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Software Radio-Based Distributed Multi-User MIMO Testbed: Towards Green Wireless Communications

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SUMMARY The present paper introduces a prototype design and experimental results for a multi-user MIMO linear precoding system. A base station and two mobile stations are implemented by taking full advantage of the software-defined radio. The base station consists of general purpose signal analyzers and signal generators controlled by a personal computer. Universal software radio peripherals are used as mobile stations. Linear spatial precoding and a simple two-way channel estimation technique are adopted in this experimental system. In-lab and field transmission experiments are carried out, and the bit error rate performance is evaluated. The impact of the channel estimation error under average channel gain discrepancy between two mobile stations is analyzed through computer simulations. Channel estimation error is shown to have a greater influence on the mobile station with the greater average channel gain.

key words: *green wireless, multi-user MIMO, software radio, distributed antenna system, field experiment*

1. Introduction

The concept of multiple-input multiple-output (MIMO) has been recognized as a key technology by which to achieve the required bandwidth efficiency [1]. However, proper space-time processing techniques should be designed in order to realize such benefits. In a multi-user scenario, MIMO systems improve the system capacity by sharing the spatial channel with multiple users simultaneously [2], [3]. For downlink transmission, a precoding technique is required in order to simplify a mobile station (MS).

In addition to the system capacity, energy efficiency becomes an important topic for future wireless communication systems. In order to address both issues, a distributed antenna system (DAS) has been proposed. The goal of our work is to investigate and demonstrate the performance of MIMO transmission technique combined with DAS in a multi-user scenario to provide high total throughput without increasing either bandwidth or transmit power.

When the base station (BS) has perfect channel state information (CSI), a MIMO system that uses a sophisticated precoding scheme at the BS can simplify multi-user receivers through interference suppression. However, for frequency division duplex (FDD) systems, this assumption leads to an unacceptable feedback rate requirement [4]. A number of studies have investigated precoding schemes in a limited feedback scenario in which only finite sets, or codebooks, of possible precoding configurations are known to both the transmitters and receivers [5]–[7]. One problem with the limited feedback method is that its codebook is not sufficiently precise for interference suppression. In addition, a complex signal processing is required at the MS.

A two-way MIMO channel estimation technique, which has the advantage of simple implementation compared to feedback techniques in a limited feedback scenario, has been proposed [8]. In this technique, the key is that the MS amplifies and forwards (AF) the received training signals (TS), which are sent out by the BS. In addition to the one-way incoming TS from the MS, the BS is able to acquire the downlink CSIs for all BS/MS pairs of antenna elements by using these round-trip TSs. Thus, applying this channel estimation technique, MSs can demodulate the precoded signals without a complex signal processing.

Few studies have investigated linear precoding techniques in practical situations [9], [10]. MIMO precoding requires precise control over transmit signals of multiple BS antennas 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 in evaluating such practical issues. However, to the best of our knowledge, few studies have reported implementation and transmission experiments of MU-MIMO systems [11]–[13], and these few studies consider only indoor environments.

Furthermore, since an AF-based channel estimation technique [8], [14] may have hardware requirements specific to the AF operation system [15], [16], feasibility studies using practical hardware are highly desirable. An experimental setup for a two-way channel estimation technique for multi-user MIMO systems has been reported [17].

In the present paper, a prototype design and experimental results for a multi-user MIMO linear precoding system is presented. A base station and two mobile stations are implemented by taking full advantage of software-defined radio. In the MS, channel estimation and real-time feedback are implemented using a simple universal software radio peripheral (USRP) leveraged by a simple two-way MIMO channel estimation technique.

In the present study, in-lab transmission experiments

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are conducted using a fading emulator. Computer simulations are also carried out, and the system performance is evaluated in terms of bit error rate (BER). Outdoor transmission experiments are also conducted in an actual propagation environment. The impact of channel estimation error under the average channel gain discrepancy between two MSs is analyzed through computer simulations.

