2022 International Workshop on Smart Info-Media Systems in Asia (SISA 2022), Sep. 15–16, 2022

A Low Complexity Carrier Frequency Offset Compensation for Full-Duplex with Cooperative MIMO in IEEE 802.11 WLAN

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***Abstract*—Self-interference cancellation is an important technology to achieve full-duplex communication. The self-interference in IEEE 802.11 network can be suppressed using Cooperative Multiple Input Multiple Output (Co-MIMO) applied null beamforming. This method requires a weight matrix that is obtained from the Channel State Information (CSI). However, residual CFO among the access points (APs) will impact the calculated CSI, making it harder to suppress the self-interference in a wireless hardware implementation. In this paper, we propose a low complexity method for addressing the CFO problem in joint transmission when a direct connection and common clock are not applied to the APs. We evaluate the SI cancellation of the proposed method and show the experimental results using field-programmable gate array (FPGA) and software-defined radio (SDR). In addition, we also examine the change in CFO over time. Our results show that the proposed CFO compensation has a similar performance as a system where APs share the same clock (i.e. perfect carrier frequency synchronization) in terms of interference cancellation.**

I. INTRODUCTION

Full-duplex (FD) wireless communication is a technology that can achieve high throughput while keeping the frequency resources efficient. APs and STAs can transmit and receive simultaneously. However, one of the problems with FD is self-interference (SI) signal due to the distance between receive antennas and transmit antennas being near to each other. Some methods to suppress the SI have been proposed in [1], [2], [3] using antenna cancellation, radio frequency (RF) cancellation, and digital cancellation. The antenna cancellation and RF cancellation can be categorized as analog circuit cancelling approach. The SI signals can be cancelled better than the digital cancellation, but the implementation size will be larger, especially in the MIMO communication system. Spatial cancellation has been proposed as another SI cancellation method in [4], [5]. In this method, SI can be suppressed using some of the MIMO degrees of freedom (DoF) and directing the null space to receive antennas. The DoF will be smaller than traditional MU-MIMO because it might be used for other purposes.

In this paper, we solve the carrier frequency offset (CFO) between multiple APs when performing a multi-AP channel sounding or multi-AP beamforming. This method is then applied to a specific type of Co-MIMO technique called null beamforming to self [6], [7]. Multiple APs become one virtual AP. Synchronized multiple APs increase the number of antennas, and therefore higher DoF can be achieved. In null beamforming to self, the multi-AP CSI is used to form nulls targetting some of the receive antennas in the two APs, allowing it to receive a signal while transmitting, similar to full-duplex wireless communications. In [6], hardware implementation using FPGAs and SDRs has been implemented with the null beamforming to self is applied only to the High Throughput (HT) part of IEEE 802.11n frame. In [7], similar work has been implemented with null beamforming applied to the whole IEEE 802.11n frame.

Synchronization and coordination between APs in [6] and [7] were performed using a wired connection and a signal generator as the common clock. In this way, different APs will have no CFO and accurate multi-AP CSI can be obtained [8]. Note that a low residual CFOs will still cause peak throughput degradation [9]. The effect of residual CFO for beamforming when different transmitters transmit at the same time has been discussed in [10], where the signal-to-noise ratio gain decreases. The CFO problem must be handled so that wireless coordination can be implemented.

The proposed low complexity CFO compensation method can be applied for any Co-MIMO type of transmission. However, as an extension work of [6] and [7], we describe the performance of our work in terms of the performance of the null beamforming to self, which involves the degree of self-interference cancellation to the APs' receive antennas when the APs are not connected to a common clock source.

This paper is organized as follows. More detailed explanations about null beamforming are provided in Section II. Section III describes the CFO compensation method. The implementation and experiment results are provided in Section IV. Finally, we conclude this paper in section V.

II. NULL BEAMFORMING TO SELF

Following the work done by the co-author in [7], the null beamforming to self that will be discussed in this section serves as an application of CFO compensation. The general SI theory on full-duplex communication is briefly described in Subsection II-A. In Subsection II-B, we explain how this

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This work has been supported by the Japan Science and Technology Agency (JST), Grant-in-Aid for A-STEP JPMJTM20S3.

is related to the Null Beamforming to self with Co-MIMO applied.

