Efficient MU-MIMO Beamforming Protocol for IEEE 802.11ay WLANs

Munsuk Kim, Tanguy Ropitault, SuKyoung Lee, and Nada Golmie

***Abstract*—IEEE 802.11ay supports multi-user multiple-input-multiple-output (MU-MIMO). However, the MU-MIMO beamforming training (BFT) is a time-consuming process for finding appropriate directional antenna patterns, and inefficient BFT results in a long training time. Thus, in this letter, we propose an algorithm that configures the transmit antenna with the aim of reducing the number of redundant transmissions during MU-MIMO BFT. Both analytic and simulation results show that our proposed algorithm can significantly reduce the training time.**

***Index Terms*—MU-MIMO, beamforming training, 802.11ay.**

I. Introduction

THE IEEE 802.11 Task Group ay has recently defined new physical and medium access control specifications to increase the wireless networking performance beyond the IEEE 802.11ad technologies [1]. One of the major advancements is the introduction of downlink MU-MIMO that achieves significant multiplexing gain. The MU-MIMO BFT enables an initiator and a group of responders to determine the appropriate antenna configurations for efficient downlink MU-MIMO transmissions; however, it is a time-consuming process to examine the receive antenna patterns of all responders for acquiring the transmit antenna patterns of an initiator [2]. The training time depends on how the initiator configures its antennas when transmitting BF frames during MU-MIMO BFT [3].

Recently, several studies [1] and [2] have identified and described the main design elements of the IEEE 802.11ay MU-MIMO BF protocols; however, they have not included any proposal to improve the antenna training time. Thus, in this letter, we propose an algorithm to determine antenna configuration with the aim of shortening the training time by reducing the number of transmitting BF frames. Our proposed algorithm enables the initiator to find the best transmit sector for each antenna, through which its transmission using multiple antennas simultaneously can reach the largest number of intended responders in the group. We then analyze the antenna training time of MU-MIMO BF protocols. Our numerical results were validated by a simulation study.

II. IEEE 802.11ay MU-MIMO Beamforming

A. System Model

An access point (AP) initiates MU-MIMO BFT with a group of stations (STAs). Both the AP and STAs have the architecture of hybrid BF, as shown in Fig. 1 [2]. To achieve the spatial multiplexing gain, the data streams are mapped to different radio frequency (RF) chains. After passing through the corresponding RF chain, each data stream is finally transmitted by an antenna or subarray associated with the corresponding RF chain. Each antenna/subarray is configured to cover overlapping or non-overlapping spatial sectors and generates a single beam to transmit a data stream.

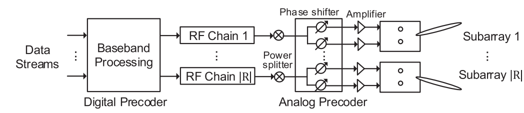

Fig. 1. Hybrid BF structure.

B. MU-MIMO Beamforming Training

The MU-MIMO BF procedure comprises two consecutive phases: single-input single-output (SISO) and MIMO. The SISO phase starts with a transmit sector sweep (TXSS) where the AP sends short sector sweep frames from different sectors of each of its transmit antennas and the STAs measure the signal quality of each transmit sector using quasi-omni patterns. The AP collects feedback on its TXSS from each STA. The feedback contains a list of sectors for each transmit antenna and their corresponding signal-to-noise ratio (SNR) values.

The MIMO phase comprises non-reciprocal (NRC) and reciprocal (RC) phases, where the latter can be performed only when both AP and STAs have antenna pattern reciprocity. The NRC MIMO phase is composed of four subphases as depicted in Fig. 2(a): BF setup, BF training, BF feedback, and BF selection. First, the AP broadcasts one or more BF setup frames to indicate parameters such as the MU group identifier (ID) and the type of MIMO phase. Next, in the BF training subphase, the AP transmits one or more beam refinement protocol-receive/transmit (BRP-RX/TX) frames to the STAs in the group, to which training (TRN) subfields are appended. The AP and each STA select transmit antenna weight vectors (AWVs) and receive AWVs, respectively, to be trained. The AP then sends the TRN subfields across all selected transmit AWVs simultaneously using multiple antennas. Each STA receives those TRN subfields across all the selected receive AWVs using multiple antennas simultaneously, and it then sends feedback to the AP in the BF feedback subphase. This feedback contains the list of transmit antennas/AWVs, each of which contains the corresponding receive antenna/AWV and measured SNR values. Finally, in the BF selection subphase, the AP announces the selected recipient STAs and their receive antenna configuration for downlink MU-MIMO transmission. In the RC type of BF training subphase, each STA sends BRP-RX/TX frames and the AP directly measures the signal quality of each pair of transmit and receive AWVs, as shown in Fig. 2(b).