2. System Models

2.1 Multi-User MIMO with Spatial Precoding

For the sake of simplicity, let us consider a single carrier frequency in a single coverage environment with coordination of the transmissions from multiple transmission points. The transmitted signal of each transmitter antenna and the received signal of each receiver antenna are collected in the transmitted vector $\boldsymbol{x}$ and the received vector $\boldsymbol{y}$, respectively. In our context, the relationship between the input $\boldsymbol{x}$ and the output $\boldsymbol{y}$ of the MIMO system with N_{TX} transmitter antennas and N_{RX} receiver antennas can be expressed as

$$\boldsymbol{y} = \boldsymbol{H}_{\mathrm{down}}\boldsymbol{x} + \boldsymbol{w}, \tag{1}$$

where $\boldsymbol{H}_{\mathrm{down}}$ is the $N_{\mathrm{RX}} \times N_{\mathrm{TX}}$ channel matrix, and $\boldsymbol{w}$ is an AWGN vector.

We introduce a zero forcing (ZF) precoder that linearly combines the transmitted signals in order to simplify multi-user receivers through interference suppression by exploiting the downlink CSI. The transmitted vector $\boldsymbol{x}$ and the received vector $\boldsymbol{y}$ are then expressed as

$$\boldsymbol{x} = \boldsymbol{H}^{\dagger}_{\mathrm{down}}\tilde{\boldsymbol{x}} \tag{2}$$

$$\boldsymbol{y} = \boldsymbol{H}_{\mathrm{down}}\boldsymbol{x} + \boldsymbol{w} = \tilde{\boldsymbol{x}} + \boldsymbol{w}, \tag{3}$$

where $[\cdot]^{\dagger}$ denotes the Moore-Penrose pseudoinverse, and $\tilde{\boldsymbol{x}}$ is the modulated symbol vector without coding.

2.2 Two-Way Channel Estimation

We apply the two-way channel estimation technique, as proposed in [8] and is expected to have the advantage of simple implementation compared to feedback methods in limited feedback scenarios. In the first step, the BS transmit round-trip TSs $\boldsymbol{X}_1 = [\boldsymbol{x}_{1,1}, \ldots, \boldsymbol{x}_{1,N_{\mathrm{TS}}}]$ are of length N_{TS}. The MSs will return $\boldsymbol{X}_1$ to the BS using the AF relay scheme with a gain of G. The received round-trip TSs at the BS $\boldsymbol{Y}_1 = [\boldsymbol{y}_{1,1}, \ldots, \boldsymbol{y}_{1,N_{\mathrm{TS}}}]$ can then be expressed as

$$z_{1,i} = \boldsymbol{H}_{\mathrm{down},i}\boldsymbol{x}_{1,i} + \boldsymbol{w}_i \tag{4}$$

$$z'_{1,i} = G(z_{1,i} + \boldsymbol{n}_i) \tag{5}$$

$$\boldsymbol{y}_{1,i} = \boldsymbol{H}_{\mathrm{up},i+\tau_1} z'_{1,i} + \boldsymbol{w}'_i, \tag{6}$$

where $\boldsymbol{H}_{\mathrm{down},i}$ is the downlink channel matrix at time i, $\boldsymbol{w}'_i$ is an AWGN vector, $\boldsymbol{Z}_1 = [z_{1,1}, \ldots, z_{1,N_{\mathrm{TS}}}]$ are the received signals of the MSs, $\boldsymbol{n}_i$ is the quantization noise vector in A/D and D/A conversion, $\boldsymbol{Z}'_1 = [z'_{1,1}, \ldots, z'_{1,N_{\mathrm{TS}}}]$ are the transmitted signals of the MSs, $\boldsymbol{H}_{\mathrm{up},i+\tau_1}$ is the uplink channel matrix at time $(i + \tau_1)$, and τ_1 is the time when the MSs initiate the relaying transmission. The channel estimate $\hat{\boldsymbol{H}}_{\mathrm{round}}$ for the round-trip channel $\boldsymbol{H}_{\mathrm{round}} = \boldsymbol{H}_{\mathrm{up}}G\boldsymbol{H}_{\mathrm{down}}$ can be obtained by applying $\boldsymbol{X}_1$ and $\boldsymbol{Y}_1$ to the least squares (LS) method.

