Beamforming Training for IEEE 802.11ay Millimeter Wave Systems

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***Abstract*—IEEE 802.11ay is a standard that enables enhanced throughput for IEEE 802.11 systems operating in the license-exempt 60 GHz band. By specifying advanced physical layer (PHY) features, improved channel access, and enhanced beamforming training, IEEE 802.11ay supports a maximum data rate of 100 Gb/s, making it a standard of great interest for applications as diverse as virtual reality, high density/throughput networking, and backhaul. In this paper, we provide a description and discussion of two important beamforming training procedures defined in IEEE 802.11ay, namely beam refinement protocol (BRP) transmit sector sweep (TXSS) and asymmetric beamforming training. Because these procedures build upon concepts defined in IEEE 802.11ad, we also examine two legacy beamforming training procedures: Sector-level sweep (SLS) and BRP. PHY definitions relevant to beamforming training are also reviewed.**

I. Introduction

When ratified in 2012, IEEE 802.11ad broke new ground and became the first IEEE 802.11 amendment to support multi-Gbps throughput by using license-exempt spectrum available in the millimeter wave (mmWave) band [1], [2]. Because signals in the mmWave band experience much higher pathloss than those in the microwave band, to keep power consumption at a practical level, mmWave communication systems must rely on *directional* channel access. As a result, the PHY and medium access control (MAC) layers defined in IEEE 802.11ad include significant differences to those defined for sub-6 GHz spectrum. As discussed in [3], for example, IEEE 802.11ad includes changes to the beacon interval structure, defines a hybrid MAC approach, and specifies various beamforming training protocols.

While most current wireless applications can be met with existing technologies, new applications and continued usage growth demand greater throughput and lower latency than what current technologies can offer, including IEEE 802.11ad. Such applications include wireless virtual reality, high density and/or throughput networking, vehicle-to-x connectivity, and backhaul. To meet the requirements of such applications, the IEEE 802.11 Task Group ay was formed in 2015 to define PHY and MAC amendments to the 802.11 standard that enable 100 Gb/s communications in the 60 GHz band [4], [5].

Compared to IEEE 802.11ad, IEEE 802.11ay, which had its first draft approved in November 2017 [4], supports channel bonding, channel aggregation, single-user and downlink multi-user MIMO transmissions, an OFDM PHY, and new modulation and coding schemes (MCSs) for the single-carrier PHY. In addition, various enhancements were made to channel access and beamforming training. For an overview of IEEE 802.11ay, the reader is referred to [5].

In this paper, we provide a description and discussion of two important beamforming training procedures defined in IEEE 802.11ay, namely BRP TXSS and asymmetric beamforming training. To this end, we first provide a summary of new beamforming training-related definitions found in IEEE 802.11ay [4] in Section II, and then review PHY definitions relevant to beamforming training in Section III. In Section IV, we examine two legacy beamforming training procedures: SLS and BRP. BRP TXSS is considered in Section V, and asymmetric beamforming training is examined in Section VI. Conclusions are drawn in Section VII.

II. IEEE 802.11ay Beamforming Training

Building upon IEEE 802.11ad [1], IEEE 802.11ay contains various enhancements and new concepts that both improve beamforming training and also extend it to support new applications and transmission modes. While the focus of this paper is on BRP TXSS and asymmetric beamforming training, it is worth listing other beamforming training-related advancements made in IEEE 802.11ay [4]:

- *First path beamforming training* is defined to support positioning-related applications. Also, *partial SLS* is defined to support applications that require low latency by enabling fast link recovery after a failure.
- *Group beamforming* is specified to reduce overhead by enabling the training of multiple stations simultaneously.
- Required training necessary to support single-user and downlink multi-user *MIMO* transmissions are defined.
- To allow simultaneous transmit and receive beamforming training, a new BRP packet termed *EDMG BRP-RX/TX packet* is specified.
- Definition of a new *EDMG Channel Measurement Feedback element* that supports feedback of multiple antenna pairs. Also, the feedback of certain training procedures was extended to include more than one measurement.
- To reduce beamforming training overhead and implementation complexity, the standard specifies *short SSW packets*, a *BRP frame* variant, and the concept of *delayed BRP feedback*.

