IEEE 802.11ay: Next-generation 60 GHz Communication for 100 Gbps Wi-Fi

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Abstract— **The IEEE 802.11ad amendment to the 802.11 standard ratified in 2012 created the first multi-Gbps Wi-Fi technology by using the large swath of unlicensed spectrum at the millimeter wave (mm-Wave) band. While enabling multi-Gbps wireless local communications was a significant achievement, throughput and reliability requirements of new applications, such as augmented reality (AR)/virtual reality (VR) and wireless backhauling, exceed what 802.11ad can offer. For this reason, building upon IEEE 802.11ad, the IEEE 802.11 Task Group ay has recently defined new physical (PHY) and medium access control (MAC) specifications that enable 100 Gbps communications through a number of technical advancements. In this article, we identify and describe the main design elements of IEEE 802.11ay, including multiple-input-multiple-output (MIMO), channel bonding, improved channel access, and enhanced beamforming training. For each of these elements, we discuss how their design is impacted by mm-Wave radio propagation characteristics and present enabling mechanisms defined in IEEE 802.11ay.**

Index Terms— IEEE 802.11ay, 60 GHz, Beamforming, mm-Wave, Wi-Fi, MIMO

I. Introduction

While local and personal wireless technologies have greatly evolved in the last few years [1, 6], new applications and continued usage growth demand greater throughput and reliability with lower latencies. AR/VR applications, mobile offloading, high-bandwidth connectivity to multiple TV and monitor displays, and indoor and outdoor wireless backhaul are just a few applications that require new wireless technologies. To meet the demanding requirements of such diverse applications, the IEEE 802.11 Task Group ay (802.11ay) was formed in 2015 to define PHY and MAC amendments to the 802.11 standard that enable Wi-Fi devices to achieve 100 Gbps using the unlicensed mm-Wave (60 GHz) band at comparable ranges to today's commercial 60 GHz devices based on the 802.11ad standard[1].

As examined in this article, 60 GHz transmissions must be directional to take advantage of beamforming gains and cope with increased path loss (e.g., 22 dB for 10 meters) and other propagation losses compared to sub 6 GHz bands. As discussed in [1], in order to support highly directional transmissions, in place of quasi-omni, IEEE 802.11ad redefined fundamental principles of Wi-Fi systems and incorporated innovative techniques and procedures to overcome unique challenges associated with mm-Wave propagation. IEEE 802.11ad supports transmission rates of up to 8 Gbps using single-input-single-output (SISO) wireless transmissions over a single 2.16 GHz channel.

IEEE 802.11ay, the next-generation Wi-Fi standard for the 60 GHz band, increases the peak data rate to 100 Gbps through supporting multiple independent data streams and higher channel bandwidth, among other advancements, while ensuring backward compatibility and coexistence with Directional Multi-Gigabit (DMG) stations (STAs). We use the terms DMG and Enhanced DMG (EDMG) stations to refer to devices that can support features of IEEE 802.11ad and IEEE 802.11ay standards, respectively.

A. Channel Bonding and Aggregation

The band allocated to unlicensed use around 60 GHz has approximately 14 GHz of bandwidth, which is divided into channels of 2.16, 4.32, 6.48, and 8.64 GHz bandwidth. The channel center frequencies for the 2.16 GHz channels are: 58.32, 60.48, 62.64, 64.80, 66.96, and 69.12 GHz for channel numbers 1 through 6, respectively [2]. Unlike IEEE 802.11ad, which only allows for single (2.16 GHz) channel transmission, 802.11ay includes mechanisms for channel bonding and aggregation; in channel bonding, a single waveform covers at least two contiguous 2.16 GHz channels, whereas channel aggregation has a separate waveform for each aggregated channel. IEEE 802.11ay mandates that EDMG STAs must support operation in 2.16 GHz channels as well as channel bonding of two 2.16 GHz channels. Channel aggregation of two 2.16 GHz or two 4.32 GHz (contiguous or non-contiguous) channels and bonding of three or four 2.16 GHz channels is optional.

