High Fidelity Simulation of IEEE 802.11ad in ns-3 Using a Quasi-deterministic Channel Model

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ABSTRACT

Supporting high data-rates and a large number of connected devices has always been challenging for wireless technologies operating in the microwave band. Wireless communication in the millimeter band is a promising solution to address this challenge and deliver gigabit throughput and very low latency. However, efficient communication in this band poses a great challenge in terms of radio resource allocation and requires adequate network planning and efficient design of wireless networking protocols. Despite the availability of commercial devices utilizing the IEEE 802.11ad protocol, these devices provide only limited access to the operations of the lower layers of the protocol stack, which hinders in-depth analysis and development of innovative solutions. For these reasons, researchers rely on high-fidelity system-level simulators to understand the interactions and behavior of millimeter-wave communication devices. In this paper, we demonstrate the capabilities of the IEEE 802.11ad model in ns-3. This model allows researchers to study the performance of the IEEE 802.11ad protocol for various deployment settings with high fidelity, using realistic phased antenna arrays and quasi-deterministic channel models. More particularly, we look at the impact of LOS blockage and the use of NLOS paths on link performance. In addition, we show the benefits of deploying multiple access points per room to guarantee gigabit throughput per user. Finally, we evaluate the performance of the IEEE 802.11ad protocol in a typical high-density scenario consisting of a single access point and ten stations.

CCS CONCEPTS

• **Networks → Network simulations**; **Wireless local area networks**;

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KEYWORDS

Millimeter Wave, IEEE 802.11ad, Q-d Channel, 60 GHz, WiGig, ns-3, Simulations

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1 INTRODUCTION

In recent years, the telecommunication industry is focusing more and more on exploiting the under-utilized spectrum between 30 GHz and 300 GHz, the so-called millimeter-wave (mmWave) bands. The large spectrum available in these bands paves the way for a new set of applications (e.g., augmented reality (AR)/virtual reality (VR), wireless back-hauling, etc.) that are not possible with the existing wireless technologies such as 4G/LTE and 802.11n/ac standards. Thanks to the mature advancements and developments in electronics components and Radio Frequency (RF) circuits operating at these frequencies, manufacturing relatively low-cost mmWave electronics circuits became possible. This resulted in multiple commercial standards operating in the 60GHz mmWave band such as the IEEE 802.15.3c, and the IEEE 802.11ad [6]. However, mmWave communication is extremely challenging compared to traditional microwave communication. The main reason lies in the mmWave signal characteristics which include high attenuation, susceptibility to blockage and human mobility, and the necessity of a Line-of-sight (LOS) path for stable communication.

In practice, network operators tend to study the performance of mmWave networks using high fidelity network-level simulators before actual deployment. At the time of writing, networking aspects of the IEEE 802.11ad protocol have been studied in great detail using commercial of-the-shelf (COTS) devices [1, 7]. However, these devices provide limited information about the operations and the performance of the medium access control (MAC) and physical (PHY) layers. In addition, analyzing the interactions between those layers and the upper layers of the protocol stack using COTS devices is challenging due to the lack of full control

Table 1: Simulations parameters

Parameter Name	Parameter Value
Application Type	OnOffApplication
Data Rate	3.6 Gbps
Flow Direction	Uplink
Payload Size	1448 Bytes
Transport Protocol	UDP
MAC Queue Size	1000 Packets
Aggregation Type	A-MSDU and A-MPDU
MAC Protocol	CSMA/CA
PHY Layer Type	SC MCS-12
Transmit Power	10 mW
Rx Noise Figure	10 dB
Operating Frequency	60.48 GHz
Number of Transmit Sectors	37 Sectors
A-BFT Sectors	13 Sectors
PAA Quantization Bits	8 Bits

over COTS devices. The latest additions to the ns-3 IEEE 802.11ad model [4] provide researchers with a framework to study and analyze the performance of the IEEE 802.11ad protocol in complex settings and with high fidelity. Moreover, using a simulation approach allows users to analyze the behavior of each component of the system, from the lowest to the highest layer, and to understand how the different components interact with each other.

In this paper, we demonstrate the capabilities of the ns-3 IEEE 802.11ad model [2–4] for various network settings using practical Phased Antenna Array (PAA) models and realistic quasi-deterministic (Q-D) channel realizations generated by our Q-D channel software [5]. For each scenario, we provide the achieved throughput for each device. Then, we analyze in detail the causes of each phenomenon for particular network deployment. Finally, we provide possible solutions to overcome each problem using standard compliant methods. In summary, our work gives detailed insights into the potential capabilities of our IEEE 802.11ad model in ns-3.

