Implementation and Evaluation of a WLAN IEEE 802.11ad Model in ns-3

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ABSTRACT

The IEEE 802.11ad amendment to the 802.11 standard for multi-gigabit communication at 60 GHz was published several years ago, but to date, no precise simulation model for networking in this band is available. In this paper, we present a model for IEEE 802.11ad implemented in the network simulator ns-3. We model new techniques that are essential for IEEE 802.11ad operation such as beamforming training and steering, relay support, and fast session transfer. We then evaluate by simulation the performance of IEEE 802.11ad as well as the gains obtained through the aforementioned techniques. The code for our simulation model is publicly available.

Keywords

Millimeter Wave, IEEE 802.11ad, 60 GHz, ns-3

1. INTRODUCTION

With the proliferation of mobile devices with data hungry applications, existing mobile networks and wireless local area networks (WLAN) technologies are becoming increasingly congested and overloaded. As a result, mobile network operators and telecommunications equipment vendors are considering leveraging the underutilized radio spectrum available between 30 GHz and 300 GHz, the so called the millimeter wave (mmWave) band, for next generation wireless networks. Wireless communication in this band is highly appealing since it provides extremly high capacity and thus allows for a several-fold increase in data rates and lower latencies. However, transmission in this band has specific signal propagation characteristics compared to existing technologies working in lower bands and thus requires major design changes for both medium access control (MAC) and physical (PHY) layers. Both the Wireless Gigabit Alliance (WiGig) and the Wi-Fi Alliance took the initiative to leverage this wide spectrum and provide multi-gigabit per second communication in the 60 GHz unlicensed band. They introduced the WLAN IEEE 802.11ad amendment [2, 9] which provides very high throughput of up to 7 Gbps for short range communication for local area networks. This allows for a range of new high-rate applications, such as wireless docking stations, wireless storage, and instant file synchronization. Compared to IEEE 802.11ac [3] which is capable of supporting multi-gigabit throughput by employing high modulation and coding schemes (MCSs) and advanced physical layer technologies such as multi-user-multiple-input and multiple-output (MIMO), IEEE 802.11ad achieves multi-gigabit throughput by utilizing only the wide channels of 2.16 GHz available at the 60 GHz band.

Experimental evaluation of networking in this band is extremely costly and available hardware has very limited capabilities. Current research studies deduce network performance from individual 60 GHz links [7, 4, 8] but cannot evaluate the behavior of an entire network. In such cases, resorting to network simulation is a very useful alternative which abstracts implementation details while providing a good grade of realism. However, there are no publicly available simulation tools supporting IEEE 802.11ad in the mmWave band. For these reasons, we provide in this paper a concrete and precise model for simulating IEEE 802.11ad with its novel techniques such as channel access periods, beamforming training, relay operation, and fast session transfer.

The paper structure is as follows. In Section 2 we provide background on IEEE 802.11ad accompanied by a survey of the existing simulation models. Section 3 presents our IEEE 802.11ad implementation in ns-3 and Section 4 presents the evaluation results for the proposed model for different scenarios. Finally, Section 5 concludes the paper.

2. BACKGROUND AND RELATED WORK

In the following subsections, we provide some background on the WLAN IEEE 802.11ad amendment and survey existing work on network level simulators for mmWave technologies.

2.1 Background on IEEE 802.11ad

Wireless communication in the 60 GHz band has different characteristics compared to IEEE 802.11 devices operating in the 2.4 GHz and 5 GHz bands. In the following paragraphs, we provide a brief description of the major design changes for both MAC and PHY layers in IEEE 802.11ad and the intuition behind them.

2.1.1 802.11ad Physical Layer

Emerging applications using the IEEE 802.11ad multi-gigabit capability have different constraints and requirements in terms of power consumption, data rates, processing capabilities and antenna design complexity. For these reasons, IEEE 802.11ad introduces four different types of PHY layers to cope with these requirements. Each PHY layer supports a set of specific MCSs.

- **Control PHY**: This PHY layer (MCS0) is dedicated to low Signal-to-Noise Ratio (SNR) operation with low

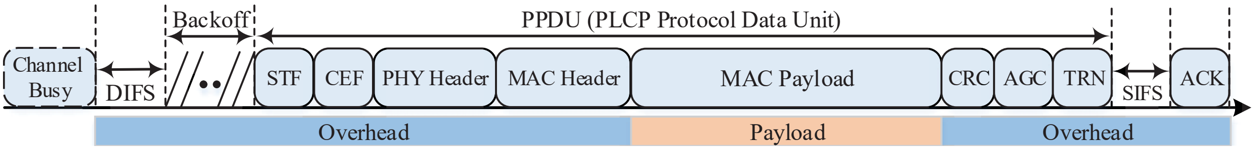

Figure 1: IEEE 802.11ad Frame Structure.

throughput communication (27.5 Mbps). It is mainly used during the Beamforming Training (BF) phase.

