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The challenges of Scheduling and Resource Allocation in IEEE 802.11ad/ay

Salman Mohebi, Mattia Lecci, Andrea Zanella, Michele Zorzi Department of Information Engineering, University of Padova, Italy E-mails: {name.surname}@dei.unipd.it

Abstract-The IEEE 802.11ad Wi-Fi amendment enables short-range multi-gigabit communications in the unlicensed 60 GHz spectrum, unlocking new interesting applications such as wireless Augmented and Virtual Reality. The characteristics of the Millimeter Wave (mmW) band and directional communications allow increasing the system throughput by scheduling pairs of nodes with low cross-interfering channels in the same time-frequency slot. On the other hand, this requires significantly more signaling overhead. Furthermore, IEEE 802.11ad introduces a hybrid MAC characterized by two different channel access mechanisms: contention-based and contention-free access periods. The coexistence of both access period types and the directionality typical of mmW increase the channel access and scheduling complexity in IEEE 802.11ad compared to previous Wi-Fi versions. Hence, to provide the Quality of Service performance required by demanding applications, a proper resource scheduling mechanism that takes into account both directional communications and the newly added features of this Wi-Fi amendment is needed. In this paper, we present a brief but comprehensive review of the open problems and challenges associated with channel access in IEEE 802.11ad and propose a workflow to tackle them via both heuristic and learning-based methods.

Index Terms—WiFi, 802.11ad, Scheduling, Reinforcement Learning, QoS, mmwave

I. INTRODUCTION

Wi-Fi is nowadays present in many devices and is common in households, offices, public institutions, and transportation. Over more than 20 years, many amendments have been made to the original standard, updating both the Physical Layer (PHY) and Medium Access Control (MAC) layers to provide higher bit-rate, robustness, and Quality of Service (QoS).

As users keep asking for higher data-rates, the current deployments struggle to keep up with the demand. One key enabler for gigabit-class communications is the use of the Millimeter Wave (mmW) band, which loosely refers to the portion of the electromagnetic spectrum with frequencies higher than 6 GHz. In this frequency range, the amount of available bandwidth is significantly larger than that of the legacy sub-6 GHz counterpart, allowing unprecedented transfer speeds.

As the research started to mature, the Wi-Fi Alliance introduced in 2012 the IEEE 802.11ad amendment [1], standardizing communication in the 60 GHz Industrial, Scientific, and Medical (ISM) unlicensed band, offering data-rates up to 6.75 Gbps. As a follow-up, its successor IEEE 802.11ay is planned to be standardized by the end of 2020 [2], introducing technologies such as Multi-User Multiple Input, Multiple Output (MU-MIMO), channel bonding, higher-order modulation, and thus even higher speeds. Such extreme data-rates make it possible to unlock new applications, such as wireless office docking, 8K Ultra High Definition video transfer, wireless Augmented Reality (AR) and Virtual Reality (VR), mobile front-hauling and offloading, etc. [3].

On the downside, given the higher carrier frequency, mmW transmission suffers from an increased propagation loss, as well as deeper diffraction shadows, and higher penetration and reflection losses, making communication more difficult and less stable.

On the other hand, these characteristics allow for extreme spatial reuse, e.g., transmissions in different rooms will hardly interfere with each other unlike in legacy Wi-Fi. Moreover, the short wavelength makes it possible to use antenna arrays with tens of elements packed in a small area, making it is possible to counteract the increased path loss by focusing the radiated power into directive *beams*, thus increasing the overall antenna gain. While this further reduces interference even where users share the same area and improves spatial reuse, it also creates the problem of directional deafness, worsens the hidden node problem, and makes mobility more complex to handle.

To meet the strict QoS requirements of some new applications and partially alleviate the hidden node problem, the standard provides the possibility to transmit data in reserved contention-free periods, that coexist with contention-based access periods, very similar to the legacy Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) channel access mechanism, and the hybrid allocation can be flexible enough to support the coexistence of traffic with vastly different QoS requirements.

In this paper, we present some of the challenges related to the scheduling of IEEE 802.11ad/ay devices in realistic scenarios, with the main focus on the already-standardized IEEE 802.11ad. Furthermore, we discuss some pre-existing works and propose some research directions.