Together with the $\boldsymbol{Z}'_1$, the MSs send their own training sets $\boldsymbol{X}_2 = [\boldsymbol{x}_{2,1}, \ldots, \boldsymbol{x}_{2,N_{\mathrm{TS}}}]$ to the BS. The received signals at the BSs $\boldsymbol{Y}_2 = [\boldsymbol{y}_{2,1}, \ldots, \boldsymbol{y}_{2,N_{\mathrm{TS}}}]$ are expressed as

$$\boldsymbol{y}_{2,i} = \boldsymbol{H}_{\mathrm{up},i+\tau_2}\boldsymbol{x}_{2,i} + \boldsymbol{w}''_i, \tag{7}$$

where $\boldsymbol{w}''_i$ is an AWGN vector, and τ_2 is the time when the MSs initiate the transmission. The channel estimate $\hat{\boldsymbol{H}}_{\mathrm{up}}$ for the uplink channel $\boldsymbol{H}_{\mathrm{up}}$ can also be obtained using the LS method. Now, we can solve for the coefficients of the downlink channel, which are given as

$$\hat{\boldsymbol{H}}_{\mathrm{down}} = (\hat{\boldsymbol{H}}_{\mathrm{up}}G)^{\dagger}\hat{\boldsymbol{H}}_{\mathrm{round}}. \tag{8}$$

3. Prototype Design

3.1 System Description

Our experimental prototype consists of a BS with two antennas and two MSs implemented in USRPs. The CSI is estimated at the BS using the two-way channel estimation method. In this method, both the downlink channel and the uplink channel are estimated.

3.2 Base Station

A block diagram and a photograph of the base station are shown in Figs. 1 and 2, respectively. Two modular RF signal generators (SGs), two modular RF signal analyzers (SAs), a field programmable gate array (FPGA) board, and a modular PC are embedded in the same chassis. The SG consists of a

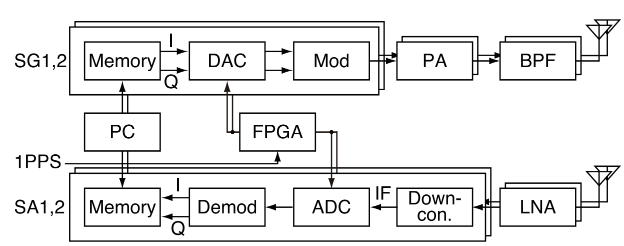

Fig. 1 Block diagram of the base station.

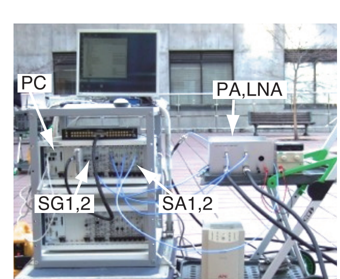

Fig. 2 Base station.

16-bit DAC and a vector modulator. A single local oscillator (LO) is shared by the SGs.

The SA consists of a downconverter and a 16-bit ADC. The two SAs also use the same LO. The received signal is translated to IF by the downconverter and then digitized by the ADC. The digital IF signal is demodulated by the on-board digital signal processor and then recorded in the on-board memory. Real-time baseband signal processing is performed on the modular PC by accessing the memories in the SGs and SAs.

For the field experiments, a power amplifier ($P_{1\,\mathrm{dB}}$ = 33 dBm, typ.), a BPF, and an omni-directional collinear antenna are connected to each SG, and a low noise amplifier (NF 1.9 dB, typ.) and an omni-directional collinear antenna are connected to each SA. A trigger generator is implemented on the FPGA in order to control the transmission and reception timing.

3.3 Mobile Station

The MS is implemented using a USRP and a laptop computer with the USRP hardware driver library. At the MS side, a host PC is responsible for baseband signal processing. A photograph of the MS is shown in Fig. 3.

As shown in Fig. 4, the USRP consists of an RF front-end daughterboard and a motherboard. The received signal is converted into the analog baseband IQ signal by the wireless-LAN transceiver chip on the daughterboard. Figure 5 shows a block diagram of the transceiver chip. The receiver circuits contain a two-stage amplifier, a low noise amplifier (LNA), and a variable gain amplifier (VGA). A phase locked loop is locked by an internal temperature compensated crystal oscillator or external 10 MHz reference.

The motherboard consists of analog-to-digital converters, digital-to-analog converters, a FPGA, and an Ethernet I/O interface. A host computer is connected to the USRP for command, digital IQ data streaming, and digital signal processing. Parameters, such as amplifier gain and frequency of the oscillator, are set using the driver software. The signal packets are tagged with a time stamp to transmit/receive precisely at the specified time using the internal timer.

