

Cooperative MIMO Applied Null Beamforming to Self in Full-Duplex Wireless Communication System and Its Implementation

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Abstract—This paper proposes a full-duplex wireless communication system applying cooperative multiple-input multiple-output (Co-MIMO). This proposal solves self-interference (SI) in full-duplex wireless communication systems by applying the block diagonalization used in multi-user MIMO (MU-MIMO). Therefore, there is no need for a radio frequency (RF) canceller, which has a large hardware size and is difficult to extend to MIMO. Furthermore, higher throughput can be achieved by applying Co-MIMO, in which multiple access points work together to communicate. We also introduce the implementation of the proposed method using a field-programmable gate array (FPGA) and software-defined radio (SDR) in this paper. It shows that SI cancellation can be realized by using them. The proposed method is implemented based on the IEEE 802.11n frame format as an example. In the experiment, a total of 30 [dB] SI cancellation is confirmed with a transmission power of -12 [dBm]. The SI cancellation amount can be further increased by increasing the transmission power.

Index Terms—Cooperative MIMO, Full-Duplex Wireless Communication, Self-Interference Cancellation,

I. INTRODUCTION

In recent years, full-duplex (FD) wireless communication, which can realize higher communication capacity and less delay communication, has attracted attention. Many issues need to be resolved to achieve FD wireless communication, but self-interference (SI) cancellation is especially important [1]. Unlike half-duplex (HD) wireless communication, which is a conventional communication method, FD wireless communication transmits and receives at the same frequency at the same time. Hence, the receiving antenna receives an exceptionally large level of SI. This factor prevents the decoding of the desired signal, which has a much lower reception level than SI. As a method for solving this problem, a method for canceling SI, which attenuates only SI at the reception time, has been actively discussed. In the papers of [1] and [2], they propose a method to realize SI cancellation by combining “antenna cancellation,” “RF interference cancellation” (RF cancellation), and “digital baseband interference cancellation” (digital cancellation) as SI canceling methods, and demonstrate it on an actual machine. The amount of SI cancellation required for each SI cancellation technique depends on the transmit power, analog-to-digital converter (ADC) resolution, and the minimum receive 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 level of the target signal is -82 [dBm]. In this case, a total of 60 [dB] of antenna cancellation and RF cancellation is required, 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. This method’s advantage is that it can achieve up to twice the communication capacity compared to HD wireless communication. On the other hand, using RF cancellers increases the hardware size, making it difficult to extend to multiple-input multiple-output (MIMO). For example, assuming 4×4 MIMO, RF cancellers should be prepared for every 16 channel paths. 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 [1] and [2], it is only implemented by single-input single-output (SISO). On the other hand, in [3], [4] and [5], “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. The amount of SI cancellation, required for each SI canceling technique in this technique also depends on the transmit power, ADC resolution, and the minimum receive level of the desired signal. As in the previous example, assume that the transmission power is 20 [dBm], the ADC resolution is 10 [bit], and the minimum reception level of the target signal is -82 [dBm]. In this case, a total of 60 [dB] for antenna cancellation, RF cancellation, and spatial cancellation, and 50 [dB] for digital cancellation are required. When this is met, the final SI power will be the same as the noise floor power. The advantage of spatial cancellation is that it can be extended to MIMO communication, and if spatial cancellation can achieve sufficient SI cancellation, RF 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.

In this paper, we propose extending spatial cancellation further and applying cooperative MIMO (Co-MIMO) to FD

wireless communication, to solve the problem of spatial cancellation. Co-MIMO is a technology in which multiple access points (APs) communicate in a coordinated manner [6] and has been actively discussed in recent years. There are two Co-MIMO methods, “joint transmission” (JT) and “coordinated beamforming” (CB) [6], but this proposal uses JT. In JT, multiple APs work together and act as if they were one large AP. For example, if you have two APs with two transmit antennas and two receive antennas and cooperate, you can think of it as one AP with four transmit antennas and four receive antennas. The main purpose of the proposed method is to increase spatial diversity by canceling the decrease in the DoF compared to the conventional method by coordinating APs while performing FD wireless communication. Another purpose is to make all APs always participate in communication by letting idle APs participate in cooperation and improve spatial channels’ utilization efficiency. As a result, FD wireless communication with a higher DoF and higher channel utilization efficiency can be realized while enjoying the benefits of spatial cancellation. From now on, this paper will refer to this proposed method as “Co-MIMO Applied Null Beamforming to Self.”

