# A Simulation Framework for Contention-Free Scheduling on WiGig

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Abstract—The latest IEEE 802.11 amendments provide support to directional communications in the Millimeter Wave spectrum and, thanks to the wide bandwidth available at such frequencies, makes it possible to wirelessly approach several emergent use cases, such as virtual and augmented reality, telepresence, and remote control of industrial facilities. However, these applications require stringent Quality of Service, that only contention-free scheduling algorithms can guarantee. In this paper, we propose an end-to-end framework for the joint admission control and scheduling of periodic traffic streams over mmWave Wireless Local Area Networks based on Network Simulator 3, a popular full-stack open-source network simulator. Moreover, we design a baseline algorithm to handle scheduling requests, and we evaluate its performance with a full-stack perspective. The algorithm is tested in three scenarios, where we investigated different configurations and features to highlight the differences and trade-offs between contention-based and contention-free access strategies.

Index Terms-WiGig, 802.11ad, 802.11ay, Periodic, Scheduling

## I. INTRODUCTION

Indoor Wi-Fi networks have had a key role in the digital revolution of the last two decades, as wireless technologies paved the way toward the design of applications for work settings (e.g., smart metering, remote control) and house entertainment (e.g., Augmented Reality (AR), Virtual Reality (VR), eXtended Reality (XR)). From a technical point of view, these new applications also changed the infrastructure requirements, with higher required data rate, lower delay thresholds, and brand new classes of Quality of Service (QoS) constraints.

To face these challenges, moving to the Millimeter Wave (mmW) spectrum has proven to be a valuable alternative to the widespread sub-6 GHz spectrum used by legacy wireless architectures, given the abundant bandwidth available in the former frequency range. For this reason, in an effort to create a common playground for researchers and manufacturers, the IEEE devised specific amendments to update the Physical Layer (PHY) and Medium Access Control (MAC) layers in what is known as Wireless Gigabit (WiGig), first with 802.11ad [1] in 2012 and now with 802.11ay [2].

In particular, WiGig standards introduced a new contentionfree strategy to access the transmission medium at specific time intervals, referred to as Service Periods (SPs). A Station (STA) can request SPs to the Personal Basic Service Set (PBSS) Central Point/Access Point (PCP/AP) asking for a specific duration and periodicity. A detailed overview of such procedure will be later described in Sec. III.

This new access strategy can be useful for applications with stringent QoS requirements, i.e., throughput, delay, and jitter, which may be heavily affected by legacy, contentionbased channel access mechanisms. Moreover, applications such as video streaming or VR can generate periodic traffic, whose performance with contention-based channel access can degrade, given the uncertain availability of resources from one time interval to another. Fortunately, WiGig provides specific scheduling mechanisms to directly support periodic applications with tight QoS constraints. From a practical point of view, however, dealing with concurrent periodic traffic streams from multiple users is not easy since the designed policy should be able to manage heterogeneous requests, while possibly guaranteeing fairness among different flows.

Considering all these aspects, in this work we propose an End-to-End (E2E) framework to manage distinct traffic flows based on the requirements provided by the WiGig standards, taking care of the admission and scheduling of new allocation requests. Besides, using this framework, we design a baseline algorithm to allocate periodic requests and validate its trade-offs through a detailed full-stack performance evaluation. To do so, we extend the module described in [3], which integrates into Network Simulator 3 (ns-3) the new features of 802.11ad, and publicly release the source code to the research community.

The rest of the paper is organized as follows. In Sec. II we overview the literature on this topic, while in Sec. III we describe the framework we designed and implemented in an open-source full-stack network simulator. Then, we accurately describe the simulation setup in Sec. IV and discuss the performance of the scheduling algorithms in Sec. V. Lastly, in Sec. VI we draw our conclusions and propose possible extensions to this work.

## II. STATE OF THE ART

The optimization of Wi-Fi's MAC layer procedures has been investigated in the literature, even before WiGig standards were introduced. Most of these works, however, mainly focus on Contention-Based Access Periods (CBAPs) and do not

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consider the possibility of using Service Periods (SPs). Starting from 802.11ad, the possibility of allocating contentionfree resources gained further momentum, considering also the directional characteristic of mmWave channels. An attempt to prioritize the traffic injected in the network was done for 802.11e, where four Access Categories (ACs) were introduced. Based on which category they belong to, packets with higher priority use a shorter Arbitration Inter-Frame Space (AIFS) and thus they wait less before being transmitted. A study of 802.11e contention-based prioritization mechanisms was provided in [4].