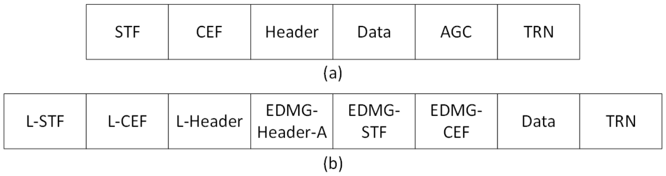

Fig. 1. (a) DMG packet format and (b) EDMG packet format.

III. Fundamental PHY Concepts

The packet formats defined in IEEE 802.11ad [2] and in IEEE 802.11ay [4] for single-user transmission, which are referred to as *directional multi-gigabit* (DMG) PLCP protocol data unit (PPDU) and *enhanced DMG* (EDMG) PPDU[1], respectively, are shown in Fig. 1.

In a DMG packet, the short training field (STF) enables detection of the packet, as well as gain control and acquisition of carrier frequency and timing. As implied by its name, the channel estimation field (CEF) is used for channel estimation. The header carries information required to demodulate the packet, such as the MCS used, the data field consists of the payload data and possible padding, and the automatic gain control (AGC) enables the receiver to re-adjust its AGC setting before processing the training (TRN) field. The definition and use of the TRN field are detailed in Section IV.B.

To ensure coexistence with DMG stations, the first portion of an EDMG packet can be detected by DMG stations. Specifically, the L-STF, L-CEF, and L-Header have the same definitions and use as the STF, CEF, and header fields of DMG packets, respectively. The second portion of an EDMG PPDU is only recognized by EDMG stations. The EDMG-Header-A field carries information required to interpret the packet, including bandwidth 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, channel aggregation, and/or MIMO are utilized. A more detailed description and analysis of the IEEE 802.11ay PHY can be found in [6].

Not all fields shown in Fig. 1 are necessarily present in a transmitted DMG or EDMG packet. For instance, the TRN field is only present in certain packets transmitted as part of a beamforming training or tracking procedure [1], [4].

Beamforming training is used by stations to determine antenna settings of their one or more *DMG antennas* and dynamically adapt to current channel conditions. A DMG antenna is defined as "a phased array, a single element antenna, or a set of switched beam antennas covered by a quasi-omni antenna pattern" [1]. The vector of complex weights that describe the excitation (amplitude and/or phase) of each element of a DMG antenna is referred to as an *antenna weight vector (AWV)* [1]. Therefore, the beamforming training procedures described in Sections IV-VI, together with others defined in [1] and [4], enable DMG and EDMG stations to determine AWVs for their DMG antennas.

[1]Loosely speaking, the modifiers DMG and EDMG refer to definitions and concepts specified in IEEE 802.11ad and IEEE 802.11ay, respectively.

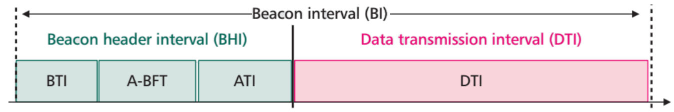

Fig. 2. Beacon interval [1], [3].

IV. Legacy Beamforming Training Procedures

SLS and BRP are two important beamforming training procedures defined in [1] and the basis of the EDMG procedures discussed in Sections V and VI. Because SLS and BRP may be performed in distinct scenarios (specifically, while the former enables two stations to establish a link, the latter requires the stations to already have a link established), it can be stated that the procedures are, to an extent, complementary.

A. SLS

Consider the following scenario: A DMG or EDMG station is turned on and searches for a PBSS control point (PCP)/access point (AP) [2] in its vicinity. In addition to not knowing if there are PCP/APs in its vicinity, the station also does not know the AWVs it should use to establish a link with a given PCP/AP. Likewise, PCP/APs also do not know what AWVs should be used to establish a link with the unassociated station. As a result, the station will begin to search for beacon frames transmitted by one or more PCP/APs, by detecting their STF or L-STF field and locking to the packet, while using a *quasi-omni antenna pattern* [1].

As discussed in the Introduction, mmWave links typically only close if beamforming gain is used to offset the higher attenuation of the band. Therefore, if PCP/APs transmitted beacon frames using a quasi-omni antenna pattern, the association process would likely fail. The solution to this problem requires two new definitions. First, it is defined in [1] that in a certain period of the beacon interval known as beacon transmission interval (BTI) [3], shown in Fig. 2, a PCP/AP must perform a *TXSS* using beacon frames. A TXSS consists of the transmission of a sequence of packets, with each of them using a different AWV, in such a way that the transmissions include all directions (that is, *sectors*) of coverage of the PCP/AP. The procedure is illustrated in Fig. 3.