The rest of the paper is organized as follows. In Section II, as the basic theory of the proposed method, we assume multiple APs with multiple transmitting antennas and multiple receiving antennas and explain how to cancel SI by spatial cancellation while applying Co-MIMO. In Section III, as a more specific implementation method, the channel estimation method required to realize the proposed method and the signal generation method to which the proposed method is applied will be explained. In this paper, the proposed method is implemented based on the IEEE802.11n frame format with unique changes. Section IV introduces an actual implementation example of a FD wireless communication system that realizes the proposed method. Next, we demonstrate that the proposed method is feasible through experiments using actual equipment and evaluate and consider the amount of SI cancellation. Lastly, we conclude this paper in Section V.

II. THEORY

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

A. Co-MIMO Applied Null Beamforming to Self (I)

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 to a specific AP. This makes it possible to cancel SI between APs. Let i be the index of AP and j be the index of STA. The i -th AP has N_i transmitting antennas, and the j -th STA has M_j receiving antennas. Let M_0 be the number of receiving antennas of the AP to which null beamforming to self is applied. In addition, we define $\sum N = \sum_{i=1}^{N_{AP}} N_i$

and $\sum M = \left(M_0 + \sum_{j=1}^{N_{STA}} M_j \right)$. Let N_{SSj} be the number of transmission streams sent to the j -th STA. In this paper, $N_{SSj} = M_j$ to simplify the theory.

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:

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

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

where $\mathbf{s}_j$ ($N_{SSj} \times 1$) is the send stream to the j -th STA, $\mathbf{W}_{i,j}$ ($N_i \times N_{SSj}$) 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, $\mathbf{N}_j$ ($M_j \times 1$) is the noise added to the receiving antenna of the j -th STA. $\mathbf{G}_i$ ($M_0 \times N_i$) is the channel matrix from the transmitting antenna of the i -th AP to the receiving antenna of the specific AP, $\mathbf{N}_0$ ($M_0 \times 1$) is the noise added to the receiving antenna of the specific AP.

In equations (1) and (2), the first term of $\mathbf{Y}_j$ represents the desired signal and the second term represents inter-user interference (IUI). In addition, $\mathbf{Y}_0$ represents SI. Here, each channel matrix and weight matrix are replaced with $\mathbf{H}_j = [\mathbf{H}_{j,1} \ \mathbf{H}_{j,2} \ \cdots \ \mathbf{H}_{j,N_{AP}}]$, $\mathbf{G} = [\mathbf{G}_1 \ \mathbf{G}_2 \ \cdots \ \mathbf{G}_{N_{AP}}]$ and $\mathbf{W}_l = [\mathbf{W}_{1,l}^T \ \mathbf{W}_{2,l}^T \ \cdots \ \mathbf{W}_{N_{AP},l}^T]^T$. At that time, $\mathbf{Y}_j$ and $\mathbf{Y}_0$ are expressed by the following equations:

$$\mathbf{Y}_j = \mathbf{H}_j \mathbf{W}_j \mathbf{s}_j + \sum_{l=1, l \neq j}^{N_{STA}} \mathbf{H}_j \mathbf{W}_l \mathbf{s}_l + \mathbf{N}_j, \quad (3)$$

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

where $\mathbf{W}_j$ ($\sum N \times N_{SSj}$) is a weight matrix for mapping the send stream to the j -th STA to the antenna of all APs, $\mathbf{H}_j$ ($M_j \times \sum N$) is the channel matrix from the transmitting antenna of all APs to the receiving antenna of the j -th STA. By replacing the formula in this way, Co-MIMO with multiple APs can be seen as MU-MIMO with one huge AP. In other words, MU-MIMO technology can be applied.