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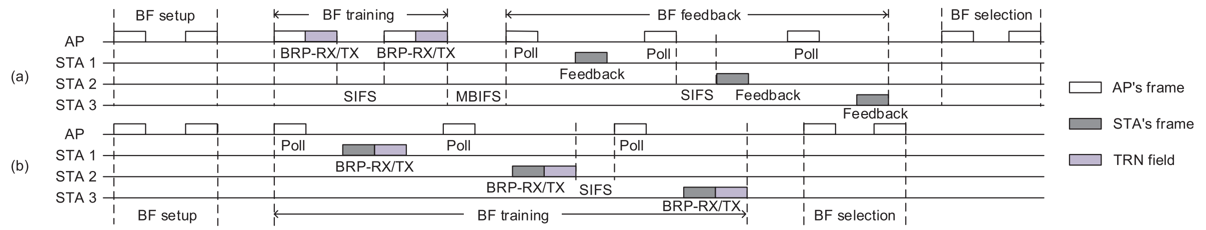

Fig. 2. The (a) NRC and (b) RC MIMO phases in the example scenario depicted in Fig. 3.

TABLE I

NOTATIONS FOR THE MODELING AND ANALYSIS OF MU-MIMO BFT

Notation	Description
M	The set of STAs included in the MU group
$\mathcal{R}$	The set of IDs of the transmit antennas supported by the AP
δ_{mu}	The SNR value that enables an STA in the MU group to be able to communicate with the AP without error
$\mathcal{C}_i$	The set of sector IDs, which are associated with antenna i and will be used by the AP to transmit a BF setup, BF selection, or BRP-RX/TX frame
T_c	The single carrier chip time (0.57 ns $= 1/1.76$ GHz)
x	The number of transmit/receive AWVs per antenna that the AP/each STA selects to transmit/receive TRN subfields

C. Proposed Transmit Antenna Configuration

In the MIMO phase, when transmitting a BF setup or selection frame to all STAs in the group, the AP may repeat its transmission several times over different transmit sectors to ensure reception by all STAs [1]. For example, let us suppose a scenario where the MU group comprises two STAs, STA1 and STA2, whose SISO feedbacks have informed that the AP can ensure reception by STA1 and STA2 when transmitting a BF frame only over sectors 1 and 2, respectively. In this scenario, to broadcast a BF setup or selection frame, the AP may first transmit that frame using the sector 1, and then repeat the same transmission using the sector 2. To reduce the number of such repeated transmissions, we propose an algorithm to determine the best transmit sector of each antenna for each transmission, through which the transmission using multiple antennas simultaneously ensures reception by the largest number of STAs in the group. Table I summarizes the notations used in the rest of this letter.

In the SISO phase, the feedback received from each STA can be represented as the list of transmit sector IDs, transmit antenna IDs, and their corresponding SNR values. Our proposed algorithm then performs the following procedure to configure the AP's antennas with the intent of reducing the number of transmitting BF frames during the MIMO phase:

1) For any STA $\in M$, the AP removes an element from its SISO feedback list if the SNR value included in the element is lower than the threshold, δ_{mu}. If the SNR values included all elements in the list are lower than δ_{mu}, the STA is removed from the set M.
2) Initialize the AP's transmit antenna ID i to 1.
3) For each sector associated with antenna i, the AP counts the number of STAs whose SISO feedback has included the ID of that sector.
4) The AP chooses the best sector among all sectors associated with the antenna i, for which the largest number of STAs have been counted in Step 3. The ID of the best sector is included in set $\mathcal{C}_i$ and then the AP removes, from the set M, the STAs whose SISO feedback has contained that best sector ID.
5) Increase i by 1 and go back to Steps 3 if the transmit antenna ID i exists in the set $\mathcal{R}$.
6) Steps from 2 to 5 are repeated until all STAs have been removed, i.e., $M = \phi$, as presented in Algorithm 1.

