Expanded Null Beamforming for Full-Duplex MIMO Communication on IEEE 802.11

Kotaro Nagano*, Masahiro Kawano*, Yuhei Nagao*, and Hiroshi Ochi*
*Graduate School of Computer Science and Systems Engineering, Kyushu Institute of Technology, Japan

***Abstract*—Cancellation of self interference (SI) is an important technology in order for wireless communication system devices to perform full-duplex communication. In this paper, we describe a novel self-interference cancellation using null beamforming by Cooperative MIMO (Multiple Input Multiple Output) for full-duplex wireless communication in IEEE 802.11 network. In addition, we propose a method to perform null beamforming by applying a weight matrix to the legacy preamble part. We evaluate the SI cancellation amount by the proposed method using a field programmable gate array (FPGA) and software defined radio (SDR), and show the experimental results. In the experiment, it is confirmed that the amount of SI cancellation by the proposed method was at least 17 dB. The SI cancellation amount can be further potentiated with more accurate CSI(channel state information) by increasing the transmission power. It is shown that SI can be suppressed whole frame include legacy preamble part.**

I. Introduction

Due to the rapid spread of wireless communication systems in recent years and the increase in communication volume due to the increase in content data volume, there is an increasing demand for higher speed and lower delay in wireless communication. Especially, Full-Duplex (FD) wireless communication technology, which can realize high-speed and low-delay communication while reducing frequency resources, is attracting attention [1], [2]. APs and STAs transmit and receive at the same frequency and time in FD wireless communications. Therefore, the antenna itself receives a huge level of self interference (SI). This SI factor makes it difficult to decode the desired signal sent by another sender. The papers in [3] and [4] proposed methods to suppress SI using hardware approaches such as antenna cancellation, RF interference cancellation (RF cancellation), and digital baseband interference cancellation (digital cancellation).

The SI cancellation amount required for each cancellation technique depends on the transmit power, analog-to-digital converter (ADC) resolution, and the minimum receive power level of the desired signal. As an example, assume that the transmission power is 20 dBm, the ADC resolution is 10 bit, and the minimum reception power level of the target signal is -82 dBm. In this case, antenna cancellation of 20 dB and RF cancellation of 40 dB respectively, and 50 dB of digital cancellation is required. When this is met, the final SI power will be the same as the noise floor power. The antenna cancellation and RF cancellation are classified analog circuit cancelling approach. The advantage of analog circuit approach is that SI can be greatly suppressed. The problem with using the analog circuit approach canceller by antenna cancellation and RF cancellation is that the implementation becomes large. In other words, as the number of antennas increases, the number of RF cancellers required increases explosively. Thus, extending this method to MIMO is exceedingly difficult, and even in [3] and [4], it is only implemented by SISO. On the other hand, in [5], [6] and [7], spatial cancellation is proposed as a new SI canceling method, and it has been demonstrated in the actual machine. Spatial cancellation is an application of block diagonalization in multi-user MIMO (MU-MIMO). Using some of the MIMO degrees of freedom (DoF) and directing the null space to the receiving antenna, SI can be canceled before the ADC passes through. Also, spatial cancellation can be used in combination with the above three methods. By using Spatial cancellation in combination with the hardware approach, the burden on the hardware part can be reduced, and a part of the hardware implementation for SI cancellation becomes unnecessary. On the other hand, the problem is that it has less DoF compared to traditional MU-MIMO with the same number of transmitting antennas because some of the DoF is used for purposes other than transmission to perform spatial cancellation.

To address the DoF reduction, it has been proposed to apply cooperative MIMO to spatial cancellation for FD wireless communication as Cooperative MIMO (Co-MIMO) Applied Null Beamforming to Self [8]. There are two Co-MIMO methods, joint transmission (JT) and cooperative beamforming (CB) [9]. JT technology is used in this proposal. The JT behaves as if they work one big AP because multiple APs are synchronized. For example, if we have two APs with two transmit antennas and two receive antennas and they work together, we can think of them as one AP with four transmit antennas. In the proposed method, idle AP participates in cooperation and the utilization efficiency of spatial channels is improved. In other words, it can be considered that the number of available antennas is increasing, so a higher DoF can be achieved. In the paper [8], null beamforming is applied only to the HT part of the IEEE 802.11n frame. The experimental on paper [8], in addition to null beamforming, antenna cancellation was obtained using a circulator, and a total SI supression of about 30 dB was achieved. In the case of SISO (Single Input Single Output) communication, antenna cancellation can be performed by using a circulator, but it is difficult to do it for mutual antennas in MIMO communication system.

In this paper, we propose a method of applying spatial cancellation to the legacy preamble part in the IEEE 802.11

frame. In addition, in order to evaluate the replacement of antenna cancellation, which achieves suppression of about 20 dB, with null beamforming, this paper evaluates the SI cancellation amount by null beamforming without applying antenna cancellation for MIMO communication system.