From Equations (3) and (4), in order to cancel IUI and SI, the related term must be $\mathbf{0}$. That is, the following equation must hold for all of ($j = 1, 2, \dots, N_{STA}$):

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

Therefore, in order to cancel IUI and SI in the proposed method, it is necessary to find and set each weight matrix $\mathbf{W}_l$ ($l = 1, 2, \dots, N_{STA}$) that satisfies equation (5). And that weight matrix must satisfy $\mathbf{H}_j \mathbf{W}_l = \mathbf{0}$ ($j = 1, 2, \dots, N_{STA}, j \neq l$) and $\mathbf{G} \mathbf{W}_l = \mathbf{0}$.

B. Co-MIMO Applied Null Beamforming to Self (2)

In this subsection, as a more specific example, the theory of the proposed method and its calculation method will be explained for the cases of 2APs and 2STAs. The configuration diagram is shown in Figure. 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:

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

$$= \begin{bmatrix} \mathbf{H}_1 \mathbf{W}_1 \mathbf{s}_1 & \mathbf{H}_1 \mathbf{W}_2 \mathbf{s}_2 \\ \mathbf{H}_2 \mathbf{W}_1 \mathbf{s}_1 & \mathbf{H}_2 \mathbf{W}_2 \mathbf{s}_2 \\ \mathbf{G} \mathbf{W}_1 \mathbf{s}_1 & \mathbf{G} \mathbf{W}_2 \mathbf{s}_2 \end{bmatrix} + \begin{bmatrix} \mathbf{N}_1 \\ \mathbf{N}_2 \\ \mathbf{N}_0 \end{bmatrix}. \quad (7)$$

In Equation (7), 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 0. From Equation (5), the following equation must hold:

$$\begin{bmatrix} \mathbf{H}_2 \\ \mathbf{G} \end{bmatrix} \mathbf{W}_1 = 0, \quad \begin{bmatrix} \mathbf{H}_1 \\ \mathbf{G} \end{bmatrix} \mathbf{W}_2 = 0. \quad (8)$$

When Equation (8) is satisfied, each received signal becomes as follows, and it can be confirmed that all IUI and SI are cancelled.

$$\begin{bmatrix} \mathbf{Y}_1 \\ \mathbf{Y}_2 \\ \mathbf{Y}_0 \end{bmatrix} = \begin{bmatrix} \mathbf{H}_1 \mathbf{W}_1 \mathbf{s}_1 \\ \mathbf{H}_2 \mathbf{W}_2 \mathbf{s}_2 \\ \mathbf{0} \end{bmatrix} + \begin{bmatrix} \mathbf{N}_1 \\ \mathbf{N}_2 \\ \mathbf{N}_0 \end{bmatrix}. \quad (9)$$

In this paper, singular value decomposition (SVD) is used as a method for determining $\mathbf{W}_1$ and $\mathbf{W}_2$ that satisfy Equation (8). Here, $\mathbf{W}_1$ is determined as an example. In Equation (8), the SVD of the left side of $\mathbf{W}_1$ gives:

$$\begin{bmatrix} \mathbf{H}_2 \\ \mathbf{G} \end{bmatrix} = \mathbf{U}_1 \mathbf{\Sigma}_1 \mathbf{V}_1^H \quad (10)$$

$$= \mathbf{U}_1 \begin{bmatrix} \mathbf{\Delta}_1 & \mathbf{0} \end{bmatrix} \begin{bmatrix} \mathbf{V}_{b1} & \mathbf{V}_{n1} \end{bmatrix}^H \quad (11)$$

$$= \mathbf{U}_1 \begin{bmatrix} \mathbf{\Delta}_1 & \mathbf{0} \end{bmatrix} \begin{bmatrix} \mathbf{V}_{b1}^H \\ \mathbf{V}_{n1}^H \end{bmatrix}, \quad (12)$$