A. Self-Interference on Full-duplex Communication

We assume that Co-MIMO is applied to all APs to transmit downlink data to all STAs. Suppose that i-th AP has N_i transmit antennas and j-th STA has M_j receive antennas. Receive antennas where null beamforming is directed, are denoted by M_0. The total number of transmit antennas is $N_{TOTAL} = \sum_{i=1}^{N_{AP}} N_i$ and the total number of receive antennas is $M_{TOTAL} = M_0 + \sum_{j=1}^{N_{STA}} M_j$. Let the N_{SS_j}, the number of transmit streams sent to the j-th STAs equals M_j. The received signals $\mathbf{Y}_j$ of j-th STA and the received signals $\mathbf{Y}_0$ of the AP can be expressed as:

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

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

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

To further simplify the equation, the channel matrix $\mathbf{H}_{j,i}$ and $\mathbf{G}_i$ can be substituted with $\mathbf{H}_j = [\mathbf{H}_{j,1}\mathbf{H}_{j,2} \ldots \mathbf{H}_{j,N_{AP}}]$ and $\mathbf{G} = [\mathbf{G}_1\mathbf{G}_2 \ldots \mathbf{G}_{N_{AP}}]$, respectively. The weight matrix $\mathbf{W}_{i,j}$ can be replaced with $\mathbf{W}_l = [\mathbf{W}_{1,l}^T\mathbf{W}_{2,l}^T \ldots \mathbf{W}_{N_{AP},l}^T]$. $\mathbf{Y}_j$ and $\mathbf{Y}_0$ now can be expressed as:

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

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

where $\mathbf{H}_j$ $(M_j \times N_{TOTAL})$ is the channel matrix from transmit antennas of all APs to the receive antenna of the j-th STA, $\mathbf{G}$ $(M_0 \times N_{TOTAL})$ is the channel matrix from all APs' transmit antennas to all APs' receive antennas, and $\mathbf{W}_l$ $(N_{TOTAL} \times N_{SS_j})$ is a weight matrix for mapping the streams $\mathbf{s}_j$ to the receive antennas of the j-th STA.

From (3) and (4), the inter-user interference (IUI) and SI can be cancelled if the related terms are $\mathbf{0}$. The following equation must satisfied for all of $(j = 1, 2, \ldots N_{STA})$:

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

Therefore, the IUI and SI can be cancelled if a weight matrix $\mathbf{W}_l$ $(l = 1, 2, \ldots N_{STA})$ that satisfies (5) is applied. The weight matrix should also satisfy $\mathbf{H}_j\mathbf{W}_l = \mathbf{0}$ $(j = 1, 2, \ldots N_{STA}, j \neq l)$ and $\mathbf{G}\mathbf{W}_l = \mathbf{0}$.

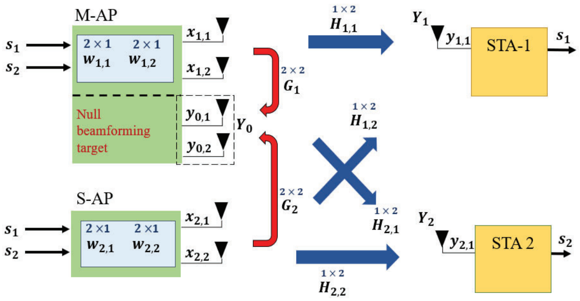

Fig. 1. Schematic diagram of the proposed system.

B. Co-MIMO Applied Null Beamforming to Self

A more concrete example is explained in this subsection based on Fig. 1. In this case, the FD is implemented in two APs while two STAs implement the half-duplex. From (3) and (4), the received signals $\mathbf{Y}_1$ and $\mathbf{Y}_2$ of each STA, and $\mathbf{Y}_0$ of the AP can be expressed as follow:

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

From (6), it is necessary to find $\mathbf{W_1}$ and $\mathbf{W_2}$ so that all terms other than $\mathbf{H_1W_1s_1}$ and $\mathbf{H_2W_2s_2}$ equal $\mathbf{0}$, since they are interference signals. Thus, the following equation must be satisfied:

$$\begin{bmatrix} \mathbf{H}_2 \\ \mathbf{G} \end{bmatrix} \mathbf{W}_1 = \mathbf{0}, \begin{bmatrix} \mathbf{H}_1 \\ \mathbf{G} \end{bmatrix} \mathbf{W}_2 = \mathbf{0} \tag{7}$$