In Fig. 3, a PCP/AP transmits 16 packets in as many sectors during the BTI. In the meanwhile, the station continuously tries to detect a packet, and when it is able to lock to a beacon frame, it decodes its header and data field. The information contained in the payload enables the station to associate to the PCP/AP in the association beamforming training (A-BFT) interval. In the A-BFT, as discussed in Section VI, the station feedback to the PCP/AP the packet it was able to successfully decode (by using the *sector ID* field transmitted within the frame), allowing the PCP/AP to determine its transmit AWV.

It is important to note that in the procedure previously described, it was implicitly assumed that the link between the PCP/AP and the station closes with the beamforming gain of the PCP/AP only (since the station uses a quasi-omni antenna pattern). However, depending on the link range, this

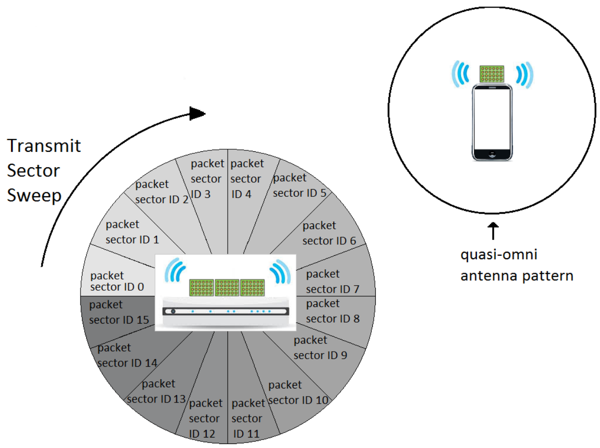

Fig. 3. Transmit sector sweep (TXSS).

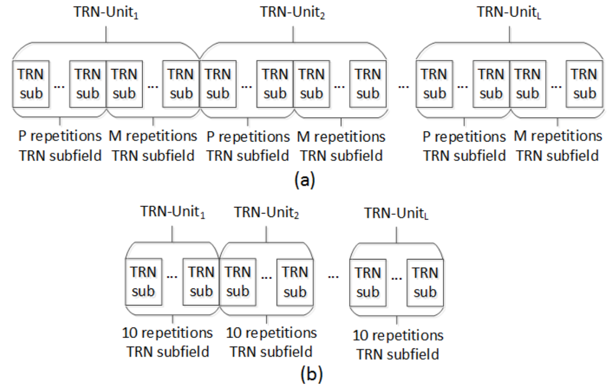

Fig. 4. Simplified representation of the TRN field of EDMG packets for (a) transmit and (b) receive beamforming training [4], [5], [7].

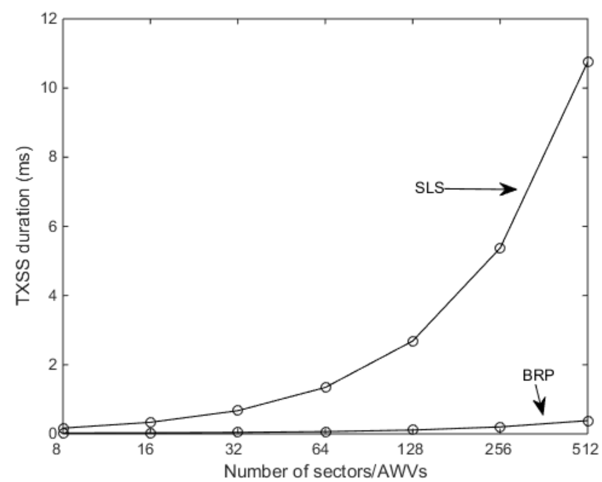

Fig. 5. Time duration of a TXSS when using SSW and BRP frames. Control mode, each packet has 40 octets of data, no antenna switch.

may not be true. To address this problem, a second concept was introduced in [1]: *Control mode*. The control mode is a transmission mode that consists of single-carrier differential BPSK modulation with a spreading factor of 32, thus offering a processing gain of approximately 15 dB. The link range obtained with the beamforming gain of the PCP/AP together with the processing gain of the control mode is sufficient to enable the association process in most cases. This matter is further discussed in Section VI.

SLS may be performed outside the BTI and the association procedure, and by using frames other than beacon frames. For example, a station may perform SLS in the data transfer interval (DTI) using sector sweep (SSW) frames. The number of sectors used in an SLS in the BTI and DTI may be different. An SLS performed in the DTI may consist of a larger number of sectors than the one used in the BTI to allow for finer beamforming training.