where $\mathbf{U}_1$ ($(\sum M - M_1) \times (\sum M - M_1)$) is a unitary matrix consisting of $(\sum M - M_1)$ left singular vectors, $\mathbf{V}_1$ ($\sum N \times \sum N$) is a unitary matrix consisting of $\sum N$ right singular vectors, and $\mathbf{\Delta}_1 = \text{diag}(\sigma_1, \sigma_2, \dots, \sigma_{\sum M - M_1})$ is a diagonal matrix whose diagonal components are singular values $\sigma_1 \geq \sigma_2 \geq \dots \geq \sigma_{\sum M - M_1} \geq 0$. $\mathbf{V}_{b1}$ ($\sum N \times (\sum M - M_1)$) is a matrix that collects right singular vectors whose singular value corresponds to $\mathbf{\Delta}_1$, and $\mathbf{V}_{n1}$ ($\sum N \times M_1$) is a matrix that collects right singular vectors whose singular value corresponds to $\mathbf{V}_1$. Finally, equation (8) can be satisfied by setting $\mathbf{W}_1 = \mathbf{V}_{n1}$. $\mathbf{W}_2$ can also be calculated by the same calculation.

III. PROPOSAL SYSTEM

In this section, as a more specific implementation method of the proposed method described in Section II, the channel estimation method required to realize the proposed method and

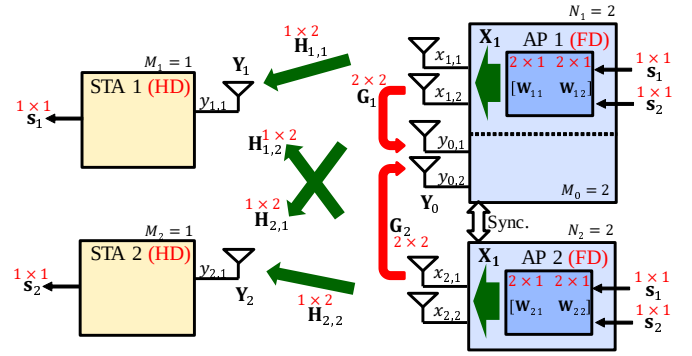


Figure. 1. Schematic Diagram of the Proposed System

the signal generation method to which the proposed method is applied are explained. Next, the magnitude of the amount of SI cancellation by the proposed method is examined using a mathematical formula.

Channel matrices $\mathbf{H}_j$ and $\mathbf{G}$ are required to apply the proposed method. Therefore, all APs first send a signal for channel matrix estimation and calculates the estimated channels $\hat{\mathbf{H}}_j$ and $\hat{\mathbf{G}}$ from the received signal. Then $\mathbf{W}_j$ is calculated and set using $\hat{\mathbf{H}}_j$ and $\hat{\mathbf{G}}$. As a result, on subsequent transmissions, the AP can send to the STA while canceling SI. In this proposal, the IEEE 802.11n standard signal is used as an 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 ($k = 1, 2, \dots, N_{\text{subc}} = 56$) is assigned to each element in the following description, where N_{subc} is the number of subcarriers.

A. Explicit Channel Estimation

To perform channel estimation, the preamble matrix $\mathbf{P}(k)$ ($\sum N \times \sum N$), which is a unitary matrix common to both the transmitting side and the receiving side, is transmitted as a transmission stream. The HT-LTF plays this role in the IEEE 802.11n frame format. Since the identity matrix is set as the weight matrix and the cyclic shift diversity (CSD) diagonal matrix $\mathbf{C}^{1st}(k)$ ($\sum N \times \sum N$) is applied to the transmit stream, the AP transmit signal $\mathbf{X}^{1st}(k)$ has the following equation:

$$\mathbf{X}^{1st}(k) = \begin{bmatrix} \mathbf{X}_1^{1stT}(k) & \mathbf{X}_2^{1stT}(k) & \dots & \mathbf{X}_{N_{AP}}^{1stT}(k) \end{bmatrix}^T \quad (13)$$