A mathematical framework to analyze E2E metrics on 802.11-based systems was proposed in [5], to compare throughput and average packet delay in scenarios where the nodes are equipped with advanced antenna systems. It also accounts in detail for the characteristics of the Distributed Coordination Function (DCF), for which a theoretical performance analysis was carried out in [6].

Likewise, the authors in [7] presented a detailed analytical model to assess the performance of CBAPs in 802.11ad, taking into account a directional channel model and the presence of scheduled SPs. Yet, the model lacked the details about how to schedule such SPs for certain types of relevant applications, such as periodic ones.

A seminal study on the use of Reinforcement Learning (RL) to solve the problem of jointly scheduling CBAPs and SPs in 802.11ad is in [8], where ns-3 was used to assess how the algorithm could decrease the Data Transmission Interval (DTI) occupancy while guaranteeing state-of-the-art QoS performance.

In general, in the context of WiGig networks, little work has been done on the scheduling of contention-free time resources. Moreover, to the best of our knowledge, little to no work in the literature faces the problem of periodic scheduling with all the constraints introduced by WiGig standards. The authors of [9], [10], for example, study the case where all SPs are allocated at the beginning of each Beacon Interval (BI), while the rest of the interval is left for a single CBAP. In [11] they propose an accurate mathematical analysis of the performance of a realistic Variable Bit Rate (VBR) traffic source in the presence of channel errors when using a periodic resource allocation scheme. How to schedule multiple allocations at once, however, has not been detailed.

On the other hand, the problem of periodic scheduling has been studied for real-time computation and task scheduling, where the goal is to complete some tasks before a certain deadline while minimizing resource utilization. For example, the authors of [12] proposed a scheduling algorithm to dynamically assign priorities, capable of achieving full processor utilization. In [13], the authors provide a framework for allocating periodic tasks in multiprocessor systems, which takes into account their requirements, while periodicity constraints are translated into time deadlines.

All these approaches, however, cannot be adapted to the WiGig framework, as the constraints imposed by the standardized resource allocation procedures are completely different.

### III. NS-3 SCHEDULING FRAMEWORK

In this section, we describe the design choices and assumptions necessary to implement our scheduling framework on top of the 802.11ad ns-3 module [3], with a focus on MAC layer mechanisms.

First of all, WiGig standards refer to the BI as the unit time interval used by the devices to organize association, beamforming, and data transmission procedures. To this aim, it is further divided into Beacon Header Interval (BHI) and DTI.

The BHI is then organized into Beacon Transmission Interval (BTI), Association-BeamForming Training (A-BFT), and Announcement Transmission Interval (ATI), and it is devoted to association, beamforming, and scheduling procedures. STAs can communicate during the DTI using Contention-Based Access Periods (CBAPs), or using dedicated and prearranged SPs, that guarantee some resources to a given user who made request to the PCP/AP.

The standards do not pose any constraint on the number, order, or type of these transmission slots in the DTI, however, each STA must follow a common procedure to request such resources. Since we are mainly interested in periodic applications, in this work we focus on *isochronous pseudostatic* allocations allocated using Add Traffic Stream (ADDTS) Request/Response scheduling elements.

First, a STA sends an ADDTS Request to the PCP/AP, specifying parameters such as the *Allocation Period* (if any), the *Minimum* and *Maximum Allocation* duration in each allocation period, the *pseudo-static* flag, which allows for persistent allocations over multiple consecutive BIs, among others. After that, if the PCP/AP can accommodate the new request, it sends back an ADDTS Response, specifying the allocated duration and the starting time.

Our work [14] mainly focused on the design and implementation of a generic scheduling interfaces, called DmgWifiScheduler, that implements the scheduling features for the MAC entity of the PCP/AP. Starting from this class, we extended it to create the PeriodicWifiScheduler, a simple scheduler for the allocation of periodic resources. Moreover, to study how a contention-based-only approach affects the overall QoS, we also created the CbapOnlyWifiScheduler, forcing STAs to transmit only over CBAP by allocating the entire DTI as such.