- **OFDM PHY**: This PHY layer (MCS 13-24) provides the highest data rates of up to 6.76 Gbps. It adopts Orthogonal Frequency Division Multiplexing (OFDM) technology which is very efficient in multi-path environments. However, its implementation is complex and therefore it targets devices with less stringent power and design constraints, such as docking stations and wireless streaming devices.
- **Single Carrier (SC) PHY**: Power limited and low complexity devices adopt this physical layer which provides a good trade-off between average throughput and energy efficiency compared to the OFDM PHY. Mobile phones and tablet devices will most likely adopt this PHY layer. SC PHY defines MCS 1-12, of which MCS 1-4 are mandatory modes to be implemented in all devices for interoperability.
- **Low Power (LP)-SC PHY**: This PHY layer with MCS 25-31 is similar to the SC PHY layer, but allows for further power reduction by using low-density parity check (LDPC) codes instead of Reed-Solomon codes.

Figure 1 depicts the IEEE 802.11ad frame structure. The frame starts with the typical IEEE 802.11 fields such as short training field (STF) and channel estimation field (CEF) which are used for detecting the type of the PHY layer. These fields are followed by the PHY header which includes information such as payload length in bytes and index of the MCS used in the payload part. This field together with the MAC header and the MAC payload are protected by a Cyclic redundancy check (CRC). Finally, IEEE 802.11ad appends optionally two fields named automatic gain control (AGC) and training (TRN). These new fields are used during the BF phase which we describe in section 2.1.3.

2.1.2 DMG Channel Access

IEEE 802.11ad organizes the access to the medium in so-called Beacon Intervals (BIs). Each BI is further subdivided into different access periods. An access period has different access rules and provides certain functionalities to nearby directional multi-gigabit (DMG) stations (STAs). Figure 2 illustrates a typical BI consisting of Beacon Header Interval (BHI) and Data Transmission Interval (DTI). The BHI compromises the following three sub-intervals:

- **Beacon Transmission Interval (BTI)**: In this sub-interval, multiple DMG Beacon frames are transmitted across different sectors by the DMG personal basic service set control point (PCP)/access point (AP) to announce the network and provide transmit sector training towards nearby stations. DMG Beacons are transmitted using MCS 0 to reach large distances.
- **Association Beamforming Training (A-BFT)**: The A-BFT is used mainly by DMG STAs to train their transmit antenna sectors towards the DMG PCP/AP in a contention based manner.
- **Announcement Transmission Interval (ATI)**: This sub-interval is used mainly for management frame exchange between the PCP/AP and beam-trained STAs. Since communication takes place with beam-trained stations, stations can use high MCSs during the ATI for more efficient communication.

In the DTI period, DMG STAs exchange data frames either in the contention-based access period (CBAP) or the scheduled service period (SP). During the CBAP, DMG STAs contend for the channel access using the IEEE 802.11 Enhanced Distributed Coordination Function (EDCF), whereas in SP, DMG STAs access the channel in a contention-free manner where the channel is reserved for communication between two dedicated DMG STAs.

2.1.3 Beamforming Training Mechanism

Propagation conditions at 60 GHz band are worse compared to the lower bands due to oxygen absorption [10], high attenuation, weak signal reflectivity, and quasi-optical propagation behavior [11]. For these reasons, IEEE 802.11ad provides a mechanism to establish a directional link through a beamforming training process to compensate for signal quality degradation. In this process, stations focus their energy towards the intended receivers only, which increases antenna gain and may result in reduced interference, allowing for high spatial reuse. The beamforming training process in IEEE 802.11ad is divided into the following two phases:

- **Sector Level Sweep (SLS) Phase**: In this phase, a DMG STA selects a coarse grain antenna sector for the initial communication. The phase can be used in two ways: 1) as transmit sector sweep (TXSS) where a DMG STA tries to select the best transmit antenna sector towards a particular DMG STA by sending Sector Sweep (SSW) frames via each of its antenna sectors or 2) as a receive sector sweep (RXSS), where a DMG STA trains its receive antenna sector by requesting a peer DMG STA to transmit SSW frames using a fixed antenna pattern while the former is sweeping across its receive antenna sectors.
- **Beam Refinement Protocol (BRP) Phase**: IEEE 802.11ad defines multiple optional mechanisms to refine the sectors obtained in the SLS phase. The most important mechanism is the beam refinement mechanism, which is an iterative process where two DMG STAs exchange a special BRP packet ending with either transmit training (TRN-T) or receive training (TRN-R) fields. Additionally, the amendment defines a Beam Tracking (BT) option to keep a track of signal

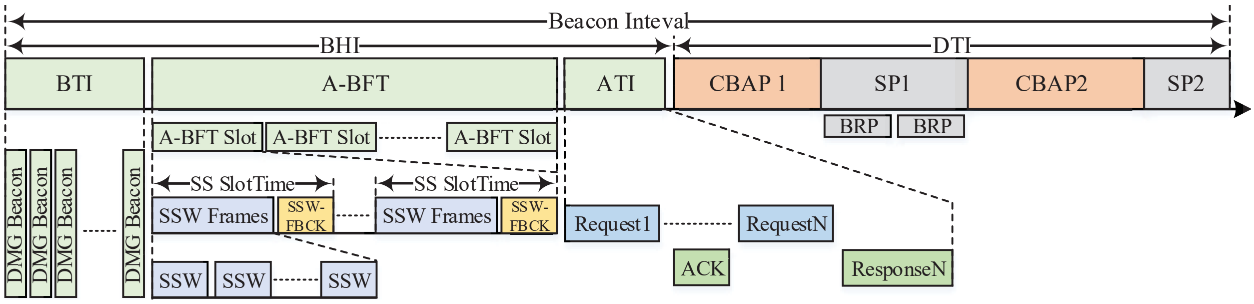

Figure 2: IEEE 802.11ad Beacon Interval with different access periods.

quality during an ongoing data transmission by adding the previous TRN fields to the PHY frames.

