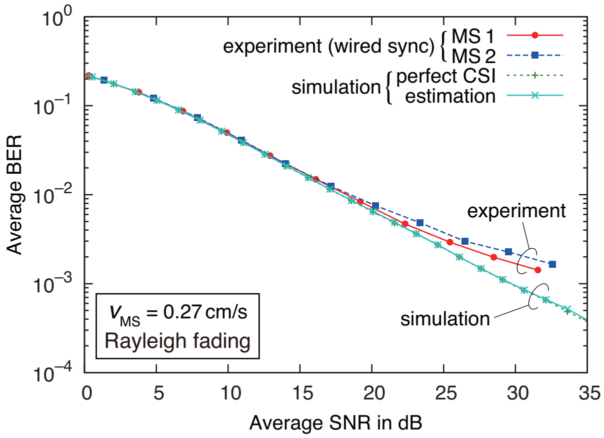

Fig. 6. BER versus SNR performance over slow Rayleigh fading channel ($v_{\mathrm{MS}} = 0.27$ cm/s).

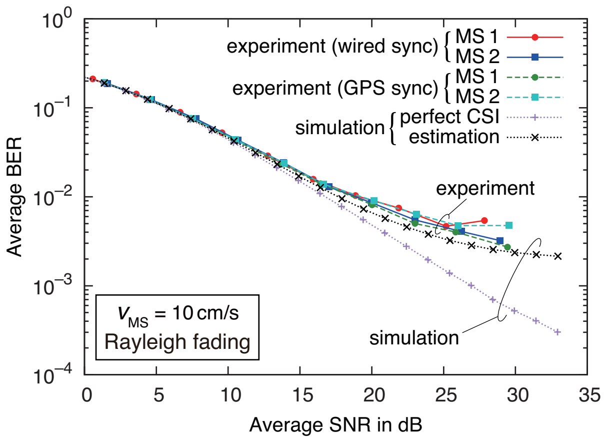

Fig. 7. BER versus SNR performance over faster Rayleigh fading channel ($v_{\mathrm{MS}} = 10$ cm/s).

B. Experimental Results

Fig. 6 shows the BER versus SNR performance over Rayleigh fading channels with mobile speed $v_{\mathrm{MS}} = 0.27$ cm/s. Computer simulation results, with channel estimation and with perfect CSI at the BS, are also shown in this figure.

In the experiments for this paper, peak transmit power of the first training packet is fixed. Peak transmit power of precoded data packet is also fixed over one BER measurement period. The horizontal axis of Fig. 6 shows average received SNR of precoded data packets.

In Fig. 6, almost no difference is seen between two computer simulation results: with perfect CSI at the BS and with channel estimation. This shows that feedback and precoding delay is negligible with this mobile speed. Experimental results shows some degradation in high SNR region.

Fig. 7 shows the performance comparison between two 1 PPS and 10 MHz signal sources for timing and frequency synchronization: individual GPS receivers (GPS sync) and the common function generator and the common rubidium oscillator (wired sync). Mobile speed v_{MS} is set to 10 cm/s.

In Fig. 7, performance degradation that arises from feedback and precoding delay can be seen. The performance with individual GPS receivers is similar to that with common synchronization signal sources.

Fig. 8. Environment for the field experiments.

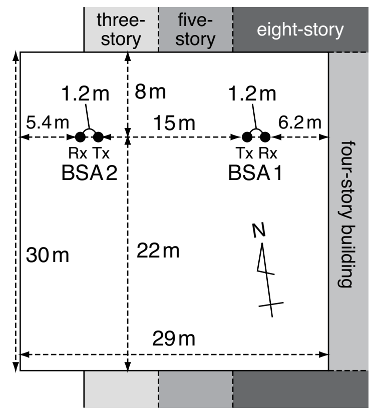

Fig. 9. Layout of the experimental place.

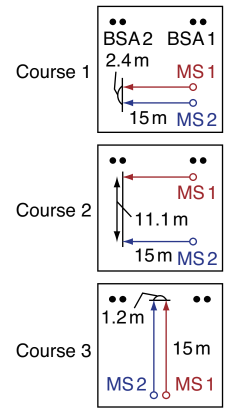

Fig. 10. Courses of the MSs.

TABLE II
ADDITIONAL PARAMETERS FOR FIELD EXPERIMENTS

Parameters	Values
BS antenna	Omni-directional, 5 dBi
BS antenna height	3.0 m
MS antenna	Omni-directional, 3 dBi
MS antenna height	0.88 m
MS speed	$v_{\mathrm{MS}} = 10$ cm/s

IV. FIELD EXPERIMENTS

A. Experimental Setup

Field transmission experiments were conducted at a rectangular space in Kyoto University shown in Figs. 8 and 9. This space is surrounded by buildings except for its west side and is mainly LOS environment. Table II shows the additional parameters for the field experiments. A transmit antenna and a receive antenna of the BS are spaced 1.2 m apart and the two transmit antennas are spaced 15 m apart. Two MSs move along the three courses shown in Fig. 10 at the speed of $v_{\mathrm{MS}} = 10$ cm/s.

