IEEE 802.11ad: Directional 60 GHz Communication for Multi-Gigabit-per-Second Wi-Fi

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ABSTRACT

With the ratification of the IEEE 802.11ad amendment to the 802.11 standard in December 2012, a major step has been taken to bring consumer wireless communication to the millimeter wave band. However, multi-gigabit-per-second throughput and small interference footprint come at the price of adverse signal propagation characteristics, and require a fundamental rethinking of Wi-Fi communication principles. This article describes the design assumptions taken into consideration for the IEEE 802.11ad standard and the novel techniques defined to overcome the challenges of mm-Wave communication. In particular, we study the transition from omnidirectional to highly directional communication and its impact on the design of IEEE 802.11ad.

INTRODUCTION

With the worldwide availability of a large swath of spectrum at the 60 GHz band for unlicensed use, we are starting to see an emergence of new technologies enabling Wi-Fi communication in this frequency band. However, signal propagation at the 60 GHz band significantly differs from that at the 2.4 and 5 GHz bands. Therefore, efficient use of this vast spectrum resource requires a fundamental rethinking of the operation of Wi-Fi and a transition from omnidirectional to directional wireless medium usage. The IEEE 802.11ad amendment addresses these challenges, bringing multi-gigabit-per-second throughput and new application scenarios to Wi-Fi users. These new uses include instant wireless synchronization, high-speed media file exchange between mobile devices without fixed network infrastructure, and wireless cable replacement (e.g., to connect to high definition wireless displays).

The most significant difference in 60 GHz propagation behavior is increased signal attenuation. At a typical IEEE 802.11ad range of 10 m, additional attenuation of 22 dB compared to the 5 GHz band is predicted by the Friis transmission equation, resulting from the frequency-dependent difference in antenna aperture. In contrast, oxygen absorption plays a minor role over short-range distances, even though it peaks at 60 GHz [1]. Furthermore, 60 GHz communication is characterized by a quasi-optical propagation behavior [2] where the received signal is dominated by the line of sight (LOS) path and first order reflections from strong reflecting materials. As an example, metallic surfaces were found to be strong reflectors and allow non-LOS (NLOS) communication [2]. Concrete materials, on the other hand, cause additional large signal attenuation and can easily create a blockage. Thus, 60 GHz communication is more suitable to in-room environments where sufficient reflectors are present.

This article discusses the design assumption resulting from the millimeter-wave (mm-Wave) propagation characteristics and related adaptation to the 802.11 architecture. We further present typical device configurations, an overview of the IEEE 802.11ad physical (PHY) layer, and the newly introduced personal basic service set network architecture. This is followed by an in-depth description of the IEEE 802.11ad beamforming (BF) mechanism and hybrid medium access control (MAC) design, which are the central elements to facilitate directional communication.

DIRECTIONAL COMMUNICATION

The IEEE 802.11ad amendment to the 802.11 standard defines a directional communication scheme that takes advantage of beamforming antenna gain to cope with increased attenuation in the 60 GHz band [1]. With quasi-optical propagation behavior, low reflectivity, and high attenuation, beamforming results in a highly directional signal focus. Based on this behavior, the standard introduces a novel concept of "virtual" antenna sectors [3] that discretize the antenna azimuth. IEEE 802.11ad sectors can be implemented either using precomputed antenna weight vectors for a phased antenna array [4] or equipping a system with multiple directional antenna elements. In both cases, the wavelength in the millimeter range allows antenna form fac-

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Device	Antenna sectors	Expected range (m)	Expected maximum throughput (Gb/s)	Traffic type	Antenna arrays
AP, docking station	32 to 64	20	7	Bursty traffic on downlink	≤3
Wireless peripheral (hard drive, memory stick)	≤ 4	0.5 to 2	4.6	Bursty	1
Wireless display, TV	32 to 64	5 to 10	7	Continuous, RX more important	≤2
Notebook	16 to 32	5 to 10	4.6 to 7	Various, symmetric TX and RX	≤2
Tablets	2 to 16	2 to 5	4.6	Various, symmetric TX and RX	1
Smartphone, handheld, camcorder, camera	≤ 4	0.5 to 2	1.2 to 4.6	Various, symmetric TX and RX, TX more important for video streaming devices	1

Table 1. Typical device configurations.

tors significantly smaller than those of legacy Wi-Fi at 2.4/5 GHz.

A sector focuses antenna gain in a certain direction. Communicating nodes thus have to agree on the optimal pair of receive and transmit sectors to optimize signal quality and throughput. This process, referred to as beamforming training, takes advantage of the discretized antenna azimuth that reduces the search space of possible antenna array configurations. After a first sector matching, a second beam training stage allows further refinement of the found sectors. During this stage, antenna weight vectors that vary from predefined sector patterns can be evaluated to further optimize transmissions on phased antenna arrays. While in general higher antenna gain is desirable, it imposes stronger directionality and a higher number of narrow antenna sectors. This increases coordination overhead to adapt the antenna steering between communicating nodes, and it has been shown that link budget loss by misalignment increases with directionality [5].

Figure 1 shows an example for two nodes communicating over virtual IEEE 802.11ad sectors. The highlighted selection of sectors that matches the LOS direction may offer the optimum link quality in the absence of blocking obstacles.

