Extending the IEEE 802.11ad Model: Scheduled Access, Spatial Reuse, Clustering, and Relaying

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ABSTRACT

Millimeter-wave technology is one of the main pillars of the future wireless networks. The main reason lies in the quantum leap of capacity it provides with respect to wireless networks operating in the sub 6-GHz band. Nevertheless, efficient and reliable communication in this band demands novel techniques to tackle all the associated barriers related to wireless propagation in those bands. In this paper, we present the extension of our ns-3 IEEE 802.11ad model and provide design and implementation details of the new techniques, including dynamic and static channel access schemes, decentralized clustering, beamformed link maintenance, spatial sharing, and half-duplex relay operation as defined in the IEEE 802.11ad amendment. We show how these techniques can boost and enhance wireless networking operation in the 60 GHz band. Our work is the first to implement these techniques in a networking simulator and make the implementation publicly available.

CCS CONCEPTS

•Networks →Network simulations; Wireless local area networks;

KEYWORDS

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

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1 INTRODUCTION

The penetration of data intensive applications in the digital market such as augmented and virtual reality services, and ultra high definition (UHD) video streaming and distribution is driving mobile network operators and telecommunications equipment vendors to boost the performance and capacity of the existing cellular and wireless technologies. These services require significantly higher capacity compared to what is currently offered by wireless technologies operating in the sub 6-GHz band. For this reason, the millimeter wave (mmWave) band between, 30 GHz and 300 GHz, is drawing the attention of the research and industry communities because of the abundant spectrum available there. There is already plenty of ongoing work and substantial effort in both industry and academia for developing novel wireless systems that utilize the mmWave band. One prime example is the IEEE 802.11ad [4, 8] protocol, which leverages the wide spectrum in the 60 GHz unlicensed band and provides multi-gigabit per second (up to 7 Gbps) for wireless local area networks (WLAN).

During the year 2016, several consumer electronics companies released the first commercial of the shelf (COTS) [6, 9] wireless devices that support the IEEE 802.11ad protocol. These devices are based on Wilocity 60 GHz multi-gigabit wireless chipsets (Wilocity was later acquired by Qualcomm). This gave an opportunity to the research community to start experimenting and testing in the 60 GHz band [7]. Unfortunately, all these devices have very limited and basic functionalities and neither provide any control over their radio frequency (RF) frontend nor access to their medium access control (MAC) parameters. These devices only allow to test the quality of the directional mmWave link under various channel conditions and examine its impact on the performance of the upper layer transport protocols [5].

In prior work [2], we implemented the first open source model for the new amendment of the WLAN operating in the mmWave band—the so-called the IEEE 802.11ad. In this paper, we extend this work and bring some new techniques to the model. These techniques include spatial sharing, decentralized clustering, static and dynamic channel access schemes, beamformed link maintenance, and half-duplex relay operation. These techniques are part of the IEEE 802.11ad amendment and each technique is intended to enhance wireless networking performance in the 60 GHz band for a particular scenario. The implementation of these techniques is optional in the consumer devices because of their complexity and most of the networking hardware vendors implement only the mandatory functions in their WLAN chipsets to reduce the total cost. Because of that, experimentation with these features is only possible within network level simulators. To the best of our knowledge, there is no available network level simulator that features these techniques. For these reasons, we took the initiative and implemented these techniques on top of our ns-3 IEEE 802.11ad model to quantify their benefits and performance. Our contribution allows research community to evaluate wireless networking in the 60 GHz band for vast and diverse simulation scenarios using a realistic implementation of the IEEE 802.11ad amendment.

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The paper structure is as follows. In Section 2, we provide background on IEEE 802.11ad techniques. Section 3 presents implementation details of new techniques in the ns-3 IEEE 802.11ad model. Section 4 presents the evaluation results of these techniques in various scenarios. Finally, Section 5 concludes the paper.

2 IEEE 802.11AD TECHNIQUES

IEEE 802.11ad features a set of MAC and physical (PHY) layer functionalities to support wireless networking at 60 GHz. This set includes a beamforming training (BF) procedure for directional link establishment, a beam refinement protocol (BRP), a beam tracking (BT), a fast session transfer (FST) mechanism, four different types of PHY layers, and full duplex relay operation. These were discussed in detail in our prior ns-3 work [2]. In the following subsections, we provide a brief background on a new set of techniques which are addressed in this paper.

2.1 Channel Access Schemes

IEEE 802.11ad defines a hybrid medium access [3, 4] scheme which complements the traditional and well-known access technology in the WLAN—the so-called carrier sense multiple access with collision avoidance (CSMA/CA). It incorporates two new access technologies namely Service Period Channel Access (SPCA) and Dynamic Period Channel Access. Each one of these access techniques serves well for a particular application.

2.1.1 CSMA/CA Channel Access. CSMA/CA is the legacy distributed MAC mechanism in all the previous WLAN amendments because of its simplicity and robustness. A WLAN network utilizing CSMA/CA does not require a centralized scheduler to manage medium access. All stations (STAs) using CSMA/CA access the wireless medium with an equal probability. CSMA/CA supports Quality of Service (QoS) operations through Enhanced distributed coordination function (DCF) channel access (EDCA) which creates virtual MAC queues for each access category (AC). Despite these merits, CSMA/CA is not well suited for mmWave wireless networks with their directional transmission and reception. The problem with directionality is that it forces a STA to listen to the medium in a certain spatial direction. This would not fit CSMA/CA operation which in principle requires determining if the channel is free in an omni-directional manner. This results in stations determining that a medium is free while it is in fact busy, thus causing collisions. Since medium access is distributed, an access point (AP) does not know from which direction it shall receive so to avoid this problem an AP has to use quasi-omni pattern for reception which reduces link budget and the achievable data rate.