Algorithm 1 Antenna Configuration for the MIMO Phase

Notation: The set of IDs of sectors associated with antenna i $\mathcal{S}_i$, the SISO feedback received from STA m $\mathcal{L}_m$

```
while M ≠ φ do                                      // Step 6
    for each transmit antenna i ∈ R do              // Step 2 & 5
        for each sector α ∈ S_i do                  // Step 3
            CountNumberOfSTAs (α, M);               // Step 3
        end for
        α_b ← GetBestSectorOfAntenna (i);           // Step 4
        C_i ← α_b;                                  // Step 4
        for each STA m ∈ M do                       // Step 4
            if L_m.isSectorIncluded (α_b) = True then
                M.erase (m);                        // Step 4
            end if
        end for
    end for
end while
```

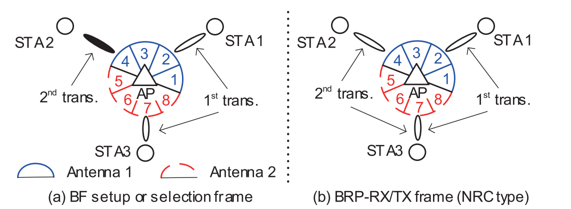

Fig. 3. Example of transmit antenna configuration in the MIMO phase.

When transmitting a BF setup or selection frame, the AP should send the minimum number of transmissions [3]; therefore, the number of its transmissions using multiple antennas simultaneously is the maximum among the numbers of elements included in set $\mathcal{C}_i$ for $\forall i \in \mathcal{R}$, i.e., $\max_{i\in\mathcal{R}} |\mathcal{C}_i|$. However, when transmitting BRP-RX/TX frames except for the TRN field in the NRC MIMO phase, the AP should test all combinations of transmit antenna configuration using all available RF chains simultaneously. Thus, the number of BRP-RX/TX transmissions is given by $\prod_{i\in\mathcal{R},|\mathcal{C}_i|\neq 0} |\mathcal{C}_i|$. For easy understanding, let us suppose a scenario depicted in Fig. 3 where the AP has two RF chains/antennas and $\mathcal{C}_1 = \{2, 4\}$ and $\mathcal{C}_2 = \{7\}$. To broadcast a BF setup or selection frame, the AP simultaneously uses the sectors 2 and 7, i.e., the sector 2 of the 1**st** antenna and the sector 7 of the 2**nd** antenna, for the first transmission, and only sector 4 for the second

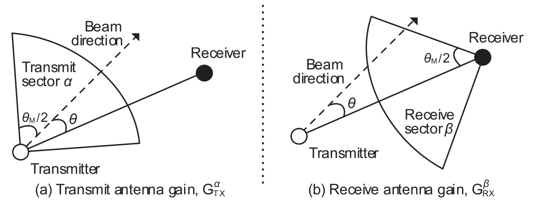

Fig. 4. Example of the azimuth angles for (a) G_{TX}^{α} and (b) G_{RX}^{β}.

transmission. In the case of BRP-RX/TX frames, the AP sends two transmissions using the sectors 2 and 7 and the sectors 4 and 7, respectively, as shown in Fig. 3.

