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Performance improvement of ZF-precoded MU-MIMO transmission by collaborative interference cancellation

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Abstract: Multi-user multiple-input and multiple-output (MU-MIMO) transmission has been extensively studied to enhance the spectral efficiency of wireless communication systems. The performance of MU-MIMO suffers due to the presence of residual multi-user interference. Linear interference cancellation can offer excellent performance when a large number of antennas are available. This, however, is impractical in a mobile station. In this paper, we apply a collaborative interference cancellation scheme to a precoded MU-MIMO system. In order to effect collaboration, we implement received signal sharing among mobile stations using wireless local area network connections. We carried out transmission experiments in an indoor environment to test the performance of our precoded MU-MIMO system with collaborative interference cancellation.

Keywords: multi-user MIMO, user cooperation, collaborative MIMO, transmission experiment, interference canceller

Classification: Wireless Communication Technologies

References

[1] H. Murata, "Collaborative interference cancellation for multi-user MIMO communication systems," IEICE Technical Report, RCS2013-201, pp. 159–164, Nov. 2013 (in Japanese).

[2] H. Murata, "Collaborative interference cancellation for future wireless communications," Proc. 2015 Vietnam–Japan International Symposium on Antennas and Propagation, Ho Chi Minh City, Vietnam, pp. 35–38, Jan. 2015.

[3] H. Kwon and J. M. Cioffi, "Multi-user MISO broadcast channel with user-cooperating decoder," Proc. IEEE Vehicular Technology Conference, Sept. 2008. DOI:10.1109/VETECF.2008.335

[4] J. Lee, S. Kim, H. Suman, T. Kwon, Y. Choi, J. Shin, and A. Park, "Downlink node cooperation with node selection diversity," Proc. IEEE Vehicular Technology Conference, pp. 1494–1498, May 2005. DOI:10.1109/VETECS.2005.1543568

[5] M. Taniguchi, H. Murata, S. Yoshida, K. Yamamoto, D. Umehara, S. Denno, and M. Morikura, "Indoor experiment of multi-user MIMO user selection algorithm based on chordal distance," Proc. Global Telecommunications Conference (GLOBECOM2013), Atlanta, GA, USA, Dec. 2013. DOI:10.1109/GLOCOM.2013.6831692

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1 Introduction

Multi-user multiple-input and multiple-output (MU-MIMO) transmission has been extensively studied in order to improve the spectral efficiency of wireless communication systems. However, precoding techniques are inherently sensitive to channel variations. In other words, the performance of MU-MIMO is significantly affected by the presence of residual multi-user interference. It is well-known that a linear interference cancellation scheme with a large number of receive antennas can offer satisfactory performance with reasonable computational complexity. However, it is impractical to expect such a number of antennas in mobile stations due to size limitations.

In this paper, we apply collaborative interference cancellation (CIC) [1, 2] to a precoded MU-MIMO system and test its performance through an experiment. We employ received signal sharing among mobile stations [3, 4] in the proposed scheme in order to enhance its interference cancellation capability. We conducted transmission experiments using wireless local area network (LAN) links for collaboration in an indoor environment in order to test the performance of our collaborative interference cancellation scheme implemented on a MU-MIMO testbed.

2 System model

2.1 Precoding

Consider downlink communication in a MU-MIMO system. For the sake of simplicity, let us consider a single-carrier frequency in a single-coverage environment. The base station (BS) equipped with K antennas is serving M mobile stations (MSs), each with a single antenna. We introduce a linear zero-forcing (ZF) precoder by exploiting the downlink channel state information (CSI). The transmitted signal to each MS is collected in the vector $\boldsymbol{s} \in \mathbb{C}^{M\times 1}$. In the context of our study, the received signal of the MSs can be expressed as

$$\boldsymbol{y} = \boldsymbol{HWs} + \boldsymbol{n} = \boldsymbol{s} + \boldsymbol{n}. \tag{1}$$

where $\boldsymbol{H} \in \mathbb{C}^{M\times K}$ is a channel matrix and $\boldsymbol{n} \in \mathbb{C}^{M\times 1}$ is an additive white Gaussian noise vector. The precoding matrix $\boldsymbol{W} \in \mathbb{C}^{K\times M}$ is given by

$$\boldsymbol{W} = \boldsymbol{H}^{\dagger} = \boldsymbol{H}^{\mathrm{H}}(\boldsymbol{HH}^{\mathrm{H}})^{-1}. \tag{2}$$