2.1.2 Service Period Channel Access. A service period (SP) in the context of IEEE 802.11ad wireless networks is designated for a reserved time allocation for communication between a pair of stations. A SP is similar to time-division multiple access (TDMA) channel access in cellular networks. Station accessing the channel in a service period communicate with each other directly in a collision freeway. This increases MAC efficiency since no more time is wasted on contending for accessing the channel. In addition, it supports applications with strict QoS requirements. Moreover, it improves energy saving since stations can go into sleep mode whenever they are not scheduled for transmission. Since communication is scheduled, a station is aware of the peer station and thus can steer its antenna beam towards that station and avoid the use of quasi-omni patterns. However, during the SP allocation phase the quasi-omni patterns are still needed by the AP. The schedule of the service period allocations is communicated during network announcement phase.

2.1.3 Dynamic Channel Access. Dynamic channel allocation in IEEE 802.11ad is based on a polling access scheme which is a master-slave protocol. The AP (the master) polls each station (slave) periodically for transmit requests. The polled station specifies the amount of time resources to meet its traffic requirements and QoS constraints. Because of the centralized approach, each station is aware of the direction of the transmission and thus can steer its directional antenna towards the master. This allows station to totally avoid using the quasi-omni patterns. Unlike SPCA where modified channel allocations can be announced at the beginning of every Beacon Interval (BI), the dynamic schedule can be adapted during the course of a BI to react to bursty download traffic. Despite these benefits, the dynamic scheme wastes time resources because of the polling process.

2.2 Spatial Sharing

Reliable communication in the mmWave band requires the use of directional antennas to compensate for the harsh propagation conditions. The directionality of the communication links allow concurrent transmissions to take place at the same time without interfering with each other thus increasing the total throughput of the wireless system. To exploit this capability, the IEEE 802.11ad amendment defines a spatial sharing and interference mitigation mechanism to examine a set of established links for parallel communication. The mechanism relies on measuring the interference among communication links separated in time and space. An AP overlaps these links in time and assess the amount of interference introduced and its implication on the quality of the communication. If the AP foresees that the amount of interference induced to each link is negligible and does not affect the performance, then the AP schedule these links in the same time thus achieving spatial sharing and boosting system performance.

2.3 Clustering

Radio propagation characteristics in the 60 GHz band are harsh compared to the microwave band, thus radio coverage in the mmWave is typically confined within single room. Extending the coverage would require dense deployments of APs to ensure high probability of radio coverage to all users. However, managing a high number of distributed APs is troublesome. In addition, non-provisioned APs might result in high interference and performance degradation thus hindering the throughput achieved in the 60 GHz band. To mitigate the previous issue and improve spatial sharing between these co-channel APs, the IEEE 802.11ad amendment features clustering of distributed APs. The clustering feature allows co-channel APs to coordinate beaconing to avoid interference and enhance operation in dense environments. This allows a group of APs to schedule their transmissions in non-overlapping time periods since each AP is able receive scheduling information contained in the directional multi-gigabit (DMG) Beacons from neighboring APs and thus takes decision on how to schedule its own transmission in way that avoids interference between these distributed APs.

2.4 Directional Link Maintenance

Efficient and reliable communication in the 60 GHz band uses directional antenna beam patterns which in turn requires beamforming training. Beamforming training in IEEE 802.11ad compromises two procedures Sector Level Sweep (SLS) and a beam refinement protocol (BRP). The execution of these procedures results in a beamformed link. However, due to the high variability of the wireless channel in the 60 GHz band, the quality of this beamformed link might degrade to a point in which a pair of STAs can no longer communicate with each other. To maintain this beamformed link and ensure its availability and reliability to deliver frames, the IEEE 802.11ad defines a mechanism to monitor and maintain each beamformed link in the network. The mechanism implies running a beam link maintenance timer to monitor the activity of each beamformed link. There is one timer per SP allocation. This timer is reset upon successful exchange of frames between pair of STAs with beamformed link. The expiration of this timer is an indication of the unavailability of the link.

2.5 Half Duplex Relay Operation

The reliance on directional antennas in the mmWave makes communication links sensitive to blockage and device orientation. For example, in the case of a crowded scenario, the directional communication link between a mobile user and an access point might experience frequent shadowing events within small interval of time which lead to severe degradation in the link quality. To tackle this issue, IEEE 802.11ad introduces relay operation mode to improve link resilience against sudden interruptions. In our previous work[2], we introduced and implemented the link switching type relay operation mode operating in full-duplex amplify-and-forward (FD-AF) mode. A relay operating in the FD-AF mode requires an 802.11ad enabled devices to have two RF chains to receive and transmit simultaneously which increases the cost and the complexity of these devices. We complement the previous work and add support for a half-duplex decode-and-forward (HD-DF) relay mode. A relay operating in HD-DF mode only has a single RF chain and thus it can either receive frames from the source STA or transmit frames to the destination STA. The HD-DF relay mode allows for lower device complexity at reduced relay throughput compared to FD-AF relay mode.