2.1.4 *Fast Session Transfer Technique*

Since communication in the 60 GHz band is limited in range and suffers high penetration loss in case of obstacles, IEEE 802.11ad included a fast session transfer (FST) technique. With this, an IEEE 802.11 capable device can change seamlessly its operational band from 60 GHz to 2.4/5 GHz. As a result, a device can extend its coverage area and maintain its current sessions. As an example of this technique, a user may stream an Ultra High Definition (UHD) video on his device from a wireless docking station over the 60 GHz band when he is in the proximity of the docking station. As the user starts to move a way from the docking station, signal quality starts to degragade so the docking station decides to transfer the session to a lower band but continues video streaming using lower video encoding techniques.

2.1.5 *DMG Relay Operation*

IEEE 802.11ad also introduces a relay mode. In this mode, two DMG STAs named source Relay Endpoint DMG STA (REDS) and destination REDS can communicate with each other with the assistance of a Relay DMG STA (RDS) which results in coverage area extension, improved link resilience against interruptions, and persistent multi-gigabit throughput. IEEE 802.11ad defines the following two types of relay operation modes:

- **Link Switching Type**: In this type, the source REDS maintains two links to the destination REDS: a direct link and a relay link through RDS. If the direct link is disrupted, the source REDS switches its transmission to the relay link. Communication over the disrupted link can resume once the direct link is recovered. Under this type, the RDS can operate either in full-duplex amplify-and-forward (FD-AF) mode or in half-duplex decode-and-forward (HD-DF) mode. In FD-AF mode, RDS amplifies the received frames and forwards them directly to the destination DMG STA. For this reason, the RDS should include at least two RF chains for sending and receiving frames at the same time. In contrast, for the HD-DF mode the RDS receives multiple frames from the source REDS in one SP and forwards them to the destination REDS in the following SP.
- **Link Cooperating Type**: Contrary to the previous mode, in this mode the source REDS utilizes both direct link and relay link simultaneously to improve received signal quality at the destination REDS. Operating in this mode requires the source DMG to be aware of propagation delays over each link.

2.2 Existing Work

Although wireless networking in the mmWave band is a hot topic, limited work has been done to provide system level simulators, particularity for IEEE 802.11ad. For example, authors in [7] propose a 5G module in ns-3 based on the LTE protocol stack. The module provides a channel model based on extensive channel measurements in the 28 GHz band. However, it does not employ any algorithms for establishing directional links nor steering antennas arrays. Authors in [4] utilize a IEEE 802.11ad PHY layer to establish multi-gigabit links in data centers using ns-3. In their implementation, they use data rates provided for both SC and OFDM PHY layers in the amendment. Additionally, since the topology of the data center is stable and known, they steer their antennas geometrically i.e. they do not simulate any of the beamforming procedures established in the standard. Finally, authors in [6] provide an architecture for simulating IEEE 802.11ad in ns-3 with a general description on modeling various BF procedures provided in the amendment. However, the implementation is not publicly available and in the validation section the author does not take into account the overhead imposed by different access periods in the BI. All of the previous works simplify the implementation and do not model essential techniques for MAC and PHY operation in the mmWave band.

3. IMPLEMENTATION

In the following section, we provide an overview of the IEEE 802.11 model in ns-3 and how we augmented it to adhere to the IEEE 802.11ad amendment. The model implementation is available on GitHub [1].

3.1 IEEE 802.11 Model in ns-3

The current Wifi model in ns-3 supports different IEEE 802.11 specifications such as a/b/e/g/n/ac with an accurate implementation of the MAC layer. The model can be divided into the following four layers:

- **MAC High Layer**: It provides some Mac layer management entity (MLME) functionalities depending on the underlying network it supports, such as Infrastructure basic service set (BSS) or Independent BSS.
- **MAC Low Layer**: This layer takes care of Ready to Send (RTS)/Clear to Send (CTS)/DATA/Normal