The rest of the paper is organized as follows. In Section II, as the basic theory of the null beamforming, we assume multiple APs with multiple transmitting antennas and multiple receiving antennas and explain how to suppress SI by spatial cancellation while applying Co-MIMO. Section III describes the signal generation for null beamforming and how to apply the method to the legacy part. Section IV introduces an actual implementation example of an FD wireless communication system that realizes the proposed method. Then, demonstrate that the proposed method is feasible through experiments using actual equipment and evaluate and consider the SI cancellation amount. Lastly, we conclude this paper in Section V.

II. Theory of Null Beamforming

This section describes about the null beamforming, Co-MIMO Applied Null Beamforming to Self. Subsection II-A presents the theory of the SI as a general formula. In Subsection II-B, we explain more in detail on the theory and calculation method for null beamforming when there are two APs and two STAs.

A. Self Interference on full-duplex communication

In this section, we assume an environment in which N_{AP} APs and N_{STA} STAs exist. All APs use Co-MIMO to perform downlink (DL) transmission to all STAs. At the same time, apply null beamforming to self. This makes it possible to suppress SI between APs.

In this paper, the AP index is described by i and the STA index is described by j. The i-th AP has N_i transmitting antennas, and the j-th STA has M_j receiving antennas. M_0 represents the number of receiving antennas on AP to which the null beam is directed. We define the total number of transmitting antennas $N_{\mathrm{TOTAL}} = \sum_{i=1}^{N_{\mathrm{AP}}} N_i$ and the total number of receiving antennas $M_{\mathrm{TOTAL}} = \left(M_0 + \sum_{j=1}^{N_{\mathrm{STA}}} M_j\right)$. $N_{\mathrm{SS}j}$ is the number of transmission streams sent to the j-th STA. In this paper, $N_{\mathrm{SS}j} = M_j$ to simplify the theory expression.

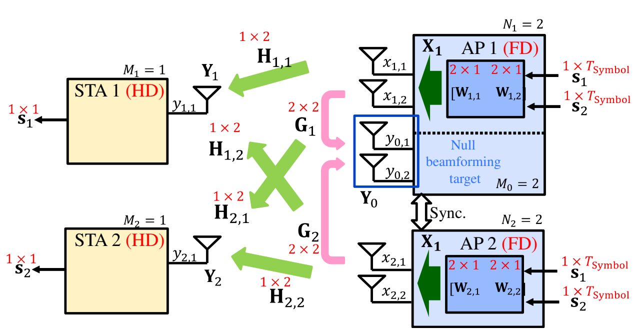

Fig. 1. Schematic Diagram of the Proposed System

In such an environment, the received signal $\mathbf{Y}_j$ of j-th STA and the received signal $\mathbf{Y}_0$ of AP are expressed by the following equations:

$$\mathbf{Y}_j = \sum_{i=1}^{N_{\mathrm{AP}}} \mathbf{H}_{j,i} \sum_{l=1}^{N_{\mathrm{STA}}} \mathbf{W}_{i,l}\mathbf{s}_l + \mathbf{N}_j, \tag{1}$$

$$\mathbf{Y}_0 = \sum_{i=1}^{N_{\mathrm{AP}}} \mathbf{G}_i \sum_{l=1}^{N_{\mathrm{STA}}} \mathbf{W}_{i,l}\mathbf{s}_l + \mathbf{N}_0, \tag{2}$$

where $\mathbf{s}_j$ $(N_{\mathrm{SS}j} \times T_{\mathrm{Symbol}})$ is the send stream to the j-th STA, $\mathbf{W}_{i,j}$ $(N_i \times N_{\mathrm{SS}j})$ is a weight matrix for mapping the send stream to the j-th STA to the antenna of the i-th AP, $\mathbf{H}_{j,i}$ $(M_j \times N_i)$ is the channel matrix from the transmitting antenna of the i-th AP to the receiving antenna of the j-th STA, $\mathbf{N}_j$ $(M_j \times T_{\mathrm{Symbol}})$ is the noise added to the receiving antenna of the j-th STA, and T_{Symbol} is the number of OFDM symbol transmitted. $\mathbf{G}_i$ $(M_0 \times N_i)$ is the channel matrix from the transmitting antenna of the i-th AP to the receiving antenna of the specific AP and $\mathbf{N}_0$ $(M_0 \times 1)$ is the noise added to the receiving antenna of the specific AP.