Even though the performance evaluation, presented in Sec. V, considers only allocations with the same period and application requirements for all STAs, scheduled starting from the beginning of the DTI back to back as long as they fit, it is crucial to elaborate on the design choices that lead to this framework.

Thus, PeriodicWifiScheduler includes the following assumptions:

• Only SP allocations with period equal to an integer fraction of a BI are supported, while the standards also support periods multiple of the BI.

TABLE I: Simulation parameters

MCS	4 (fixed)	APP period $(T_{APP})$	T
Max A-MSDU size	7 935 B	Packet size	1448 B
Max A-MPDU size	262 143 B	Traffic direction	Uplink
BI duration $(T_{BI})$	T	Simulation duration	10 s
SP period $(T_{SP})$	T	Independent runs	30
Network protocols	IPv4/UDP	T	102.4 ms

- If the period is  $t = T_{BI}/p$ , the request is accepted only if the available time in the DTI can accommodate exactly p SPs, commonly referred to as allocation blocks, each distanced by t. For example, if p = 4, the number of blocks per BI must be exactly 4.
- A STA can send an ADDTS Request to reduce the duration of the allocation, while the increase is not supported as it possibly requires a major reorganization of the DTI.
- Once an allocation is accepted, the SPs duration and blocks starting time cannot be changed by the scheduler, even if the DTI structure changes as a consequence of subsequent requests from other STAs.
- All the time that is not reserved by SPs will be allocated as CBAP.

These constraints allowed us to validate our results in a clear setting with firm requirements.

## IV. SIMULATION SETUP

The network scenario consists of a single PCP/AP in the center of a room, surrounded by STAs with perfect channel conditions, with simulation parameters listed in Table I.

To emulate periodic traffic, we implemented a *periodic application* that generates periodic packet bursts, whose size and period can be set as a parameter of the application, with every single packet being of size 1 448 B. Traffic is generated by the STAs and sent to the PCP/AP.

Since we expect CBAP-only scheduling to yield good performance when a small amount of traffic is sent over the network, and the SP scheduling to show its full potential for highly loaded networks, we defined the *normalized offered* traffic which we refer to as  $\eta$ . By varying  $\eta$  in (0, 1], we control the traffic injected in the network, equally distributed among the number of stations.

For instance, in a scenario with N = 4 STAs transmitting using Modulation and Coding Scheme (MCS) 4 with a nominal PHY rate of  $R_4 = 1\,155$  Mbps, for  $\eta = 0.5$  the aggregate average offered traffic should be  $\eta R_4 = 577.5$  Mbps, and thus each STA will generate about  $\eta R_4/N \approx 144$  Mbps.

Note that with  $\eta = 1$ , the offered PHY rate would be exactly 1155 Mbps, thus overloading the network. In fact, a portion of each BI is always reserved for the BHI where STAs are not allowed to transmit information, reducing the overall network capacity. On the other hand,  $\eta = 0$  would translate in no traffic injected into the network. For this reason, in Sec. V we will show results for traffic loads  $\eta \in [0.01, 0.9]$ .

In all our simulations, the period of all periodic applications  $T_{APP}$ , the period of all scheduled SPs  $T_{SP}$ , and the duration

of the BI  $T_{BI}$  are all the same, and thus simply noted as T = 102.4 ms. Based on the value of  $\eta$ , the number of packets making up a burst is constant as well, and they are all generated at the beginning of each application period.

The duration of each SP is computed based on the MCS and the application rate for the full transmission burst to fit exactly into the SP. The minimum and maximum duration fields in the ADDTS Request are thus equal, meaning that the request is either accepted by the PCP/AP guaranteeing the exact amount of resources necessary to serve its application, or rejected, and the rejected STA will remain silent for all the simulation.

If the ADDTS Response for a given STA is accepted, its application will start randomly over a period T, and thus, by default, will not be aligned with the beginning of its assigned SPs. To fully take advantage of the scheduling concept, however, application and SPs should be aligned to yield the best possible performance. To do so, the APP layer has to be aware that the transmission will happen over a WiGig network as well as the details of the scheduled SPs, requiring some information exchange with the MAC layer. This might be possible for some types of applications running on specific hardware, e.g., VR headsets and, in general, for high-end hardware running applications that require tight delay constraints. For this reason, we defined a smart mode which, if activated, makes the application start at the beginning of the first allocated SP, thus assuming a cross-layer interaction and alignment. Nonetheless, this does not take into account applications with non-deterministic periods, which could lose the alignment in the following SPs.