B. Experimental Results

Figs. 11 and 12 shows the BER performance and received power of precoded data packets, respectively, both being

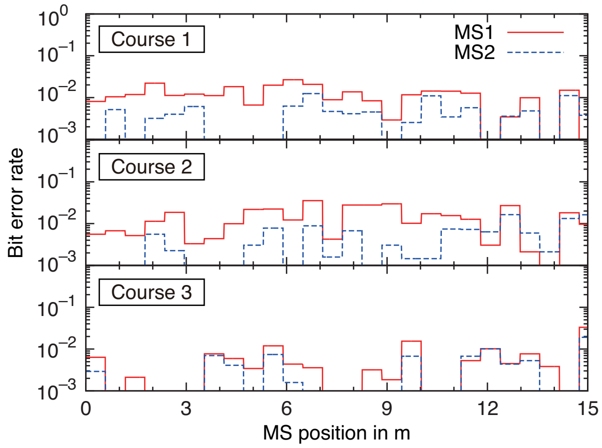

Fig. 11. BER performance in the three MS courses. BER is calculated every 59 cm $\simeq 10\lambda$.

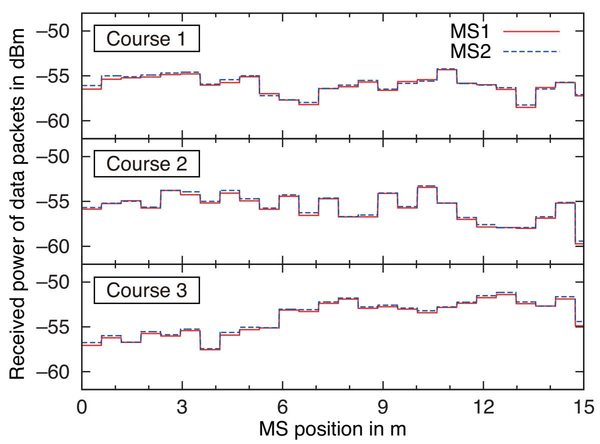

Fig. 12. Received power of precoded data packets in the three MS courses, averaged every 59 cm $\simeq 10\lambda$.

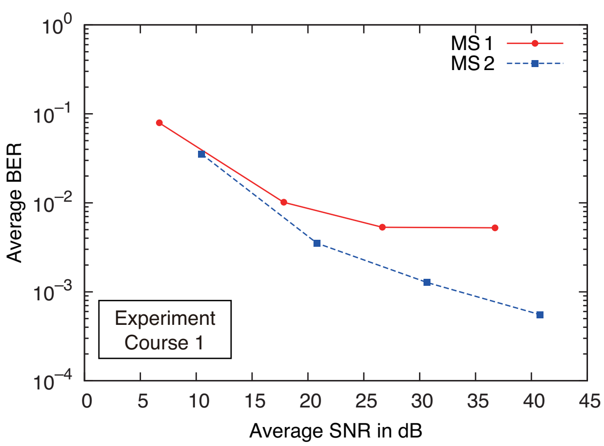

Fig. 13. BER versus SNR performance in Course 1. The horizontal axis shows received SNR of the data packet averaged over the entire course, i.e., 15 m. Transmit power of the first training packet is fixed. Transmit power of precoded data packet is attenuated by 0, 10, 20, 30 dB.

averaged every 59 cm $\simeq 10\lambda$. Received power of the data packet at the two MSs is kept equal by channel inversion at the BS. The fluctuation of the received power is due to the fixed

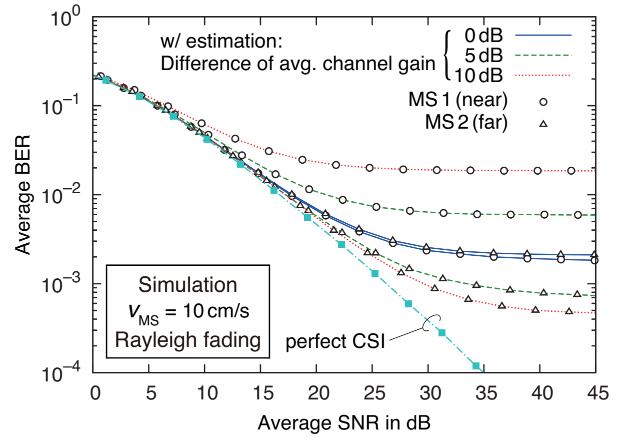

Fig. 14. SNR versus BER performance with channels from/to MS 2 attenuated by 0, 5, 10 dB.

peak transmit power of the precoded data packet. Although the system works stably at the BER under 10^{-2} in average, the BER at MS 1 is higher than MS 2 in Course 1 and Course 2, where MS 1 is nearer than MS 2 from BSAs.

Fig. 13 shows the BER versus SNR performance with different transmit power of the data packet in Course 1. Transmit power of the first training packet is kept fixed. The difference of BER is large at high SNR, which implies the impact of residual inter-user interference which arises from channel estimation error.

C. Impact of Channel Estimation Error under Channel Gain Discrepancy

The impact of channel estimation error under average channel gain discrepancy between two MSs is analyzed by means of computer simulation. Independent Rayleigh fading channels are simulated and the channels from/to MS 2 are attenuated by 0, 5, 10 dB. Mobile speed is set to $v_{\mathrm{MS}} = 10$ cm/s, which is the same as in the field experiments.

Fig. 14 shows the result of the computer simulation. With estimated channel, the performance is degraded because of feedback and precoding delay. The degradation is larger at MS 1, which is with greater average channel gain. This implies that some kind of power control is desired to reduce this degradation.

V. Conclusion

The implementation of the MU-MIMO experimental system has been presented. A single 2×2 system has been considered for basic performance evaluation and in-lab and field experiments have been carried out. With faster mobile speed, the BER performance was degraded because of channel estimation error. Through field experiments and computer simulation, it has been shown that the degradation is large at the MS with greater downlink channel gain.

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