The channel matrices $\mathbf{H}_{j,i}$, $\mathbf{G}_i$ and weight matrices $\mathbf{W}_{i,j}$ are compiled into $\mathbf{H}_j$, $\mathbf{G}$ and $\mathbf{W}_l$. where $\mathbf{H}_j = \begin{bmatrix}\mathbf{H}_{j,1} & \mathbf{H}_{j,2} & \cdots & \mathbf{H}_{j,N_{\mathrm{AP}}}\end{bmatrix}$, $\mathbf{G} = \begin{bmatrix}\mathbf{G}_1 & \mathbf{G}_2 & \cdots & \mathbf{G}_{N_{\mathrm{AP}}}\end{bmatrix}$ and $\mathbf{W}_l = \begin{bmatrix}\mathbf{W}_{1,l}^T & \mathbf{W}_{2,l}^T & \cdots & \mathbf{W}_{N_{\mathrm{AP}},l}^T\end{bmatrix}^T$. Then, received signals $\mathbf{Y}_j$ and $\mathbf{Y}_0$ are expressed by the following equations:

$$\mathbf{Y}_j = \mathbf{H}_j \sum_{l=1}^{N_{\mathrm{STA}}} \mathbf{W}_l\mathbf{s}_l + \mathbf{N}_j, \tag{3}$$

$$\mathbf{Y}_0 = \mathbf{G} \sum_{l=1}^{N_{\mathrm{STA}}} \mathbf{W}_l\mathbf{s}_l + \mathbf{N}_0, \tag{4}$$

where $\mathbf{W}_j$ $(N_{\mathrm{TOTAL}} \times N_{\mathrm{SS}j})$ is a weight matrix for mapping the stream $\mathbf{s}_j$ into the j-th STA's transmitting antenna, $\mathbf{H}_j$ $(M_j \times N_{\mathrm{TOTAL}})$ is the channel matrix from the transmitting antenna of all APs to the receiving antenna of the j-th STA.

IUI and SI term must be $\mathbf{0}$ in equations (3) and (4) in order to suppress interference. That is, the following equation must be satisfied for all of $(j = 1, 2, \cdots, N_{\mathrm{STA}})$:

$$\mathbf{H}_j \sum_{l=1, l\neq j}^{N_{\mathrm{STA}}} \mathbf{W}_l\mathbf{s}_l = \mathbf{0}, \quad \mathbf{G} \sum_{l=1}^{N_{\mathrm{STA}}} \mathbf{W}_l\mathbf{s}_l = \mathbf{0}. \tag{5}$$

Thus, it is necessary to find and set each weight matrix $\mathbf{W}_l$ $(l = 1, 2, \cdots, N_{\mathrm{STA}})$ that satisfies equation (5). That weight matrix must satisfy $\mathbf{H}_j\mathbf{W}_l = \mathbf{0}$ $(j = 1, 2, \cdots, N_{\mathrm{STA}},\ \ j \neq l)$ and $\mathbf{G}\mathbf{W}_l = \mathbf{0}$.

B. Co-MIMO Applied Null Beamforming to Self [8]

In this subsection, as a more specific example, the theory of the proposed Co-MIMO null beamforming method is explained for the cases of 2 APs and 2 STAs network system. The schematic diagram of proposed system is shown in Fig. 1. From the equations (3) and (4), the received signals $\mathbf{Y}_0$, $\mathbf{Y}_1$,

$\mathbf{Y}_2$ of the AP and each STA are expressed by the following equation:

$$\begin{bmatrix}\mathbf{Y}_1\\ \mathbf{Y}_2\\ \mathbf{Y}_0\end{bmatrix} = \begin{bmatrix}\mathbf{H}_1\mathbf{W}_1\mathbf{s}_1 & \mathbf{H}_1\mathbf{W}_2\mathbf{s}_2\\ \mathbf{H}_2\mathbf{W}_1\mathbf{s}_1 & \mathbf{H}_2\mathbf{W}_2\mathbf{s}_2\\ \mathbf{G}\mathbf{W}_1\mathbf{s}_1 & \mathbf{G}\mathbf{W}_2\mathbf{s}_2\end{bmatrix} + \begin{bmatrix}\mathbf{N}_1\\ \mathbf{N}_2\\ \mathbf{N}_0\end{bmatrix}. \quad (6)$$

In Equation (6), all terms other than $\mathbf{H}_1\mathbf{W}_1\mathbf{s}_1$ and $\mathbf{H}_2\mathbf{W}_2\mathbf{s}_2$ are interference signals, so it is necessary to determine $\mathbf{W}_1$ and $\mathbf{W}_2$ so that they become $\mathbf{0}$. From Equation (5), the following equation must hold:

$$\begin{bmatrix}\mathbf{H}_2\\ \mathbf{G}\end{bmatrix}\mathbf{W}_1 = \mathbf{0}, \quad \begin{bmatrix}\mathbf{H}_1\\ \mathbf{G}\end{bmatrix}\mathbf{W}_2 = \mathbf{0}. \quad (7)$$

When Equation (7) is satisfied, each received signal becomes as follows, and it can be confirmed that all IUI and SI are cancelled out.

$$\begin{bmatrix}\mathbf{Y}_1\\ \mathbf{Y}_2\\ \mathbf{Y}_0\end{bmatrix} = \begin{bmatrix}\mathbf{H}_1\mathbf{W}_1\mathbf{s}_1\\ \mathbf{H}_2\mathbf{W}_2\mathbf{s}_2\\ \mathbf{0}\end{bmatrix} + \begin{bmatrix}\mathbf{N}_1\\ \mathbf{N}_2\\ \mathbf{N}_0\end{bmatrix}. \quad (8)$$