As defined in [1] and [4], a device performing TXSS may transmit packets with different DMG antennas. The corresponding receive beamforming training procedure of *receive sector sweep* (RXSS) is also defined in [1] and [3].

B. BRP

The goal of SLS is to determine antenna settings that enable two devices to communicate at the control mode rate or higher. Once two devices have a link established, they may *optimize* their antenna settings through the use of BRP. As opposed to SLS, BRP does not rely on predefined sector patterns.

BRP makes use of the TRN field. A simplified representation of the TRN field of EDMG packets is shown in Fig. 4. The TRN field consists of multiple repetitions of a basic sequence known as TRN subfield (denoted by “TRN sub” in the figure), which is formed by the concatenation of Golay sequences [4].

The TRN field is logically divided into TRN-Units. When the packet is used for *transmit training*, as shown in Fig. 4.a, each TRN-Unit consists of $P+M$ TRN subfields. In this case, within a TRN-Unit, the first P TRN subfields are transmitted with the same AWV as the other PPDU fields and thus may be used to maintain synchronization, for example. In the transmission of the other M TRN subfields, the station may change AWVs. This process allows a station to “try” different AWVs for a fixed receive AWV setting of its peer station.

When the packet is used for *receive training*, as shown in Fig. 4.b, each TRN-Unit consists of 10 TRN subfields. In this case, all TRN subfields that compose the TRN field are transmitted with the same AWV as the other PPDU fields. This provides a fixed frame of reference for the peer station to determine an improved receive AWV setting.

In addition to having a smaller overhead than SLS, as discussed next, by allowing multiple measurements to be made using the same packet, BRP enables *coherent* (transmit and/or receive) measurements to be obtained. This fact may lead to significant performance improvement compared to SLS-based training, and is a key characteristic of BRP.

C. Overhead of SLS and BRP

While a packet transmitted in an SLS allows for the training of a single sector, packets used in a BRP allow for the training of multiple transmit AWVs per packet. Thus, the time required for training the same number of sectors/AWVs using SLS may be significantly larger than when using BRP. This behavior is shown in Fig. 5 using IEEE 802.11ad numerology.

V. BRP TXSS

There are different cases where it is desirable for stations that already have a link established to perform a new TXSS. The procedure could be performed again, for example, when stations change the bandwidth of their transmissions. However, as previously discussed, the overhead of SLS may be quite large depending on the number of sectors used. For this reason, a new beamforming procedure known as *BRP TXSS* was adopted by [4] that enables stations to efficiently perform TXSS using BRP packets [8][2].

Let us consider an example to understand the operation and outcome of a BRP TXSS. In this case, both the station that requests the BRP TXSS (*initiator*) and its peer (*responder*) have *strong reciprocity*; that is, for each station, "the transmit antenna pattern associated with an AWV is the same as the receive antenna pattern for the same AWV" [1]. Also, both stations have multiple DMG antennas but only one RF chain. The initiator and responder have 3 and 2 DMG antennas, respectively. The BRP TXSS for this case is shown in Fig. 6.

After exchanging frames with setup information, the initiator sends six EDMG BRP packets for transmit training (denoted by EDMG BRP-TX packet). All fields except for the TRN field of each EDMG BRP-TX packet are transmitted with the same DMG antenna and AWV used in the setup phase. At the beginning of the TRN field, the transmitter may switch DMG antennas to train a different DMG antenna. Similarly, all fields except for the TRN field of each packet are received with the same DMG antenna and AWV used in the setup phase. At the beginning of the TRN field, the receiver may switch DMG antennas. The TRN field of each packet in this case is received with a quasi-omni antenna pattern.

The TRN field of the first three EDMG BRP-TX packets are transmitted with DMG antennas 1, 2, and 3, and are received with the responder's first DMG antenna. This allows the initiator to perform TXSS with all of its DMG antennas for the responder's first DMG antenna. The initiator then repeats the transmission of the three EDMG BRP-TX packets for the responder's second DMG antenna, thus training the responder's second DMG antenna.

The responder then sends feedback to the initiator, which contains the best transmit configuration (AWV and DMG antenna) used by the initiator, denoted by AWV_init and ANT_init. As indicated in the figure, the responder also has knowledge of the best receive DMG antenna, denoted by ANT_resp, when the initiator uses AWV_init and ANT_init. However, the responder does not know the AWV it should use. For this reason, the initiator sends an EDMG BRP packet for *receive* training (denoted by EDMG BRP-RX packet) using AWV_init and ANT_init in the transmission of its TRN field.