3 IMPLEMENTATION

In the following section, we provide implementation details for the previous techniques in ns-3. The implementation is available at [1].

3.1 DMG Channel Access

3.1.1 CSMA/CA Channel Access. We modify DCF function to support operation using directional transmission and reception in IEEE 802.11ad. During a transmission, a STA should steer its antenna beam towards the intended receiver. Whereas if the station is in idle state, it configures its receive antenna to quasi-omni pattern to receive any frames transmitted by nearby STAs covered by this antenna. A special case is when an DMG STA expects frames exchange only with the personal basic service set control point (PCP)/AP, then it directs its receiving antenna towards the PCP/AP.

3.1.2 Service Period Channel Access. To allocate a SP, a non-PCP/non-AP DMG STA sends an `ADDTS Request` to the PCP/AP. The `ADDTS Request` carries `DMG TSPEC` element which identifies the source association identifier (AID) and the destination AID of the allocation. An AID is a unique identifier that distinguishes a STA within basic service set (BSS). It is assigned to the STA upon successful association with the PCP/AP. In addition, the `DMG TSPEC` characterizes the SP allocation in terms of duration and format. An allocation can compromise multiple SPs. The format describes the type of the traffic as either isochronous or asynchronous. An isochronous traffic type satisfies applications with periodic payload such as wireless display applications. In contrast, the asynchronous traffic type is convenient for applications with non-periodic traffic, e.g, rapid file download.

The PCP/AP either accepts or rejects the request based on the employed admission control policy and the available time resources in the Data Transmission Interval (DTI) access period. The PCP/AP sends `ADDTS Response` to the STAs identified as source and destination. If the request is accepted, the PCP/AP announces the schedule of the allocation in next the DMG Beacon or Announcement Frame. In addition, the PCP/AP decides the position of the SPs that makes up the allocation within the BI. Communication in a service period is allowed in uni-directional direction from source DMG STA towards destination DMG STA. The source DMG STA holds the channel and initiates the transmission of data frames towards the destination DMG STA which stays in receive mode.

In our implementation, we leave the decision of allocating the requested resources in the `ADDTS Request` to the user. This is done by adding a new trace source *ADDTSReceived* in the `DmgApWifiMac` class. Once the PCP/AP receives an `ADDTS Request` it invokes this trace source. This trace source provides two parameters: the MAC address of the requesting STA and the allocation characteristics. The user accumulates all the requests for SP allocations and provides an implementation for admission and resource scheduling algorithms.

3.1.3 Dynamic Allocation of Service Period. The dynamic allocation mechanism in IEEE 802.11ad takes place during DTI access period. It compromises two periods: the Polling Period (PP) and the Grant Period (GP). During the PP, the PCP/AP polls each station that has declared its willingness to participate in the dynamic allocation. A station declares its wish to participate by setting the `PP Available` in the `STA Availability` element to true. The previous block of poll frames is answered by a series of Service Period Request (SPR) frames. In the SPR frame, each station declares its resource requirements to satisfy its traffic constrains. Then, the PCP/AP allocates resources based on these requests and announces the allocation in a separate GP period. STAs are allowed to transmit frames exclusively during the allocated time in the GP period.

Similar to Section 3.1.2, the admission of the requested resources is left to the user. This provides the user with flexibility to design its custom resource scheduler. To accomplish this task, we provide one call back *RegisterSPRequestFunction* in the `DmgStaWifiMac` class

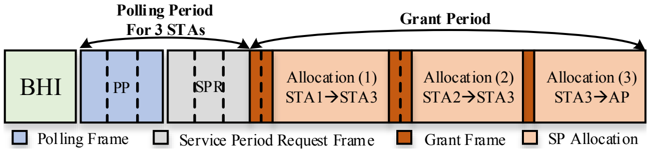


Figure 1: Example of dynamic channel allocation for 3 STAs.

and one trace source (*PPCompleted*) in the `DmgApWifiMac`. The *RegisterSPRequestFunction* callback is invoked each time the PCP/AP polls a station. A user registers a function to this callback and declares the resources required in a dynamic way. The PCP/AP triggers the trace source (*PPCompleted*) upon the completion of PP period. At this point, the PCP/AP has received all the resource requests and the user can decide the allocation of the resources in the following GP period. Figure 1 illustrates an example of a PCP/AP polling 3 STAs for transmission opportunity.

3.2 Beacon Generation in Infrastructure BSS

To minimize the interface caused by the transmission of DMG Beacons to nearby PCPs/APs, a PCP/AP changes the sequence of directions through which a DMG Beacon is transmitted at the beginning of each beacon interval. The PCP/AP chooses the sequence of directions pseudorandomly from a set of directions that fully cover all the spatial directions. Figure 2 depicts an example of DMG Beacon transmission by PCP/AP for a set of N directions.