3.4 Packet Structure

A simple two-way channel training method [18], [19] is used for downlink channel estimation. Using this method, the computational complexity of the MS can be reduced because channel estimation is performed at the BS.

Figure 6 shows the packet structure in a frame. First, the BS transmits the training sequences (TSs) for round-trip channel estimation at time $t = 0$. The TSs from the BS are orthogonal sequences and are transmitted at the same time. 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 TSs have $N_{TS} = 16$ symbols. The BS estimates the downlink channel using the two TSs and then transmits 64-symbol-long precoded data packet at $t = 8$ ms. Figure 7 shows the actual waveform of these packets. It can be confirmed that 2 ms feedback is achieved.

3.5 Synchronization

In order to establish frequency and timing synchronization between the BS and the MSs, a 1 PPS pulse signal and a 10 MHz reference signal are used. As the source of these

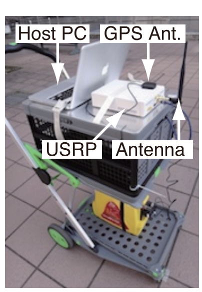

Fig. 3 Mobile station.

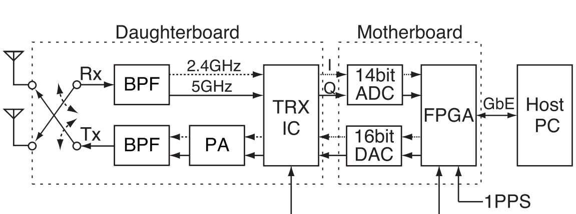

Fig. 4 Block diagram of the USRP.

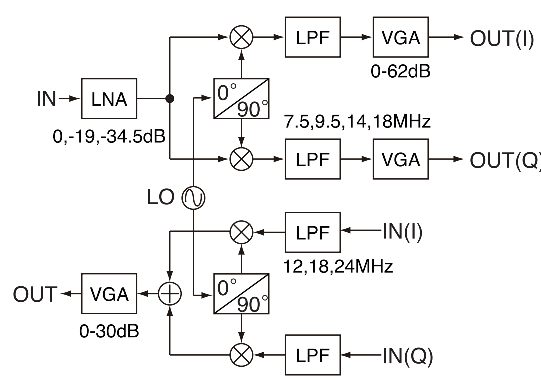

Fig. 5 Block diagram of the transceiver chip.

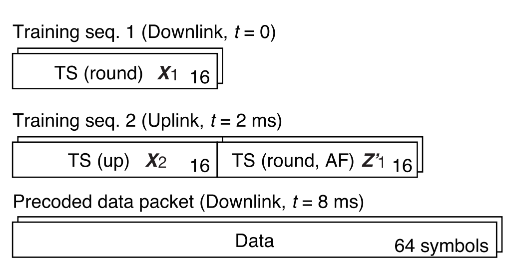

Fig. 6 Packet structure. Two training packets are used for channel estimation.

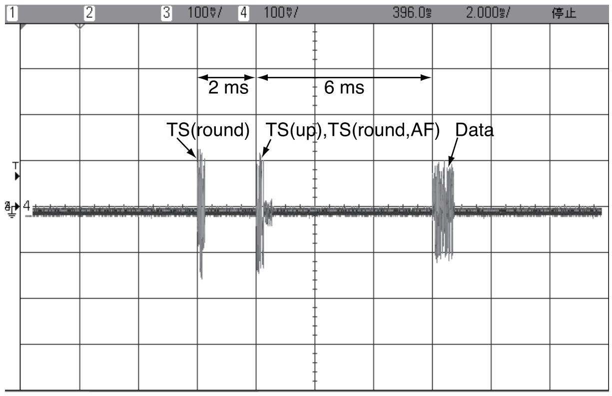

Fig. 7 Timing of packets observed using the oscilloscope.

signals, GPS receiver modules with oven-controlled crystal oscillators are installed in the BS and the USRPs. As long as the GPS modules are in good reception condition, the 10 MHz reference signal and the 1 PPS pulse signal have sufficiently high accuracy for frequency and timing synchronization. The trigger signals for SGs and SAs are synchronized with this 1 PPS pulse signal.

4. In-lab Experiments

As the first setup, 2 × 2 MU-MIMO transmission experiments with zero-forcing linear precoding are conducted. Table 1 shows the parameters for the experiments. Figure 8 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.