III. Performance Analysis

A. Interference for Concurrent Transmissions

From the Friis power transmission formula, the received power at a receiver using sector β from a transmitter using sector α is [4]

$$P_{RX}^{\alpha,\beta} = P_{TX} G_{TX}^{\alpha} G_{RX}^{\beta} \frac{\lambda^2}{(4\pi d)^2} \tag{1}$$

where P_{TX} is the transmit power, G_{TX}^{α} and G_{RX}^{β} are the gains of the transmit and receive antennas, d is the transmission distance, and λ is the free-space wavelength. To estimate the gains, G_{TX}^{α} and G_{RX}^{β}, we employ the most widely used antenna model with a main lobe of Gaussian form and constant level of side lobes [5]. Let θ, θ_M, and $\theta_{3\text{dB}}$ be the azimuth angle of the beam for a transmit or receive sector, the beamwidth of main lobe, and the half-power beam width, respectively. Then, if $0 \leq |\theta| \leq \frac{\theta_M}{2}$, the main lobe gain is $G_M = G_0 - 12(\frac{\theta}{\theta_{3\text{dB}}})^2$ where G_0 is a maximum antenna gain and $\theta_{3\text{dB}} = \theta_M/2.6$; otherwise, the side lobe gain is $G_S = -0.4111 \cdot \ln(\theta_{3\text{dB}}) - 10.597$. We can obtain the azimuth angle θ, as shown in Fig. 4. Let us suppose a scenario where the transmitter transmits two or more beams simultaneously over different sectors. When the receiver using sector β receives the beam transmitted over sector α, the interference from the other concurrent beams is $I_{\alpha,\beta} = \sum_{\alpha' \neq \alpha} P_{RX}^{\alpha',\beta}$.

B. Transmit/Receive Antenna Training Time

We analyze the training time of the NRC and RC MIMO phases. The former is defined as the duration of BF training and BF feedback subphases, whereas the latter is the duration of BF training subphase. We assume that all BF frames use the control mode and are transmitted over a single 2.16 GHz channel [3]. A single frame format comprises legacy-short training field (L-STF), legacy-channel estimation field (L-CEF), L-Header, enhanced directional multi-gigabit beam refinement protocol (EDMG)-Header-A, and TRN fields in addition to its payload data. The EDMG-Header-A field is composed of two parts: EDMG-Header-A1 and EDMG-Header-A2.

The L-STF and L-CEF fields are composed of 50 and 9 repetitions, respectively, for a Golay sequence of length 128. Then, the duration of the L-STF and L-CEF fields is given by

$$D_P = (50 + 9) \cdot 128 \cdot T_c \tag{2}$$

The scrambled stream of the L-Header, EDMG-Header-A, and data fields is broken into more than two low-density parity check codewords. Let l_H, l_{A_1}, l_{A_2}, and l_D be the length of L-Header, EDMG-Header-A1, EDMG-Header-A2, and data fields, respectively, in octets. Then, the total number of codewords is $n_{cw} = 1 + \lceil \frac{(l_{A_2}+l_D)\cdot 8}{168} \rceil$. The bits of the first codeword is then given by $L_f = (l_H + l_{A_1}) \cdot 8$. The bits of the second or any subsequent codeword except the last one is $L_s = \lceil \frac{(l_{A_2}+l_D)\cdot 8}{n_{cw}-1} \rceil$. The bits of the last codeword is given by $L_t = (l_{A_2} + l_D) \cdot 8 - (n_{cw} - 2) \cdot L_s$ [3].

Then, 168 parity bits are added to each codeword. The output bit stream generated from the codewords is spread using a Golay sequence of length 32. Thus, using Eq. (2), the duration of all fields except the TRN field is given by

$$D_F(l) = D_P + \{\Gamma(L_f) + \Gamma(L_s) \cdot (n_{cw} - 2) + \Gamma(L_t)\} \cdot 32 \cdot T_c \tag{3}$$

where $\Gamma(L) = L + 168$ and $l = l_H + l_{A_1} + l_{A_2} + l_D$.

The basic unit of the TRN subfield comprises six Golay sequences of length 128 each. Let n_b be the number of basic units included in a TRN subfield. Let n_s and n_u denote the number of TRN subfields concatenated into a single TRN unit (TRN-Unit) and the number of TRN-Units included in the TRN field, respectively. Then, the duration of the TRN field can be obtained as follows:

$$D_T(n_u) = n_b \cdot (n_t + n_s \cdot n_u) \cdot 6 \cdot 128 \cdot T_c \tag{4}$$

where n_t is the number of TRN subfields for the transition interval between the processing of the data and TRN fields and for tracking the frequency offset of the last TRN-Unit.