B. Directional MIMO Communication

In typical DMG implementations, one or more phased arrays are driven by a single Radio Frequency (RF) chain and thus only a single data stream is transmitted at a time. Therefore, the multiple antenna elements used by DMG STAs only provide beamforming gain but not multiplexing gain. To achieve both beamforming and multiplexing gain, IEEE 802.11ay defines new mechanisms to enable MIMO operation

[1]According to the official IEEE 802.11 Working group timeline, the draft of the IEEE 802.1ay amendment is scheduled to go for a vote (WG letter ballot) in November 2017.

including both Single-User MIMO (SU-MIMO) and downlink Multi-User MIMO (MU-MIMO). The maximum number of spatial streams per station is eight, and downlink MU-MIMO transmission can be made to up to eight stations.

EDMG STAs may also use digital pre-coding at baseband to compliment analog beamforming to minimize or ideally cancel the inter-stream interference in MIMO transmissions. Such hybrid analog/digital beamforming architectures have been studied in the literature employing single-polarized phased antenna arrays [3, 5]. IEEE 802.11ay also supports stations with dual-polarized antenna arrays. The use of polarization is of great value in mm-Wave communications since, for example, it allows for diversity gains and spatial multiplexing in Line-of-Sight (LoS) environments. To obtain spatial and polarization separation, signal streams must be independently steerable and be transmitted and received with different polarizations. Experimental results have shown that practical phased antenna arrays can have a cross polarization discrimination factor of approximately -24 dB [4]. Therefore, in a 2×2 SU-MIMO configuration with dual-polarized antenna array, both streams can operate under LoS conditions with orthogonal horizontal and vertical polarizations. In general, the number of streams that a given MIMO link supports is determined by different factors including the environment, the directivity of the antenna used, and on whether antenna polarization is exploited.

The remainder of this article is as follows: We discuss the main advances made to the baseline PHY and MAC design to support MIMO (and channel bonding) in Sections II and III, respectively. We present a summary of IEEE 802.11ay beamforming protocols in Section IV.

II. IEEE 802.11ay Physical Layer (PHY) Overview

Building upon the DMG PHY, IEEE 802.11ay defines a new PHY specification that includes both single carrier (SC) and orthogonal frequency division multiplexing (OFDM) modulations. As described in this section, to support MIMO transmissions and channel bonding while guaranteeing backward capability, a new packet structure is defined in IEEE 802.11ay. The EDMG packet contains new fields necessary to support the additional capabilities defined for EDMG stations, as well as a redefined training (TRN) field that is more flexible and efficient than the one defined in IEEE 802.11ad.

A. EDMG Packet Format

A single packet format is defined for the three EDMG PHY modes: SC, OFDM, and control. This packet is shown in Fig.1 with all of its possible fields. Not all fields are transmitted in an EDMG packet: Fields are included depending on whether the packet is used for single channel or channel bonding operation, for SISO or MIMO transmission, and if it is used for beamforming training/tracking.

To enable backward compatibility, the first portion of an EDMG packet, referred to as non-EDMG portion, is defined to be recognizable by DMG stations. The L-STF (legacy-short training field) and L-CEF (legacy-channel estimation field) are compatible with the preamble defined in IEEE 802.11ad, and enable detection of the packet and acquisition of carrier

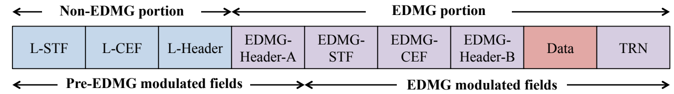

Figure 1: IEEE 802.11ay packet structure.

frequency and timing. The L-Header field is the same as the header field in an IEEE 802.1ad packet, with the exception that some of its bits are re-defined.

The second portion of an EDMG packet, referred to as the EDMG portion, includes fields that are only recognized by EDMG STAs. The EDMG-Header-A field carries information required to interpret EDMG packets, including bandwidth, Modulation and Coding Scheme (MCS), and number of spatial streams. The EDMG-STF and EDMG-CEF fields enable EDMG stations to estimate various signal parameters and the channel when channel bonding and/or MIMO are utilized. The EDMG-Header-B is only included in MU-MIMO packets.

The non-EDMG portion of the packet together with the EDMG-Header-A is transmitted with the IEEE 802.11ad rate. When channel bonding is utilized, these fields are transmitted in duplicate mode over the channels being bonded. In MIMO transmissions, identical copies of these fields are transmitted in each stream with different cyclic shifts. Due to these characteristics, the first four fields of an EDMG packet are said to be pre-EDMG modulated. The remaining fields, which are said to be EDMG modulated, are transmitted in bonded and/or MIMO mode when these features are employed.