In particular, in Sec. II the main characteristics of IEEE 802.11ad will be described. Sec. III will briefly discuss the literature on channel access and scheduling. Sec. IV will showcase our research plan, and finally Sec. V will draw the conclusions.

II. IEEE 802.11AD OVERVIEW

To introduce the main concepts and nomenclature of IEEE 802.11ad, in this section we provide a short summary of the standard [1], while referring to other sources for more details [4].

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Fig. 1: Graphical representation of sector structure in IEEE 802.11ad.

•	— BHI -		Beacon Interval — DTI —					
BTI	A-BFT	ATI	CBAP	SP		CBAP	$^{\mathrm{SP}}$	Time

Fig. 2: Representation of a Beacon Interval (BI).

Being a mmW-based standard, directional communication with all the added overhead and the possibility of spatially multiplexing users are included in the amendment. To simplify beam management, both the Personal Basic Service Set (PBSS) Central Point/Access Point (PCP/AP) and the Stations (STAs) divide their surrounding space into sectors as shown in Fig. 1. STAs and PCP/AP will then need to keep beam alignment, which increases the signaling overhead.

Fig. 2 shows that in IEEE 802.11ad time is divided in Beacon Intervals (BIs) of about 100 ms. Each BI is further divided into Beacon Header Interval (BHI) and Data Transmission Interval (DTI), briefly described in the following sections.

A. Beacon Header Interval

The PCP/AP does most of the managing, such as beaconing, beamforming training, and scheduling, during the BHI. This period can last hundreds of microseconds up to a few milliseconds, and is further divided into three subintervals: Beacon Transmission Interval (BTI), Association-BeamForming Training (A-BFT), and Announcement Transmission Interval (ATI).

The BTI is used to send Directional Multi-Gigabit (DMG) Beacons to announce the network, give the basic synchronization and BI structure information, start the beamforming training with new stations, and, if needed, do some basic traffic management. Beacons are sent over the different sectors, covering all possible directions to maximize coverage for untrained STAs.

After receiving a DMG Beacon during the BTI, new STAs can use the A-BFT to complete the basic beamforming training by sending Sector Sweep (SSW) frames in different sectors. Beam alignment is completed once the PCP/AP responds with an SSW Feedback.

Finally, advanced scheduling mechanisms setup and further network management can be done during the optional ATI.

B. Data Transmission Interval

The DTI is mainly used for the actual data transmission, but it can also be used to improve communication links and for further scheduling. The DTI comprises Contention-Based Access Periods (CBAPs) and Service Periods (SPs), which can appear in arbitrary combinations and are scheduled during the BHI.

Transmission in Contention-Based Access Period (CBAP) follows the rule of Enhanced Distributed Channel Access

(EDCA), slightly modified to account for directional transmission, in which STAs compete with each other in order to transmit their data.

Instead, Service Periods (SPs) are scheduled contentionfree intervals that are dedicated to exclusive transmission between a pair of STAs¹ to guarantee QoS. The standard also allows for spatial sharing, meaning that multiple pairs of STAs with low cross-interference can be scheduled in the same SPs. This, however, comes at the cost of increased overhead since interference measurements must periodically take place.

III. SCHEDULING IN IEEE 802.11AD

IEEE 802.11ad allows for great flexibility in the scheduling of radio resources, but we will hereby describe only some of these possibilities in their simplest form.

We want to stress the fact that, unlike in traditional contention-based medium access, scheduled SPs guarantee QoS. Access Categories (ACs) introduced in 802.11e, in fact, only allow for stochastic traffic prioritization according to the DiffServ paradigm, which ceases to work in congested networks. For this reason, allocated traffic is especially important for those applications with strict QoS constraints. Instead, more realistic applications, such as data transfer or asynchronous bursty traffic, can simply rely on CBAP.

As shown in Fig. 3, a STA can set up an allocation by sending an Add Traffic Stream (ADDTS) Request frame to the PCP/AP during the DTI and embedding a DMG Traffic Specification (TSPEC) element. The DMG TSPEC element is created by the requesting STA and comprises information such as the allocation period, and the minimum and maximum allocation duration.