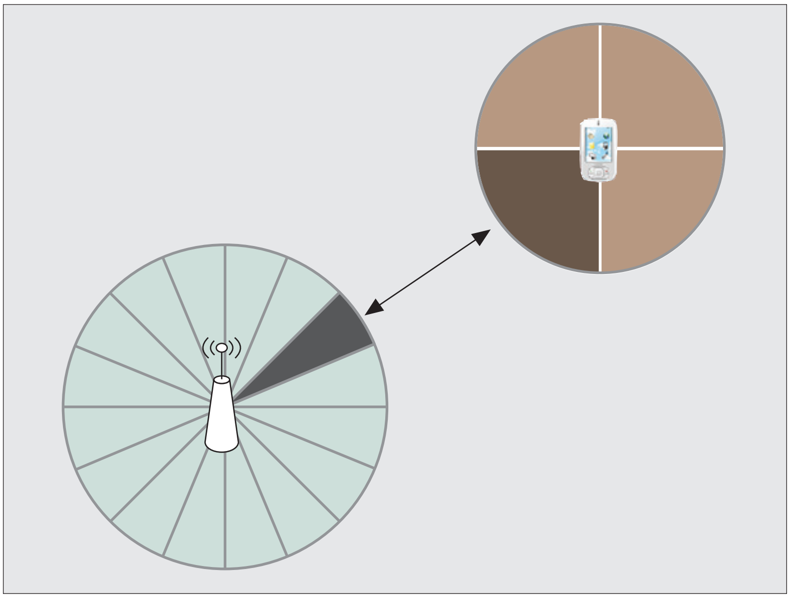

Figure 1. Virtual antenna sectors.

IEEE 802.11AD DEVICE CLASSES AND USE CASES

Communication in the mm-Wave band enables extremely high throughput at short-ranges (< 10 m), with high potential for spatial reuse. Thus, not only does it suit typical Wi-Fi usage, it also expands the uses of Wi-Fi to other application areas. Among these areas are wireless transmissions of high definition video, wireless docking stations, connection to wireless peripherals, or high-speed download of large media files.

To meet the requirements for these novel use cases, the IEEE 802.11ad standard allows for a broad variety of directional multi-gigabit (DMG) devices ranging from energy constrained handheld equipment with low complexity antennas (1–4 antenna elements) to stationary access points with multiple antenna arrays and permanent power supply. Table 1 shows typical configurations for several device classes. It states the number of sectors that correlates with range and throughput, differences between receive and transmit direction, and special traffic characteristics for every class. Furthermore, the expected

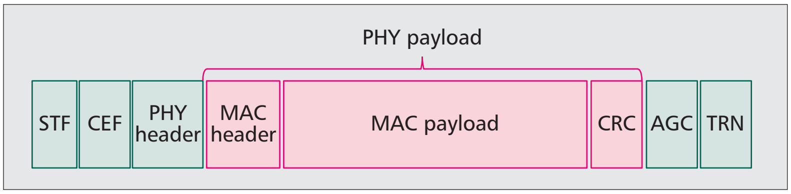

Figure 2. IEEE 802.11ad packet structure.

number of antenna arrays is given for every device class. Multiple phased antenna arrays enable high gain coverage in all directions. They are not used in a multiple-input multiple-output (MIMO) fashion, but treated like a set of additional sectors with only one antenna array used at a time.

IEEE 802.11AD DESIGN ASSUMPTIONS

Communication in the mm-Wave frequency band has different characteristics than legacy 2.4/5 GHz Wi-Fi frequencies. Thus, the development of the IEEE 802.11ad amendment followed a number of design assumptions that result from the change of frequency band.

Highly directional transmissions: Increased transmission loss and the application of high gain beamforming techniques lead to a strong directional signal focus. In contrast to omnidirectional legacy Wi-Fi signal propagation, IEEE 802.11ad communicates over narrow beams that follow quasi-optical propagation characteristics.

Quasi-omnidirectional antenna patterns: Implementation of truly omnidirectional mm-Wave antenna patterns is not practical, as signal blockage and deviation by device components in the vicinity of the antenna have a much stronger effect than on legacy Wi-Fi frequencies. Therefore, IEEE 802.11ad introduces quasi-omnidirectional patterns that allow gain fluctuations over the pattern. Further measures are taken to cope with the resulting inaccuracies.

Inefficient omnidirectional communication: The increased attenuation in the mm-Wave band leads to severely reduced transmission range and throughput when quasi-omnidirectional antenna patterns are used. However, when the direction to a communication partner is unknown (e.g., during beamforming training), quasi-omni patterns are still needed. Thus, directional antenna gain is added at least at one side of a link to achieve a sufficient communication range. Typically, quasi-omnidirectional antenna configurations are used at the receiver side. Only devices with extreme space or energy restrictions are expected to implement quasi-omnidirectional transmit modes. These devices will be severely limited in range and throughput (Table 1).

Extreme efficiency loss on poorly trained beams: The throughput difference between the highest and lowest transmission scheme defined by IEEE 802.11ad lies in the range of 6.5 Gb/s. A poorly trained beam that uses a low-throughput scheme severely reduces the system performance and should be avoided at all costs.

Reduced interference footprint: Highly directional transmission properties of IEEE 802.11ad devices strongly reduce interference outside of the beam direction. This allows spatial reuse of the same frequency band and can significantly increase the system's overall throughput.

Deafness and directional communication drawbacks: Highly directional IEEE 802.11ad transmissions have hindering effects on common Wi-Fi MAC mechanisms. Directional transmit patterns prevent devices from passively overhearing ongoing transmissions, leading to additional collisions during channel access. Furthermore, the deafness effect caused by misaligned transmit or receive antenna patterns may lead to frame loss, unnecessary long contention backoff, and lower throughput. An in-depth discussion of these impairments can be found in [6]. IEEE 802.11ad adapts the 802.11 carrier sense multiple access with collision avoidance (CSMA/CA) mechanism and further introduces a multi-MAC architecture, with alternative medium access schemes suited to directional communication.