We compare the performance of four scheduling configurations, namely:

- CBAP-only: all STAs transmit during the CBAP.
- *SP Config. #1*: the *smart start* mode is enabled. STAs are also allowed to transmit in the CBAP if necessary.
- SP Config. #2: smart start is disabled and STAs cannot transmit in the CBAP.
- SP Config. #3: smart start is disabled and STAs are allowed to transmit in the CBAP if necessary.

The performance evaluation of the proposed scheduling schemes has been carried out in three distinct scenarios.

- *First scenario*: four STAs transmit at different values of  $\eta$  using a deterministic application with period *T*.
- Second scenario: all applications offer the same APPlayer rate of R = 50, 100, 200 Mbps with a deterministic period of T, varying number of STAs up to 10.
- Third scenario: four STAs transmit a heavy traffic load  $(\eta = 0.75)$  using applications with random period. Periods are independently sampled one after the other  $\mathbf{T}_i = \mathcal{N}(\mu, \sigma^2)$ , where  $\mu = T$  and  $\sigma = \rho T$ , calling  $\rho$  the period deviation ratio. Thus, for a given STA, bursts will occur at times  $\mathbf{t}_k = t_0 + \sum_{i=1}^k \mathbf{T}_i$ .

## V. RESULTS

In this section, we evaluate the performance of the different configurations considering a number of packet-based Key

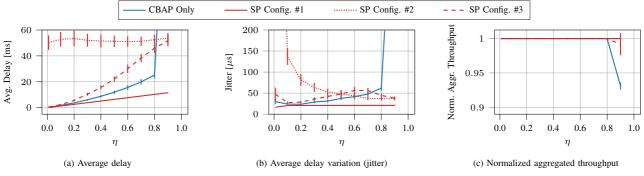


Fig. 1: Performance of the different scheduling configurations with a bursty application with deterministic period T = 102.4 ms.

Performance Indicators (KPIs). First of all, the *average delay* takes into account only successfully received packets. For some relevant scenarios we also show the packet *jitter* [15], defined as the average absolute delay variation among successive packets. The *aggregated throughput* is also considered as a metric for network utilization, sometimes normalized by the amount of aggregated offered traffic. Finally, all metrics also show the 95% confidence intervals computed as  $1.96 \frac{\sigma_{runs}}{\sqrt{N_{runc}}}$ .

*a) First Scenario:* Fig. 1 shows the results for the first proposed scenario, where we compare the four scheduling configurations against traffic load, considering a deterministic application, as described in Sec. IV.

In Fig. 1a we show the *average delay* for this scenario. Note that an increasing  $\eta$  directly translates into an increased burst size, since more packets have to be delivered in a given period T, thus increasing the achievable average delay.

When the scheduling of SPs is not allowed, CBAP-only offers almost ideal delay performance for low traffic loads, which however degrades for higher loads and even becomes unstable for  $\eta > 0.8$ .

Instead, SP configuration #1, i.e., using *smart start*, is clearly the optimal strategy and represents a lower bound for all other configurations, since packets are sent immediately and back-to-back.

SP configuration #2, where *smart start* is not used and STAs with scheduled SPs are *not* allowed to access the CBAP, shows an almost constant average delay of about 51.2 ms = T/2. It can be proven that an application with period T with a uniformly distributed start time, which can only transmit during an SP of the same periodicity T and with a duration equal to what is needed to transmit the packet burst, has an expected average delay of exactly T/2, irrespective of the traffic load or the number of transmitting nodes. In fact, application bursts will happen either (i) sometime during the ongoing SP, so that the next SP will also be needed to finish sending the whole burst causing a large increase of the average delay, or (ii) outside an SP, thus needing to wait for the start of the next SP but being able to send the whole burst at once.

Finally, for SP configuration #3, where *smart start* is not used but STAs with scheduled SPs are allowed to also access the CBAP, the performance is lower bounded by the CBAP-only scheduling and upper bounded by SP configuration #2.