If there exist channel variations $\Delta\boldsymbol{H} \in \mathbb{C}^{M\times K}$, the off-diagonal elements of $(\boldsymbol{I} + \Delta\boldsymbol{HW})$ cause multi-user interference.

$$\boldsymbol{y} = (\boldsymbol{H} + \Delta\boldsymbol{H})\boldsymbol{Ws} + \boldsymbol{n} = (\boldsymbol{I} + \Delta\boldsymbol{HW})\boldsymbol{s} + \boldsymbol{n} \tag{3}$$

2.2 User selection algorithm

In order for the linear precoder to suppress interference, we need to select MSs (also referred to as users) to serve simultaneously. The number of users cannot be greater than the number of BS antennas. As a low-complexity user selection method exploiting the CSI, we introduce the chordal distance-based user selection (CDUS) algorithm [5].

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The chordal distance is given by

$$d_{\mathrm{cd}}(\boldsymbol{H}_{\mathrm{cand}}, \boldsymbol{H}_{\mathrm{sel}}) = \sqrt{\sum_{j=1}^{J} \sin^2 \theta_j} = \sqrt{J - \mathrm{tr}(\tilde{\boldsymbol{H}}_{\mathrm{cand}} \tilde{\boldsymbol{H}}_{\mathrm{sel}}^{\mathrm{H}} \tilde{\boldsymbol{H}}_{\mathrm{sel}} \tilde{\boldsymbol{H}}_{\mathrm{cand}}^{\mathrm{H}})} \tag{4}$$

where $\boldsymbol{H}_{\mathrm{cand}} \in \mathbb{C}^{J \times K}$ is the downlink CSIs of candidate users, $\boldsymbol{H}_{\mathrm{sel}} \in \mathbb{C}^{N_{\mathrm{selected}} J \times K}$ is the downlink CSIs of the selected users, θ_j is the principal angle between the two subspaces spanned by row j of $\boldsymbol{H}_{\mathrm{cand}}$ and the rows of $\boldsymbol{H}_{\mathrm{sel}}$, N_{selected} is the number of selected users, J is the number of receive antennas of MS, $[\tilde{\cdot}]$ represents the Gram–Schmidt orthonormalization of the rows.

Therefore, by selecting users with greater channel chordal distance among one another, we can bring the channels of the selected users closer to the orthogonal, hence improving the performance of linear precoding.

2.3 Collaborative interference cancellation

In order to suppress residual multi-user interference, we apply a collaborative interference cancellation scheme by utilizing the short-range wireless interface of a mobile station. In this paper, we employed a simple minimum mean squared error (MMSE) weight $\boldsymbol{W}_{\mathrm{MMSE}} \in \mathbb{C}^{M \times M}$. The weight is given by

$$\boldsymbol{W}_{\mathrm{MMSE}} = (\boldsymbol{H}\boldsymbol{W})^{\mathrm{H}} \boldsymbol{R}_{yy}^{-1} = (\boldsymbol{H}\boldsymbol{W})^{\mathrm{H}} (\boldsymbol{H}\boldsymbol{W}\boldsymbol{W}^{\mathrm{H}}\boldsymbol{H}^{\mathrm{H}} + \boldsymbol{\Sigma})^{-1}, \tag{5}$$

where $\boldsymbol{R}_{yy} \in \mathbb{C}^{M \times M}$ and $\boldsymbol{\Sigma} \in \mathbb{C}^{M \times M}$ are autocorrelation matrices of the received signals and the noise, respectively.