In this paper, singular value decomposition (SVD) is used as a method for determining $\mathbf{W}_1$ and $\mathbf{W}_2$ that satisfy Equation (7). Here, $\mathbf{W}_1$ is determined as an example. In Equation (7), the SVD of the left side of $\mathbf{W}_1$ gives:

$$\begin{bmatrix}\mathbf{H}_2\\ \mathbf{G}\end{bmatrix} = \mathbf{U}_1\boldsymbol{\Sigma}_1\mathbf{V}_1^H \quad (9)$$
$$= \mathbf{U}_1\begin{bmatrix}\boldsymbol{\Delta}_1 & \mathbf{0}\end{bmatrix}\begin{bmatrix}\mathbf{V}_{\mathrm{b}1} & \mathbf{V}_{\mathrm{n}1}\end{bmatrix}^H \quad (10)$$
$$= \mathbf{U}_1\begin{bmatrix}\boldsymbol{\Delta}_1 & \mathbf{0}\end{bmatrix}\begin{bmatrix}\mathbf{V}_{\mathrm{b}1}^H\\ \mathbf{V}_{\mathrm{n}1}^H\end{bmatrix}, \quad (11)$$

where $\mathbf{U}_1$ $((M_{\mathrm{TOTAL}} - M_1) \times (M_{\mathrm{TOTAL}} - M_1))$ is a unitary matrix consisting of $(M_{\mathrm{TOTAL}} - M_1)$ left singular vectors, $\mathbf{V}_1$ $(N_{\mathrm{TOTAL}} \times N_{\mathrm{TOTAL}})$ is a unitary matrix consisting of N_{TOTAL} right singular vectors, and $\boldsymbol{\Delta}_1 = \mathrm{diag}(\sigma_1, \sigma_2, \cdots, \sigma_{M_{\mathrm{TOTAL}}-M_1})$ is a diagonal matrix whose diagonal components are singular values $\sigma_1 \geq \sigma_2 \geq \cdots \geq \sigma_{M_{\mathrm{TOTAL}}-M_1} \geq 0$. $\mathbf{V}_{\mathrm{b}1}$ $(N_{\mathrm{TOTAL}} \times (M_{\mathrm{TOTAL}} - M_1))$ is a matrix that collects right singular vectors whose singular value corresponds to $\boldsymbol{\Delta}_1$, and $\mathbf{V}_{\mathrm{n}1}$ $(N_{\mathrm{TOTAL}} \times M_1)$ is a matrix that collects right singular vectors whose singular value corresponds to $\mathbf{V}_1$. Finally, equation (7) can be satisfied by setting $\mathbf{W}_1 = \mathbf{V}_{\mathrm{n}1}$. $\mathbf{W}_2$ can also be calculated by the same manner as $\mathbf{W}_1$. Matrices $\mathbf{W}_1$ and $\mathbf{W}_2$ can be compiled in $\mathbf{W} = \begin{bmatrix}\mathbf{W}_1 & \mathbf{W}_2\end{bmatrix}$. The norm of p-th row in $\mathbf{W}$ represents the transmitting power of p-th transmitting antenna.

III. Proposed System

In this section, as a more concrete implementation of the proposed method described in Section II, we explain the signal generation method applying the proposed method. Next, we explain how to apply the proposed method to the legacy part of the IEEE 802.11n frame to perform null beamforming. In this paper, we used the IEEE 802.11n standard to simplify proposed method expression. The proposed method can be applied to IEEE 802.11ac / ax / be as well.

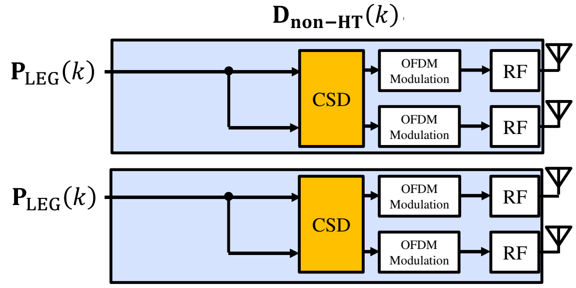

Fig. 2. Generator block diagram for legacy part (conventional) [10]

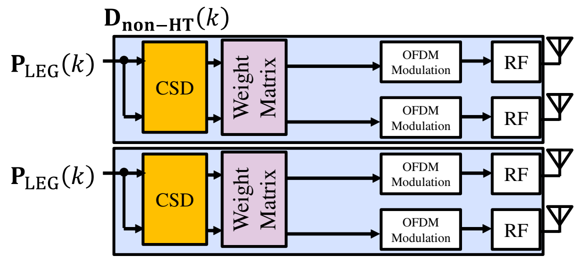

Fig. 3. Generator block diagram for legacy part (proposed)

In order to apply the proposed method, the channel matrix $\mathbf{H}_j$ and $\mathbf{G}$ are required. Therefore, the AP first transmit a signal for channel matrix estimation and estimate channel as $\widehat{\mathbf{H}}_j$ and $\widehat{\mathbf{G}}$ from the received signal. Then, in subsequent transmissions, the AP can transmit to the STA with suppressing the SI. In this proposal, we use signal follow IEEE 802.11n standard are used for implementation example. In this standard, the signal is OFDM-modulated and has 56 subcarriers. Therefore, all the formulas described so far apply to each subcarrier, and the subcarrier index $(k = 1, 2, \cdots, N_{\mathrm{subc}} = 56)$ is assigned to each element in the following description, where N_{subc} is the number of subcarriers.