2 SIMULATION SCENARIOS

In this section, we evaluate three different scenarios that demonstrate the versatility of our ns-3 IEEE 802.11ad model. All the scenarios use a 10 x 19 x 3 m room. Device parameters are summarized in Table 1. We configure each directional multi-gigabit (DMG) station (STA) to perform beamforming training (BF) each 10 Beacon Intervals (BIs) during the Data Transmission Interval (DTI) access period. The BF is limited to transmit sector sweep (TxSS) only. Both DMG STA and DMG access point (AP) use 2x8 elements Uniform Rectangular Array (URA) PAA. This choice has been made as usually, for indoor scenarios, the steering of the PAA is done in the azimuth plane rather than in the elevation plane. All the DMG APs are mounted on the ceiling at a height of 3 m and all DMG STAs are placed at a height of 1.2 m.

2.1 Blockage Scenario

Electromagnetic-waves in the mmWave band propagate in a quasi-optical way. As a result, the received signal is dominated by the LOS path and first order reflections coming from reflecting materials. Diffraction in this band is almost negligible, and thus electromagnetic-waves in this band cannot bend over corners. This makes communication in this band sensitive to blockage and human mobility. In addition, due to the high frequency, the Free Space Path Loss (FSPL) is 20 dB higher compared to wireless technologies operating in the microwave band. For these reasons, communication in this band is more suitable for indoor scenarios where coverage is confined to a small area. In this scenario, we study the impact of a blockage on a mmWave communication link for a single AP deployed in the corner of an L-shaped room.

Figure 1 depicts the user mobility stages within the L-shaped room. The thick black line represents the LOS component and the other lines represent the multipath components (MPCs) coming from specular reflections from side walls, floor, and ceiling. Figure 2 shows both the variations of the application layer throughput for modulation and coding scheme (MCS)9 and MCS12 and the Signal-to-Noise Ratio (SNR) changes over the course of the simulation. The vertical dashed lines represent the time the DMG STA completes its TxSS BF. We observe the effect of the beamforming training (BF) as the SNR value increases after its completion.

At the first stage (a), the DMG STA has a clear LOS path towards the DMG AP which results in a high SNR value and thus the DMG STA can use MCS-12 for communication. At stage (b), the DMG STA has moved to the other part of the room, where the LOS component is blocked by the corner of the room, and communication with the DMG AP is Non-line-of-sight (NLOS) through a first order reflection coming from the wall facing the AP. As a consequence, the received SNR decreases considerably, which in turn increases the packet error rate (PER) and requires a lower MCS, and thus affects application throughput. This stage starts at time 13 s. The SNR becomes too low to sustain a communication link using MCS-12 and thus the links break down. However, the SNR value is suitable for communication using MCS-9 which is the value then selected by the rate adaptation mechanism. In the last stage (c) which starts at time 16.2, the DMG STA cannot sustain the NLOS link with the DMG AP anymore since the reflections become too weak, and the communication link breaks down for any MCS value.

Several solutions can be envisioned to overcome the previous problem. For example, a relay node could be installed at the opposite side from the DMG AP. The relay node could maintain a LOS path towards the DMG AP and at the same time, it could reach the user at the other side of the room. This is a standard compliant solution as the IEEE 802.11ad standard supports two types of relay operation modes namely full-duplex amplify-and-forward (FD-AF) and half-duplex decode-and-forward (HD-DF). Another solution would be to deploy two APs inside the room. However, this solution would require the support of a handover mechanism between those DMG APs through a centralized controller.

2.2 Spatial Sharing

Unlike wireless technologies operating in the microwave band where device antennas typically radiate omni-directionally, mmWave devices rely on electronically steerable PAA to generate directional beams for communication. The usage of directional beams can allow multiple concurrent communication links to take place at the

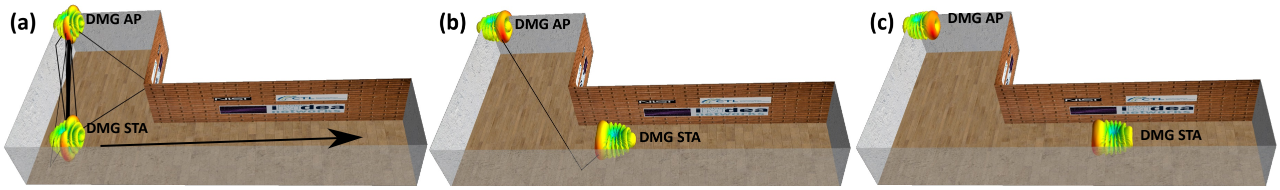

Figure 1: L-Shaped Room Scenario: (a) LOS Communication (b) NLOS Communication (c) No Communication