$$= \mathbf{C}^{1st}(k) \mathbf{P}(k). \quad (14)$$

At this time, the received signal of the AP $\mathbf{Y}_0(k)$ is

$$\mathbf{Y}_0^{1st}(k) = \mathbf{G}^{1st}(k) \mathbf{X}^{1st}(k) + \mathbf{N}_0^{1st}(k) \quad (15)$$

$$= \mathbf{G}^{1st}(k) \mathbf{C}^{1st}(k) \mathbf{P}(k) + \mathbf{N}_0^{1st}(k), \quad (16)$$

and the estimated channel $\hat{\mathbf{G}}^{1st}(k)$ is

$$\hat{\mathbf{G}}^{1st}(k) = \mathbf{Y}_0^{1st}(k) \mathbf{P}^{-1}(k) \mathbf{C}^{1st^{-1}}(k) \quad (17)$$

$$= \mathbf{G}^{1st}(k) + \mathbf{N}_0^{1st}(k) \mathbf{P}^{-1}(k) \mathbf{C}^{1st^{-1}}(k) \quad (18)$$

$$= \mathbf{G}^{1st}(k) + \Delta \mathbf{G}^{1st}(k), \quad (19)$$

where $\Delta \mathbf{G}^{1st}(k) = \mathbf{N}_0^{1st}(k) \mathbf{P}^{-1}(k) \mathbf{C}^{1st^{-1}}(k)$ is the channel estimation error of $\mathbf{G}^{1st}(k)$. We can also get the estimated channel matrix from AP to j -th STA $\hat{\mathbf{H}}_j^{1st}(k)$ in the same way.

B. Co-MIMO Applied Null Beamforming to Self

This subsection describes how the proposed method can be used to generate a signal that cancels SI using the estimated channels $\hat{\mathbf{G}}^{1st}(k)$ and $\hat{\mathbf{H}}_j^{1st}(k)$ found in the previous subsection. First, calculate $\mathbf{V}_{nl}(k)$ from the estimated channel and apply it as $\mathbf{W}_l^{2nd}(k) = \mathbf{V}_{nl}(k)$, using the method described in the previous section. The transmission stream to be sent to each STA is represented by $\mathbf{s}^{2nd}(k) = [\mathbf{s}_1^{2ndT}(k) \ \mathbf{s}_2^{2ndT}(k) \ \dots \ \mathbf{s}_{N_{STA}}^{2ndT}(k)]^T$. At this time, the transmission signal $\mathbf{X}^{2nd}(k)$ is represented by the following equation:

$$\mathbf{X}^{2nd}(k) = [\mathbf{X}_1^{2ndT}(k) \ \mathbf{X}_2^{2ndT}(k) \ \dots \ \mathbf{X}_{N_{AP}}^{2ndT}(k)]^T \quad (20)$$

$$= \begin{bmatrix} \mathbf{V}_{n1}^T(k) \\ \mathbf{V}_{n2}^T(k) \\ \vdots \\ \mathbf{V}_{n_{N_{STA}}}^T(k) \end{bmatrix}^T \mathbf{C}^{2nd}(k) \mathbf{s}^{2nd}(k) \quad (21)$$

$$= \mathbf{V}_n(k) \mathbf{C}^{2nd}(k) \mathbf{s}^{2nd}(k), \quad (22)$$

where $\mathbf{C}^{2nd}(k)$ is the CSD diagonal matrix.

We also assume that the channel matrix fluctuates over time. The difference between the channel matrix when estimating the channel and the channel matrix when applying the proposed method is expressed as $\Delta\mathbf{G}^{1 \rightarrow 2}(k)$. At this time, the channel matrix $\mathbf{G}^{2nd}(k)$ when the proposed method is applied is expressed by the following equation:

$$\mathbf{G}^{2nd}(k) = \mathbf{G}^{1st}(k) + \Delta\mathbf{G}^{1 \rightarrow 2}(k). \quad (23)$$