In the current setup, the gain G is not fed back to the BS since the modulation scheme is QPSK. All of the variable gains of the USRP are adjusted beforehand, and fixed during the experiments. This adjustment ensures that the transmit power of $\boldsymbol{Z}'_1$ is less than the maximum transmit power.

For frequency and timing synchronization, wired synchronization and GPS synchronization are considered. In the case of wired synchronization, a function generator and a rubidium frequency standard are used. In this section, wired synchronization is first employed for basic performance evaluation. Then, signals from individual GPS receivers are used, and the performance is compared.

In the experiments of the present paper, the peak transmit power of the first training packet is fixed. The peak transmit power of the precoded data packet is also fixed over one BER measurement period.

Figure 9 shows the BER versus SNR performance over Rayleigh fading channels with mobile speed v_{MS} = 0.27 c/ms. Computer simulation results, with the estimated CSI and with the perfect CSI at the BS, are also shown in this figure. The horizontal axis of Fig. 9 shows the average received SNR of precoded data packets. Figure 9 shows that there is little difference between the two computer simulation results, i.e., the results obtained with the perfect CSI at the BS and the results obtained with the estimated CSI. This suggests that feedback and precoding delay are negligible for this mobile speed. Experimental results show some degradation in the high-SNR region.

Figure 10 shows the performance comparison between two synchronization schemes. The mobile speed v_{MS} is set to 10 c/ms. The performance with GPS synchronization is

Table 1 Experimental parameters.

System parameters	Values
Number of BS antennas	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
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

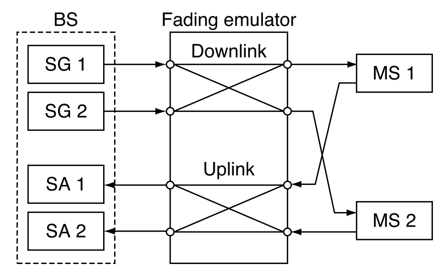

Fig. 8 Experimental setup for in-lab experiments. SGs and SAs of the BS equipment are directly connected with the fading emulator.

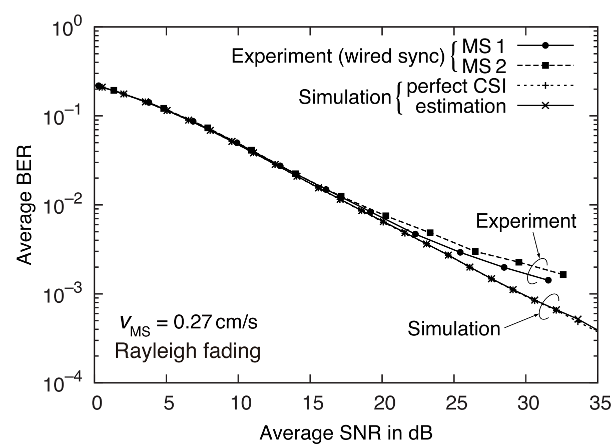

Fig. 9 BER versus SNR performance over the slow Rayleigh fading channel (v_{MS} = 0.27 c/ms).

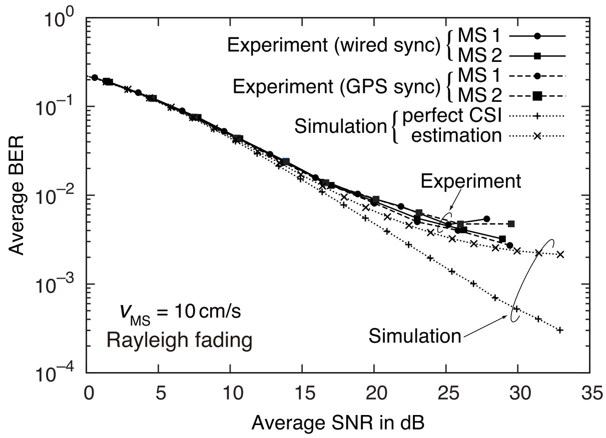

Fig. 10 BER versus SNR performance over the faster Rayleigh fading channel (v_{MS} = 10 c/ms).