A. Signal generation precoded by weight matrix

This subsection describes how the proposed method can be used to generate a signal that cancels SI using the estimated channels $\widehat{\mathbf{G}}(k)$ and $\widehat{\mathbf{H}}_j(k)$. To determine the estimated channels $\widehat{\mathbf{G}}(k)$ and $\widehat{\mathbf{H}}_j(k)$ from the AP to the j-th STA and AP receiving antennas, for example, the AP sends an null data packet (NDP) and uses the packet to estimate the channel. First, calculate $\mathbf{W}_l(k)$ from the estimated channel. The transmission stream to be sent to each STA is represented by $\mathbf{s}(k) = \begin{bmatrix}\mathbf{s_1}^T(k) & \mathbf{s_2}^T(k) & \cdots & \mathbf{s}_{N_{\mathrm{STA}}}{}^T(k)\end{bmatrix}^T$. At this time, the transmission signal $\mathbf{X}(k)$ is represented by the following equation:

$$\mathbf{X}(k) = \begin{bmatrix}\mathbf{X_1}^T(k) & \mathbf{X_2}^T(k) & \cdots & \mathbf{X}_{N_{\mathrm{AP}}}{}^T(k)\end{bmatrix}^T \quad (12)$$
$$= \begin{bmatrix}\mathbf{V}_{\mathrm{n}1}{}^T(k)\\ \mathbf{V}_{n2}{}^T(k)\\ \cdots\\ \mathbf{V}_{n\,N_{\mathrm{STA}}}{}^T(k)\end{bmatrix}^T \mathbf{C}(k)\,\mathbf{s}(k) \quad (13)$$
$$= \mathbf{W}_{\mathrm{n}}(k)\,\mathbf{C}(k)\,\mathbf{s}(k), \quad (14)$$

where $\mathbf{C}(k)$ is the cyclic shift diversity (CSD) diagonal matrix [10].

TABLE I
SYSTEM OVERVIEW

Device	Model (Manufacturing Company)
FPGA Board	ZC706 (Xilinx, Inc.)
SDR Card	ADRV9371-W/PCBZ (Analog Devices, Inc.)
Antenna	DELTA6C/x/SMAM/S/S/11 (Siretta Ltd)
Signal Generator (SG)	SMIQ06B (Rohde & Schwarz USA, Inc.)

B. Applying Weight Matrix to Legacy Preamble Part

This subsection describes how to apply the proposed method to perform null beamforming in the legacy preamble and HT-SIG parts. The legacy preamble and HT-SIG parts $\mathbf{x}(k)_{\mathrm{LEG}}$ is generated by the following equation [10]:

$$\mathbf{x}(k)_{\mathrm{LEG}} = \left[\mathbf{x}_1(k)^T \quad \mathbf{x}_2(k)^T \quad \cdots \quad \mathbf{x}_{N_{\mathrm{AP}}}(k)^T\right]^T \tag{15}$$
$$= \mathbf{D}_{\mathrm{non-HT}}(k)\,\mathbf{P}_{\mathrm{LEG}}(k), \tag{16}$$

where, $\mathbf{P}_{\mathrm{LEG}}(k)$ is constructed with the tone patterns for PHY layer process and packet information for decode. $\mathbf{D}_{\mathrm{non-HT}}(k)$ is a CSD diagonal matrix for non-HT portion in packet.

The weight matrix is not used to generate $\mathbf{x}(k)_{\mathrm{LEG}}$ on legacy system as shown in the Fig. 2. In other words, null beamforming cannot be performed by applying the weight matrix as in Eq. (14). As an example, the case of $N_{\mathrm{SSTOTAL}} = \sum_j M_j = 2$ and $N_{\mathrm{TOTAL}} = 4$ is shown, in the figure.

Now, we consider applying a weight matrix to the legacy preamble part. In order to point the null beam in the direction of $\mathbf{Y}_0$ using the weight matrix $\mathbf{W}$ calculated in subsection A, it is necessary to complete the CSD shift for each antenna before multiplying by $\mathbf{W}$. Therefore, as shown in Fig. 3, we propose a system that first performs CSD shift and then applies weight matrix $\mathbf{W}$. Transmission signal $\mathbf{x}(k)_{\mathrm{LEG-P}}$ is generated by the following equation:

$$\mathbf{x}(k)_{\mathrm{LEG-P}} = \mathbf{W}_{\mathrm{n}}(k)\,\mathbf{D}_{\mathrm{non-HT}}(k)\,\mathbf{P}_{\mathrm{LEG}}(k). \tag{17}$$

Here, the CSD diagonal matrix $\mathbf{D}_{\mathrm{non-HT}}(k)$ for CSD shift differs between the legacy preamble part and the HT-SIG part and beyond ($\mathbf{C}(k)$). $\mathbf{C}$ and $\mathbf{D}_{\mathrm{non-HT}}$ are diagonal matrices related to the cyclic delay [10].