Let $l^{(P)}$, $l^{(F)}$, and $l^{(T)}$ denote the length of the BF polling, BF feedback, and BRP-RX/TX frames except for the TRN field, respectively. Then, $l^{(P)}$, $l^{(F)}$, and $l^{(T)}$ can be calculated by referring to l in Eq. (3). The BF training and BF feedback subphases are separated by medium beamforming interframe space (MBIFS), and all transmissions in the BF training or feedback subphase are separated by short interframe space (SIFS). Thus, using Eqs. (3) and (4) and referring to Fig 2(a), the nanosecond duration of the BF training and feedback subphases in the NRC MIMO phase is

$$\begin{aligned} T_{NRC}(n_u) = {} & MBIFS - 2 \cdot SIFS \\ & + \prod_{i \in \mathcal{R}, |\mathcal{C}_i| \neq 0} |\mathcal{C}_i| \cdot \{D_F(l^{(T)}) + D_T(n_u) + SIFS\} \\ & + |M| \cdot \{D_F(l^{(P)}) + D_F(l^{(F)}) + 2 \cdot SIFS\} \end{aligned} \tag{5}$$

Likewise, referring to Fig 2(b), the duration of the BF training subphase in the RC MIMO phase is

$$\begin{aligned} T_{RC}(n_u) = {} & (2 \cdot |M| - 1) \cdot SIFS + |M| \cdot [D_F(l^{(P)}) \\ & + D_F(l^{(T)}) + D_T(n_u)] \end{aligned} \tag{6}$$

where, for ease of exposition, we assume that all STAs trains the same number of receive AWVs using the TRN field.

IV. Simulation Results and Discussion

The MU-MIMO BF protocols were implemented in the ns-3 simulator, and we compared the training time of the NRC and RC MIMO phases. For the millimeter-wave communication stack, we extended the open source implementation

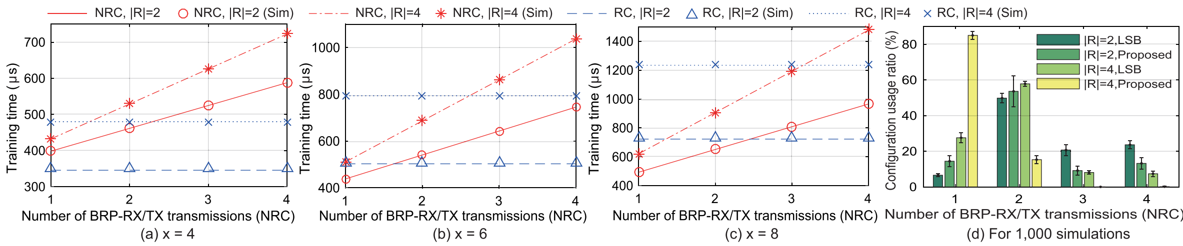

Fig. 5. For each number of BRP-RX/TX transmissions in the NRC type, (a-c) the training time and (d) the ratio of transmit antenna configuration used.

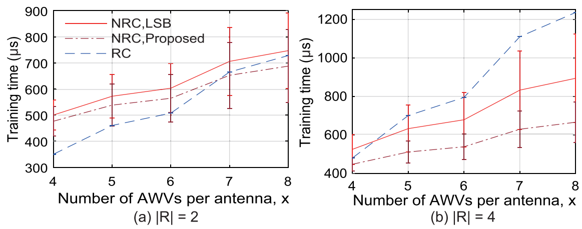

Fig. 6. Training time of the MIMO phase for 1 000 simulations.