At the end of the procedure, the initiator knows its best transmit configuration and the responder its best receive

[2]It should be noted that BRP as defined in [1] enables a station to perform TXSS with a single DMG antenna. The contribution of [8] is to define a complete procedure that allows stations to perform TXSS with more than one DMG antenna, and that also includes the necessary receive training so that stations may change their AWVs at the end of the procedure.

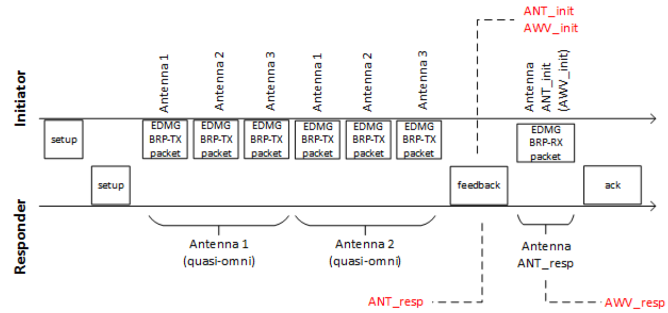

Fig. 6. Example of BRP TXSS: Strong reciprocity.

configuration. However, given that both stations have strong reciprocity, the best transmit and best receive configurations (AWV and DMG antenna) are the same. If a station does not have strong reciprocity, its best transmit and receive settings could be different. The BRP TXSS for the case when both the initiator and the responder do not have reciprocity is shown in Fig. 7. Compared to the procedure shown in Fig. 6, the BRP TXSS in this new case is noticeably longer because transmit and receive settings must be determined separately.

The first part of the procedure in Fig. 7 (transmission of EDMG BRP-TX packets, feedback, and transmission of an EDMG BRP-RX packet) is identical to the procedure shown in Fig. 6. However, the outcome is different. Since the stations are now assumed to not have reciprocity, the configuration determined for the initiator is only valid for transmission (AWV_TX_init and ANT_TX_init), and not for reception. Similarly, the configuration determined for the responder is only valid for reception (AWV_RX_resp and ANT_RX_resp).

To allow the initiator to determine its receive configuration (AWV_RX_init and ANT_RX_init) and the responder its transmit configuration (AWV_TX_resp and ANT_TX_resp), the responder sends six EDMG BRP-TX packets. The TRN field of the first two EDMG BRP-TX packets are transmitted with DMG antennas 1 and 2, respectively, and are received with the initiator's first DMG antenna. The responder then repeats the transmission of the two EDMG BRP-TX packets two more times to allow the initiator to train its other two DMG antennas. After feedback is sent by the initiator, the responder sends an EDMG BRP-RX packet to allow the responder to determine AWV_RX_init.

In addition to strong reciprocity and no reciprocity, DMG and EDMG stations may also have *weak reciprocity* ("best transmit DMG antenna of the STA is the same as the best receive DMG antenna of the STA" [1]). BRP TXSS procedures for all possible reciprocity level combinations can be found in [4]. The reciprocity level of the stations performing the BRP TXSS define the complete flow of the procedure, including the total number of packets transmitted. Therefore, as shown in Fig. 8, the duration of the procedure is a function of the reciprocity characteristics of the stations, as well as of their number of DMG antennas.

An extension of BRP TXSS for the case when stations have more than one RF chain is also given in [4].