IEEE 802.11AD PHYSICAL LAYER

IEEE 802.11ad introduces three different PHY layers dedicated to different application scenarios. The *control PHY* is designed for low signalt-to-noise ratio (SNR) operation prior to beamforming. The *single carrier (SC)* PHY enables power-efficient and low-complexity transceiver implementation. The low-power SC PHY option replaces the low-density parity check (LDPC) encoder by a Reed-Solomon encoder for further processing power reduction. The orthogonal frequency-division multiplexing (*OFDM*) *PHY* provides high performance in frequency selective channels achieving the maximum 802.11ad data rates.

Despite having different PHYs, all of them share the same packet structure with common preamble properties. Specifically, the same Golay sequences are used for the preamble training fields. Also, a common rate 3/4 LDPC structure is used for channel encoding. Moreover, 802.11ad defines a single bandwidth of 2.16 GHz, which is 50 times wider than the channels available in 802.11n and roughly 14 times wider than the channels defined in 802.11ac.

The single IEEE 802.11ad packet structure is shown in Fig. 2. The packet consists of typical IEEE 802.11 elements, for example, a short training field (STF) and a channel estimation field (CEF) that is also used for auto-detection of the PHY type. They are followed by the PHY header and PHY payload, which is protected by a cyclic redundancy check (CRC). Finally, optional automatic gain control (AGC) and training (TRN) fields, unique to IEEE 802.11ad, might be appended. These are used for the beamforming mechanism described later.

To provide robust discovery and detection, the control PHY has a longer STF than the SC and OFDM PHYs, comprising 48 Golay sequences, each 128 samples long. The SC and OFDM PHY only use 17 Golay sequences for the STF. The channel estimation field that follows the STF has nine Golay sequences. The OFDM PHY uses a different combination of

Golay sequences in the CEF to distinguish between OFDM and SC modulation.

The control PHY defines modulation and coding scheme (MCS) 0. It implements a 32-sample Golay spreading sequence along with rate 1/2 LDPC encoding (spread from the common rate 3/4 LDPC code) to extend range and reliability for management frames, giving a throughput of 27.5 Mb/s. The control PHY uses π/2-differential binary phase shift keying (BPSK) modulation to further enhance robustness to distortion like phase noise. The mandatory control PHY defines the minimum rate all devices may use to communicate before establishing a high-rate beamformed link. It is used for transmitting and receiving frames such as beacons, information request and response, probe request and response, sector sweep, sector sweep feedback, and other management and control frames.

The SC PHY (MCS 1-12) and low-power SC PHY (MCS 25-31) allow for low-complexity and energy-efficient transceiver implementations with a throughput of up to 4.62 Gb/s. The lowest SC data rate is 385 Mb/s (MCS 1). It is implemented using BPSK modulation and rate 1/2 code with a symbol repetition of two. All modulation types use π/2 rotation to reduce the peak-to-average power ratio for BPSK and enable Gaussian minimum shift keying (GMSK) equivalent modulation. To provide interoperability between different device types, MCS 1–4 are mandatory for all devices. These four MCSs are all based on π/2-BPSK modulation. MCS 2, 3, and 4 use code rate 1/2, 5/8, and 3/4, respectively.

The OFDM PHY (MCS 13-24) is an optional mode for maximum throughput at the cost of a more complex and energy intensive transceiver structure. The OFDM PHY type utilizes 64-QAM and a rate 13/16 code to achieve the highest 802.11ad data rates of up to 6.75 Gb/s.

In order to keep transceiver complexity and energy consumption low, mobile and low-cost devices are likely to implement only SC PHYs. In contrast, stationary devices with fixed power supply and high throughput requirements (access points, wireless displays) implement the full spectrum of MCSs including complex OFDM transceivers.

IEEE 802.11AD Network Architecture

This section describes the changes to the IEEE 802.11 network architecture defined by IEEE 802.11ad. First, we describe the changes to the beacon interval (BI). Next, a novel network type called personal basic service set (PBSS) is introduced, followed by the description of the network and schedule announcement mechanisms.

Beacon Interval

IEEE 802.11 in lower frequency bands organizes the medium access through periodically recurring beacon intervals that are initiated by a single beacon frame transmitted omnidirectionally by the access point (AP) or coordinating station. The beacon announces the existence of a Wi-Fi network and carries further management data.

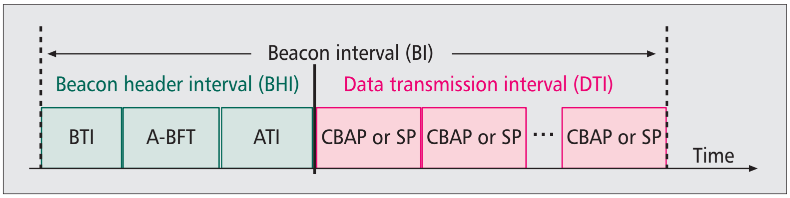

Figure 3. IEEE 802.11ad beacon interval structure.

The rest of the BI is used for data transmissions between stations, usually following a contention-based access scheme. The length of a BI is limited to 1000 ms, but typically chosen in the range of 100 ms. While longer BI durations increase the connection delay for nodes waiting for the beacon, a longer interval reduces management frame transmission and increases throughput.

The IEEE 802.11ad amendment to the IEEE 802.11 standard extends this concept in several ways to cope with the challenges of mm-Wave propagation. First, a BI is initiated with the *beacon header interval* (BHI), which replaces the single beacon frame of legacy Wi-Fi networks. The BHI facilitates the exchange of management information and network announcements using a sweep of multiple directionally transmitted frames. The BHI sweeping mechanism overcomes increased attenuation and unknown direction of unassociated devices. Additional functionality of the BHI is described later on. The BHI is followed by a *data transmission interval* (DTI), which can implement different types of medium access. The schedule and medium access parameters, which are necessary for stations to participate in a BI, are announced by the central network coordinator, the PBSS control point (PCP) or AP, during the BHI. This ensures that stations receive this information even though no efficient broadcasting mechanism is available.