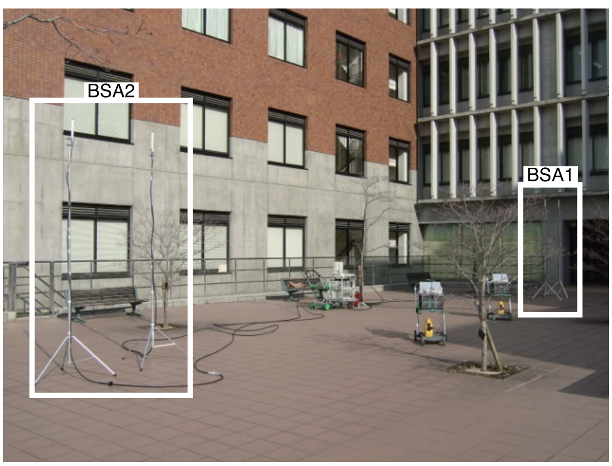

Fig. 11 Environment for the field experiments.

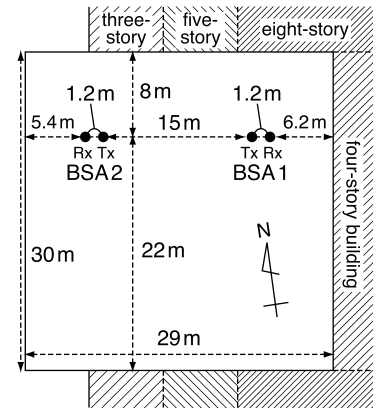

Fig. 12 Layout of the experimental location.

Table 2 Additional parameters for the 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_{MS} = 10 c/ms

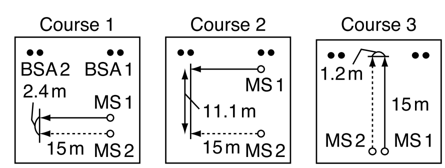

Fig. 13 Courses of the MSs.

similar to that with wired synchronization. In Fig. 10, performance degradation due to feedback and precoding delay is observed.

5. Field Experiments

Field transmission experiments were conducted at a field in Kyoto University, as shown in Figs. 11 and 12. This field is surrounded by buildings, except on the west side and is primarily an LOS environment. Table 2 shows the additional parameters for the field experiments. Since the target system is a distributed antenna system, the two transmit antennas are spaced 15 m apart. A transmit antenna and a receive antenna of the BS are spaced 1.2 m apart. Two MSs move along the three courses shown in Fig. 13 at a speed of v_{MS} = 10 c/ms. The course 1 is almost the same course of [20] in which the propagation characteristics are measured. The courses 2 and 3 are employed in order to investigate the effect of the path loss on the transmission performance.

Figures 14 and 15 show the BER performance and the received power of the precoded data packets, respectively, both being averaged every 30 cm $\simeq 5\lambda$. The received power of the data packet at the two MSs is maintained equal by channel inversion at the BS. The fluctuation of the received power is due to the fixed 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 that at MS 2 in Course 1 and Course 2, where MS 1 is nearer than MS 2 from the BS antennas.

Figure 16 shows the BER versus SNR performance for different transmit powers of the data packet in Course 1. The transmit power of the first training packet is maintained constant. The difference in the BER is large at high SNR, which implies that the degradation is caused by residual inter-user interference due to the channel estimation error.

The impact of channel estimation error under the average channel gain discrepancy between two MSs is analyzed through computer simulations. Independent Rayleigh fading channels are simulated and the channels from/to MS 2 are attenuated by 0, 5, and 10 dB. The mobile speed is set to v_{MS} = 10 c/ms, which is the same as in the field experiments.

Figure 17 shows the computer simulation results. Using the estimated CSI, the performance is degraded due to feedback and precoding delay. The degradation is larger at MS 1, which has the greater average channel gain. This performance degradation can be compensated by transmit power control.