In fact, application bursts can either start during an ongoing SP or a CBAP and thus have to be split among different SPs or CBAPs. For low traffic loads  $\eta$ , traffic will mostly be sent during the CBAP, mimicking the CBAP-only scheduler's performance. Instead, considering node k, as  $\eta$  increases, SPs allocated for nodes  $\neq k$  will prevent it from freely transmitting over the whole BI, forcing it to either wait for its next SP or to concur with an increasingly busy and shorter CBAP, getting closer to the behavior (and the performance) of SP configuration #2. Contrary to what happens for the CBAP-only scheduler, though, the PCP/AP has a way to control the traffic flow by rejecting ADDTS Requests, preventing the traffic from becoming unstable even for higher loads, at the cost of possibly denying some STAs to transmit.

In Fig. 1b we show the *jitter* performance for the first scenario. Again, as expected, CBAP-only scheduling shows an increasing jitter with an increasingly loaded network and becomes unstable for  $\eta > 0.8$ , while SP configuration #1 shows constant jitter irrespective of the traffic load, always lower than any other scheduling schemes.

Similar to what happened for the average delay, SP configuration #2 has to account for two opposing trends. Note that bursts starting during the CBAP will have extremely low jitter since they will be sent entirely during the next SP. On one hand, a lower  $\eta$  translates to shorter SPs, making it more likely for application bursts to start during a CBAP. Bursts starting during a CBAP will be sent entirely during the next SP, resulting in a low jitter, while those starting during an SP will have to be split among two consecutive SPs, making one packet increase the jitter significantly. On the other hand, a lower  $\eta$  also reduces the burst size and, conversely, the number of packets composing the burst, making the single packet with higher delay variation weigh more in the average and thus affecting the jitter. This second effect appears to be predominant and thus the jitter decreases as the traffic load increases.

SP configuration #3 shows higher jitter than CBAP-only for lower values of  $\eta$ , since other nodes' SPs possibly interfere with the transmission of a full uninterrupted burst, while higher values of  $\eta$  show a decreasing jitter. This suggests that as the CBAP is reduced to leave space for the allocated SPs, nodes will be forced to use it less in favor of their allocated SPs,

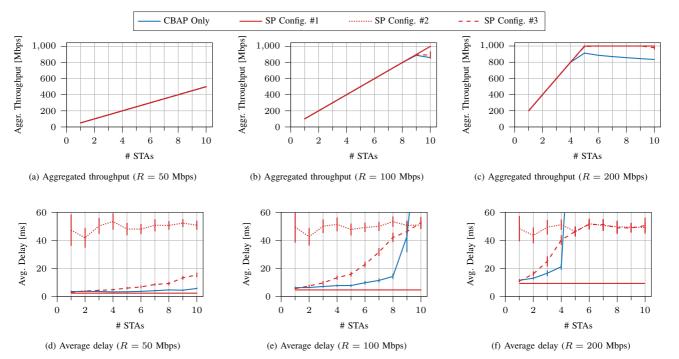


Fig. 2: Performance of the four scheduling configurations using a bursty application with period equal to T = 102.4 ms, and an offered rate R for each user.

where transmissions are ensured and more stable but at the cost of a higher delay.

Finally, we show the *aggregated throughput* normalized by the offered traffic in Fig. 1c. Clearly, all SP configurations can fully allocate the BI, resulting in unit normalized throughput. The only exception to this is SP configuration #3: allowing allocated users to also exploit the CBAP resources might prevent new users from transmitting in a timely fashion. In fact, for high traffic loads, not only is the CBAP greatly reduced, but allocated STAs also contend for those resources, starving new users who might want to transmit non-QoS traffic or, as it happens in this case, send an ADDTS Request to schedule additional SPs, an event that clearly cannot happen when allocated users do not exploit CBAP resources.

Instead, the CBAP-only scheduler can only withstand the traffic demand for  $\eta \leq 0.8$ , then, as also noted for other metrics, the Wi-Fi contention mechanism loses its effectiveness making the traffic unstable and starting to lose packets.

*b)* Second scenario: In Fig. 2 we show the performance for the second scenario, where a fixed application rate was considered with a varying number of users.