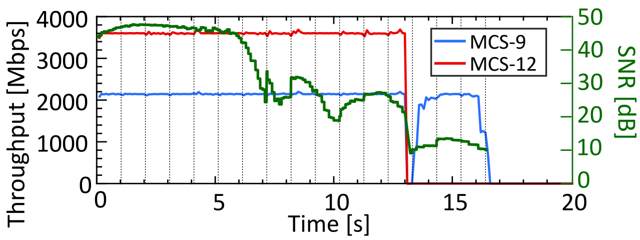

Figure 2: L-Shaped Room Throughput and SNR Variations

same time and in the same frequency channel without interference, which is one of the attractive features of communication in the mmWave band. Our spatial sharing scenario is composed of two DMG basic service sets (BSSs). Each DMG BSS comprises one DMG APs and one DMG STAs associated with it. Figure 3 shows our scenario for two different locations of DMG STA (2).

In this scenario, a single DMG AP would be sufficient to provide full coverage for all the DMG STAs within the room. However, all the devices would share the wireless medium since they utilize the carrier sense multiple access with collision avoidance (CSMA/CA) protocol. To maintain multi-gigabit throughput for all wireless devices, we increase the number of DMG APs. This would be a typical case for a cubical office environment, where multiple DMG APs are deployed on the ceiling. Each DMG AP serves a single cubicle office to ensure gigabit of throughput for the user. Due to the use of directional beam patterns, each DMG AP will have its collision domain and all of the devices within the same collision domain will be sharing the wireless medium in a fair way.

Figure 4 shows the evolution of the application layer throughput with respect to time PAA. At time 0 s, the DMG STAs achieve full spatial sharing as the directionality of the chosen patterns minimizes the interference between the two links. Each DMG STA is thus able to reach its maximum throughput (3.6 Gbps). Then, DMG STA (2) starts moving on a straight line towards DMG STA (1). Until time 3.8 s, the two DMG STAs are still capable of achieving full spatial sharing. After this point the two DMG STAs start overhearing each other's transmissions, since the PAAs have strong side-lobes which are capable of hearing nearby transmissions. Thus, as CSMA/CA is utilized to access the channel for data transmission, the two DMG STAs start sharing the wireless medium. At time 7.1 s, DMG STA (2) starts to move away from DMG STA (1) on the same line and stops in the middle of the room, yielding a throughput increase.

In general, utilizing a PAAs with a high number of antenna elements is not sufficient to improve spatial sharing in a network. To achieve full spatial sharing, all the devices must estimate the wireless channels between each other. This implies decomposing the channel using the singular-value decomposition (SVD) technique to understand how many MPCs exist between all the nearby devices. Based on this information, those devices can optimize their beam patterns to generate directional beams aligned with the strong path towards the intended receiver, while avoiding signal energy on the paths leading to the neighboring devices.

2.3 Dense Deployment

Finally, we look into the performance of the IEEE 802.11ad protocol in a dense deployment setting. In this scenario, up-to ten clients are associated with a single DMG AP. This is a typical scenario for a meeting room within an office environment, where multiple 802.11ad capable devices in close proximity are connected to the same DMG AP. Figure 5(a) shows the distribution of the DMG STAs around the DMG AP. All of the DMG STAs are beamforming towards the DMG AP. Figure 5(b) shows the results of the TxSS BF in Association Beamforming Training (A-BFT) for DMG STA (6).

Figure 6 depicts throughput values for the 10 wireless links when using Transmission Control Protocol (TCP) protocol. We observe that all the links equally share the wireless medium as they have approximately the same median for the throughput. This is a complex wireless networking scenario, and there is a broad range of parameters which impact the overall system throughput. These parameters include TCP layer transmit buffer size, queue size at the MAC layer, frame capture effect, resource allocation algorithms, traffic prioritization, etc.

3 CONCLUSIONS AND FUTURE WORK

In this paper, we evaluated typical deployment scenarios for 802.11ad networks. For each scenario, we generated a realistic propagation environment using our Q-D channel realization software. Based on the obtained results, we conclude the following: (1) To ensure persistent connectivity and maintain high Quality of Experience (QoE) for the end user, network operators must deploy either multiple DMG APs or a single DMG AP with multiple relay nodes. (2) Achieving full spatial sharing requires phased antenna arrays with good steering capabilities accompanied by intelligent beamforming techniques. (3) Improving the performance of a dense wireless local area networks (WLAN) network requires implementing complex cross-layer solutions that optimize various parameters at each layer of the protocol stack.