At this time, the received signal of the AP $\mathbf{Y}_0^{2nd}(k)$ is represented by the following equation:

$$\mathbf{Y}_0^{2nd}(k) = \mathbf{G}^{2nd}(k) \mathbf{X}^{2nd}(k) + \mathbf{N}_0^{2nd}(k) \quad (24)$$

$$= (\hat{\mathbf{G}}^{1st}(k) - \Delta\mathbf{G}^{1st}(k) + \Delta\mathbf{G}^{1 \rightarrow 2}(k)) \cdot \mathbf{V}_n(k) \mathbf{C}^{2nd}(k) \mathbf{s}_1(k) + \mathbf{N}_0^{2nd}(k) \quad (25)$$

$$= (\Delta\mathbf{G}^{1 \rightarrow 2}(k) - \Delta\mathbf{G}^{1st}(k)) \cdot \mathbf{V}_n(k) \mathbf{C}^{2nd}(k) \mathbf{s}^{2nd}(k) + \mathbf{N}_0^{2nd}(k). \quad (26)$$

The first term of Equation (26) represents the SI signal that could not be canceled, and it can be seen that it depends on the channel estimation error $\Delta\mathbf{G}^{1st}(k)$ and the time variation of the channel $\Delta\mathbf{G}^{1 \rightarrow 2}(k)$. Here, $\mathbf{V}_n(k)$ is a matrix consisting of orthonormal bases, and $\mathbf{C}^{2nd}(k)$ is a diagonal matrix in which the absolute values of all diagonal components are 1, so the norm is invariant. Therefore, the interference-to-noise-ratio (INR) at subcarrier k when using the proposed method is

$$\text{INR}(k) = \frac{\|(\Delta\mathbf{G}^{1 \rightarrow 2}(k) - \Delta\mathbf{G}^{1st}(k)) \mathbf{s}^{2nd}(k)\|^2}{\|\mathbf{N}_0^{2nd}(k)\|^2}, \quad (27)$$

and the average INR for all subcarriers is

$$\text{INR} = \frac{1}{N_{\text{subc}}} \sum_{k=1}^{N_{\text{subc}}} \text{INR}(k). \quad (28)$$

And this term contains the transmit stream $\mathbf{s}^{2nd}(k)$ and can be further canceled using a digital cancellation.

IV. IMPLEMENTATION AND EXPERIMENT

In this section, we will introduce an actual implementation example of a FD wireless communication system that realizes the proposed method described so far. Next, we will demonstrate that the proposed method is feasible through experiments using actual equipment, and evaluate and consider the amount of SI cancellation.

A. Overview of the Implemented System

The proposed method is implemented on the field-programmable gate array (FPGA) ZC706 board, software-defined radio (SDR) ADRV9371-W/PCBZ, and PC.¹ The block is shown in Figure. 2 and the photograph is shown in Figure. 3. Details of the equipment used are shown in Table I. The details of the implementation is described below.

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. This AP has two transmitting antennas and two receiving antennas per AP. The number of antennas is reduced by using a circulator, and the actual number of antennas is two per AP. Prepare two APs configured in this way, and connect and install them as shown in Figure. 2. 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 is a leader AP, AP2 is a follower AP, and the leader AP notifies the follower AP of the transmission/reception timing so that these APs can transmit/receive at the same time. In this paper, notification of transmission/reception timing is performed by wire using general-purpose input/output (GPIO) of FPGA for easy implementation. Furthermore, as a backbone network, each AP connects to the same PC via an Ethernet cable. The purpose of this PC is to take on some of the features of the AP for ease of implementation and experimentation. Specifically, it receives the received signal of the AP, generates a signal to which the proposed method is applied, and passes it to the AP.

B. Actual Machine Experiment and its Result

The procedure of the experiment is shown below. First, to estimate the self-channel matrix $\hat{\mathbf{G}}^{1st}(k)$, the AP generates and sends a channel estimation signal using the method shown in Subsection III-A. The parameters at this time are shown in Table II. The estimated self-channel matrix calculated from the received signal is then used to calculate the appropriate weight matrix using the method shown in Subsection III-B. The AP then generates and sends a signal with the calculated weight matrix applied. The parameters at this time are shown in Table III. Finally, the AP receives this signal and evaluates the amount of SI cancellation from the received signal and received power. In this experiment, SI cancellation is applied only to AP 1 of the two APs.