The IUI and SI can be suppressed, and the received signals become:

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

To satisfy (8), $\mathbf{W_1}$ and $\mathbf{W_2}$ can be determined using singular value decomposition (SVD). Taking $\mathbf{W_1}$ as an example, the SVD of the left side of $\mathbf{W_1}$ becomes:

$$\begin{bmatrix} \mathbf{H}_2 \\ \mathbf{G} \end{bmatrix} = \mathbf{U}_1\mathbf{\Sigma}_1\mathbf{V}_1^H \tag{9}$$

$$= \mathbf{U}_1 \begin{bmatrix} \mathbf{\Delta}_1 & \mathbf{0} \end{bmatrix} \begin{bmatrix} \mathbf{V}_{b1}^H \\ \mathbf{V}_{n1}^H \end{bmatrix} \tag{10}$$

where U_1 $((M_{TOTAL} - M_1) \times (M_{TOTAL} - M_1))$ is a unitary matrix with $(M_{TOTAL} - M_1)$ left singular vectors, $\mathbf{\Delta}_1 = \mathrm{diag}(\sigma_1, \sigma_2, \ldots \sigma_{M_{TOTAL}-M_1})$ is a diagonal matrix whose diagonal components are singular values, $\mathbf{V}_1$ $(N_{TOTAL} \times$

N_{TOTAL}) is a unitary matrix with N_{TOTAL} right singular vectors. $\mathbf{V}_{n1}$ ($N_{TOTAL} \times M_1$) is a matrix that collects right singular vectors whose singular values correspond to $\mathbf{V}_1$. Thus, to satisfy (7), $\mathbf{W_1}$ is equal to $\mathbf{V_{n1}}$. The same method can be applied to determine $\mathbf{W_2}$.

III. CFO COMPENSATION IN CO-MIMO

The CFO problem in Co-MIMO is explained in Subsection III-A, especially when multi-AP transmit simultaneously. Subsection III-B describes the general transmission procedure. Lastly, in Subsection III-C, we provide an explanation of the proposed CFO compensation.

A. CFO problem in Co-MIMO

The Co-MIMO describes in this paper requires multi-AP to transmit simultaneously, with an M-AP coordinating the transmission over another S-AP. Multi-AP transmission has been discussed and is being developed for the new IEEE 802.11be standards. One of the methods for multi-AP transmission is Joint Transmission (JT), where strict clock synchronization and coordination are necessary for joint transmission or reception among different APs. However, those requirements are harder to be realized in practice because a high-speed backhaul is required to connect the APs. In [6], [7], multi-AP transmission has been experimented with by using a wired connection between APs and a common clock source. If strict synchronization and common clock are not satisfied, high CFOs exist. The impact of CFO is more severe in coordinated transmission such as JT than in point-to-point communication [10]. In the Co-MIMO system, the residual CFOs decrease the accuracy of beamformer [11], causing the uncancelled receive signals at the null target antennas.

B. Proposed Transmission Procedure

In this section, we describe the requirements needed to coordinate the M-AP and S-AP before explaining the transmission in each phase. In [6], [7], S-AP knows when to transmit because it is triggered by M-AP directly through a wired connection. In this paper, the M-AP sends a trigger signal to S-AP to let the S-AP knows when to transmit. Therefore, S-AP will always wait for a trigger signal. The delay after M-AP sends the trigger signal and before M-AP sends an actual packet must be considered. If the delay is known, the M-AP holds its transmission for the delay duration while S-AP processes the trigger signal. After the delay, S-AP should have finished processing the trigger signal. Then, it begins transmitting its packet. In this way, M-AP and S-AP will transmit their packets at the same time.