Based on its admission policy, the PCP/AP will either reject or accept the request, immediately notifying the requesting STA via an ADDTS Response. If accepted, the allocation is made effective by including it in the Extended Schedule Element (ESE) transmitted in the next DMG Beacons, which will contain details such as the effectively allocated period duration and the SP start time. In this way, STAs not involved in the communication will not create interference and will be able to switch to power-saving mode. Otherwise, the PCP/AP can either reject or propose a change in the DMG TSPEC. A STA can later update the DMG TSPEC by sending another ADDTS Request with the updated element and follow again the same procedure.

Allocating the right duration to SPs is clearly a trade-off between QoS traffic, which needs resources to fulfill the minimum requirements imposed by the application, and elastic traffic, which still needs resources even though with less stringent requirements. Since resource availability, as well as channel quality, are time-varying, the standard supports SP extension and truncation services, which let the stations keep transmitting and/or relinquishing the unused occupied channel. Still, these features bring extra overhead and should thus be used carefully.

A mathematical model for preliminary allocation of SP for Variable Bit Rate (VBR) flows is presented in [5], which helps determine how to set the TSPEC parameters to meet QoS requirements while minimizing the amount of allocated time. Unfortunately, SPs are assumed to be placed at the

¹A PCP/AP also contains a STA, i.e., a logical entity that is a singly addressable instance of a MAC and PHY interface to the wireless medium [1].



Fig. 3: Representation of ADDTS scheduling in IEEE 802.11ad.

beginning of the DTI, which is not possible in general for applications with tight delay constraints. For example, for virtual or augmented reality services, latencies should be below 20 ms to avoid motion sickness.

Other works in the literature consider different aspects of the DTI. For example, [6] derives the theoretical maximum throughput for CBAPs when two-level MAC frame aggregation is used. Beamforming is also considered in [7], which proposes a joint optimization of beamwidth selection and scheduling to maximize the effective network throughput, while other works, though not specifically concerning IEEE 802.11ad, deal with transmission scheduling for mmW communications [8].

IV. FUTURE RESEARCH

In this section, we highlight some possible research directions. In particular, in Sec. IV-A we describe the main tools that are currently available to study the subject. Then, in Sec. IV-B we propose a possible research plan.

A. Available Research Tools

Although commercial devices supporting the IEEE 802.11ad standard are currently available, manufacturers do not provide tools to access low-level functionalities. Ultimately, it is more flexible, timely, and cost-effective, although arguably less realistic, to simulate the behavior of such devices.

In particular, significant effort has already been done implementing the IEEE 802.11ad standard into Network Simulator 3 (ns-3) [9], a popular open-source network-level simulator. The last release of the simulator also supports quasi-deterministic channel modeling based on ray-tracing, making simulations extremely accurate and realistic at the cost of a long preliminary channel generation phase, although some works already tried to improve this aspect [10]. While the implementation already covers most parts of the standard, it is still missing the scheduling mechanisms necessary for this project. The authors of [9] are also working on the implementation of the IEEE 802.11ay amendment [11], making their work even more valuable.

Historically, scheduling algorithms have been mainly based on heuristics, trying to balance performance and adaptiveness versus complexity. In the last years, instead, the Machine Learning (ML) revolution has brought many innovations also to the telecommunication field at all layers of the stack and, in particular, Reinforcement Learning (RL) is especially applicable to optimize or even replace legacy scheduling algorithms [12]. Following the principle of *selfdriving networks* [13], ML algorithms can learn from real online data and supersede manually-designed protocols, which are becoming increasingly complex. OpenAI Gym is one of the most used RL toolkits and has been adopted by all popular ML frameworks. Given their potential in many fields of networking and telecommunications in general, OpenAI Gym APIs have also been integrated into ns-3 [14] with the name of *ns3-gym*.

With these powerful tools, it will be possible to further advance the state of the art, create a comprehensive performance evaluation of available algorithms and further improve upon them once the weak points are clearly identified.