IV. IMPLEMENTATION AND EXPERIMENT

In this section, we introduce an implementation of an FD wireless communication system of proposed method. Then, we show that the proposed method is workable in experiments using implemented system, and evaluate the SI cancellation amount by the method. In this section, the combined AP1 and AP2 is expressed as 'AP-N'.

A. Overview of the Implemented System

In this experiment, we implement the proposed method system on the field programmable gate array (FPGA) ZC706 board, software-defined radio (SDR) ADRV9371-W/PCBZ, and PC. Implemented system block architecture is shown in Fig. 4. Details of the devices used are shown in Table I.

TABLE II
EXPERIMENT CONDITIONS

Parameter	Value: Channel Estimation	Value: Null Beamforming to Self
Frame Format	IEEE 802.11n	IEEE 802.11n
MCS	25 (4stream, QPSK)	9 (2stream, QPSK)
# of Transmit Antenna	4 (2 + 2)	
# of Receiving Antennas (Subject to SI cancellation)	4 (None)	4 (2)
Total Transmit Power	-12 dBm	-
Null Beamforming Target	-	AP 1 RX : $\mathrm{RX}_{0,1,1}$, $\mathrm{RX}_{0,1,2}$
Center Frequency	5640 MHz	
Channel Bandwidth	20 MHz	
Weight Matrix $\mathbf{W}_l(k)$	Identity Matrix $\mathbf{I}$	$\mathbf{V}_{nl}(k)$

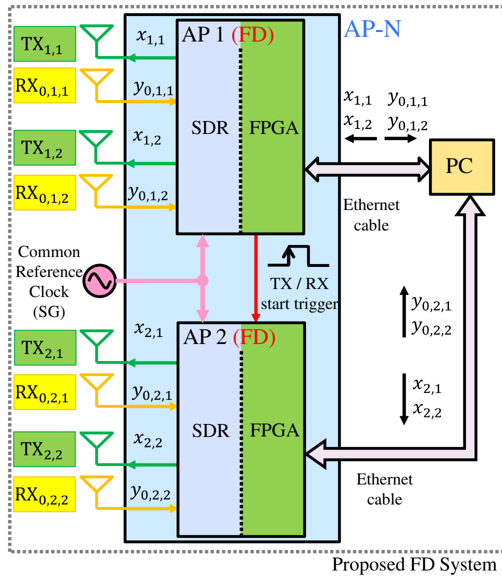

Fig. 4. Schematic Diagram of an Experiment

First, in order to implement the AP to which the proposed method was applied, the FPGA board and SDR were combined and implemented on it. These APs each have two transmitting antennas and two receiving antennas. Prepare two APs configured in this way, and connect and install them as shown in Fig. 4 and Fig. 5. Each AP needs to synchronize the clock, but for the sake of simplicity in this paper, the clock is completely synchronized by inputting the common clock generated by a signal generator (SG) to each AP. AP 1 roles a leader AP, AP 2 roles follower AP. The leader AP notifies the follower AP of a signal for synchronizing the transmission timing on Co-MIMO system. In this experiment, transmission timing signal is notified by wire using general-purpose input/output (GPIO) on FPGA. In practical operation, the synchronization is performed by the backbone network to which each AP is connected. In this experiment, the PC performs channel estimation and transmission signal generation on behalf of the AP to facilitate the implementation of the AP. This system does not have antenna canceller, RF canceller or digital canceller implemented. Therefore, in this experiment, SI cancellation is performed and evaluated using only the proposed method.