3.3 Spatial Sharing Technique

The spatial sharing technique allows SP allocations for different DMG STAs in the same spatial domain with the same DMG BSS to be scheduled concurrently during a DTI access period. To support spatial sharing, a DMG PCP/AP sets the `SPSH and Interference Mitigation` field equal to 1 in the `DMG Capabilities` information element. Establishing spatial sharing requires executing the following two phases:

3.3.1 *Assessment Phase.*

In this phase, the PCP/AP initiates radio resource measurement procedure with the intended STAs to assess the possibility to perform spatial sharing. Initially, the PCP/AP sends a `Directional Channel Quality Request` as part of the `Radio Measurement Request` action frame to the intended STAs. These STAs should have done beamforming training before starting any radio measurements. In the context of spatial sharing, we use the term `candidate SP` to refer to an SP to be assessed for spatial sharing with existing SPs. A candidate SP could be either a new SP to be scheduled in the next BI or a scheduled SP with an allocated channel time in the DTI access period. The PCP/AP sets the `Target STA` field in the `Directional Channel Quality Request` to the peer STA's MAC address involved in the candidate SP and the `Measurement Method` field to indicate the average noise plus interference power indicator (ANIPI). If the candidate SP is already allocated, the PCP/AP additionally transmits a `Directional Channel Quality Request` to the STAs involved in the existing SP to assess the possibility for spatial sharing with the candidate SP. In this request, the PCP/AP sets the `Target STA` to the corresponding peer STA involved in the existing SP and the `Measurement Method` field to indicate ANIPI. The recipient of the `Directional Channel Quality Request` carries out channel measurements using same receive antenna configuration as is used when receiving from the target STA. When the recipient STA completes the requested measurements, it reports back to the PCP/AP the result of these measurements using the `Directional Channel Quality Report` as part of the `Radio Measurement Response` action frame.

Figure 3 shows an example of spatial sharing assessment between two SPs where SP1 is the existing SP and SP2 is the candidate SP. At the beginning, the PCP/AP transmits a `Directional Channel Quality Request` to STA C and STA D to perform channel measurement over SP1's channel allocation. Then, it transmits a `Directional Channel Quality Request` to STA A and STA B to measure over SP2's channel allocation.

3.3.2 *Execution Phase.*

Based on the channel measurements results in the previous phase, the PCP/AP estimates the channel quality across STAs and decides whether to implement spatial sharing. The PCP/AP overlaps the candidate SP with the existing SP in its BI if the performance is expected to maximize. The determination of the performance improvement is based on the measurements reports received by the PCP/AP and it is implementation dependent. Figure 3 (b) depicts the allocation of SPs in the BI due to spatial sharing. To ensure those SPs involved in the time-overlapped schedule do not exhibit additional interference to each other due to sudden changes in the propagation environments, the PCP/AP periodically transmits a `Directional Channel Quality Request` to each STA involved in those SPs. The PCP/AP sets the `Target STA` to the peer STA involved in the same SP and set the `Measurement Method` field to indicate received signal to noise indicator (RSNI). Then, each STA performs channel measurements as indicated in the request and sends back `Directional Channel Quality Report` to the PCP/AP. Based on the report, the PCP/AP decides whether to sustain spatial sharing between SPs based on the quality of the link links involved in the spatial sharing. However, the decision is beyond the scope of the standard.

We provide the user with a new trace source *ChannelQualityReportReceived* in the `DmgApWifiMac` class. This trace source is triggered every time the PCP/AP receives a `Directional Channel Quality Report` and it provides two parameters: the MAC address of the reporting STA and the measurement report. The measurement report is calculated based on the measurement method specified in the `Directional Channel Quality Request`. Based on these reports, a user can decide whether to re-allocate existing SPs allocations in the BI and achieve spatial sharing or to stop spatial sharing between these SPs if the performance is degraded.

3.4 DMG PCP/AP Clustering

IEEE 802.11ad defines two types of clustering: decentralized clustering and centralized clustering. The former one requires no centralized controller between the distributed PCPs/APs, whereas the later requires the existence of a single centralized coordination service set (CCSS) entity. In this work, we focus on the decentralized clustering implementation. Forming a decentralized cluster among a group of spatially distributed PCPs/APs operating on the same channel requires one of these PCPs/APs to act as synchronization PCP (S-PCP)/synchronization AP (S-AP). Each cluster has a unique ID which corresponds to the MAC address of the S-PCP/S-AP. The

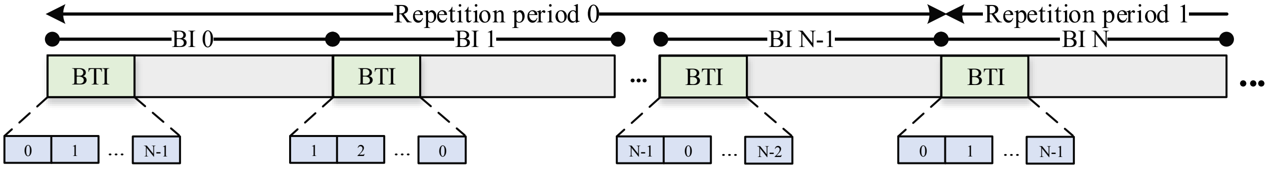
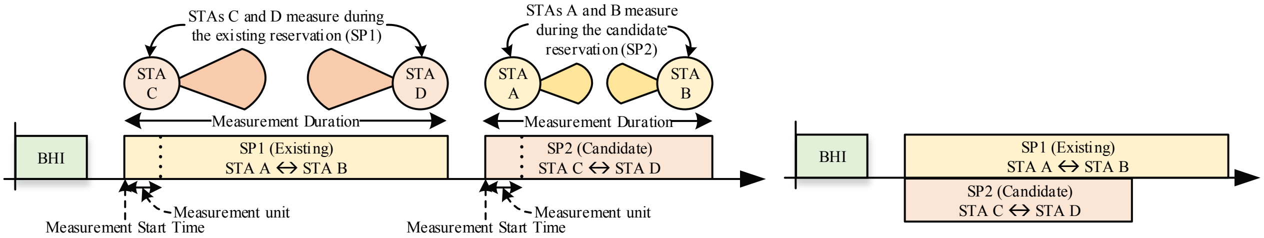