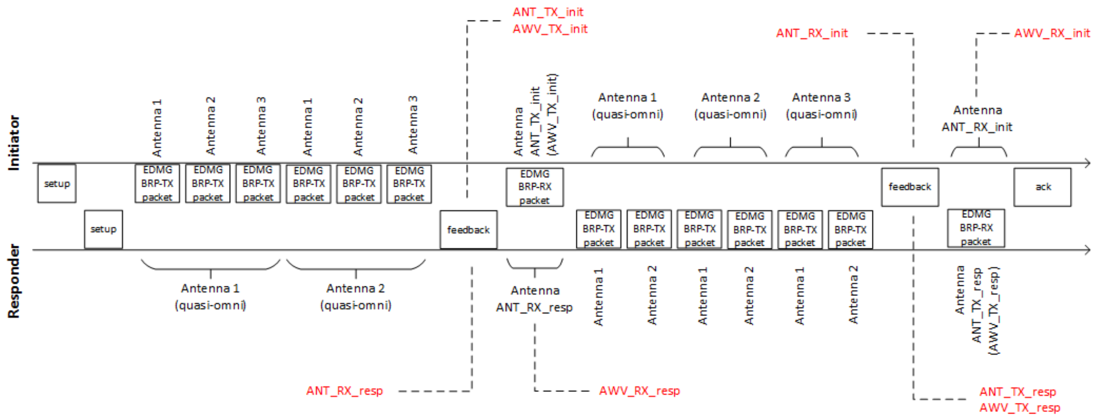

Fig. 7. Example of BRP TXSS: No reciprocity.

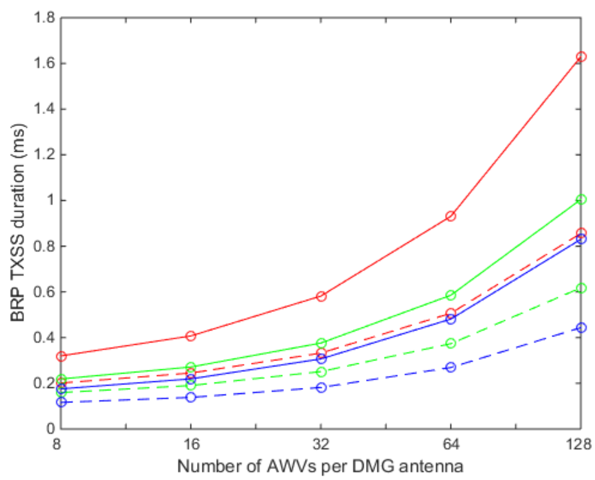

Fig. 8. Time duration of a BRP TXSS when the stations have no reciprocity (red), weak reciprocity (green), or strong reciprocity (blue). Solid lines: Each station has 3 DMG antennas. Dashed line: Each station has 2 DMG antennas.

VI. Asymmetric Beamforming Training

A. Motivation

As described in Section IV.A, after detecting one or more beacon frames sent by a PCP/AP during the BTI, a station continues the association process by attempting to reach the PCP/AP during the A-BFT.

As discussed in detail in [3], to allow multiple stations to attempt to reach the PCP/AP without coordination, the A-BFT is a contention-based period. Specifically, as illustrated in Fig. 9, the A-BFT consists of multiple *A-BFT slots*. Stations select an A-BFT slot to transmit randomly, and contending stations may interfere if the same A-BFT slot is selected. Each A-BFT slot consists of a fixed time allocation that allows stations to perform TXSS, as well as time for the PCP/AP to send feedback to a station that successfully reached it. The feedback sent by the PCP/AP contains the "best" transmit sector(s) used by the station.

The procedure used in the A-BFT relies on an assumption similar to the one made in the BTI procedure: It is assumed that the link between the PCP/AP and the station closes with the beamforming gain of the *station* and the use of the control

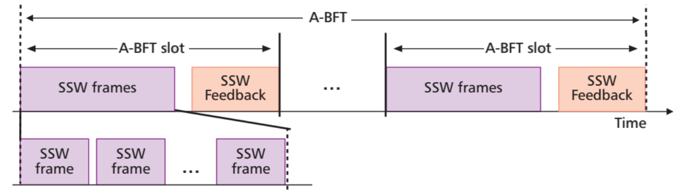

Fig. 9. Association beamforming training [1], [3].

mode. However, it is reasonable to expect that antenna arrays used by PCP/APs have more elements than the ones used by stations. Thus, the beamforming gain of PCP/APs may be many dBs larger than the one of stations. In this case, a station that detects a beacon frame sent by the PCP/AP *in directional mode* may have insufficient link budget to send a response that can be detected by the PCP/AP *in quasi-omni mode*. This issue is commonly referred to as *asymmetric links*.

As a result, the effective range of the system could be limited by the beamforming gain of stations. According to the analysis given in [9], the system range in this case may be fairly short in practical scenarios (about 30 meters); however, it could be increased by a wide margin with the use of the *asymmetric beamforming training* procedure described next (to about 270 meters). The procedure requires changes to the beacon frame and the definition of a new beamforming training allocation in the DTI [4], [9], [10].