B. Data Field Format

The data field consists of the payload data and possible padding. The bits to be transmitted are padded with zeros if necessary, scrambled, encoded, and modulated according to an EDMG MCS. Then, symbols are grouped and each group is prepended by a modulated Golay sequence, forming a block. The SC block size consists of 512 × N_{CB} symbols for both SISO and MIMO transmissions, where N_{CB} is the number of utilized 2.16 GHz channels.

The control mode, which corresponds to MCS 0 in both DMG and EDMG PHYs, enables low SNR operation prior to beamforming with BPSK modulation and a spreading factor of 32. The other MCSs defined in IEEE 802.11ay for the SC mode are based on BPSK, QPSK, 16 QAM, and 64 QAM modulations and LDPC codes with rates of 1/2, 5/8, 3/4, 13/16, and 7/8. The achievable data rate for each MCS index depends on the number of spatial streams, N_{SS} ($1 \leq N_{ss} \leq 8$), and the number of 2.16 GHz channels, N_{CB} ($1 \leq N_{CB} \leq 4$), used in the transmission of the packet.

C. Training (TRN) Field Format

The TRN field enables transmit and receive beamforming training and is appended to packets used in a beam refinement protocol (BRP). As discussed in Section V, BRP is a process in which a station can improve its antenna configuration for transmission and/or reception. The TRN field was redesigned in IEEE 802.11ay to increase efficiency and make it configurable based on the characteristics of the particular beamforming training procedure being executed.

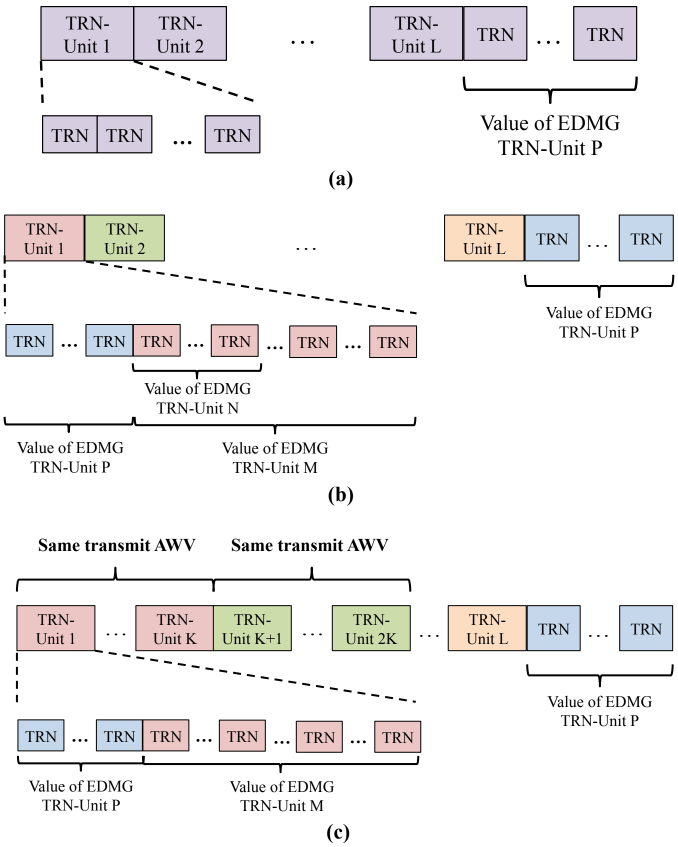

Figure 2: EDMG TRN field structure for (a) EDMG BRP-RX packets, (b) EDMG BRP-TX packets, and (c) EDMG BRP-RX/TX packets.

The "basic unit" of the TRN field is the *TRN subfield*, which is composed of 6 Golay complementary sequences. By concatenating a variable number of TRN subfields, a TRN-Unit is formed. The format of a TRN field is shown in Fig.2. The TRN field is composed of a variable number of TRN-Units, which is defined by the parameter EDMG TRN Length, denoted by L in Fig.2.

In a BRP procedure used for receiver training, all TRN subfields are transmitted with the same Antenna Weight Vector (AWV) as the data field. Such packets are referred to as EDMG BRP-RX packets in [2] and their TRN field structure is shown in Fig.2.a. As defined in [2], AWV is a vector of weights describing the excitation (amplitude and phase) for each element of an antenna array. This configuration allows the receiver to switch AWVs when receiving the different TRN subfields and thus searches for an improved antenna configuration setting.