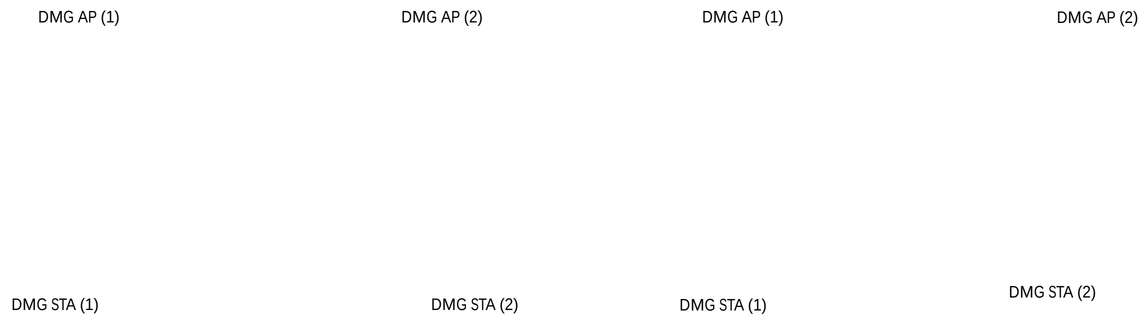

Figure 3: Spatial Sharing Scenario.

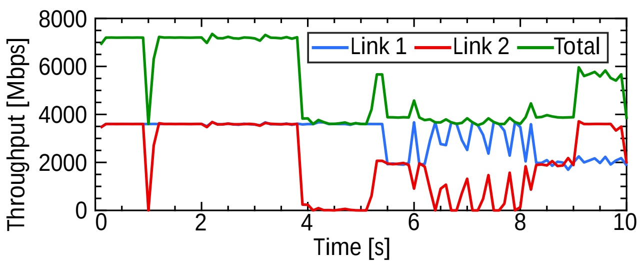

Figure 4: Spatial Sharing Scenario Throughput Evolution during Mobility for 2x8 PAA

Figure 5: Dense Deployment Scenario (a) All the DMG STAs Beamforming Towards the DMG PCP/AP (b) SLS TxSS Phase output between DMG STA (6) and the DMG PCP/AP

For future work, we plan to conduct a detailed and comprehensive study to analyze the performance of the IEEE 802.11ad protocol in more diverse scenarios with devices of heterogeneous capabilities. In addition, we plan to model head rotation and self-blockage for VR and AR applications. Finally, since the WLAN module in ns-3 does not support any mechanism to perform handover between

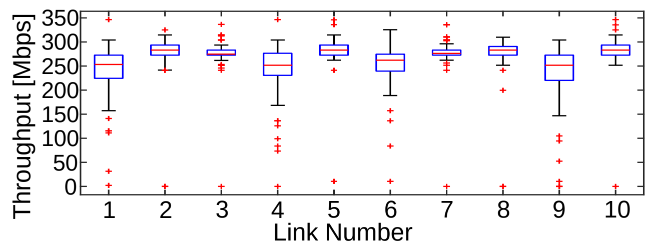

Figure 6: Links Throughput in the Dense Deployment

APs, we plan to add the support for both IEEE 802.11r for fast BSS transition and the IEEE 802.11k amendments for fast handover.

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REFERENCES

[1] H. Assasa, S. Kumar Saha, A. Loch, D. Koutsonikolas, and J. Widmer. 2018. Medium Access and Transport Protocol Aspects in Practical 802.11 ad Networks. In *2018 IEEE 19th International Symposium on "A World of Wireless, Mobile and Multimedia Networks" (WoWMoM)*.
[2] H. Assasa and J. Widmer. 2016. Implementation and Evaluation of a WLAN IEEE 802.11ad Model in ns-3. In *Proceedings of the 2016 Workshop on ns-3*.
[3] H. Assasa and J. Widmer. 2017. Extending the IEEE 802.11Ad Model: Scheduled Access, Spatial Reuse, Clustering, and Relaying. In *Proceedings of the Workshop on ns-3*.
[4] H. Assasa, J. Widmer, T. Ropitault, and N. Golmie. 2019. Enhancing the ns-3 IEEE 802.11ad Model Fidelity: Beam Codebooks, Multi-antenna Beamforming Training, and Quasi-deterministic mmWave Channel. In *Proceedings of the Workshop on ns-3*.
[5] T. Ropitault H. Assasa. 2019. A Collection of Open-source Tools to Simulate IEEE 802.11ad/ay WLAN Networks in ns-3. https://github.com/wigig-tools
[6] IEEE. 2012. Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 3: Enhancements for Very High Throughput in the 60 GHz Band. *IEEE Std 802.11ad-2012* (2012).
[7] S. K. Saha, H. Assasa, A. Loch, N. M. Prakash, R. Shyamsunder, S. Aggarwal, D. Steinmetzer, D. Koutsonikolas, J. Widmer, and M. Hollick. 2018. Fast and Infuriating: Performance and Pitfalls of 60 GHz WLANs Based on Consumer-Grade Hardware. In *2018 15th Annual IEEE International Conference on Sensing, Communication, and Networking (SECON)*.