3 Transmission experiments

3.1 Equipment

The testbed used in this research consisted of a BS with four antennas ($K = 4$) and six MSs, both implemented using software-defined radio features. We employed amplify-and-forward (AF) based channel estimation, CDUS, and linear spatial precoding [5]. The major parameters of the experiment are shown in Table I.

The BS consisted of two instrument chassis and a radio frequency (RF) front end that included RF amplifiers and RF switches. Power amplifiers (output power at 1 dB compression $P_{1\mathrm{dB}} = 34.6$ dBm, typical) and low-noise amplifiers (noise figure 1.9 dB, typical) were connected to signal generators (SGs) and signal analyzers, respectively. RF switches were used for duplexing. The control signals of the RF switches were generated by a field-programmable gate array (FPGA). The trigger signal was sent from an SG to the FPGA in order to synchronize the transmission timing of the SGs with the control signals of the RF switches.

A universal software radio peripheral (USRP) was used as a mobile station. We connected a general-purpose PC to a USRP N210, and carried out baseband signal processing on the host PC. The motherboard of USRP N210 was equipped with 14-bit analog-to-digital converters, 16-bit digital-to-analog converters, and an FPGA. Digital signal processing, such as frequency translation, decimation, and interpolation, was performed on the FPGA.

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Table I. Major parameters of experiment.

System parameters	Value
Number of BS antennas	4
Number of MSs	6
Carrier frequency	5.11 GHz
Modulation	QPSK
Symbol rate	312.5 k symbols/s
Tx/Rx filter	Square root Nyquist (roll-off factor = 0.4)
BS parameters	**Value**
Channel estimation	AF-based two-way method
Precoding	Linear (ZF)
Transmission power of TS1	7 dBm
Antenna height	2 m
Antenna gain	5 dBi
MS parameters	**Value**
Transmission power of TS2	7 dBm
Antenna height	88 cm
Antenna gain	3 dBi

3.2 Signaling format

A transmission frame was composed of three time slots. The BS first transmitted the training sequences (TS1s) for round-trip channel estimation at time $t = 0$. The TS1s from the BS were orthogonal sequences, and were transmitted at the same time and frequency. Each MS sent back the received round-trip TS1 using amplify-and-forward relaying along with another training sequence (TS2) for uplink estimation at $t = 2$ ms. The BS estimated the downlink channel using the two TSs, and then transmitted the precoded data packet at $t = 10$ ms. The data packet consisted of the synchronization word (SW) used for timing synchronization, the training sequence (TS3) used for demodulation, the control signal used for measurement automation, and the data sequence along with its cyclic redundancy check.

We established timing synchronization using the SW, which was transmitted by the BS in the third timeslot. Each MS detected the timing of the SW by means of a sliding correlator. Channel estimation, user selection, and precoding weight generation were carried out at every transmission frame. The duration of a transmission frame was set to 50 ms in order to ensure that the MSs had sufficient time to calculate and display the measurement results.

3.3 Experimental setup

We tested the performance of our proposed collaborative interference cancellation scheme through a transmission experiment in an indoor environment. The experiment was conducted in the foyer of the faculty of engineering building no. 3. The foyer and the plan for it are shown in Fig. 1. The four mobile stations MS1~MS4 moved at 40 cm/s. The other mobile stations MS5 and MS6 remained stationary.