In a BRP procedure used for transmitter training, the transmitter uses different AWVs in the transmission of the TRN field while the receiver uses the same AWV in its reception. The TRN field structure for transmit training is shown in Fig.2.b. As shown in this figure, three parameters define the format and length of a TRN-Unit used for transmit beamforming training (referred to as EDMG BRP-TX packets in [2]): EDMG TRN-Unit P, EDMG TRN-Unit M, and EDMG TRN-Unit N, which are referred to as P, M, and N in what follows for ease of notation. In a TRN-Unit, the first P TRN subfields are transmitted with the same AWV as the data field. Therefore, the receiver may use such TRN subfields to maintain synchronization and estimate the channel. In the transmission of the remaining M TRN subfields of a TRN-Unit, the transmitter may change AWV at the beginning of each TRN subfield. In order to improve the robustness of the beamforming training process, of the last M TRN subfields of a TRN-Unit, more than one consecutive TRN subfield may be transmitted with the same AWV. The number of consecutive TRN subfields transmitted with the same AWV is N.

To enable simultaneous training of the transmitter and receiver, a given TRN-Unit may be re-transmitted a number of times. In this case, the same AWV is used in the transmission of the last M TRN subfields of a given TRN-Unit, and the same TRN-Unit is repeated a number of times. Such packets are referred to as EDMG BRP-RX/TX packets in [2] and are shown in Fig.2.c. The number of TRN-Units transmitted with the same AWV is given by the parameter RX TRN-Units per Each TX TRN-Unit, which is noted as K in Fig.2.c. In such packets, the value of N is not applicable. For all EDMG BRP packets, following the transmission of all TRN-Units, there are P repetitions of the TRN subfield to allow the receiver to track frequency offset for the last transmitted TRN-Unit.

III. IEEE 802.11ay Medium Access Control Layer

This section describes the main changes made to the IEEE 802.11ad MAC layer specification to support MIMO transmission and multi-channel operation.

A. Beacon Interval

IEEE 802.11ay organizes access to the medium in Beacon Intervals (BIs), similar to 802.11ad. Fig.3 illustrates a typical BI consisting of two main access periods: Beacon Header Interval (BHI) and Data Transmission Interval (DTI). The BHI enables beam training of unassociated DMG and EDMG STAs and network announcements through a sweep of multiple directionally transmitted frames. The BHI is further subdivided into three sub-intervals: 1. **Beacon Transmission Interval (BTI)** used by the AP or the personal basic service set control point (PCP) for transmission of beacon frames; 2. **Association Beamforming Training (A-BFT)** used by DMG/EDMG STAs to train their receive antenna configurations; 3. **Announcement Transmission Interval (ATI)** used for management frame exchange between the AP/PCP and beam-trained stations.

A-BFT is slotted (up to 8 slots for 802.11ad) and stations randomly choose one of the slots for transmitting their sector sweep (SSW) frames; consequently, collisions may occur when more than one STA choose the same slot. To accommodate a larger number of STAs attempting access during A-BFT, IEEE 802.11ay supports up to 40 A-BFT slots in each BI.

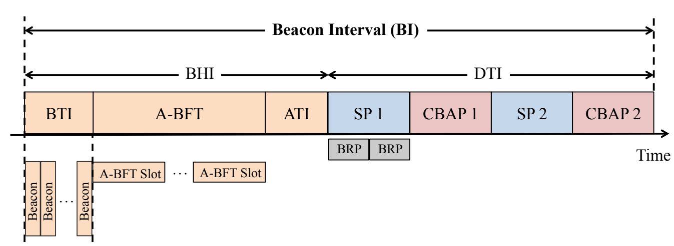

Figure 3: IEEE 802.11ay beacon interval structure.

The BHI is followed by the DTI, which facilitates different types of medium access for data transmission and beamforming training. In the DTI, data frames can be exchanged either in contention-based access periods (CBAPs) or scheduled service periods (SPs) for contention-free communications. A description of IEEE 802.11ad channel access rules can be found in [1].