As a result of the experiment, the transmitted/received signals of the AP are shown in Figure. 4, and the 20-point

¹We also tested the system using ZCU102 and ADRV9009 which is faster and more accurate.

TABLE I
DETAILS OF THE EQUIPMENT USED

Device Name	Model (Manufacturing Company)
FPGA Board	ZC706 (Xilinx, Inc.)
SDR Board	ADRV9371-W/PCBZ (Analog Devices, Inc.)
Circulator	UIYBCC2528A3T6SF (UIY Inc.)
Antenna	Dipole antenna for 5GHz band
Signal Generator (SG)	SMI06B (Rohde & Schwarz USA, Inc.)

moving average of the received power is shown in Figure. 5. From Figure. 4, if you look at the received signals $y_{0,1,1}$ and $y_{0,1,2}$ of the receiving antenna to which SI cancellation by the proposed method is applied, you can see that SI is canceled and the amplitude is very small. Also, from Figure. 5, it can be confirmed that the SI cancellation amount is 30 [dB]. 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. In this experiment, 30 [dB] SI cancellation is achieved, but this value depends on the transmit power of the AP. This is because the channel estimation error depends on the transmit power of the AP. In this experiment, the transmission power of the AP is as small as -12 [dBm], but in actual wireless communication, it is possible to transmit with larger transmission power. For example, when transmitting at 20 [dBm], you can expect to achieve a maximum of 62 [dB] SI cancellation. Looking at Figure 5, the received power after SI cancellation is 20 [dB] higher than the noise floor, which is SI that could not be canceled. This can be further canceled by digital cancellation. That is, $\text{INR} = 20$ [dB].

Finally, we will validate this result. The proposed method assumes that the digital cancellation performs 50 [dB] SI cancellation, as described in Section 1. In other words, if the INR is less than 50 [dB] using only Co-MIMO Applied Null Beamforming to Self, the digital cancellation will eventually provide sufficient SI cancellation. As shown in Table IV, this is believed to have been achieved because $\text{INR} = 20$ [dB] was achieved in this experiment.

V. CONCLUSION

In this paper, we have proposed Co-MIMO Applied Null Beamforming to Self as a new proposal of the SI canceling method in FD wireless communication. The advantages of this method are that it is possible to achieve sufficient SI cancellation without using RF canceling, which enables MIMO communication, and because it supports Co-MIMO, communication with higher throughput is realized. This proposed method was implemented using an FPGA board and SDR, and SI cancellation of 30 [dB] was realized by an actual machine experiment. The amount of SI cancellation depends on the transmission power, and higher SI cancellation can be achieved by transmitting with higher transmission power. As a future task, we will realize a higher SI cancellation amount by adding a digital canceller to this mounting system.

TABLE II
EXPERIMENT CONDITIONS (CHANNEL ESTIMATION)

Parameter	Value
Frame Format	IEEE 802.11n
MCS	25 (4stream, QPSK)
# of Transmit Antenna	4 (2 + 2)
Total Transmit Power	-12 [dBm]
Center Frequency	5640 [MHz]
Channel Bandwidth	20 [MHz]
Weight Matrix $\mathbf{W}_l^{2nd}(k)$	Identity Matrix $\mathbf{I}$

TABLE III
EXPERIMENT CONDITIONS (NULL BEAMFORMING TO SELF)

Parameter	Value
Frame Format	IEEE 802.11n based original
MCS	9 (2stream, QPSK)
# of Transmit Antennas	4 (2 + 2)
# of Receiving Antennas Subject to SI cancellation	2
Total Transmit Power	-12 [dBm]
Center Frequency	5640 [MHz]
Channel Bandwidth	20 [MHz]
Weight Matrix $\mathbf{W}_l^{2nd}(k)$	$\mathbf{V}_{nl}(k)$