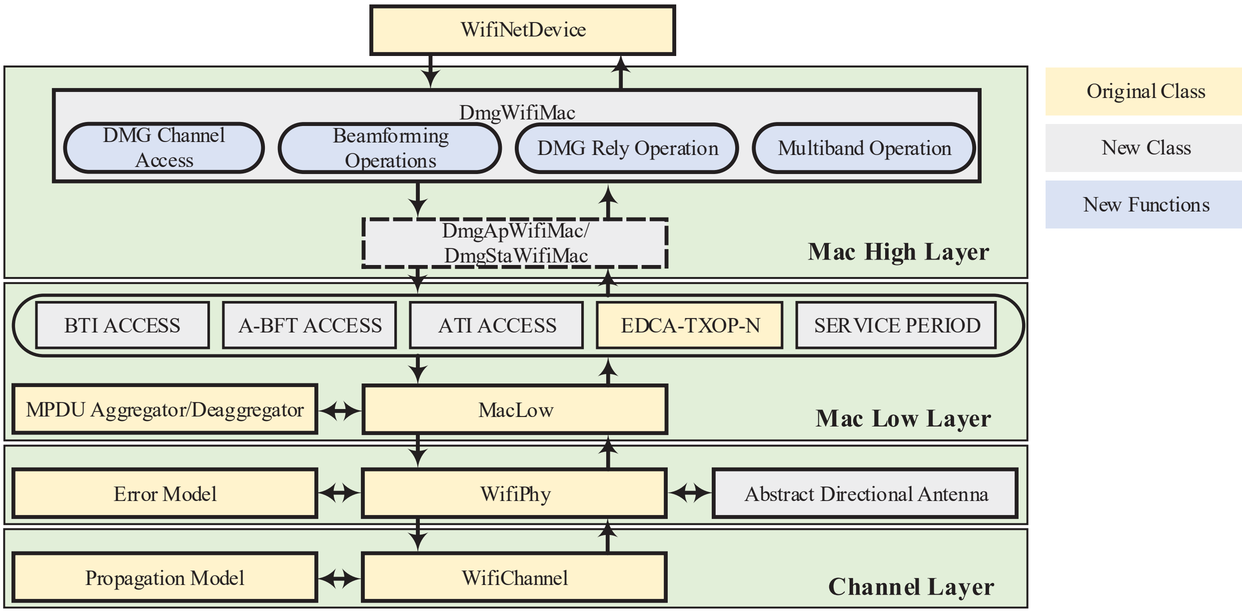

Figure 3: Our implemented IEEE 802.11ad Architecture in ns-3

Acknowledgment (ACK)/BlockACK transmission using the distributed coordination function (DCF) and Enhanced DCF channel access (EDCA) functions. Additionally, it is provides both MAC service data unit (MSDU)/MAC protocol data unit (MPDU) aggregation and deaggregation capabilities.

- **Physical Layer**: It is a simplified model of the real Wifi PHY layer. This layer handles packet transmission and reception over the underlying channel. It calculates interference among different STAs and provides some probabilistic error model for packet reception.
- **Channel Layer**: This layer interconnects different PHY layers of different wireless STAs. Additionally, it simulates and models propagation effects that wireless signals encounter in real environments.

The IEEE 802.11 model in ns-3 is well suited for wireless technologies that use a carrier sense multiple access with collision avoidance (CSMA/CA) scheme with omni-directional transmission and reception. However, IEEE 802.11ad has characteristics that require some major changes to this model. Figure 3 shows the existing ns-3 IEEE 802.11 architecture together with the new blocks for the mechanisms introduced in IEEE 802.11ad. An abstract *DmgWifiMac* class provides common capabilities and techniques for DMG operation. From this class, we derive two classes to represent different BSS types. The first class *DmgStaWifiMac* implements procedures specific to DMG STA such as TXSS in A-BFT, responding to request frames in the ATI period, and the association state machine. The second class, *DmgApWifiMac*, represents the DMG AP and provides DMG Beaconing, BRP Setup Subphase, and BRP transaction initiation.

The following subsections provide an in-depth description of implementation and design assumptions for each block. Since ns-3 provides packet-level granularity, it was important to provide an accurate implementation of the newly introduced MAC frames and Wifi Information Elements to support various procedures defined in IEEE 802.11ad. Furthermore, representing the actual frame structure facilitates packet flow analysis using any network protocol analyzer that supports the IEEE 802.11ad extension.

3.2 DMG PHY Layer

ns-3 provides a simple PHY layer for the operation of IEEE 802.11. In this layer, the reception of the Physical Protocol Data Unit (PPDU) frame is modeled as simulation delay corresponding to the transmission time of this frame plus propagation delay. To model the multi-gigabit throughput of IEEE 802.11ad, we provide all the mathematical equations required for the calculation of PHY frame transmission time including preamble, header and payload using either control, SC, or OFDM PHYs.

3.3 DMG Access Periods

The *DmgApWifiMac* class organizes medium access by initiating BI through transmission of DMG Beacons across all its antenna sectors. The remaining time for each access period is announced in the duration field of the MAC header. This allows DMG STAs to synchronize their clocks with the DMG AP clock. During BTI, the DMG AP ensures the medium is free before it starts DMG beacon transmission. For this reason, the value of the duration field is calculated once the DMG AP is granted access to the channel. A DMG STA that receives at least one DMG beacon from the DMG AP schedules an event to start the A-BFT access period at the end of the current BTI. The DMG APs divides the A-BFT into slots, where the duration of each slot is calculated based on the number of SSW frames to be transmitted. DMG STAs choose one of these slots randomly using a uniform distribution. If two DMG STAs select the same slot, they will collide and do not receive an SSW-Feedback (FBCK) frame within a pre-determined period of time. These two DMG STAs then have to select a new slot while ensuring that they do not exceed the duration of the A-BFT. This period is followed by the ATI access period, where the DMG AP initiates management frame transmission. Currently, we use this period to perform the BRP setup phase and exchange BRP transactions. Any packet that arrives during the previous access periods is queued for transmission until the beginning of the DTI.