Figure 2: DMG Beacon transmission by PCP/AP during the BTI [4].



(a) Example of Spatial Sharing Assessment

(b) Example of Spatial Sharing between SP1 and SP2

Figure 3: Spatial sharing and interference assessment [4].

BI in a cluster is divided into `ClusterMaxMem` Beacon SPs. A member can transmit exclusively during one of these SPs while other members stays in receive mode. The duration of each SP equals the length of the beacon interval of the S-PCP/S-AP divided by `ClusterMaxMem`. The first Beacon SP is reserved for S-PCP/S-AP. Establishing a decentralized cluster requires the following steps:

3.4.1 Cluster Formation. Forming a decentralized cluster requires at least one S-PCP/S-AP. A PCP/AP becomes PCP/S-AP by transmitting DMG Beacon that includes `Clustering Control` field with the `Cluster Member Role` subfield set to the value for an S-PCP/S-AP. Each PCP/AP on the channel that receives a DMG Beacon from an S-PCP/S-AP starts monitoring the channel for DMG Beacon transmission during each Beacon SP for a duration of at least equals to 1.024*s*. A Beacon SP is considered empty if no DMG Beacon is received during the monitoring interval. Figure 4 illustrates an example of decentralized clustering with three PCPs/APs.

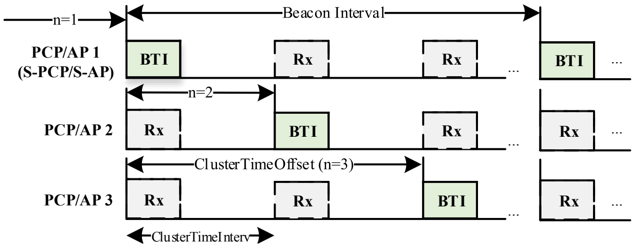


Figure 4: Decentralized clustering for 3 PCPs/APs [4].

3.4.2 Cluster Maintenance. The S-PCP/S-AP is responsible for providing synchronization among cluster members. This facilities sharing medium resources fairly among all the members. For this reason, it is important to provide a procedure for cluster maintenance in case of S-PCP/S-AP failure. This is done through S-PCP/S-AP handover. The handover procedure compromises two *Cluster Monitoring Periods*. The first period ends when a member of the decentralized cluster stops receiving DMG Beacons from the S-PCP/S-AP within 8 beacon intervals. In the second period, the PCP/AP monitors the channel for DMG Beacons transmitted by other members and at the same time it keeps transmitting its own DMG Beacons in the selected Beacon SP. Hence data communication in the existing allocations is not affected. At the end of this period, if the member PCP/AP receives DMG Beacon with the `Cluster Member Role` equals to the S-PCP/S-AP, the member PCP/AP forms a cluster as described in Section 3.4.1. Otherwise, each member compares its own MAC address against all the MAC addresses of the received DMG Beacons. If a PCP/AP has the lowest MAC address, then it shall become S-PCP/S-AP. However, if the MAC address is not the lowest then the PCP/AP starts a new *Cluster Monitoring Period*.

3.5 DMG Beamformed Link Maintenance

To maintain a beamformed link between STAs, these STAs should negotiate the value of the *Link Maintenance Timer* during beamforming training. If one of the STAs sets this value to 0, then beamformed link maintenance is not supported. Figure 5 shows the the operation of the beam link maintenance timer between STA-A and STA-B. In BI (n), STA-A and STA-B complete beamforming training and establish link maintenance timer. In the following BI (n+1), the STAs have two SPs for direct communication. The beam link maintenance timer is set-up, halted, and released according to the rules described in Section 2.4. During the last frame exchange of the first SP, the beamformed link gets blocked so the frame exchange fails and as a result the timer continues counting down. In the following SP, the link is still interrupted so that STA-A and STA-B cannot reliably exchange frames and thus the timer keeps counting down until it expires. Upon the expiration of the timer, the STAs redo re-beamforming.