B. Multiple Channel Access

EDMG transmissions always involve a primary channel with 2.16 GHz bandwidth to maintain compatibility with 802.11ad. EDMG stations can occupy secondary 2.16 GHz, 4.32 GHz or 6.48 GHz channels which might be adjacent or non-adjacent to the primary channel. EDMG STAs must be capable of performing physical and virtual carrier sensing (i.e., network allocation vector or NAV) in the primary channel and at least energy detection in the secondary channels. Physical carrier sensing is a measurement of the received signal strength of an incoming Wi-Fi signal preamble, whereas energy detection determines if the medium is busy by measuring the total energy received at the station, regardless of whether it is a valid Wi-Fi preamble or not. Both methods compare the measurements with a pre-defined threshold.

To enable the coexistence of DMG and EDMG STAs, network announcement and management frames need to be transmitted through the primary channel; hence, the BHI is present on the primary channel. IEEE 802.11ay supports the presence of A-BFT on secondary channels to provide more slots for contention-based transmission of SSW frames in dense use cases. Transmissions within the DTI (CBAP or SP) can use more than one channel or be performed over a bonded channel. IEEE 802.11ay supports channel access over multiple channels through scheduling and within Transmission Opportunity (TXOP). With scheduling, the AP/PCP specifies the channel width for the following DTI, whereas in TXOP, STAs expand their bandwidth opportunistically when secondary channels are idle. Next, we elaborate on these two approaches.

1) Multiple Channel Access Through Scheduling

The AP/PCP can allocate aggregated and bonded channel(s) using the EDMG Extended Schedule Element (ESE), which can be transmitted by the AP in the BTI. Fig.4 depicts four possible channel allocations. When the used channels are adjacent, both channel bonding and channel aggregation are possible (allocation #1); however, channel aggregation is the only option for allocation #2 since it includes non-adjacent channels. An EDMG AP/PCP can also schedule allocations over different channels overlapping in time (e.g., allocations #3 and #4). As shown in Fig.4, allocation #4 does not include the primary channel. Such allocations that do not include the primary channel are limited to a single 2.16 GHz channel. If the allocation is a CBAP that does not include the primary channel, the STAs must perform full carrier sensing in the secondary channels. In addition, when the AP/PCP is the transmitter or receiver in an allocation, the allocation must include the primary channel so that the transmission would not be hidden from the DMG STAs.

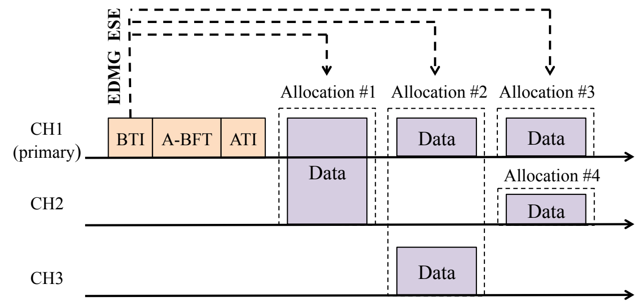

Figure 4: Example of IEEE 802.11ay multiple channel access via scheduling.

2) Multiple Channel Access Through TXOP

Medium access in CBAPs follows Enhanced Distributed Channel Access (EDCA) rules in which the AP/PCP and STAs obtain a transmission opportunity (TXOP) either by winning an instance of EDCA contention or by receiving a Grant frame. When EDMG STAs and AP/PCP support multiple channel widths, an EDCA TXOP is obtained based solely on the activity of the primary channel, i.e., if the primary channel is idle. However, the width of the transmission is determined by the occupancy status of the non-primary channels. Hence, the TXOP initiator monitors the status of its primary channel during the PIFS (Point Coordination Function Inter-frame Space) interval immediately preceding the expiration of the backoff counter to determine which secondary channels are idle.

Once the TXOP initiator finds the primary and secondary channels to be idle, it performs an RTS/DMG CTS exchange to inhibit collision on the secondary channel(s). The TXOP initiator sends RTS frames in the primary and secondary channels if they are determined to be idle to determine the available bandwidth at the responder. The TXOP responder then transmits a DMG CTS in the idle channels in order to help the TXOP initiator determine which channels are available for data transmission.

C. MIMO Channel Access

To perform a MIMO transmission, the transmitter must obtain a TXOP. To this end, EDMG STAs that support MIMO maintain physical and virtual carrier sensing and perform the backoff procedure. The MIMO channel is said to be *idle* when all the MIMO transmit antennas intended to be used in the TXOP (determined by MIMO beamforming protocols defined in Section V) are sensed to be *idle* for a period of PIFS before the backoff timer reaches zero. In this case, the EDMG STA is permitted to obtain a TXOP for a SU-MIMO transmission. In downlink MU-MIMO, the AP/PCP is the transmitter, which needs to obtain a TXOP.