3.4 Directional Antenna Pattern

Unlike the previous IEEE 802.11 specifications which are able to exploit omni-directional communication, IEEE 802.11ad requires a directional communication link towards its intended receiver, and thus a directional antenna pattern model. We provide a generic directional antenna model named *AbstractDirectionalAntenna* which divides the 2D plane into a user defined number of virtual sectors with equal apertures and coverage range. Concrete antenna models are inherited from this base model. In this derived model it is possible to define the attributes of the radiation pattern such as maximum gain, side lobe gain, and the gain based on the selected sector and the geometric angle between the transmitter and the receiver. In our implementation, we use the antenna model provided in [5] for evaluating IEEE 802.11ad in a conference room. In this antenna model, the authors provide a simple mathematical model to characterize a directional antenna with averaged side lobe. For frame transmission, a DMG STA should be using one of the predefined antenna transmit sectors. For reception, the antenna can be either in omni receive mode or directional receive mode depending on the current access period.

3.5 DMG Beamforming Operation

We provide a generic implementation for both SLS and BRP phases in the *DmgWifiMac* class. The implementation can be used either as part of the initial BT between DMG AP and DMG STAs or as a scheduled SP between two DMG STAs. The *DmgWifiMac* class has two data structures: one for storing and mapping antenna sector configurations for each received frame from a peer DMG STA with its corresponding SNR and another data structure for storing the best transmit and receive antenna sectors towards a particular station. The latter is updated at the end of each BF operation. In the current implementation, all decisions regarding the best transmit and receive antenna sectors are based on SNR measurements. The *MacLow* class uses the second data structure to select the antenna sector based on the receiver address in the MAC header. In the current implementation, we assume DMG STAs perform TXSS in the A-BFT. In addition, the BRP phase will be utilized to train antenna receive sectors for all DMG STAs instead of refining the selected antenna transmit sector. All BF frames are transmitted using MCS 0.

To model TRN field transmission in ns-3, we modify the current Physical Layer Convergence Protocol (PLCP) transmission model which handles PHY preamble, header and payload transmission and reception only. For example, a MAC frame that requires TRN fields to be appended to its end pass this information in the TxVector together with the length and type of the TRN fields to be appended (either TRN-T or TRN-R). Since each TRN field corresponds to a unique antenna sector pattern, we schedule the transmission of each TRN field separately to allow DMG to change its active sector. At the end of each TRN field transmission, the receiver calculates the received SNR value for this particular field and reports it to the *DmgWifiMac*. Once all TRN fields are received, the *DmgWifiMac* determines the best antenna sector.

3.6 Fast Session Transfer

IEEE 802.11ad supports multi-band operation for fast session transfer (FST). FST operation can be either in transparent or non-transparent mode. In transparent mode, all MAC sub-layers in the STA expose a single MAC-Service Access Point (SAP) to the upper layers, i.e., a single MAC address. In non-transparent mode, each MAC sub-layer exposes its own MAC-SAP to the higher layers which adds more complexity. In our implementation, we use the transparent mode where we design a new *NetDevice* named *MultiBandNetDevice*. This new *NetDevice* encapsulates different IEEE 802.11 technologies as depicted in Figure 4. For each technology, a user defines a *WifiMac*, *WifiPhy*, *WifiRemoteStation* and *WifiChannel* object. One technology should be active at any point for any pair of devices. A STA that supports multi-band operation should announce this in its Beacon, Association Request, Association Response, Probe Request, Probe Response, and DMG Beacon a MultiBand Information Element.

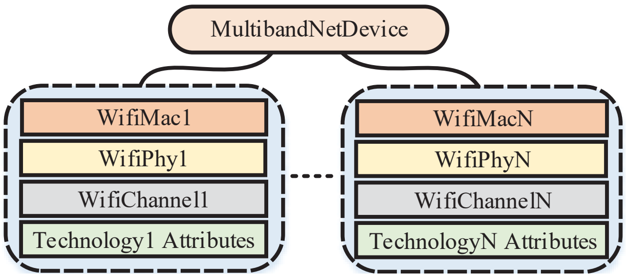

Figure 4: MultiBandNetDevice Implementation

Figure 5 illustrates various states a STA goes through to establish a unique fast session transfer session (FSTS) ID with a peer STA. At the beginning, each STA is in the **INITIAL_STATE** where they communicate in the old band/channel. A station that wishes to set-up a FSTS is called FST Initiator and the peer station is FST Responder. To proceed to the **SETUP_COMPLETION_STATE** and obtain a unique FSTS ID, both Initiator and Responder have to exchange FST Setup Request/Response frames successfully. In this new state, STAs keep communicating in the old band/channel. However, depending on the value of the link loss timeout (LLT) field in the Session Transfer Information Element, both STAs shall either transfer their current session to the new band/channel immediately if the value of LLT is equal to zero, or they shall start a Link Loss countdown equal to $LLT * 32\mu s$ if $LLT > 0$. The LLT defines the amount of time that has to elapse since the initiating STA received an MPDU frame from the responding STA until the initiating STA should perform FST. Once the value of LLT reaches zero, both Initiator and Responder move to the **TRANSITION_DONE_STATE** and start communicating in the new band/channel. If the two STAs exchange normal MPDU frames or FST ACK Request/Response in the new band/channel successfully, the two STAs move to the **TRANSITION_CONFIRMED_STATE**, otherwise