3.6 DMG Relay Operation

In this work, we extend our relay implementation in [2] and add support for the HD-DF relay mode. In addition, we incorporate frame exchange rules during a service period allocation as defined in the amendment for both FD-AF and HD-DF relay modes. At

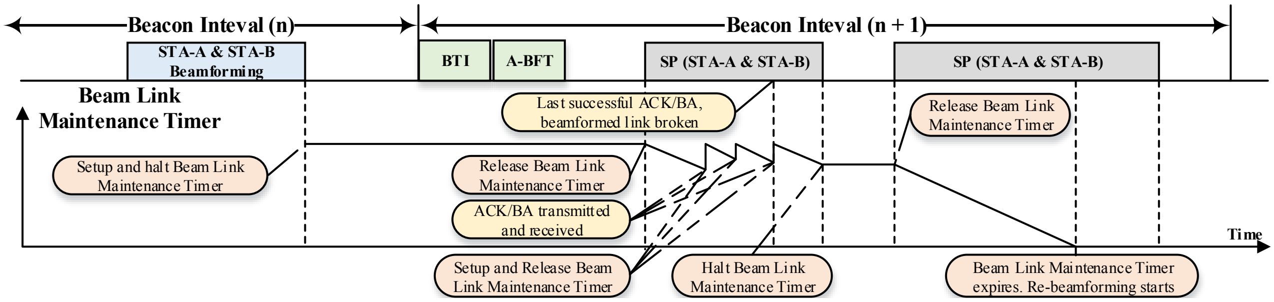


Figure 5: Example of beamformed link maintenance [4].

the beginning, a source Relay Endpoint DMG STA (REDS) and a destination REDS sets up a relay link with a Relay DMG STA (RDS) following the Relay Link Setup (RLS) signaling procedure. Later, if the PCP/AP receives `ADDTS Request` frame with the `Source AID` and the `Destination AID` fields within the `DMG TSPEC` element are equal to the previous pair of source REDS and destination REDS then frame exchange rules follow the ones depicted in Figure 6.

3.6.1 Common Frame Exchange Rules.

Following the completion of the RLS procedure and SP allocation, the contiguous SP shall be divided into *Link Change Intervals*. This interval indicates when the link between source REDS and destination REDS is changed i.e. at each time instant of the *Link Change Interval* can change the current operating link. This implies that source REDS, destination REDS, and RDS within a *Link Change Interval* should all use the same link at the beginning of the *Link Change Interval* period.

If the source REDS transmits frames to the destinations REDS via the direct link but does not receive an Acknowledgment (ACK)/block acknowledgment (BA) from the destination REDS during the *Link Change Interval*, the source REDS should fall back to the relay link at the beginning of the next *Link Change Interval* and forward frames via the RDS to the destination REDS. In the following SPs, the source REDS uses the link in which the frame exchange towards the destination REDS was successful.

3.6.2 Additional Rules for FD-AF RDS.

To inform the destination REDS about the link switch, the source REDS defers its transmission by *Data Sensing Time*. This gives an implicit signaling to the destination REDS to switch to the relay link and steer its antenna beam towards the RDS. However, the source REDS might not have any frame at the beginning of a *Link Change Interval* to transmit. In this case the destination inspects the value of the `More Data` field in the last frame it received from the source REDS. If the value is equal to 0, then the destination REDS shall keep the direct link.

3.6.3 Additional Rules for HD-DF RDS.

When the current link is the relay link, the frame exchange is performed in two periods. The SP is divided into alternating periods named *First Period* and *Second Period*. In the *First Period*, the source REDS transmits a frame to the RDS and then the RDS acknowledges the reception after a short interframe space (SIFS). In the *Second Period*, the RDS forwards the received frames from the source REDS to the destination REDS and then the destination REDS acknowledges the reception after SIFS. If the source REDS decides to change to the relay link, it should suspend its frame transmission to the destination REDS and starts its frame transmission towards the RDS in the following *Link Change Interval* which will be the start of the *First Period*. The destinations REDS stops receiving frames in the following of *Link Change Intervals*. This gives an implicit signaling to the destination REDS that link switching happened.

Table 1: Simulations parameters

Parameter Name	Parameter Value
Application Traffic Pattern	Continuous Data Stream
Payload Size	1000 Bytes
Transport Protocol	UDP
MAC Queue Size	1000 Packets
PHY Layer Type	OFDM MCS24
Rx Noise Figure	10 dB
Propagation Loss Model	Friis loss model

4 EVALUATING 802.11AD TECHNIQUES

In this section, we evaluate some of the implemented IEEE 802.11ad techniques for various scenarios. In all the experiments, we assume all DMG STAs and PCPs/APs have a single phased antenna array covering all directions. This phased antenna array can generate 8 predefined virtual sectors where each sector covers 45°. We use the parameters listed in Table 1 in our simulations:

4.1 Comparing Channel Access Schemes

In this experiment, we compare between two channel access schemes the contention-based access period (CBAP) and the Service Period Channel Access (SPCA) in terms of achievable application goodput. The scenario consists of a single PCP/AP and one DMG STA and they are separated by 1m. An `OnOffApplication` is installed on the DMG STA and it generates traffic towards the `PacketSinkApplication` running on the PCP/AP. Figure 7 shows the obtained goodput with respect to the frame aggregation level. We plot the results using both MCS12 with a Single Carrier (SC) PHY layer and MCS24 with an Orthogonal Frequency Division Multiplexing (OFDM) PHY layer. From the figure, we can notice the difference in the achievable goodput even for the case of a single packet transmission. The goodput for both access schemes increases with the aggregation level until we saturate the channel. The high efficiency of the SPCA comes from the fact that the a DMG STA using SPCA can transmit immediately without having to contend for access to the wireless medium.