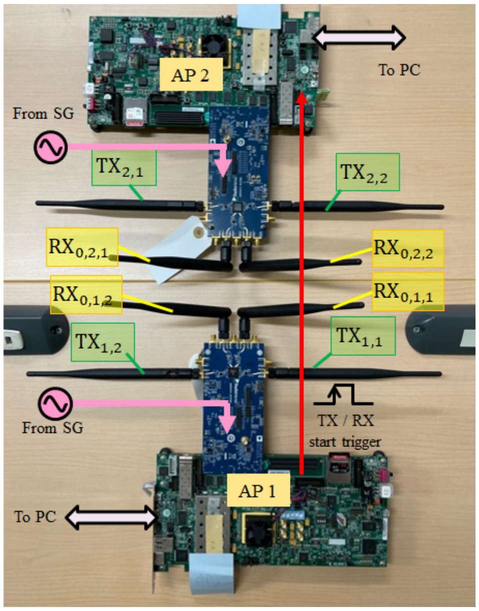

Fig. 5. Implemented System

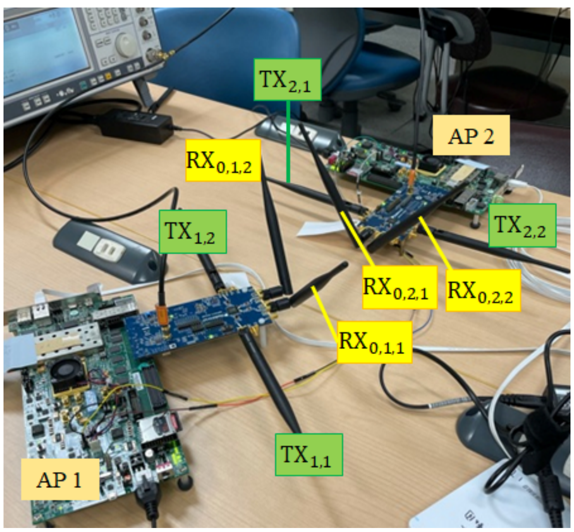

Fig. 6. Experimental Environment (Arrangement AP 1 and AP 2)

B. Experiment and Result

AP 1 and AP 2 are arranged as shown in Fig. 6. The experiment is executed in an indoor environment as shown in in Fig. 7. Experimental parameters are shown in Table II. The distances $d_{\mathrm{TX}_n,\mathrm{RX}_m}$ between central point of transmitting antenna TX_n and receiving antenna RX_m are shown in Table III.

First of all, the AP-N sends the NDP for channel estimation. The AP-N receives the packet and estimates the channel matrix $\mathbf{G}$. Then, the estimated self-channel matrix $\mathbf{G}$ is used to calculate the appropriate weight matrix $\mathbf{W}$ using the method shown in Subsection III-A. The AP-N generates and sends a signal with the calculated weight matrix applied. The parameters at this time are shown in Table II. Finally, the AP-N receives this null beamformed signal. And we evaluate the SI cancellation amount on received power. In this experiment, SI cancellation is applied only to receiving antenna of AP 1 on the AP-N.

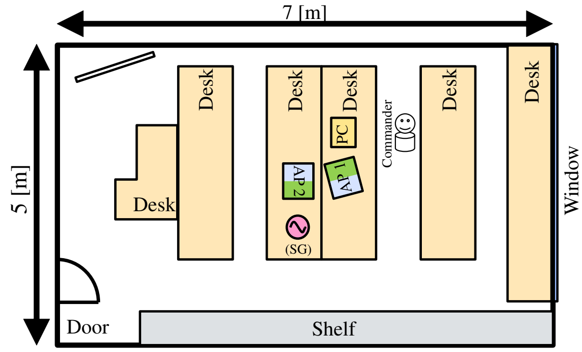

Fig. 7. Indoor Experiment Environment

TABLE III
DISTANCES $d_{\mathrm{TX}_n,\mathrm{RX}_m}$ BETWEEN ANTENNAS

$d_{\mathrm{TX}_n,\mathrm{RX}_m}$	
$d_{\mathrm{TX}_{1,1},\mathrm{RX}_{0,1,1}}$ $d_{\mathrm{TX}_{1,2},\mathrm{RX}_{0,1,2}}$ $d_{\mathrm{TX}_{2,1},\mathrm{RX}_{0,2,1}}$ $d_{\mathrm{TX}_{2,2},\mathrm{RX}_{0,2,2}}$	10 cm
$d_{\mathrm{TX}_{1,1},\mathrm{RX}_{0,1,2}}$ $d_{\mathrm{TX}_{1,2},\mathrm{RX}_{0,1,1}}$ $d_{\mathrm{TX}_{2,1},\mathrm{RX}_{0,2,2}}$ $d_{\mathrm{TX}_{2,2},\mathrm{RX}_{0,2,1}}$	15 cm
$d_{\mathrm{TX}_{1,2},\mathrm{RX}_{0,2,1}}$ $d_{\mathrm{TX}_{2,1},\mathrm{RX}_{0,1,2}}$	17 cm
$d_{\mathrm{TX}_{1,1},\mathrm{RX}_{0,2,1}}$ $d_{\mathrm{TX}_{1,1},\mathrm{RX}_{0,2,2}}$ $d_{\mathrm{TX}_{1,2},\mathrm{RX}_{0,2,2}}$ $d_{\mathrm{TX}_{2,1},\mathrm{RX}_{0,1,1}}$ $d_{\mathrm{TX}_{2,2},\mathrm{RX}_{0,1,1}}$ $d_{\mathrm{TX}_{2,2},\mathrm{RX}_{0,1,2}}$	25 cm

As a result of the experiment,the received power of each receiving antenna on AP-N is shown in Fig. 8. Center column of Fig. 8 shows the received power of a frame in which the weight matrix $\mathbf{W}$ is applied only to the HT part. In other words, the difference between the received power of the legacy part and the received power of the HT part indicates the SI cancellation amount by null beamforming. In this case, we apply the transmit power of each antenna calculated by norm of row in $\mathbf{W}$ to the legacy part to make the transmit power equal to the HT part. It can be confirmed that the SI cancellation amount is 17 dB. Right column of Fig. 8 shows the received power of a frame in which the weight matrix $\mathbf{W}$ is applied to the whole frame. These results show that the SI cancellation can be achieved on whole frame include legacy part by using proposed method. At the received signals $y_{0,2,1}$ and $y_{0,2,2}$, SI cancellation is not applied and a constant amplitude is maintained. Therefore, it does not affect the receiving antenna to which SI cancellation is not applied.