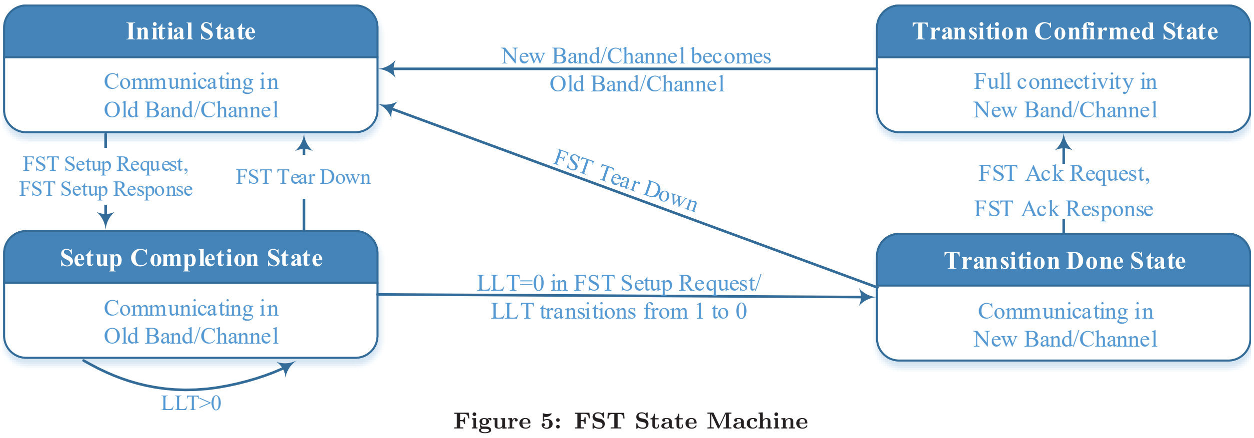

Figure 5: FST State Machine

the two STAs move to the **INITIAL_STATE** and resume communication in the old band/channel.

3.7 DMG Relay Operation

We implement link switching type relay operating in FD-AF mode. Figure 6 summarizes different procedures to establish a relay link with a destination Relay Endpoint DMG STA (REDS) in a DMG BSS. A STA should acquire the DMG capabilities of the DMG STA it wishes to establish a relay operation with before it initiates any relay setup operation. This is done by sending an Information Request frame to the DMG AP after the DMG STA completes its association with the DMG AP.

- **RDS Discovery Procedure**: In this phase, a source REDS searches for candidates Relay DMG STAs (RDSs) in the DMG BSS. The DMG AP informs both source REDS and destination REDS about the available REDS in the network with their DMG capabilities.
- **RDS Selection Procedure**: At this point, the DMG AP schedules several SPs for BF training between all the available RDSs together with source REDS and destination REDS consecutively. After that, the source REDS request for channel measurements with the candidates RDSs. Later on, the DMG AP schedules a SP for BF between source REDS and destination REDS. After finishing the BF, the source REDS requests destination REDS to send channel measurements with the available RDSs. As a result, the source REDS will be aware of all channel states in the network. Based on this information, the source REDS selects the best RDS for relaying. In our implementation, we select the RDS which receives frames from both source REDS and destination REDS with the highest SNR.
- **Relay Link Setup (RLS) Procedure**: In this phase, the source REDS decides to forward its current transmission through the selected REDS in the previous phase. Thus, it sends an RLS Request frame to the selected RDS. The selected RDS in return forwards this frame to the destination REDS. At this point, the destination REDS replies back to the selected RDS with an RLS Response with a status equal to Success if it accepts to communicate through the relay link. The selected REDS forwards this frame to the source REDS with a status equal to Success if it accepts to act as relay. If both destination REDS and RDS accept to switch the link, the source REDS sends an announcement frame to the DMG AP regarding the newly established relay link in the network.
- **Relay Teardown Procedure**: If the source REDS decides to terminate its relay link through the selected RDS, it shall transmit an RLS Tear Down frame to the selected RDS, destination REDS and DMG AP.

4. MODEL EVALUATION

In this section we provide some evaluation results for our new IEEE 802.11ad model. In all the experiments, we assume all DMG STAs and DMG AP have one antenna array with 8 sectors. We use a Friis propagation loss model to calculate received signal strength (RSS) and UDP as transport protocol. All STAs support both MSDU and MPDU aggregation, and data transmission is done in CBAP mode.

4.1 Evaluating 802.11ad Beamforming Overhead and Achievable Throughput

In this experiment, we calculate the amount of time it takes to establish directional communication between two DMG STAs. We also demonstrate the obtained throughput for different MCSs for both SC and OFDM PHY layers.