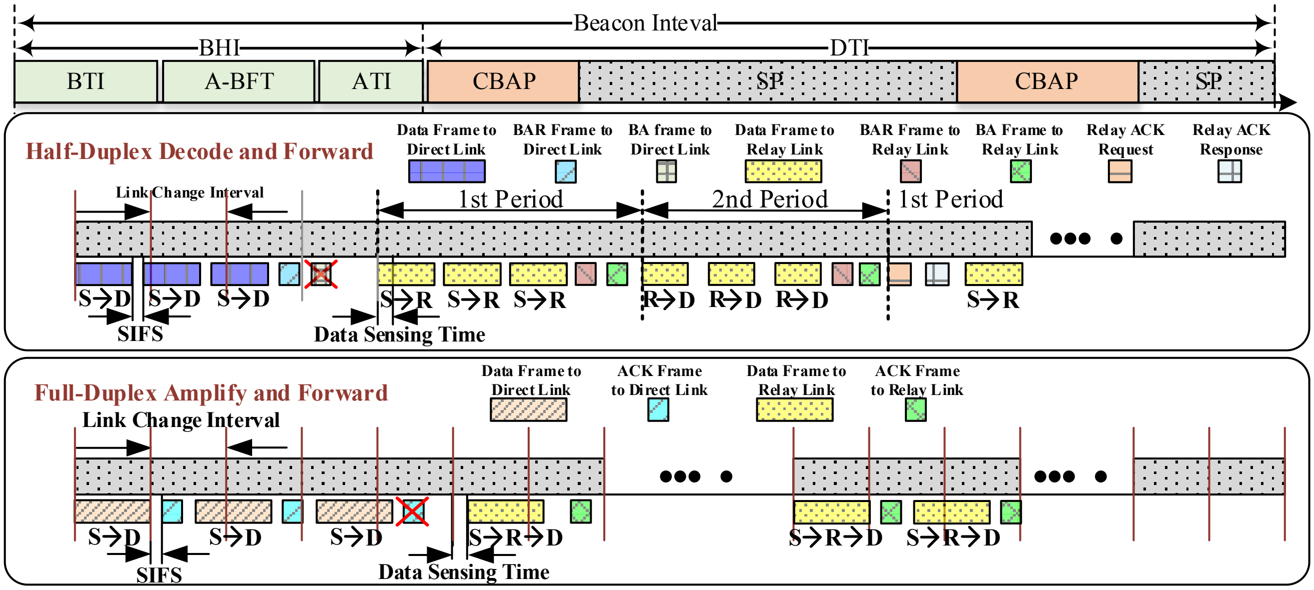


Figure 6: Relay operation modes in IEEE 802.11ad [4].

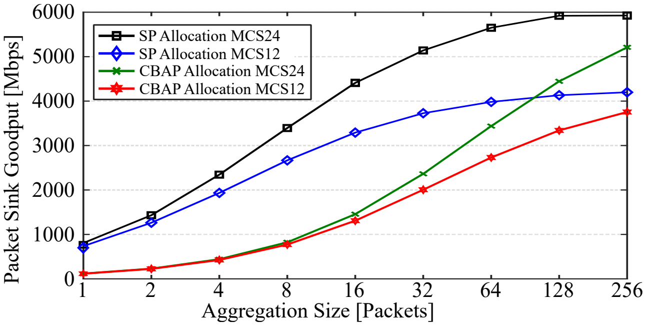


Figure 7: Comparing channel access schemes.

4.2 Evaluating Half-Duplex Relay Operation

Here, we study the impact of using HD-DF relay operation on the application goodput. Theoretically using a relay node operating in half duplex mode should reduce the throughput of a wireless link by half. Figure 8 depicts the simulation setup which consists of one PCP/AP with 3 DMG STAs. Two DMG STAs act as REDS and one DMG STA supports RDS. The source REDS runs `OnOffApplication` and generates data flow towards the `PacketSinkApplication` installed on the destination REDS.

At the beginning, the source REDS executes the RLS procedure to establish a half-duplex relay link towards the destination REDS through the RDS to protect any prospective SP allocations. Later on, the source REDS requests the PCP/AP to allocate a SP for data communication with the destination REDS. The PCP/AP accepts the allocation request and announces the schedule of this SP allocation in the following BIs. The RDS receives this schedule and switches into relay mode at the start time of this SP allocation for possible link switching. During the course of data communication, we explicitly signal all the STA to switch to the relay link.

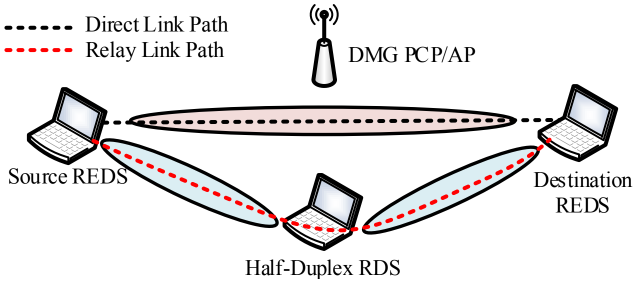


Figure 8: Relay network topology.