A typical BI, consisting of BHI and DTI, is shown in Fig. 3. The BHI consists of up to three sub-intervals. First, the *beacon transmission interval* (BTI) comprises multiple beacon frames, each transmitted by the PCP/AP on a different sector to cover all possible directions. This interval is used for network announcement and beamforming training of the PCP/AP's antenna sectors. Second, the *association beamforming training* (A-BFT) is used by stations to train their antenna sector for communication with the PCP/AP. Third, during the *announcement transmission interval* (ATI), the PCP/AP exchanges management information with associated and beam-trained stations. While communication during BTI and A-BFT uses MCS 0 to increase range for untrained beams, communication during the ATI takes place with beam-trained stations and thus is more efficient.

The DTI comprises one or more *contention-based access periods* (CBAPs) and scheduled *service periods* (SPs) where stations exchange data frames. While in CBAP multiple stations can contend for the channel according to the IEEE 802.11 enhanced distributed coordination function (EDCF), an SP is assigned for communication between a dedicated pair of nodes as a contention-free period.

Dynamic channel time allocation is an extension of the IEEE 802.11 PCF mode. It provides higher flexibility in resource allocation (polled stations request channel time instead of just transmitting one frame) and adaptation to directional communication.

Personal Basic Service Set

IEEE 802.11ad introduces the PBSS, where nodes communicate in an ad hoc like manner. However, one of the participating nodes takes the role of the PCP. This PCP acts like an AP, announcing the network and organizing medium access. This centralized approach allows the directional network and schedule announcement process described in the next section to be used for an ad hoc like network. The PBSS network has been introduced to satisfy new applications targeted by IEEE 802.11ad, such as wireless storage and peripherals or wireless display usage. For these applications, usually no preinstalled infrastructure exists, and communication takes place between a set of personal devices.

An ad hoc like network with a centralized controller poses two main challenges. First, for energy-constrained devices, increased power consumption at the PCP penalizes a single device while fair sharing of the energy costs is desirable. Second, outage of the PCP paralyzes the entire PBSS. To respond to these challenges, a PCP handover procedure is defined [3]. This procedure can be used for explicit (initiated by the current PCP) or implicit (after a PCP becomes unavailable) handovers. Furthermore, when selecting between a set of possible PCPs, the unique capabilities of PCP candidate stations are considered to choose the PCP providing the most complete number of services to the network.

Network and Schedule Announcements

Network announcements in legacy IEEE 802.11 are traditionally propagated periodically, using beacon frames, by the AP. Due to the limited antenna gain of quasi-omnidirectional mm-Wave transmissions, the coverage range is severely restricted. Consequently, the beacon is sent as a series of directionally transmitted beacon frames. To have the largest possible range, the beacon frames are transmitted at the most robust MCS (MCS 0). IEEE 802.11ad also specifies additional signaling for network scheduling and beam training appended to every beacon frame. Collectively, this results in a significantly increased overhead in comparison to legacy Wi-Fi. Thus, it becomes critical to control the amount of information transmitted in each BTI. In addition, transmissions during the A-BFT, which also use MCS 0, create overhead recurring with every BI where the A-BFT is present. The overhead problem gets especially relevant when short BI durations are applied for delay-critical application such as video streaming.

The IEEE 802.11ad amendment defines a number of counter strategies. First, it is possible to split a beacon sweep over several BIs. This, however, increases the time a node needs to set up its link to the PCP/AP, as not every direction is served at every BI. The result is an increased association delay. Second, it is possible to periodically schedule BIs without A-BFT, which also results in additional association delays. Third, IEEE 802.11ad introduces the ATI. During the ATI, beam-trained and associated nodes can be served with management data using individually addressed directional transmitted frames encoded with a more efficient MCS. Thus, it is possible to move information from the spectrally inefficient beacon frames to the frames transmitted during the ATI, limiting beacons to the minimal information necessary.

Also, for beacon intervals with split beacon sweeps, stations that do not receive a beacon miss network and timing information. Without this information, stations cannot participate in a BI. Implementing an ATI solves this problem, as scheduling and management information is transmitted individually to associated stations.

IEEE 802.11ad MAC Layer

In contrast to legacy Wi-Fi, IEEE 802.11ad uses a hybrid MAC approach to address its various use cases [3, 7]. The standard supports contention-based access, scheduled channel time allocation, and dynamic channel time allocation. The latter two schemes correspond to time-division multiple access (TDMA) and polling mechanisms. Polling-based access shares similarities with the IEEE 802.11 point coordination function (PCF) mode, but is adapted to directional transmissions and provides a higher flexibility when it comes to distribution of resources among the nodes. The scheduled allocation mechanism extends the traffic stream concept known from the IEEE 802.11 hybrid coordination function (HCF) to request time shares of the DTI for TDMA-like medium access. Next, the three methods are described.

Contention-Based Medium Access

Medium access in CBAPs follows IEEE 802.11 enhanced distributed channel access (EDCA), including traffic categories to support quality of service, frame aggregation, and block acknowledgments. However, when using contention-based access with directional antennas, the problem of deafness arises. A deaf node does not receive directionally transmitted information due to misaligned antenna patterns. A detailed description of the effect can be found in [6]. While the beam training process in IEEE 802.11ad prevents deafness for intended transmissions, it poses a problem for carrier sensing during contention-based access and can lead to increased collisions. A further problem for contention-based access is that a receiver typically does not know where a signal comes from. Thus, usage of quasi-omnidirectional beam patterns is necessary, which reduces link budget and throughput.

The contention-based medium access in IEEE 802.11ad is adapted for directional medium usage and multi-MAC usage. This includes support for multiple network allocation vector (NAV) timers (one per peer station), which allows a transmission to be initiated to a peer device where the NAV for that device is zero, even though the NAV for another peer device might be nonzero. Details about 802.11 EDCA and its use in 802.11ad can be found in [3, 8].