of IEEE 802.11ad by Assasa and Widmer [4]. We used the directional antenna pattern model provided in [5]. In this model, the sectors discretize the antenna azimuth in the two-dimensional plane, as shown in Fig. 3. The number of STAs included in the MU group was 4, and they were randomly distributed over a $30 \times 30\ m^2$ field. The AP was located at the center, and it performed the BFT at every beacon interval of 102.4 ms. We ran 1 000 simulations of 10 s per trial. Both the AP and the STAs had two- or four-RF chains/antennas, i.e, $|\mathcal{R}| = 2$ or 4. The number of sectors per antenna was 4, and n_b was 1 or 2 when $|\mathcal{R}| = 2$ or 4, respectively. The number of transmit/receive AWVs selected to be trained per antenna, x, increased in the range [4,8]. Other parameters were defined as follows: $l_H = 5$, $l_{A_1} = 6$, $l_{A_2} = 3$, $n_t = 5$, $n_s = 9$, $n_u = x \cdot \lceil x/2 \rceil$, $l^{(T)} = 69$, $l^{(P)} = 52$, $l^{(F)} = 167$, $\delta_{mu} = 20$ dB, $SIFS = 3\ \mu s$, $MBIFS = 9\ \mu s$, $\theta_M = \frac{\pi}{2|\mathcal{R}|}$, and $G_0 = (1.6162/\sin(\frac{\theta_{3\text{dB}}}{2}))^2$ [3], [5].

Figs. 5(a)-(c) plot the training time of the NRC and RC types when the number of the AP's RF chains/antennas was 2 or 4. The simulation results were almost the same as the numerical ones. This is because all transmissions are scheduled and separated by the fixed time interval, i.e., SIFS or MBIFS. Figs. 5(a)-(c) show that as the number of BRP-RX/TX transmissions in the NRC MIMO phase, i.e., $\prod_{i\in\mathcal{R},|\mathcal{C}_i|\neq 0} |\mathcal{C}_i|$, increased, the training time of the NRC type increased whereas that of the RC type was constant. Fig. 6 illustrates the training time of the NRC and RC types versus the number of the selected AWVs per antenna, x. The error bars represent 95 % confidence intervals. Unlike the RC type, the NRC type of MIMO phase has a different number of BRP-RX/TX transmissions according to the positions of STAs as shown in Fig 3, and thus the large variation in its training time was observed for 1 000 simulations. To evaluate our antenna configuration algorithm proposed in Section II-C, we defined another NRC type using the largest SNR-based (LSB) antenna configuration. For the LSB antenna configuration, the sets, $\mathcal{C}_i$ for $\forall i \in \mathcal{R}$ include the transmit sector with the largest SNR among all transmit sectors known from the SISO feedback of each STA. Fig. 5(d) shows that the proposed algorithm used less BRP-RX/TX transmissions than the LSB one, and thus its training time was shortened, as shown in Fig. 6. We calculated the interference for concurrent transmissions as described in Section III-A and then obtained the signal-to-interference plus noise ratio. In our simulation, the interference had little effect on the packet error rate because there was a significant difference among the directions of beams simultaneously generated by different transmit antennas.

In the case of four antennas, Fig. 6(b) shows that the training time of the proposed NRC type was lower than that of the RC one. This can be attributed to the fact that the NRC type outperformed the RC type when the number of BRP-RX/TX transmissions was 1, as shown in Fig. 5(a)-(c), and the number of BRP-RX/TX transmissions in the proposed NRC type was more likely to be 1, rather than 2, 3, or 4, for 1 000 simulations, as shown in Fig. 5(d). Conversely, in the case of two antennas, Fig. 6(a) demonstrates that the training time of the RC type was less than that of the proposed NRC one when $x = 4$, 5, and 6, and we can find its reason in the same manner as in the above four-antenna case. These results indicate that the training time of both types depends on the number of antennas, selected AWVs, and STAs in the group and on the sets of transmit antenna configuration, $\mathcal{C}_i$ for $\forall i \in \mathcal{R}$. However, if the total number of STAs was equal to or greater than the number of BRP-RX/TX transmissions in the NRC type, the RC type always outperformed the NRC type because the RC MIMO phase removes the BF feedback subphase.

V. Conclusion

In the IEEE 802.11ay, the MU-MIMO BFT is a time-consuming process. Thus, in this letter, we proposed the transmit antenna configuration to reduce the BFT time. We then analyzed the transmit/receive antenna training time during the NRC and RC MIMO phases. The simulation results demonstrated that the proposed antenna configuration algorithm can significantly reduce the training time of the MIMO phase.

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