B. Research Plan

One of our first goals is to extend the already existing IEEE 802.11ad ns-3 module with the necessary mechanisms to make it properly support the hybrid channel access and advanced scheduling (see Sec. IV-A), and add the support to the ns3-gym framework. A significant development effort will be put into the creation of a proper simulation environment, with particular attention to the computational complexity since a high data-rate simulation of just 10 s of simulated time may currently take one hour or more of run-time. This makes the design, evaluation, and optimization of scheduling protocol a lengthy process, which may be even infeasible if RL is involved since many training episodes are needed to learn even basic mechanisms.

Indeed, decisions such as admission policy, resource allocation, smart SP truncation or extension, and spatial sharing are often difficult to accurately model in terms of trade-offs and usually comprise several tunable parameters. However, if trained correctly, an RL agent is often capable of learning extremely complex rules and optimize the network for different networking metrics (e.g., delay, jitter, throughput, fairness) even beyond complicated heuristics.

Resource allocation can be divided into two subproblems. Specifically, STAs have to translate information given by the application into DMG TSPEC elements and the PCP/AP subsequently has to efficiently schedule the DTI especially considering the Modulation and Coding Scheme (MCS) used. Regarding the former, applications may not yield constant inter-packet arrival time (e.g., frame-rate drop in video applications) nor packet size (e.g., when compression is considered). At the same time, transmission conditions may vary mainly due to environmental changes, mobility, or even blockage, thus increasing performance variability. If QoS requirements are not met, the RL agent of a STA could thus update the TSPEC.

On the other hand, the PCP/AP has to allocate SPs for a BI based on the available resources. Effective scheduling must take into account, in addition to network metrics, the possible evolution of the MCS since the packet transmission time largely depends on it. Given the significant differences in channel dynamics of IEEE 802.11ad with respect to sub-6 GHz Wi-Fi, new ones can be proposed to account for the specific characteristics of the mmW channel. An RL agent could thus jointly adapt the MCS and perform scheduling to optimize the network performance by observing the evolution of both channel statistics and network traffic.

One way to overcome the problem of slow simulations is to quickly pre-train the RL agent to make it learn at least simple decisions, such as understanding when a new request does not fit the available resources, avoid overlapping SPs during scheduling, and avoid scheduling highly crossinterfering users with spatial sharing. Thus, we plan to build a very simple and fast simulator that will only model relevant notions, e.g., basic channel and traffic modeling and the BI structure defined in IEEE 802.11ad, but eliminating the fine details which make ns-3 realistic but extremely slow. In this way, the agent can learn very broadly which actions it should take and then fine-tune its behavior via more realistic simulations. Then, to further decrease ns-3 simulation runtime, a database of simulation results can be created and multiple agents can passively learn from it [15] before finetuning their performance on ad hoc simulations. Transfer learning will also be considered to speed up convergence to effective policies in different scenarios.

Another objective will be to understand the traffic behavior of target applications. For example, it could be possible to acquire real-world traffic traces of AR/VR applications, characterizing and modeling their traffic patterns with focus on packet size, and variability of inter-packet arrival accounting for variable frame-rate statistics. These models would ultimately be integrated with standardized scenarios [16], [17] to further increase simulation realism.

Furthermore, understanding how the current state of the art performs in a realistic simulator will allow understanding the strong and weak points of the proposals in realistic settings. From detailed studies, it will be possible to understand how the state of the art can be improved upon with heuristics or, when modeling becomes too complex or inaccurate, MLbased approaches.

These results will then be easily transferred to the future IEEE 802.11ay standard, which will add further complexity on top of the already existing one, by introducing channel bonding and MU-MIMO. Even more complex schedulers will then have to be designed, but starting from the solid ground of the proposed work further improvements will be possible.

V. CONCLUSIONS

In this paper we briefly described the main characteristics of IEEE 802.11ad, mainly focusing on the MAC layer and especially on the newly introduced scheduling mechanisms, allowing different types of traffic to coexist and potentially improving the performance of QoS-sensitive applications. As shown in Sec. III, some research has already been done in this direction but lacks a common and realistic testing ground, making it unclear whether the assumptions may hold.

Our future work will focus on proposing solutions for the many open problems described in Sec. IV-B. Models and source code that will be considered of interest for the community will be published, making it possible to fairly compare results from different groups in a common and realistic simulation environment.

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