Dynamic Channel Time Allocation

IEEE 802.11ad defines a dynamic channel time allocation mechanism that implements polling-based channel access. Dynamic channel time allocation is an extension of the IEEE 802.11 PCF mode. It provides higher flexibility in resource allocation (polled stations request channel time instead of just transmitting one frame) and adaptation to directional communication. Polling-based channel access brings several advantages for mm-Wave communication. First, due to the centralized approach with a PCP/AP, stations are aware of the direction of incoming signals. Thus, the deafness problem that affects contention-based access is prevented, and quasi-omnidirectional receive patterns can be avoided. Second, centralized scheduling at a PCP/AP also helps to efficiently react to bursty downstream traffic, as dynamic scheduling can be adapted in the course of a BI. In contrast, pseudo-static scheduling, described in the following section, can only announce modified allocation parameters with the beginning of every BI.

When applying the dynamic allocation mechanism, the medium access during DTI is organized as follows. The PCP/AP acquires the medium and sends a series of polling frames to associated stations. This is answered with a block of service period requests (SPRs) used by the polled stations to request channel time. The PCP/AP allocates the available channel time according to these requests, announcing each allocation with a separate grant period, consisting of individual grant frames for the stations involved in the allocation.

IEEE 802.11ad foresees integration of the dynamic allocation mechanism into both CBAPs and SPs. When integrated in a CBAP, associated stations try to acquire the medium and may interfere with the dynamic allocations. To prevent this, the PCP/AP makes use of prioritized medium access using the short PIFS inter-frame spacing, and the channel is protected by extension of the frame duration fields. This extension causes nodes that overhear a frame to assume that the channel is occupied until the time specified in the duration field. This mechanism is used such that polling and SPR frames protect the polling phase, while every dynamic allocation is protected by its preceding grant frames.

To simplify the scheduling mechanism and reduce implementation complexity, dynamic allocations are scheduled back to back, with every allocation immediately following its Grant period. To reliably reach the nodes that are involved in an allocation, individual directional frames are transmitted during the grant period. In case of an allocation between PCP/AP and a station, only one grant frame is sent to the non-PCP/AP station.

When not all available channel time is allocated dynamically, the PCP/AP can repeat the entire polling process. For integration into a CBAP, remaining channel time can also be used for CSMA/CA access.

An example for three polled stations is shown in Fig. 4. The PCP/AP commences a polling phase at the beginning of the DTI, transmitting a polling frame for every associated station, which is answered with a series of three SPRs by the stations. The second station requests communication with another non-PCP/AP station, while stations one and three intend to communicate with the AP (not shown). The resulting allocations are scheduled back to back, each preceded by a grant period. For communication with the AP, the grant period consists of one frame; otherwise, two. The time until which preceding frames protect the channel is indicated by separating lines.

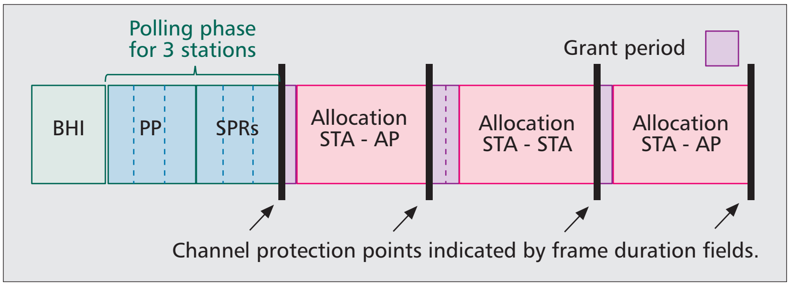

Figure 4. Dynamic channel allocation.

Pseudo-Static TDMA Channel Time Allocation

During pseudo-static channel time allocation, SPs that recur every BI are dedicated exclusively to a pair of communicating nodes. Accessing the channel using this TDMA mechanism provides reliability and is the best way to comply with quality of service demands. Furthermore, the schedule of SPs is propagated by the PCP/AP to all associated stations. Thus, every node that is not communicating during a SP can go into sleep mode, which allows efficient power saving.

For pseudo-static medium allocation, the concept of traffic streams for IEEE 802.11 HCF, as described in [8], is extended. A traffic stream is defined as a flow of MAC service data units that has to be delivered subject to certain quality-of-service parameters characterized by a traffic specification.

The IEEE 802.11ad amendment defines stations to use traffic specifications to request scheduling of pseudo-static channel allocations at the PCP/AP. A requesting station defines the properties of its traffic demand in terms of allocation duration and isochronous or asynchronous traffic characteristic. Calculating the allocation duration requires a complete beam-trained link with known rate between source and destination. Otherwise, the traffic specification has to be modified after beam training when the link's throughput rate is known. An isochronous traffic stream results in pseudo static SP allocations that satisfy a constant rate of recurring payload (typical, e.g., for wireless display applications) with certain latency demands. Asynchronous traffic streams, in contrast, satisfy non-recurring payload demand. A typical example application is rapid file download.

The actual schedule that includes the requested allocations is broadcasted by the PCP/AP in an extended schedule element in the next BTI or ATI.