The setup compromises two nodes: one DMG AP and one DMG STA. These nodes are spaced 2m apart from each other. The DMG STA generates a flow of User Datagram Protocol (UDP) messages towards the DMG AP. The announced A-BFT by the DMG AP consists of 8 sector sweep (SS) slots where each slot contains 8 SSW frames.

From simulations, we find that the two nodes spends almost 572 μs to complete an SLS phase for TXSS. The RXSS is performed during the BRP which takes around 396 μs. Figure 7 depicts the obtained throughput for two different sets of MCSs. The highest throughput achieved for SC is almost 4 Gbps and for OFDM is 5.2 Gbps. However, the achieved throughput for OFDM is 1.5 Gbps less than the theoretical maximum IEEE 802.11ad throughput of 6.72 Gbps. This is mainly due to the overhead imposed by the CBAP access mechanism. Besides that, the data rate reported in the standard assumes a continues stream of OFDM symbols without any PHY and MAC overhead and any Interframe Space (IFS).

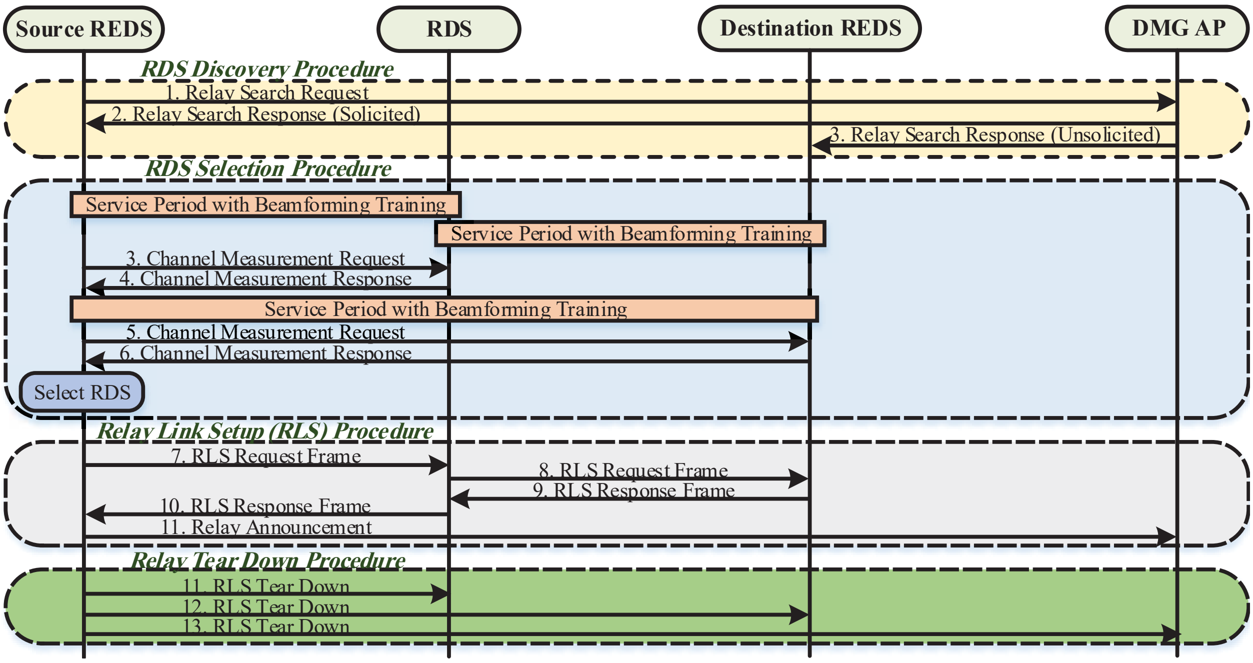

Figure 6: Relay Signaling Procedure

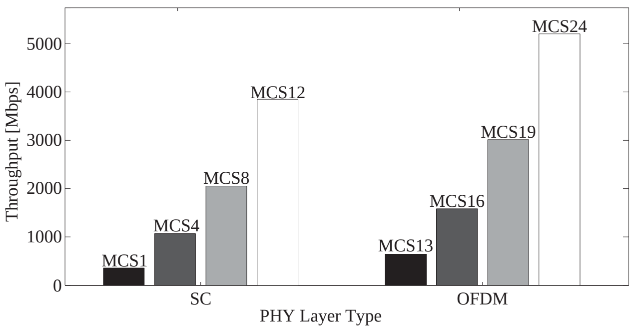

Figure 7: Throughput for different MCSs

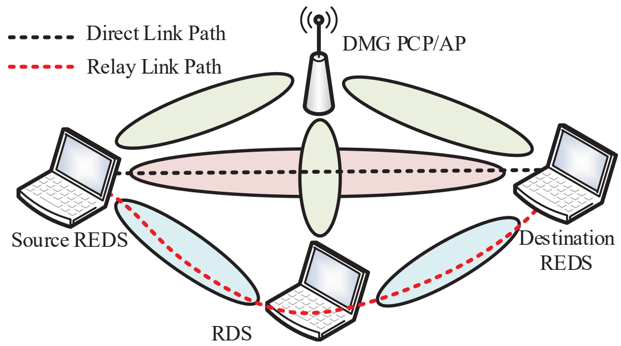

Figure 8: Relay Test Setup Topology

4.2 Evaluating DMG Relay Operation

Here, we measure how much time it takes to switch a directional communication link between two REDSs and use an alternative path through an RDS operating in full-duplex amplify-and-forward (FD-AF). Additionally, we calculate the throughput gain we obtain by using this alternative path compared to the case where we do not have any available RDS in the DMG network.