Through this experiment, we confirmed that 17 dB SI cancellation can be achieved by the proposed method. In addition, the right side of Fig. 8 shows that SI cancellation can be realized in the Legacy part as well. Since the SI cancellation amount depends on the estimation accuracy of the channel, in order to increase the SI cancellation amount, it is necessary to increase the transmission power of NDP in the step of channel estimation to improve the accuracy

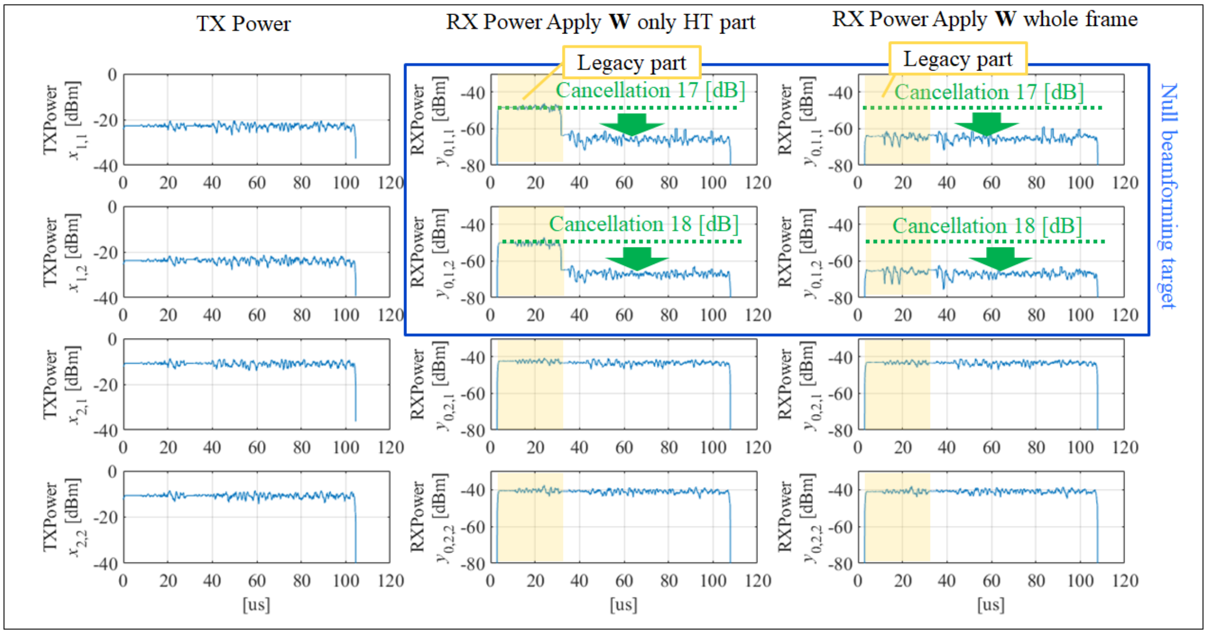

Fig. 8. Experimental Result: Transmitted / Received Signal Power

of channel estimation. In addition, in this experiment, about 30 sec. passed between the time when NDP was transmitted for Channel estimation and the time when Null beamforiming was applied and the packet was transmitted, so a change in the channel state occurred during that time. The SI cancellation amount also depends on the difference between the estimated channel and the current channel. To deal with this, you need to perform channel estimation just before sending the packet to which null beamforming is applied.

Finally, we validate this result. Through our experiments, we have confirmed that the proposed method can achieve SI cancellation at least 17 dB. This fact shows that null beamforiming on the Co-MIMO system may be able to replace the antenna cancellation 17 dB required for full-duplex communication, as described in section I.

V. Conclusion

In this paper, we have described the SI cancellation method using null beamforming in full-duplex wireless communication, and shown the method of applying the weight matrix to the legacy part in the IEEE 802.11 frame. In addition, using the proposed method, it is confirmed by experiments that the SI of the entire IEEE 802.11n frame including the legacy part can be suppressed by 17 dB without antenna cancellation. The SI cancellation amount can be further potentiated by increasing the transmission power and estimating more accurate CSI. We have shown the possibility that the analog cancellation, which is difficult to use in the conventional MIMO system, can be replaced by the proposed method. Future tasks include verification using more APs, application to IEEE 802.11ac / ax / be standards, and improvement of the SI cancellation amount by highly accurate channel estimation.

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