IEEE 802.11AD Beamforming Concept

Beamforming training determines the appropriate receive and transmit antenna sectors for a pair of stations. This is achieved by transmission of a bidirectional training frame sequence. Throughout the training process, double-sided

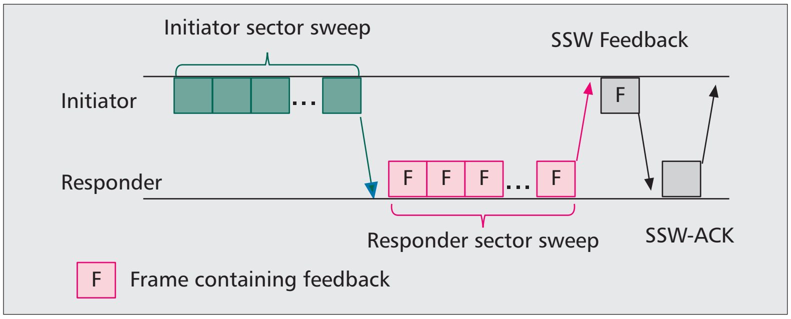

Figure 5. Sector-level sweep.

omnidirectional transmissions are avoided as they are severely limited in range.

The beamforming phase is split into two subphases. First, during the sector-level sweep (SLS), an initial coarse-grained antenna sector configuration is determined. This information is used in a subsequent optional beam refinement phase (BRP), which fine-tunes the selected sectors. During SLS each of the two stations trains either its transmit antenna sector or the receive antenna sector. When devices are capable of reasonable transmit antenna gain, the most common choice is to train only transmit sectors during SLS and derive receive antenna configuration during a following BRP. Fully refined transmit and receive sectors at both sides of a link allow multi-gigabit-per-second speeds to be reached over ranges up to 10 m.

This section explains the general approach to beamforming introduced in the IEEE 802.11ad standard. The beamforming concept allows a significant amount of implementation-dependent customization and has a variety of optional features. Therefore, we first focus on the mandatory SLS phase followed by a description of the mandatory parts of the BRP.

Sector-Level Sweep Phase

During the SLS, a pair of stations exchanges a series of sector sweep (SSW) frames (or beacons for transmit sector training at the PCP/AP) over different antenna sectors to find the one providing the highest signal quality. During the SLS, each station acts once as a transmitter and once as a receiver of a sweep, as shown in Fig. 5. The station that transmits first is called the initiator, the second the responder. Both initiator and responder sweep can be used in two different ways, as depicted in Fig. 6. During a transmit sector sweep (TXSS), shown in the left part of the figure, frames are transmitted on different sectors while the pairing node receives with a quasi-omnidirectional pattern. To identify the strongest transmit sector, the transmitter marks every frame with an identifier for the used antenna and sector. During a receive sector sweep (RXSS), shown in the right part of Fig. 6, transmission on the same sector (best known sector) allows to test for the optimum receive sector at the pairing node. Overall, there are four possible sweep combinations for an SLS. Transmit sector sweeps at both initiator and responder receive sector sweeps at both stations, initiator RXSS and responder TXSS, and initiator TXSS and responder RXSS.

The achieved optimum SNR and, in the case of a TXSS, the sector and antenna identifier are reported to the pairing node. SLS feedback follows the structure described in Fig. 5.

Feedback for the initiator is carried by every frame of the responder sector sweep, which ensures reception under still unknown optimum antenna configuration. The feedback for the responder is transmitted with a single SSW Feedback frame on the determined optimum antenna configuration. Finally, the SSW Feedback frame is acknowledged with an SSW-ACK by the responder. The last frame is further used to negotiate the details of a following BRP.

If two stations have sufficient transmit antenna gain, their SLS phase can be realized as pure transmit sector training, with the receive sector training postponed to a following BRP. Devices with few antenna elements have to add antenna gain at the receiver side in order to achieve sufficient link budget to establish a link. Thus, these devices are likely to include a receive sector sweep in their part of the SLS.

The initiator can request that a receive sector sweep be done by the responder by specifying the number of receive sectors to train during the initiator sweep. When the initiator sweep is a receive sector training, additional signaling has to precede the SLS, as described later.

The Beam Refinement Protocol Phase

The BRP refines the sectors found in the SLS phase. These sectors are determined using heterogeneous quasi-omnidirectional antenna patterns and may have suboptimal signal quality. Furthermore, the BRP foresees optimization of antenna weight vectors, independent of the predefined sector patterns, for phased antenna arrays. This can yield additional throughput gains while increasing the beam training search space. Even though free variation of the antenna weight vectors can result in arbitrary antenna patterns, the directional nature remains for antenna configurations that yield high throughput. Thus, the training process for predefined directional sectors and antenna weight vector optimization remains the same. Finally, the BRP is used to train receive antenna configurations in case this was not part of the preceding SLS. Multiple optional pattern refinement mechanisms are defined for the BRP and are out of scope of this article. We focus on the mandatory beam refinement transactions, an iterative process in which both initiator and responder can request training for receive or transmit antenna patterns.

A BRP transaction evaluates a set of directional transmit or receive patterns against the best known directional configuration at the pairing node. Thus, the imperfection of quasi-omnidirectional patterns is avoided. As the BRP relies on a preceding SLS phase, a reliable frame exchange is ensured, and different antenna configurations can be tested throughout the same frame. This severely reduces transmission overhead in contrast to the SLS, where a full frame is necessary to test a sector. To sweep antenna configurations throughout a frame, transmit and receive training fields (TRN-T/R) are appended to the frames exchanged during BRP transactions. Each field is transmitted or received with an antenna configuration that is to be tested for its signal quality. The remaining portion of the frame is transmitted and received with the best known antenna configuration.

BRP receive antenna training is requested by specifying the number of configurations to be tested in a frame's L-RX header field. The pairing node will append the according number of TRN-R fields to its next frame. A transmit training is requested by setting the TX-TRN-REQ header field and appending TRN-T fields to the same BRP frame. Optionally, no training fields are attached, and an acknowledgment frame with the TX-TRN-OK field set is transmitted by the recipient before the requester appends the TRN-T fields to its following frame. Equal to the SLS, BRP feedback is given in form of SNR for the best found configuration and the best configuration ID in case offor a transmit training.