The transmission procedure that is used in this paper is shown in Fig. 2. The transmission is divided into three phases. In the first phase, called CFO estimation, S-AP estimates the CFO from the Null Data Packet (NDP) frame sent by M-AP. The first phase is done multiple times to get multiple estimated CFOs that will be filtered. If there is more than one S-AP, then the first phase will be applied to each S-AP. The CFO compensation is calculated from the estimated CFOs and applied to packets sent from the S-AP in the next two parts. In the second part, channel sounding is performed with explicit CSI feedback. NDPs sent by M-AP and S-AP are transmitted at almost the same time. Based on the estimated CSI in this phase, a weight matrix is computed and will be used in the last part, null beamforming to self.

C. CFO Compensation

To see how the CFO compensation is applied in the channel sounding and null beamforming to self, an example is made as follows. For each subcarrier k, let $\mathbf{X}(k)$ be the S-AP transmit signal, then for n-th transmission in the first phase, the received signal $\mathbf{Y}^{1st}$ at M-AP is:

$$\mathbf{Y}^{1st}(k) = \mathbf{H}^{1st}(k)\mathbf{X}^{1st}(k) + \mathbf{N}^{1st} \tag{11}$$

where $\mathbf{H}^{1st}(k) = \hat{\mathbf{H}}^{1st}(k) \exp j\Delta\phi^{1st}$ represents the actual channel matrix, $\hat{\mathbf{H}}^{1st}$ is the estimated channel matrix, and $\Delta\phi^{1st}$ is the phase offset where $\Delta\phi^{1st} = 2\pi\Delta f^{1st}t$. At this point, there are n number of CFOs Δf^{1st} that have been obtained by M-AP. The estimated CFOs will be filtered using Infinite Impulse Response (IIR) filter, and it will be conjugated and used at the S-AP. In the second phase, the received signal $\mathbf{Y}^{2nd}(k)$ at M-AP can be expressed as:

$$\begin{aligned} \mathbf{Y}^{2nd}(k) &= \mathbf{H}^{2nd}(k) \cdot \mathbf{X}^{2nd}(k) e^{-j2\pi\Delta f^{2nd}t} + \mathbf{N}^{2nd} \\ &= \hat{\mathbf{H}}^{2nd}(k) e^{j\Delta\phi} \cdot \mathbf{X}^{2nd}(k) \cdot e^{-j2\pi\Delta f^{2nd}t} + \mathbf{N}^{2nd} \\ &= \hat{\mathbf{H}}^{2nd}\mathbf{X}^{2nd} + \mathbf{N}^{2nd} \end{aligned} \tag{12}$$

In this way, the CFO can be eliminated even when a common clock is not applied. The residual CFOs might still exist, but the impact will not be as harsh as when the CFO compensation is not applied.

IV. IMPLEMENTATION AND EXPERIMENT RESULTS

In this section, we explain the implementation of the proposed method that has been described in Section II and Section III. Applying the weight matrix to the generated signals is explained in Subsection IV-A. The hardware configuration and requirements used in this paper are described in Subsection IV-B. Finally, we show the experiment results and discuss them in Subsection IV-C.

A. Signal Generation and Applying Weight Matrix

The estimated channel matrix $\hat{\mathbf{H}}_j$ and $\hat{\mathbf{G}}_j$ are required to apply the proposed method. The APs transmit NDP frames to estimate the channel matrix $\hat{\mathbf{H}}_j$ and $\hat{\mathbf{G}}_j$ from the received signals. In the third phase, the calculated weight matrix $\mathbf{W}_l(k)$ is applied in the next transmission. In this paper, the IEEE 802.11ac frame is used for transmission. The CFO compensation, obtained from the first phase, is also applied to the second and third phases. In the third phase, the transmitted signal $\mathbf{X}^{3rd}(k)$ can be expressed as:

$$\mathbf{X}^{3rd}(k) = \begin{bmatrix} \mathbf{X}_1^{3rd^T}(k) & \mathbf{X}_2^{3rd^T}(k) & .... & \mathbf{X}_{N_{AP}}^{3rd^T}(k) \end{bmatrix}^T \tag{13}$$