Before the transmitter accesses the channel, it must indicate to one or more EDMG STAs its intention to transmit an SU-MIMO or a MU-MIMO packet to them. To this end, the EDMG transmitter can send a RTS frame, a DMG CTS-to-self frame, or a Grant frame to the intended EDMG STAs. This frame indicates whether the following transmission is SU-MIMO or MU-MIMO and also the antenna configuration to be used. The receiving EDMG STAs can infer the operating channel number and bandwidth from this frame and respond with a DMG CTS frame or an ACK frame. This response frame confirms the availability of the STA for MIMO reception and protects it from hidden STAs.

IV. IEEE 802.11AY BEAMFORMING PROTOCOL

Beamforming (BF) training is used to determine the appropriate transmit and receive antenna configurations for a pair of stations through two sub-phases [1]: (1) Sector Level Sweep (SLS) enables communication between two participating stations at the control mode rate or higher MCS. Normally, the SLS phase provides only transmit beamforming training. (2) BRP enables receive training and iterative refinement of the AWV at both participating STAs. IEEE 802.11ay includes several new beamforming training protocols, including SU-MIMO/MU-MIMO beamforming training, BRP transmit sector sweep, and beamforming for asymmetric links. These BF procedures are performed in the DTI after STAs have an established link. In this section, we focus on MIMO beamforming and a description of other IEEE 802.11ay BF procedures can be found in [2].

A. SU-MIMO Beamforming

The SU-MIMO BF protocol determines transmit and receive antenna configurations for simultaneous transmission of multiple spatial streams between two SU-MIMO capable EDMG STAs. The SU-MIMO beamforming protocol consists of two consecutive phases: SISO phase and MIMO phase.

1) SISO Phase

In this phase, both STAs collect the necessary feedback for possible candidate sectors, some of which are then used in the following MIMO phase. The station that initiates the beamforming training is called the initiator, and the other the responder. All transmissions in this phase use the DMG control mode to extend the range. Fig.5.a depicts the SISO phase, which comprises three sub-phases: an optional initiator transmit sector sweep (I-TXSS), an optional responder transmit sector sweep (R-TXSS) sub-phase and a mandatory SISO feedback sub-phase.

The optional I-TXSS and R-TXSS subphases allow the responder and initiator to estimate the received SNR value for the different sectors being trained. These two sub-phases may be skipped and information obtained in the immediately preceding TXSS can be used instead. During the I-TXSS, the initiator transmits *short SSW* packets using different sectors while the pairing STA receives with a quasi-omnidirectional pattern. This procedure enables the responder to create an ordered list of best transmit sectors for the initiator according to their corresponding estimated SNR values. Similarly, in the R-TXSS, the initiator creates an ordered list of the best sectors based on their estimated SNR values.

In the mandatory SISO feedback sub-phase, the stations exchange BRP frames with TXSS feedback information. The BRP frame transmitted by the initiator contains a list of sector identifiers and corresponding SNR values of the transmit sectors trained in the last R-TXSS. Similarly, the BRP feedback frame transmitted by the responder reports a list of sector identifiers and corresponding SNR values estimated in the last I-TXSS.

1) MIMO Phase

The MIMO phase enables the simultaneous training of transmit and receive sectors for each DMG antenna (e.g., phased antenna array). The MIMO phase, depicted in Fig.5.b, comprises four mandatory sub-phases: an SU-MIMO BF setup, an initiator SU-MIMO BF training (SMBT), a responder SMBT, and an SU-MIMO BF feedback sub-phase.

First, in the SU-MIMO BF setup sub-phase, both the initiator and responder select a subset of candidate transmit sectors per DMG antenna based on the SNR values provided in the SISO phase. The two STAs announce candidate sectors through exchanging *MIMO BF setup* frames. Since these sectors need to be further trained in SMBT, *MIMO BF setup* frames contains the number of BRP frames to be transmitted in the following initiator SMBT (or responder SMBT) sub-phase, and the order that candidate sectors will be trained in each BRP frame. Furthermore, the MIMO BF setup frame indicates a *decision maker* for each link (from the initiator to the responder and vice versa) defined as the STA responsible for determining the final transmit and receive antenna configurations for SU-MIMO transmissions.