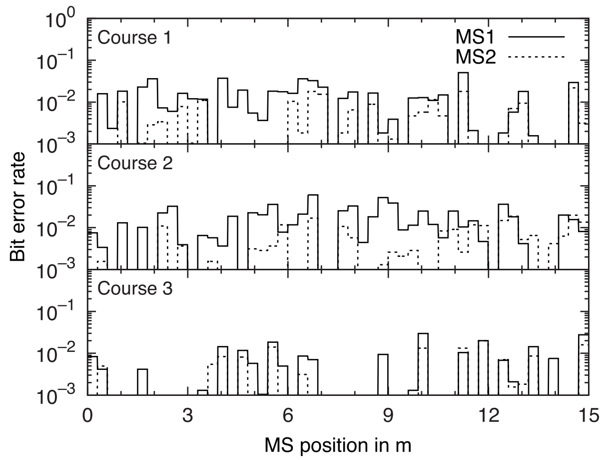

Fig. 14 BER performance for the three MS courses. BER is calculated every 30 cm ≃ 5λ.

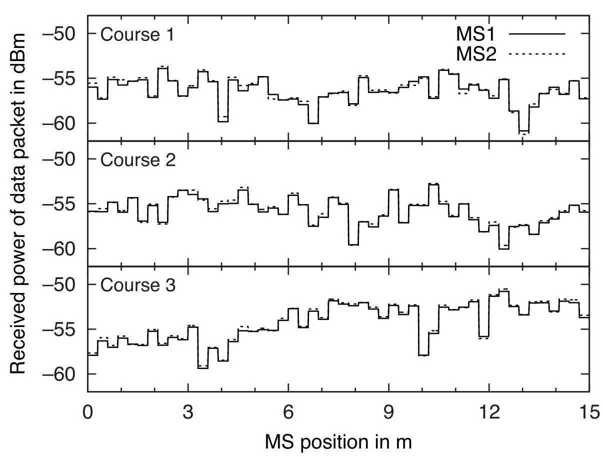

Fig. 15 Received power of precoded data packets for the three MS courses, averaged every 30 cm ≃ 5λ.

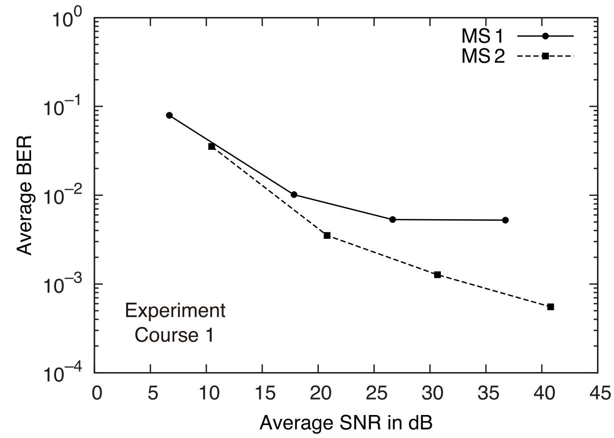

Fig. 16 BER versus SNR performance for Course 1. The horizontal axis shows the received SNR of the data packet averaged over the entire course, i.e., 15 m. The transmit power of the first training packet is fixed. The transmit power of the precoded data packet is attenuated by 0, 10, 20, and 30 dB.

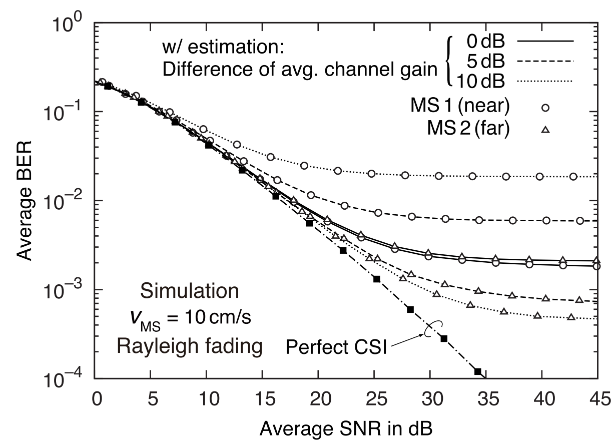

Fig. 17 SNR versus BER performance with channels from/to MS 2 attenuated by 0, 5, 10 dB.

6. Conclusion

A prototype design and experimental results for a multi-user MIMO linear precoding system have been presented. A simple two-way channel estimation technique is used in this experimental system. A base station and two mobile stations are implemented by taking full advantage of the software-defined radio. A single 2 × 2 system has been considered for basic performance evaluation, and in-lab and field experiments have been carried out. For the faster mobile speed, the BER performance was degraded because of channel estimation error. Field experiments and computer simulations reveal that channel estimation error has a greater influence on the mobile station with the greater average channel gain.

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