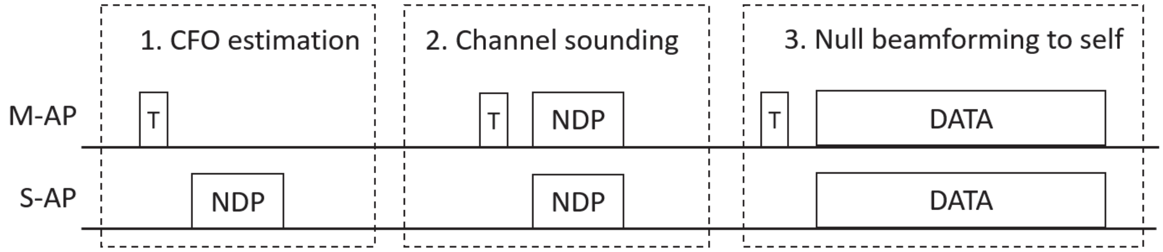

Fig. 2. Transmission procedure.

TABLE I
SYSTEM OVERVIEW

Device	Model (Manufacturing Company)
FPGA board	ZCU102 (Xilinx, Inc.)
SDR board	ADRV9009-W/PCBZ (Analog Device, Inc.)
Antenna	DELTA6C/x/SMAM/S/S/11 (Siretta, Ltd.)

$$= \begin{bmatrix} \mathbf{V}_{n1}^{T}(k) \\ \mathbf{V}_{n2}^{T}(k) \\ .... \\ \mathbf{V}_{N_{STA}}^{T}(k) \end{bmatrix}^{T} \mathbf{C}^{3rd}(k)\mathbf{s}^{3rd}(k) \qquad (14)$$

$$= \mathbf{W}_{n}(k)\mathbf{C}^{3rd}(k)\varepsilon_{f}(k)\mathbf{s}^{3rd}(k) \qquad (15)$$

where $\mathbf{s}^{3rd}(k) = [\mathbf{s}_1^{3rd^T}(k)\mathbf{s}_2^{3rd^T}(k)\ldots\mathbf{s}_{N_{STA}}^{3rd^T}(k)]^T$ is the transmission streams to be sent to each STA, $\varepsilon_f(k)$ is the CFO compensation, and $\mathbf{C}^{3rd}(k)$ is the cyclic shift diversity (CSD) diagonal matrix.

B. Overview of the Implemented System

The proposed method has been implemented with the configuration shown in Fig. 3. One FPGA and SDR pair performs the function of M-AP, and another pair performs the function of S-AP. Each pair has two transmit and receive antennas. Since M-AP plays the role of leader AP, it notifies the S-AP by sending IEEE 802.11n NDP as a trigger signal. S-AP has been designed to transmit the buffered packet whenever a trigger signal is received. Table I shows the details of the equipment used in this paper. To facilitate the implementation, the PC is used for generating signals and estimating the channel on behalf of all APs. The experiments were conducted in an indoor environment with hardware arrangement shown in Fig. 4. The distance between transmit antennas and receive antennas of different APs was 20 cm, while the distance between transmit antennas and receive antennas in an AP was 5 cm. Antenna canceller, RF canceller, and digital cancellation were not implemented in this system.

C. Experiments and Results

Experiments have been performed to evaluate the effect of CFO compensation and the amount of SI cancellation. In the first experiment, we compare the estimated CFOs of three different cases: 1) a common clock source is applied, 2) the

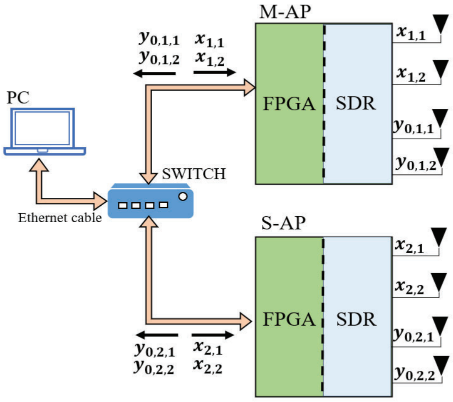

Fig. 3. Proposed system.

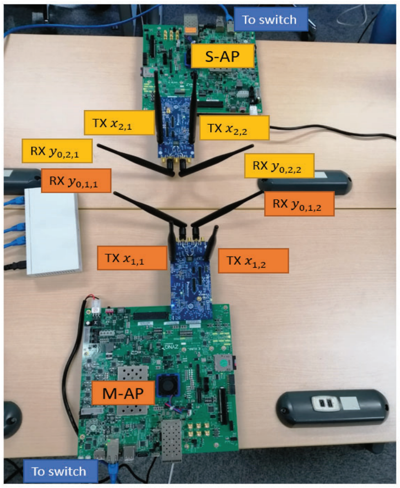

Fig. 4. Implemented system.