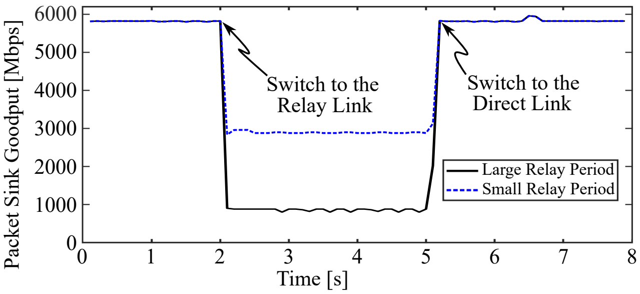


Figure 9: Relay setup results.

Figure 9 illustrates the achievable application goodput before and after link switching for two different values of *Relay Period*, where $RelayPeriod = FirstPeriod + SecondPeriod$. The large relay period corresponds to $8ms$, whereas the small relay period corresponds to $2ms$. We can notice the impact of the time the RDS remains communicating with each REDS. The shorter the period is the lower the impact of switching to the relay link on the application goodput. This is related to the size of the MAC queue. For the large relay period case, the queue keeps buffering frames for a long time and at some point it gets full and starts dropping incoming frames. In contrast, for the small relay period case, the queue of the relay node does not reach its limit and can drain frames much faster.

4.3 Evaluating Spatial Sharing

In this simulation, we demonstrate the importance of spatial sharing in the context of mmWave wireless networks. Figure 10 shows our simulation setup which compromises 4 STAs and a single PCP/AP. Once all STAs have successfully associated with the PCP/AP, the PCP/AP allocates two SPs for beamforming training between STA A and STA B and between STA C and STA D. Upon completion of the beamforming training, the PCP/AP schedules two recurring SPs allocations for data communication as in Figure 3. Table 2 summarizes allocation parameters for each SP.

Table 2: Service periods allocations parameters

SP	Start Time[ms]	Length[ms]	Flow Direction
SP1	0	20	STA A → STA B
SP2	20	12	STA C → STA D

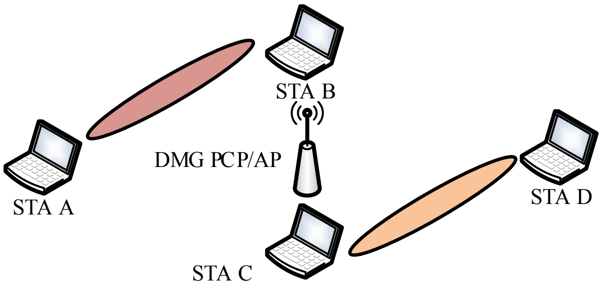


Figure 10: Spatial sharing evaluation topology.

During the course of data communication, the PCP/AP decides to evaluate the two SPs for spatial sharing, so it follows the procedure described in Section 3.3. After receiving *Channel Quality Reports* from all the STAs, the PCP/AP evaluates ANIPI values in those reports and decides that it is safe to proceed with the spatial sharing. As a result, the PCP/AP reallocates SP2 to start at the same time of SP1. In addition, the PCP/AP exploits the extra time resource gained in the DTI access period due to the spatial sharing and decides to extend the lengths of the two SP to be 32ms. As a result of this operation the total network goodput increases. Figure 11 shows the total network goodput before and after performing spatial sharing.

5 CONCLUSION AND FUTURE WORK

In this paper, we extended the ns-3 IEEE 802.11ad model to support additional techniques that enhance network operation in the 60 GHz band. We provide design and implementation details for dynamic and static channel access schemes, beamformed link maintenance, decentralized clustering, spatial sharing, and half-duplex relay operation. In the evaluation section, we demonstrate the achievable application goodput for both the legacy channel access scheme, i.e, the contention-based access period (CBAP), and the TDMA like access scheme—the so called Service Period Channel Access (SPCA). Then, we demonstrate the performance of half duplex relay operation which is likely to be widely deployed due to its hardware simplicity compared to the FD-AF relay mode. Finally, we show how utilizing the spatial sharing in the mmWave improves the overall network goodput.

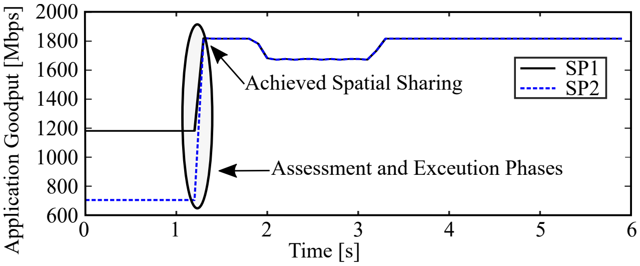


Figure 11: Spatial sharing results.

Our next implementation step is to extend the ns-3 IEEE 802.11ad model to support the first draft of the IEEE 802.11ay amendment. IEEE 802.11ay provides modifications to the operation of MAC and PHY layer to boost the wireless networking performance far beyond the IEEE 802.11ad amendment. For example, it targets much higher throughput of at least 20 Gbps. In addition, it is envisioned to support a range of new use cases such as mobile offloading, data center inter-rack connectivity, wireless back-hauling, and mobile front-hauling. To support these techniques, IEEE 802.11ay utilizes a set of novel wireless communication technologies such as channel bonding, single user multiple-input and multiple-output (MIMO) (SU-MIMO) and multi-user MIMO (MU-MIMO).

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