Clearly, since MCS 4 was used with a PHY rate of 1155 Mbps, for rates R = 50 and 100 Mbps, all scheduled SP allocations were able to meet the offered data rate (see Figs. 2a and 2b). Only SP configuration #3 was not fully able to support the full 1 Gpbs as previously discussed for the first scenario. Furthermore, also the CBAP-only case was unable to meet the aggregate demand since 1 Gbps of offered traffic or more corresponds to  $\eta > 0.8$  and, as suggested by the results shown for the first scenario, is thus unstable.

Regarding the average delay performance shown in Figs. 2d

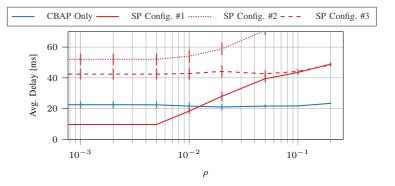


Fig. 3: Average delay of the different scheduling configurations with a bursty application with normally distributed period, with mean equal to T = 102.4 ms and standard deviation equal to a fraction of its mean  $\sigma = \rho T$ .

to 2f, similar results to the first scenario can be observed.

Using only the CBAP yields good performance for low traffic loads, which in this case corresponds to a lower number of users, while it remains unstable for high traffic loads.

Instead, while SP configuration #1 is the lower bound achievable by any configuration consistently across all cases, SP configuration #2 is the upper bound for all SP configurations. As the offered traffic load increases, i.e., as more STAs transmit with higher application rates R, SP configuration #3 tends to have the same performance as SP configuration #2, as less CBAP is available.

c) Third scenario: Fig. 3 shows the average delay for the third proposed scenario, where we compare the four scheduling strategies considering a load of  $\eta = 0.75$  and an application with random period against its *period deviation* 

ratio  $\rho$ , as described in Sec. IV. Note that  $\rho = 0$  coincides with a deterministic application.

As expected, the CBAP-only case is not affected by the random periodicity of the application.

Similar to the first scenario, SP configuration #3 shows worse performance than the CBAP-only scheduler, as users can only transmit in their own SPs or during the CBAP. Since the applications are not synchronized with the SPs to begin with, also in this case the performance is not affected by the random periodicity of the application.

On the other hand, SP configuration #1, appears to be optimal only for almost-deterministic applications, i.e., for extremely low values of  $\rho$ . In fact, *smart start* only synchronizes the application with the first allocated SP, meaning that if an application has a random period, bursts starting from the second one will be out of sync. Since we allowed STAs to use the CBAP for SP configuration #1, as  $\rho$  increases, performance gets worse reaching the same average delay as SP configuration #3, where cross-layer alignment is not enabled.

Even worse, SP configuration #2 shows by far the worst behavior. Not only is its performance bad for the deterministic case, but since STAs are only allowed to transmit during their own SPs and the SP duration was computed to be exactly the time required to send the whole burst, the random periodicity of the application further worsens the performance. In fact, if one period is longer than T, part of an SP might never be used, although the average traffic will still require all SPs to be fully utilized. The more random the application, the more likely this event, possibly leaving more and more portions of SPs not utilized.

d) Results Overview: To summarize, the simulation results show that when the network load is low, contention-based channel access is capable of yielding overall good performance, but as the amount of offered traffic increases, average delay and jitter are quickly affected. Instead, SP scheduling shows its full potential only when cross-layer information is exchanged between the APP and the MAC layer, allowing the application to synchronize with the scheduled SPs.

Furthermore, we showed that if (i) the application and the SP allocations share the same period T, (ii) STAs can only transmit during their own SPs, (iii) the SP duration coincides with the time required to transmit the burst, and (iv) the application start time is uniformly distributed over a period T, then the average delay is equal to T/2, irrespective of the burst size, the number of users, or the network traffic load.

On top of this, SP scheduling allows the PCP/AP to accept and reject incoming traffic flows, allowing better control of the network even in the most intensive traffic regimes, thus being able to ensure to a limited number of users the required amount of resources without making the transmission unstable, unlike contention-based access alone.

Finally, we showed that small amounts of randomness in the period duration can easily favor the simpler contentionbased access over the more complex SP scheduling, but further studies need to be done as the setup was extremely simple.