In initiator SMBT, multiple transmit configurations of the initiator and multiple receive configurations of the responder are trained. This becomes possible when the initiator transmits EDMG BRP-RX/TX packets appending the TRN field. As explained in Section III, the TRN field structure is defined by the parameters "TRN length (L)" and "RX TRN-Units per Each TX TRN-Unit (K)" (see Fig.2.c). Here, K should be set to the number of candidate receive sectors (at responder) and

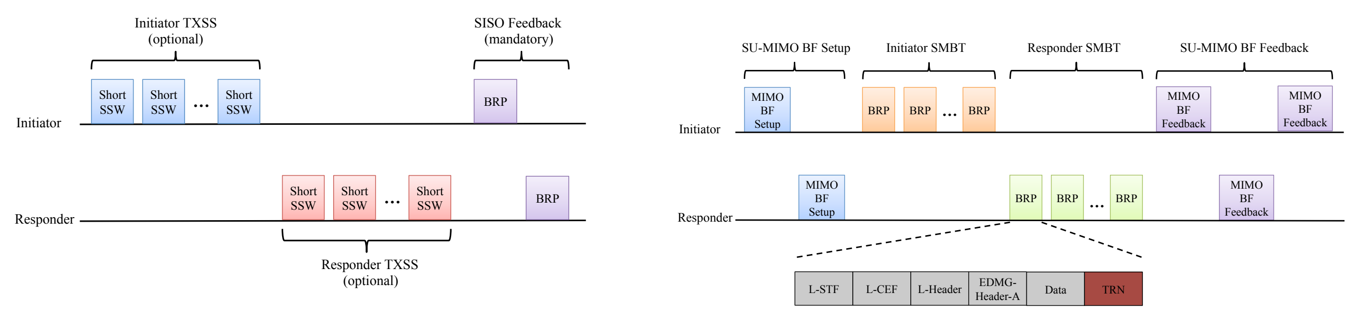

Figure 5: (a) The SISO phase of SU-MIMO beamforming, (b) The MIMO phase of SU-MIMO beamforming.

L should be set to the number of initiator's candidate transmit sectors multiplied by the number of responder's candidate receive sectors. Similarly, the responder performs the responder SMBT sub-phase by sending EDMG BRP-RX/TX packets to evaluate multiple transmit configurations of the responder and the receive configurations of the initiator.

Finally, two STAs exchange two or three (depending on the decision makers) *MIMO BF feedback* frames. If the initiator is the decision maker for the responder link (from responder to initiator), its MIMO BF feedback specifies N_R best transmit and receive combinations discovered on the prior responder SMBT sub-phase. Otherwise, the initiator includes the training feedback (from the responder SMBT) and lets the responder decide on the suitable antenna configurations. Similarly, the responder sends a MIMO BF feedback frame which either contains the N_I best transmit and receive sectors combinations or feedback of the initiator SMBT sub-phase. Additionally, if the responder is the decision maker for the responder link, the N_R best sector combinations are also included in this feedback frame. When the responder is the decision maker for the initiator link, the beamforming procedure terminates here since both STAs have already determined their antenna configuration for SU-MIMO operation. Otherwise, the initiator sends another MIMO BF feedback frame to announce the N_I best transmit and receive sector combinations. Note that the selection of the best sector combinations is implementation dependent; however, in general, only one transmit and one receive sector is selected per DMG antenna.

B. MU-MIMO Beamforming

MU-MIMO BF enables an initiator and a group of responders to determine appropriate antenna configurations for simultaneous transmission of multiple data streams with minimum inter-stream interference. Here, we describe the BF procedure for a given *multi-user (MU) group;* mechanisms of forming such a group are discussed in [6]. IEEE 802.11ay only supports downlink MU-MIMO transmission; hence, the initiator (AP/PCP) only trains the *transmit* antenna configurations per DMG antenna while the responders only train their *receive* antenna configurations. The MU-MIMO beamforming protocol is started and controlled by the initiator, which is always the decision maker. Fig.6 depicts the MU-MIMO BF procedure consisting of SISO and MIMO Phases.