TABLE II
EXPERIMENT CONDITIONS

Parameter	Value	
	Channel Estimation	Null Beamforming to Self
Frame Format	IEEE 802.11ac	IEEE 802.11ac
MCS	0	1
# of Transmit Antennas	4 (2 + 2)	
# of Receive Antennas	4	4
(Subject to SI cancellation)	-	2
Null BF Target	-	M-AP: $RX_{0,1,1}$, $RX_{0,1,2}$
Center Frequency	5640 MHz	
Channel Bandwidth	20 MHz	
Weight matrix	Identity Matrix $\mathbf{I}$	$\mathbf{V}_{nl}(k)$

common clock source is not used, and 3) the common clock source is not used, but CFO compensation is applied. In the first case and second case, the estimated CFOs were obtained by performing the first phase of the transmission procedure shown in Fig. 2 once every minute. In the third case, the first phase was done twice every minute, but at the second transmission, the CFO compensation was performed at the S-AP.

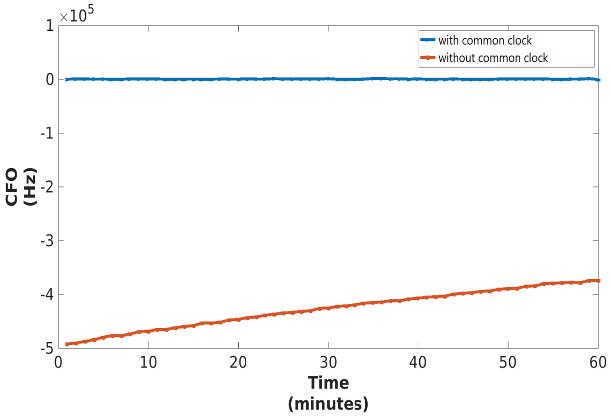

Fig. 5. CFO comparison when 1) the common clock is used and 2) common clock is not used

Fig. 5 shows the estimated CFO when a common clock is used in one case and not applied in another. Fig. 6 shows the following three cases: 1) the estimated CFO when a common clock is applied, 2) the common clock is not used, but CFO is compensated, and 3) the common clock is not used, but CFO is compensated and filtered. An infinite impulse response (IIR) filter, given by:

$$\mathbf{y}(n) = 0.8 \cdot \mathbf{y}(n-1) + 0.2 \cdot \mathbf{x}(n) \tag{16}$$

was used to smooth the estimated CFO in the case when CFO compensated. The proposed CFO compensation has a similar estimated CFOs to the case where a common clock is applied. If CFO compensation and common clock are not applied, the CFO could be as high as hundreds of kilohertz.

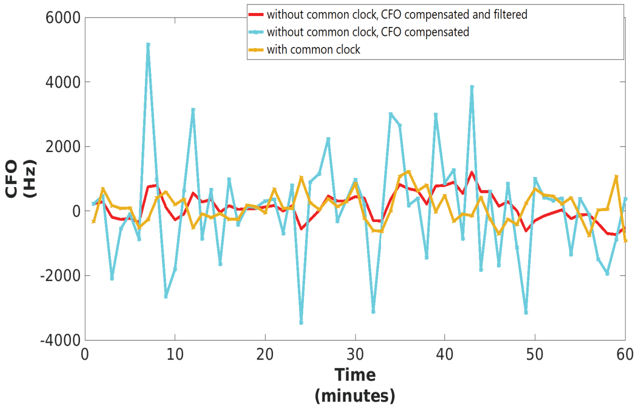

Fig. 6. CFO comparison when 1) the common clock is used, 2) common clock is not used, but CFO is compensated, and 3) common clock is not used, but CFO is compensated and filtered

In the second experiment, we performed null beamforming to the receive antennas at M-AP, $\mathbf{Y}_{0,1,1}$ and $\mathbf{Y}_{0,1,2}$. In the case of the common clock is not applied, but the CFO is compensated, the whole transmission procedure shown in Fig. 2 was performed. Only the last two phases, channel sounding and null beamforming were performed in the other two cases.