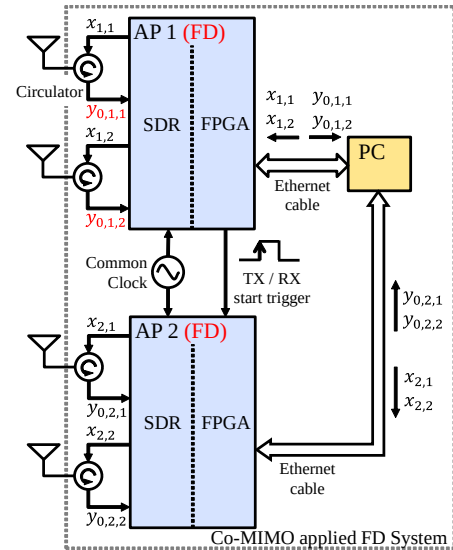


Figure. 2. Schematic Diagram of an Actual Machine Experiment

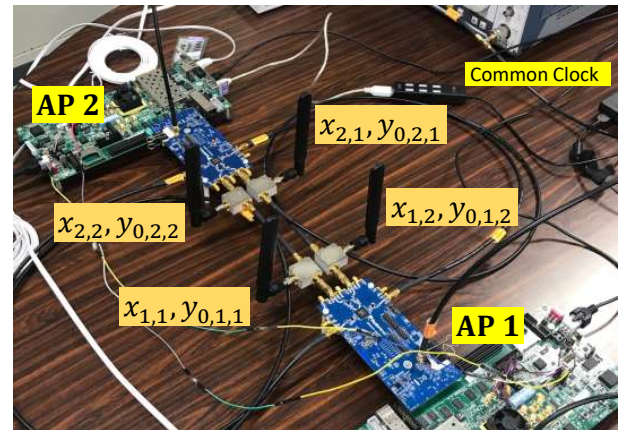


Figure. 3. Implemented System and Experimental Environment

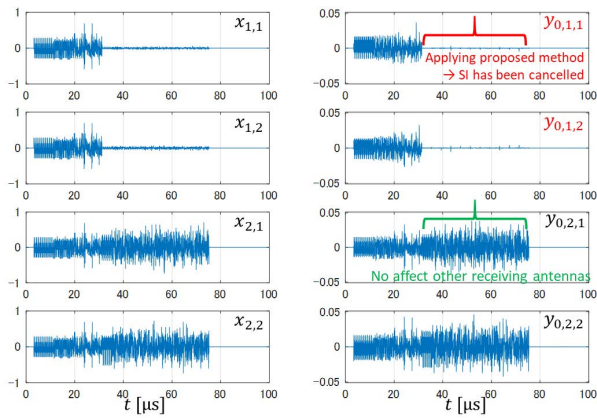


Figure 4. Experimental Result: Transmit / Received Signal Waveform

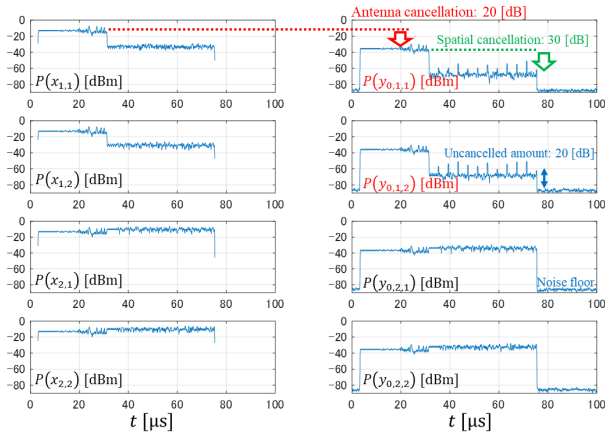


Figure 5. Experimental Result: Transmit / Received Signal Power

TABLE IV
EXPERIMENTAL RESULTS AND VERIFICATION

Appropriate range of INR	Experimentally obtained INR
< 50[dB]	20[dB]

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