Figure 7 shows a BRP transaction that first trains the receive configuration between two stations, followed by additional transmit training refinement. Note that station B combines the request for transmit and receive training in one frame using the request variation explained above. Station A, in contrast, uses two frames to request the two transmit directions. The frames and training fields belonging to one of the different training requests are marked in the same color.

A BRP phase can immediately follow the SLS, using the SSW ACK frame for parameter exchange. Alternatively, it can be initiated by a special BRP setup sub-phase, consisting of training-field-free BRP frames. In either case, L-RX and TX-TRN-REQ fields are used to exchange the BRP parameters.

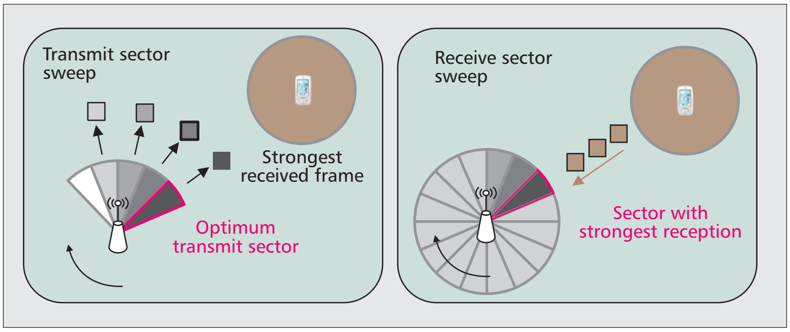

Figure 6. Transmit and receive sector training.

IEEE 802.11AD Beamforming Protocol

The general beamforming concept described earlier integrates into the different IEEE 802.11ad medium access schemes and the association processes. Before association, stations use an adapted version of the beamforming process to connect with the PCP/AP without preceding coordination. This training is further realized in a way that allows the PCP/AP to do sector training to all stations at the same time rather than separately.

This section explains the association beamforming training, followed by a description of beam training between non-PCP/AP stations in accordance with the three different MAC schemes.

Association Beamforming Training

Beamforming training between the PCP/AP and an unassociated station cannot rely on coordination preceding to the beam training. To overcome the challenges of directional link setup, the PCP/AP uses its beacon sweep during the BTI, as an initiator sector sweep for all stations. To this aim, SSW frame specific control fields are added to the beacon frame. To allow multiple stations to respond to a beacon sweep without coordination, the A-BFT interval implements a contention-based response period. The A-BFT reserves channel time for multiple responder sector sweeps (A-BFT slots) from the stations. An overview for the association beamforming training during BTI and A-BFT is shown in the upper left of Fig. 8.

Each A-BFT slot consists of a fixed time allocation for a number of SSW frames (transmitted by the connecting station) and one SSW Feedback frame sent by the PCP/AP as depicted in the lower part of Fig. 8. Contending stations randomly select which slot to access.

The contention process during an A-BFT does not apply carrier sensing. Instead, a colli-

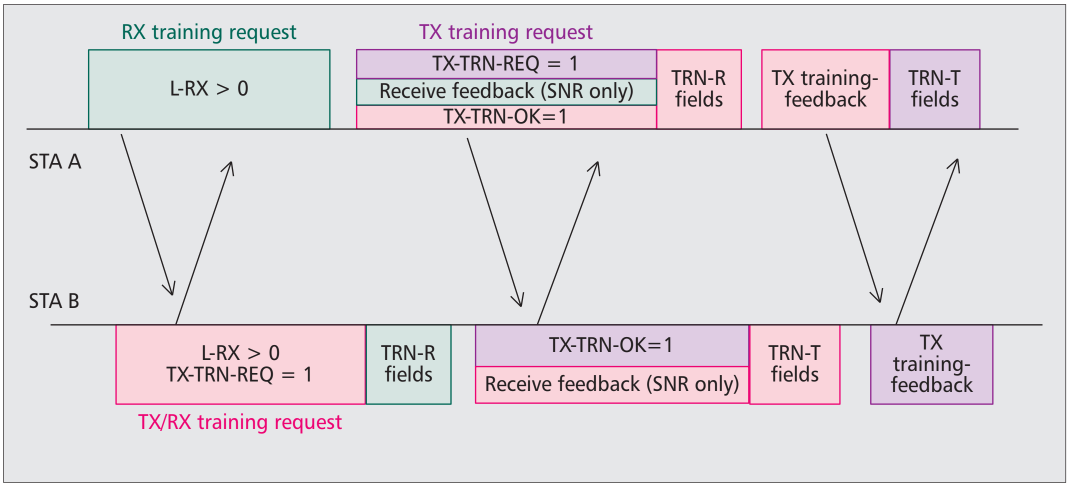

Figure 7. Beam refinement transactions.

Beamforming training during the DTI can be initialized following two different methods. First, the initiator can directly begin a sector level sweep when it gains control over the channel. Second, the PCP/AP can convey beam training parameters between two nodes, during dynamic or pseudo-static channel allocation.