Fig. 7 shows the received power level from three different cases. When a common clock is applied, the amount of SI cancellation at $\mathbf{Y}_{0,1,1}$ and $\mathbf{Y}_{0,1,2}$ is 16 dB. When the common clock is not applied but the CFO compensation is applied, the amount of SI cancellation is 15 dB at both receive antennas. In these two cases, the received power levels at the S-AP antennas are relatively the same and not affected by the null beamforming. The benefit of using a common clock is that it provides stability. The proposed system has relatively the same amount of SI cancellation with 1 dB difference even though the clock source was not applied. In both cases, the uncancelled signals at $\mathbf{Y}_{0,1,1}$ and $\mathbf{Y}_{0,1,2}$ are the legacy preamble parts. The received signals at M-AP could not be suppressed when the common clock was not applied.

V. CONCLUSIONS

The SI cancellation using null beamforming with wireless coordination has been described in this paper. The hardware prototypes have been implemented using FPGAs and SDRs. We evaluate the SI cancellation of the proposed method and the effect of CFO compensation in the IEEE 802.11ac frame. Based on our experiments, the CFO compensation is required to lower the CFOs and obtain better channel estimation. The amount of SI cancellation is 15 dB. We have shown the possibility of performing wireless coordination between different APs for null beamforming. We will continue to improve the amount of SI cancellations in the future task.

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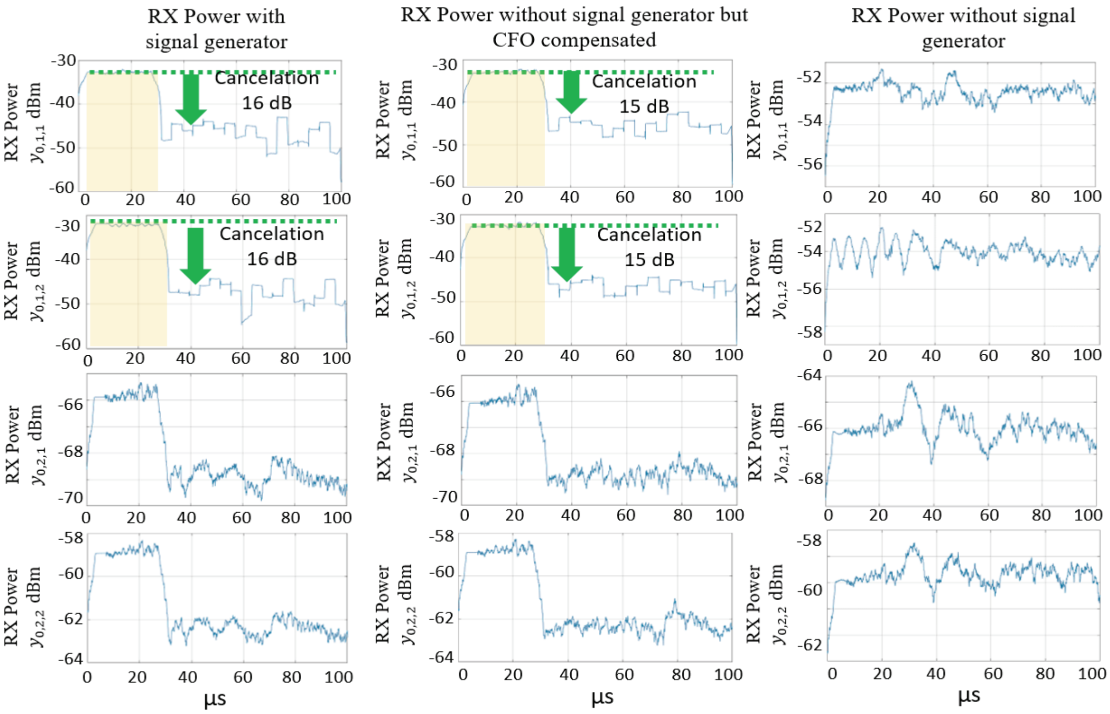

Fig. 7. Received signal power from three different cases

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