B. Beacon frame

The asymmetric links problem previously described can be solved in part by removing a restriction existent in [1] and allowing beacon frames to have a TRN field, which enables stations to perform *receive* training while the PCP/AP performs *TXSS* in the BTI. This is illustrated in Fig. 10.

For stations that have strong reciprocity, the AWV found through this procedure is also valid for transmission. Therefore, instead of performing a TXSS in the A-BFT, the station could instead transmit with the determined AWV. Because the beamforming gain obtained with the use of an AWV found with a BRP may be larger than the one obtained with a TXSS (since BRP does not rely on predefined sector patterns), the range of a station in the A-BFT may thus increase. The

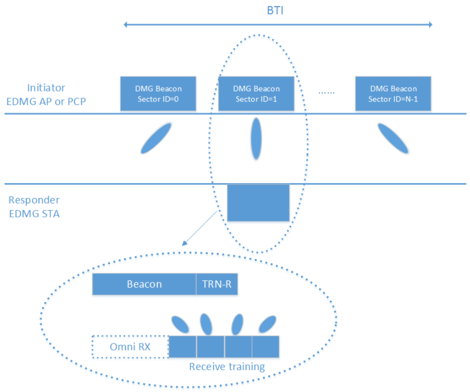

Fig. 10. Asymmetric beamforming training, BTI.

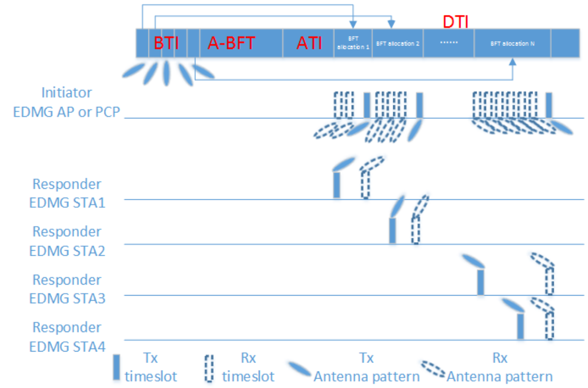

Fig. 11. Beamforming training allocation.

possible gain obtained, however, may still not be enough to close the link depending on the difference of beamforming gains between the PCP/AP and the station.

C. Beamforming training allocation

In order for the beamforming gain of the PCP/AP be used when stations are attempting to reach it during association, the PCP/AP must *receive* the station's transmission using a *directional* antenna pattern. For this reason, as shown in Fig. 11, IEEE 802.11ay specified a new beamforming training allocation in the DTI that is as follows:

- A beacon frame transmitted in the BTI includes an EDMG Extended Scheduled element that defines a *beamforming training allocation* in the DTI when the PCP/AP will be in receive mode using a directional antenna pattern. The receive antenna pattern used in the allocation is the one associated with the transmit antenna pattern used in the transmission of the frame that defined the allocation (that is, the PCP/AP will receive in the same direction of transmission of the beacon frame).
- If a station fails to associate with the PCP/AP during the A-BFT, whether due to asymmetric links, to a packet collision, or for any other reason, it may attempt to reach the PCP/AP during the beamforming training allocation.
- Packets sent by a station in a beamforming training allocation are transmitted with the AWV determined by processing the TRN field attached to the beacon frame that specified the allocation, as described in Section VI.B.
- Similar to the A-BFT, to allow multiple stations to attempt to reach the PCP/AP without coordination, the beamforming training allocation is a contention-based period with a random access scheme.
- At the end of each beamforming training allocation, the PCP/AP transmits a packet with the same antenna pattern used for directional reception to acknowledge packets that were successfully decoded. With this step, the association between the PCP/AP and the STA is established.

As a final comment on asymmetric beamforming training, it is worth mentioning that its use was considered in [11] to enable the use of IEEE 802.11ay-based small cells as part of LTE-based heterogeneous networks.

VII. Conclusions

Building upon IEEE 802.11ad, IEEE 802.11ay specifies advanced PHY features, improved channel access, and enhanced beamforming training. In this paper, we provided a description and discussion of two new EDMG beamforming training procedures: BRP TXSS and asymmetric beamforming training. We showed that BRP TXSS is a very efficient procedure to perform TXSS, allowing stations to determine improved antenna configuration for transmission and reception with reduced overhead. We also showed that asymmetric beamforming training can notably increase the range of EDMG systems, as well as reducing failures in the association process. A more general description of IEEE 802.11ay can be found in [5], and an analysis of the EDMG single-carrier PHY in [6].

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