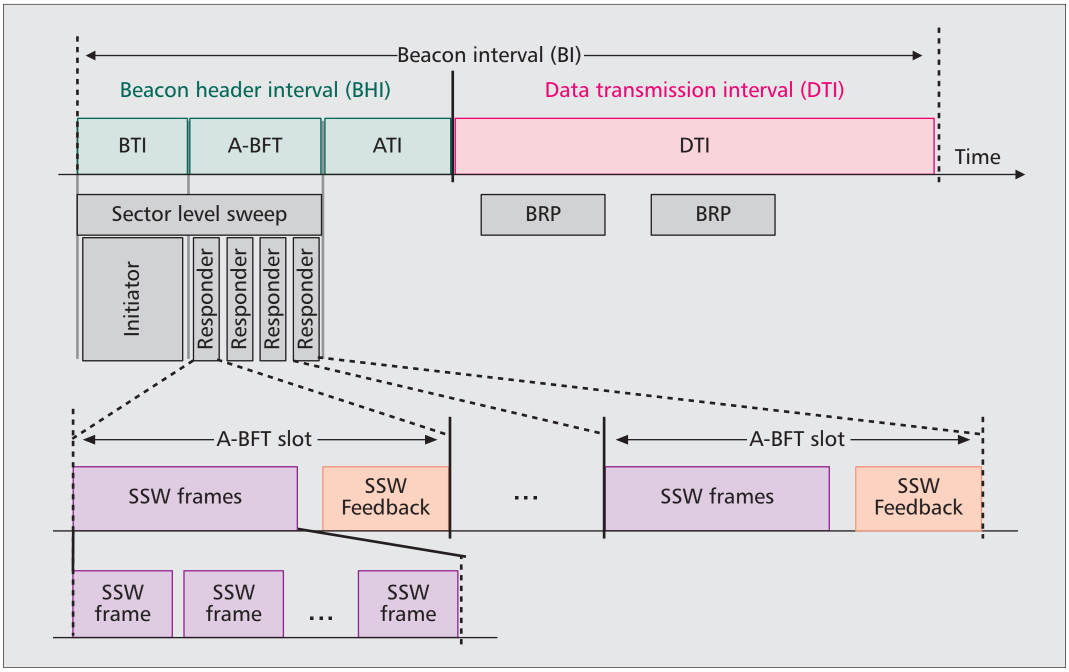

Figure 8. Association beamforming training.

sion is detected by a missing SSW Feedback frame from the PCP/AP. In addition, a station might be unable to finish its sweep because its sectors exceed the number of SSW frames per slot. To handle such cases, several measures can be taken. First, the PCP/AP can answer an incomplete sweep with an SSW Feedback frame, forcing the selection of a suboptimal transmit sector. Second, a station might contend for further slots during the A-BFT in the same or a following BI. To resolve congestion of the association beamforming training interval, a station has to draw an additional amount of backoff slots when its retries exceed a given limit. Also, the beam training can be moved into a dedicated SP by the PCP/AP according to the procedures described below. BRPs for the links between the PCP/AP and stations are scheduled in the DTI, as indicated in the upper right of Fig. 8.

A PCP/AP can announce an A-BFT for receive sector training. Hereby, the slot size indicates the number of receive sectors the PCP/AP intends to train, and associating stations transmit the according number of SSW frames.

Beam Training in the Data Transmission Interval

Beamforming training during the DTI can be initialized following one of two methods. First, the initiator can directly begin an SLS when it gains control over the channel. This method is required during CSMA/CA access. Second, the PCP/AP can convey beam training parameters between two nodes, during dynamic or pseudo-static channel allocation. Using the second mechanism, the PCP/AP learns about the pending beam training and can integrate that information into the scheduling process.

For direct beam training initialization, a station that has seized the channel initiates the beamforming process with a transmit sector sweep to the responder. However, if the initiator intends to start receive antenna training, additional signaling is necessary. In that case, the initiator inquires the number of receive sectors at the responder via the PCP/AP or higher-level protocols. Then, to initialize the SLS, a Grant/Grant-ACK exchange is used to request a receive sector sweep. Following that, both nodes start the training after the Grant-ACK frame. During contention-based access, short inter frame spacing between beamforming frames ensures that no other node wins a transmit opportunity and causes interference.

Beam training via the PCP/AP during pseudo static channel allocation is requested with the initial traffic specification that is transmitted. The beam training parameters are included by the PCP/AP in the extended schedule element that announces the first allocation, which causes both nodes of a traffic stream to commence training at the beginning of their first allocation.

To initiate beam training via the PCP/AP during dynamic channel allocation, a node requests an allocation to the beam training partner. In its corresponding SPR frame, the initiator indicates the parameters for the intended training. When granting the corresponding allocation request, the PCP/AP includes the beam training parameters into the Grant frames sent to both stations involved in the allocation.

Beam refinement during the DTI typically follows immediately after a SLS. The initiator uses the SSW ACK frame to request transmit or receive training as described above. A station that has seized the channel can also initiate a standalone BRP using a BRP setup phase. To request mandatory beam refinement transactions only, the setup phase comprises a single BRP frame initiating the refinement sequence.

CONCLUSIONS

In this article, we present the IEEE 802.11ad standard, which brings consumer wireless communication to the millimeter wave band. We highlight the standard's hybrid MAC layer design that defines three different medium access schemes: CSMA/CA, Polling, and TDMA. Every scheme addresses different aspects of mm-Wave communication and supports varying quality of service mechanisms, making it suitable for different IEEE 802.11ad use cases.

Furthermore, we address the elaborate beam training protocol, which enables highly directional communication. The association beamforming training and two-level beam training are the fundamental elements of this protocol. First, association beam training aligns antenna beams between a station and a central network controller while the direction between the two devices is unknown. Second, two-level training reduces the beam training search space using its primary coarse-grained training stage that relies on predetermined virtual antenna sectors. Its second stage further refines the found antenna configuration varying from predefined sectors and also addresses the challenges of imperfect omnidirectional antenna patterns. With fully trained transmit and receive antenna configurations, IEEE 802.11ad reaches its maximum throughput of up to 7 Gb/s. In addition, the beamforming protocol supports a training procedure for low antenna gain devices and can convey training parameters to a central network coordinator for channel access scheduling.

The combination of the hybrid MAC layer and the novel beam training protocol is key to enabling new IEEE 802.11ad use cases, and addressing specific device and millimeter wave propagation characteristics.

The combination of the hybrid MAC layer and the novel beam training protocol is key to enabling new IEEE 802.11ad use cases and addressing specific device and millimeter wave propagation characteristics.

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