1) SISO Phase

The SISO phase (Fig.6.a) starts with an optional initiator TXSS sub-phase and is followed by a mandatory Feedback sub-phase. As described in Section V-A, the initiator performs TXSS by sending short SSW packets from different transmit sectors of each of its DMG antennas. During this time, the stations in the MU Group use quasi-omni pattern and measure the link quality of each transmit sector. In the SISO Feedback sub-phase, the initiator polls every station in the MU group via sending a BRP frame. The polled STA responds with a list of sectors per each transmit DMG antenna and their corresponding quality indicators (e.g., measured SNR values).

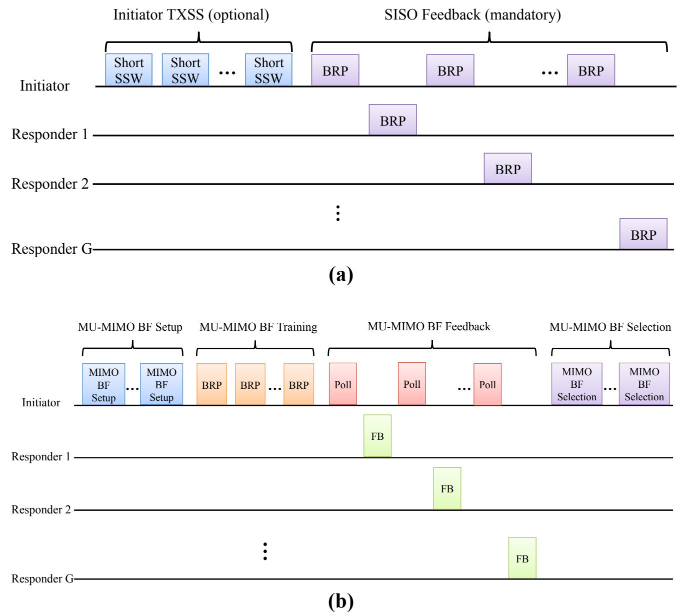

Figure 6: The MU-MIMO Beamforming (a) The SISO phase, (b) The MIMO phase.

2) MIMO Phase

The MIMO phase is depicted in Fig.6.b and is comprised of four consecutive sub-phases, MU-MIMO BF setup, MU-MIMO BF training, MU-MIMO BF feedback, and MU-MIMO BF selection sub-phase.

First, the initiator sends a *MIMO BF setup* frame to each intended responder. Based on the feedback provided by the SISO phase and to reduce training time, the initiator may select only a subset of STAs in the initial MU group. This frame specifies the selected responders, the transmit sectors for each DMG antenna that will be trained, and the order of transmission/training. The setup frame is transmitted to all intended responders employing their best known directional configuration; hence, the initiator may repeat its transmission several times to ensure reception by all intended responders.

Second, in the MU-MIMO BF training sub-phase, the initiator sends *BRP frames* similar to initiator SMBT sub-phase of SU-MIMO BF. To sweep antenna configurations throughout a frame, TRN fields are appended to the BRP frames. Next, the initiator polls each remaining intended responder for its BF feedback. The MIMO BF feedback transmitted by each responder contains the list of the initiator's transmit DMG antennas/sectors, each with its corresponding responder's receive DMG antenna/sector and the associated signal quality.

Finally, with the help of the obtained feedback, the initiator selects and announces a set of recipient STAs along with their antenna configurations. The set of selected STAs does not have to be the same as the initial MU group or the intended responders of the MU-MMO BF training sub-phase.

V. CONCLUSION AND FUTURE DIRECTIONS

In this article, we presented highlights of the IEEE 802.11ay standard, which provides 100 Gbps Wi-Fi communications in unlicensed mm-Wave bands and enables new applications such as augmented reality, virtual reality, and wireless backhauling. We described the new PHY and MAC specifications that built upon IEEE 802.11ad. The main design elements of IEEE 802.11ay include MIMO, channel bonding, improved channel access, and enhanced beamforming training.

Lastly, these IEEE 802.11ay advances provide opportunities for new research topics including *(i)* design and experimental analysis of MIMO policies under different LoS and Non-LoS conditions, different antenna directivities, and with single-polarized or dual-polarized transmissions; *(ii)* design and implementation of adaptive dual-polarized arrays [7]; and *(iii)* design of low-power and low-complexity MIMO architectures for millimeter-wave that allow for flexible analog and digital beamforming and advanced signal processing techniques [8].

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