The simulation setup shown in Figure 8 contains one DMG AP with 3 DMG STAs. Two DMG STAs act as REDS and one DMG STA supports RDS. During the DTI acess period, all DMG STAs communicate using MCS 24.

At the beginning, the two REDSs are able to communicate with each other over the direct link. At a certain point in the simulation, we introduce a blockage in the direct link. This blockage does not result in a complete link failure. The source REDS starts to miss some ACKs from the destination REDS and the achievable application throughput is halved. As a counter measure, the source REDS decides to perform an RLS procedure with the selected RDS to obtain a better link quality with the destination REDS. Figure 9 shows the received throughput with and without relay support. From the simulations, we find that it takes around 117 μs to switch from the direct link to the relay link. In addition, using the relay link results in a throughput gain of 2.5 Gbps.

4.3 Evaluating Fast Session Transfer

In this experiment, we demonstrate the capability of transferring an on-going data session smoothly from the 60 GHz band to the 2.4 GHz band.

The simulation setup is similar to the one in Section 4.1 with the addition that the nodes can communication in the 2.4 GHz band using IEEE 802.11n. We set the value of LLT to 1000 which corresponds to a link loss countdown value of 32 ms. After the nodes establish the directional link, they setup a unique FSTS between each other.

A the beginning of the simulation, the nodes communicate with each other normally and the achieved throughput is

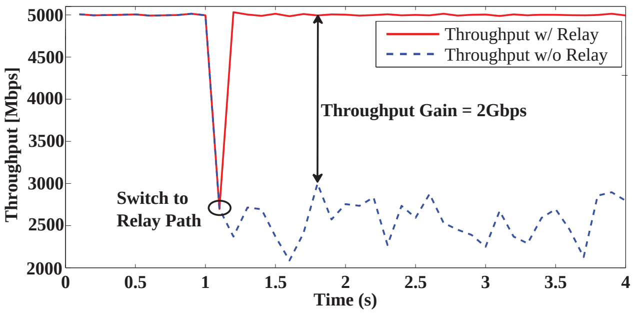

Figure 9: Relay Setup Results

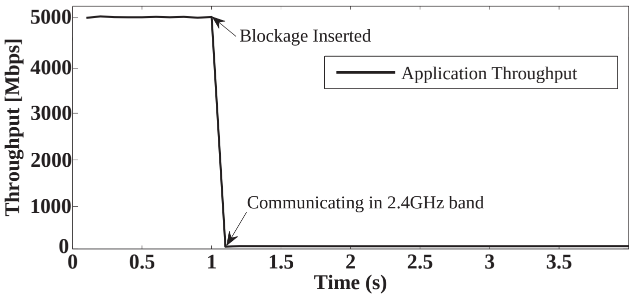

Figure 10: FST Setup Results

around 5 Gbps as shown in Figure 10. After one second, we introduce a blockage in the link of -45 dBm. This blockage results in complete link failure so the DMG STA starts a link loss timer. When the timer expires, the two nodes switch to the 2.4 GHz band and continue their session. We notice the degradation in the received throughput to around 60 Mbps due to the limited capacity available in the lower frequency band.

5. CONCLUSION AND FUTURE WORK

We provide an architecture for modeling WLAN IEEE 802.11ad with its various enhancements in ns-3. We implement beamforming training and steering, relay operation, and fast session transfer. We discuss a range of implementations details and how the model integrates into ns-3. In the evaluation section, we demonstrate the overhead required to establish a directional communication link and the average throughput achieved for different MCSs for both SC and OFDM PHY layers. Then, we show that swapping a transmission from a direct link to an alternative link through a relay takes around 117 μs and the throughput gain is almost double. Finally, we demonstrate the capability of fast session transfer of maintaining an on-going session alive. The source code of our implementation is publicly available.

IEEE 802.11ad provides many mechanisms to either avoid communication disruption for certain cases or improves the achievable data rate. The current implementation considers only CBAP access period in the DTI and lacks a hybrid MAC model which provides dynamic channel allocations for applications with strict Quality of Service (QoS) requirements. In our current DMG relay implementation, we model full-duplex amplify-and-forward relay operation mode only and we omit the half-duplex decode-and-forward mode. Additionally, the standard defines a new type of frame aggregation named PPDU aggregation. In this aggregation mode, a DMG STA transmit two or more PPDUs without any separation. Next steps in the further development of our model are to implement these missing features. The current implementation provides all MAC frames and Information Elements necessary for modeling missing MAC sublayer functionalities. Besides, our implementation can also serve as a base line for implementing and evaluating the next generation 60 GHz WLAN IEEE 802.11ay amendment.

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