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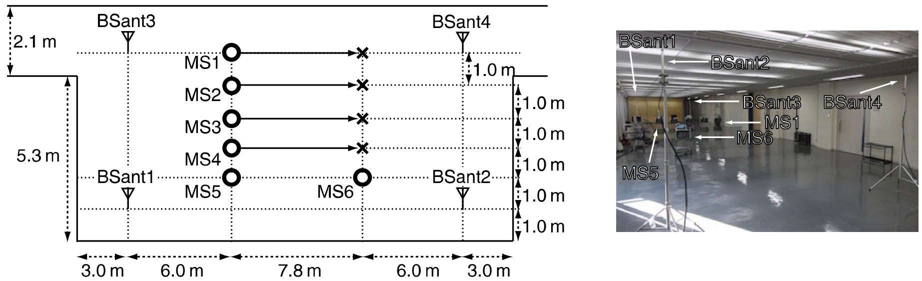


(a) plan (b) photograph

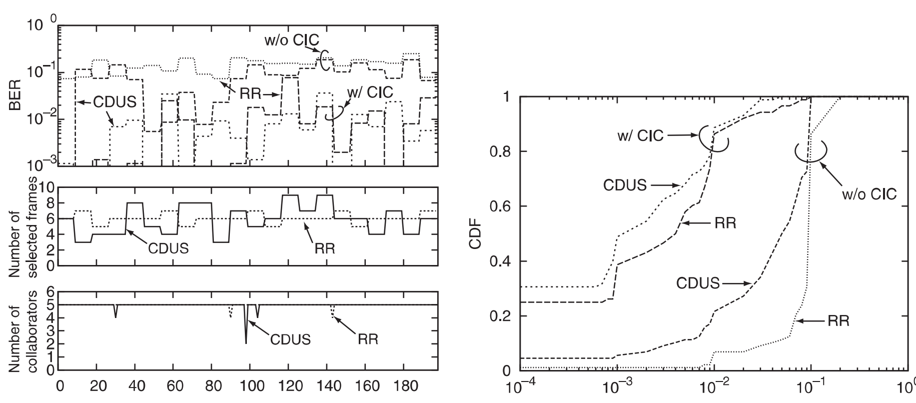
Fig. 1. Experimental equipment installation.

Wireless LAN modules of the host PCs were employed as collaboration links among mobile stations. The independent BSS mode channel 48 was used. The received training signal (TS3) and the received data signal were sampled and expressed in 20-bit I/Q data streams with 16-bit gain information. Due to possible packet losses, the number of received signals available for interference cancellation was not always six. Each MS independently demodulated the available signals. The performance of the system was evaluated in terms of bit error rate (BER), and data throughput is beyond the scope of this study.

3.4 Experimental results

In our experiments, we examined the CDUS and round robin (RR) schemes frame by frame. In the RR scheme, $\binom{6}{4} = 15$ groups of four MSs ($M = 4$) were scheduled once for transmission. The target received signal power of the precoded data signal was set to -90 dBm. The performance was evaluated in terms of the BER of BS–MS links, the number of MSs selected in nine frames, and the number of gathered quantized received signals through Wi-Fi links. The BER was also averaged over nine packets of each user selection scheme.

Fig. 2(a) shows the performances of MS1 against the packet index. As can be seen, in the case not involving CIC (w/o CIC), CDUS offered better BER than RR at all times, except for the packet index from 10 to 18 and from 28 to 36. In the case involving the use of CIC (w/ CIC), there was no obvious difference between the performance of CDUS and RR.



(a) Performances of MS1 vs. packet index (b) CDF of BER performance (MS1,2,3,4)

Fig. 2. Measured performance.

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Fig. 2(b) shows the cumulative distribution function (CDF) of the measured BER of MS1~MS4. As can be seen from this figure, the collaborative interference cancellation scheme clearly outperformed independent reception (w/o CIC) for both the cases involving CDUS and RR. This also confirmed that CDUS is superior to RR. Moreover, we confirmed that CIC was effective even when a user selection scheme took orthogonality among users' channels into account in a user mobility scenario.

4 Conclusion

In this paper, we applied a collaborative interference cancellation scheme to a ZF-precoded MU-MIMO system to eliminate residual multi-user interference. Through a transmission experiment, we confirmed that received signal sharing among mobile stations can enhance transmission performance, especially among dynamic mobile stations.

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