### VI. CONCLUSIONS

In this paper, we presented an open-source scheduling framework for WiGig based on the ns-3 implementation of the IEEE 802.11ad standard [14]. We implemented two schedulers, one based on contention-based channel access, the other based on periodic SP allocations, and compared their performance on three different scenarios. Results show that SP scheduling is able to surpass contention-based channel access and yield the best performance only when cross-layer information between the MAC and APP layers is exchanged. Moreover, adding even small amounts of randomness to the periodic application results in great performance degradation for periodic SP scheduling, making contention based-access the preferred option in most cases. Future works will mainly focus on more complex scenarios and schedulers involving, e.g., more realistic traffic models or dynamic mmW channel modeling.

#### REFERENCES

- [1] Task Group ad, 802.11ad-2012 IEEE Standard for Information technology – Telecommunications and information exchange between systems – Local and metropolitan area networks – Specific requirements-Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 3: Enhancements for Very High Throughput in the 60 GHz Band, IEEE P802.11 Std., Dec. 2012, superseded.
- [2] Task Group ay, "Status of project IEEE 802.11ay," 2015. [Online]. Available: http://www.ieee802.org/11/Reports/tgay\_update.htm
- [3] H. Assasa and J. Widmer, "Implementation and evaluation of a WLAN IEEE 802.11ad model in ns-3," in *Workshop on Ns-3 (WNS3)*, Seattle, WA, US, Jun. 2016.
- [4] G. Bianchi, I. Tinnirello, and L. Scalia, "Understanding 802.11e contention-based prioritization mechanisms and their coexistence with legacy 802.11 stations," *IEEE Network*, vol. 19, no. 4, pp. 28–34, 2005.
- [5] F. Babich and M. Comisso, "Throughput and delay analysis of 802.11based wireless networks using smart and directional antennas," *IEEE Trans. Commun.*, vol. 57, no. 5, pp. 1413–1423, May 2009.
- [6] G. Bianchi, "Performance Analysis of the IEEE 802.11 Distributed Coordination Function," *IEEE Journal on Selected Areas in Communications*, vol. 18, no. 3, pp. 535–547, Mar. 2000.
- [7] C. Pielli, T. Ropitault, N. Golmie, and M. Zorzi, "An Analytical Model for CBAP Allocations in IEEE 802.11ad," *IEEE Transactions* of Communications, vol. 69, no. 1, pp. 649–663, Jan. 2021.
- [8] T. Azzino, T. Ropitault, and M. Zorzi, "Scheduling the Data Transmission Interval in IEEE 802.11ad: A Reinforcement Learning Approach," in *International Conference on Computing, Networking and Communications (ICNC)*, Big Island, HI, US, Feb. 2020.
- [9] C. Hemanth and T. G. Venkatesh, "Performance Analysis of Contention-Based Access Periods and Service Periods of 802.11ad Hybrid Medium Access Control," *IET Networks*, vol. 3, no. 3, pp. 193–203, Sep. 2014.
- [10] M. U. Rajan and A. Babu, "Saturation Throughput Analysis of IEEE 802.11ad Wireless LAN in the Contention Based Access Period (CBAP)," in *IEEE Distributed Computing, VLSI, Electrical Circuits and Robotics (DISCOVER)*, Mangalore, India, Aug. 2016.
- [11] E. Khorov, A. Ivanov, A. Lyakhov, and V. Zankin, "Mathematical Model for Scheduling in IEEE 802.11ad Networks," in *IFIP Wireless and Mobile Networking Conference (WMNC)*, Colmar, France, Jul. 2016.
- [12] C. L. Liu and J. W. Layland, "Scheduling Algorithms for Multiprogramming in a Hard-Real-Time Environment," *Journal of the ACM*, vol. 20, no. 1, pp. 46–61, Jan. 1973.
- [13] K. Ramamritham, "Allocation and Scheduling of Precedence-Related Periodic Tasks," *IEEE Transactions on Parallel and Distributed Systems*, vol. 6, no. 4, pp. 412–420, Apr. 1995.
- [14] SIGNET group. [Online]. Available: https://github.com/signetlabdei/ ns3-802.11ad-scheduling
- [15] C. M. Demichelis and P. Chimento, "IP Packet Delay Variation Metric for IP Performance Metrics (IPPM)," RFC 3393, Nov. 2002.