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Simulation based IEEE 802.11ad performance assessment in factory workshop

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Abstract—**The IEEE 802.11ad standard exploits the millimeter wave (mmWave) spectrum, concretely the license-free frequency band in the 57-71 GHz range. Nowadays, this frequency band is mostly unused for use cases related to communication systems, and applications that require a throughput of several Gbit/s are proposed to fully exploit all the resources that are offered in this spectrum. Another option could be to exploit the advantages offered in the mmWave spectrum to increase the reliability and timing requirements of the networks, which are key aspects in industrial communications. However, this approach has not been tested yet due to the novelty of mmWave bands for communication systems, which is the main motivation behind this work. This paper performs an assessment of the expected performance of an IEEE 802.11ad managed industrial backhaul network using a simulation based approach. The simulation is split in two: an individual link is tested first under several conditions with a realistic channel model and the whole network is evaluated after, using the previously generated metrics to represent the links. The obtained results show that, even if 802.11ad does not provide a sufficient performance to cope with the most stringent use case, the standard has potential to operate in this kind of environment.**

Index Terms—**Industrial communications, statistical analysis, telecommunication network performance**

I. INTRODUCTION

The IEEE 802.11ad standard [1] has included the mmWave spectrum to the communication systems field, concretely the 60 GHz range. This frequency band makes several GHz of bandwidth available in a frequency domain that nowadays is mostly unused, unlike conventional WiFi amendments that operate over the 2.4 and 5 GHz Industrial, Scientific and Medical (ISM) frequency bands, where multiple application coexist and interference is unavoidable.

This technology has not been widely adopted yet, since most of nowadays equipment is not capable of operating in the mmWave spectrum. Some commercial devices as the Talon AD7200 from TP-Link [2] or the Nighthawk X10 from Netgear [3] have already implemented it but they are not widely used and one of their main applications is the testing and validation of the standard. In relation to this, several characterization efforts can be found in the literature, where most of them are oriented to obtaining the achievable throughput as it is the main appeal of this technology.

As for the use cases of the mmWave spectrum, the typical applications include backhaul networks, radio access in dense scenarios or low latency applications as augmented reality or remote gaming [4]. Some works address the potential of mmWaves for industrial settings as well [5], where the reliability and time-critical aspects of the communications are marked as challenges that this technology needs to overcome. The 802.11ad standard could be helpful to understand the performance that a generic communication protocol can provide in this settings and to locate the key aspects that need to be improved in order to cope with the demands. However, as most works are oriented to the assessment of the achievable throughput, there are not many contributions that address the reliability and time-critical aspects of the technology, which is the main motivation behind this work.

The main contribution of this paper is a simulation based performance assessment of an 802.11ad managed industrial backhaul network, focusing on the reliability and time-critical aspects. Two separate simulations are carried out to achieve this: one in Matlab where the Packet Error Rate (PER) of individual links is computed with a realistic channel model under several conditions and another in NS-3, where the performance of the backhaul network is evaluated using the previously generated metrics.

The rest of the document is as follows. Section II provides a literature review of the existing 802.11ad performance assessment studies, including both experimental and simulation based approaches. The complete simulation setup is detailed in Section III, and the requirements of the network, as well as the existing equipment that can be simulated are discussed as well. Section IV covers all the link level simulation, where the simulation parameters are provided and the results are discussed. Similarly, the network level simulation is presented in Section V, where the simulation parameters and obtained results are provided. Finally, Section VI exposes the conclusions drawn from this work.

II. EXISTING 802.11AD CHARACTERIZATION WORKS

The existing works that provide a performance assessment of the IEEE 802.11ad standard are reviewed in this section. The aspects that have been considered are the equipment (which is the employed Hardware (HW) for real testing or the simulator), the type of traffic used for testing, the scenario that each work considers (including the environment and topology) and the results that each work has obtained with the testing. All the mentioned fields are summarized in Table I for the analysed works, and details regarding each individual publication are discussed next.

In [6], 802.11ad radio modules that are produced by Panasonic [14] are used to test Modulation and Coding Schemes (MCSs) 1-9 in a typical office environment. A single link is generated in this work, where information is exchanged between the Access Point (AP) and a client in the form of Transmission Control Protocol (TCP)/User Datagram Protocol (UDP) packets. Two separate channels are tested: with and without interference. The provided results show that multi-Gigabit throughput is achievable for both TCP/UDP traffic if the appropriate MCS and packet size are selected. On the other hand, the paper shows that interference can cause a significant degradation in the throughput of the system and concludes that this effect should be mitigated or minimized.

Two laptops with 802.11ad capability are used in [7] to test the throughput of a link in several sites inside a university building. Both TCP/UDP traffic are generated during the testing, and the results prove that a Gigabit throughput can be achieved in all the cases if the orientation is correct and the Line of Sight (LoS) is present.

Three Commercial-Off-the-Shelf (COTS) equipment models (two routers and a laptop) that work with the 802.11ad standard are evaluated in [8]. In this work, three setups are deployed in a typical office environment, each having an AP and one or several clients. The throughput and Round-Trip Time (RTT) of TCP traffic is measured with several amounts of clients, and additional mechanisms as frame aggregation or spatial reuse are analysed as well.

A 802.11ad compliant smartphone is tested in [9]. Here, the selected MCS and achievable throughput are observed for various distances inside a lobby and a corridor, and scenarios with mobility are considered as well. The provided results show that the phone can operate effectively in this frequency band but that the beam pattern selector does not work optimally in the presence of mobility.

In [10], the TGad channel model [15] is used to evaluate the performance of a simulated 802.11ad link in a conference room. Several configurations that include the Single Carrier (SC) and Orthogonal Frequency-Division Multiplexing (OFDM) modes are used in order to determine the effective throughput of the link for each case, which is given in the form of Bit Error Rate (BER) and PER. Results show that the system is not well suited to operate with multipath fading and emphasises in the need of the LoS component and directivity.

A custom model is implemented in Matlab in [11] to test the behaviour of Contention Based Access Period (CBAP) and Service Period (SP) channel access methods defined in 802.11ad. A Markov chain is used to compute the backoff counter in CBAP traffic, and a stochastic model is proposed to represent SP scheduling delay as well. Simulations test various configurations where CBAP and SP occupy variable portions of the data section and the amount of stations, as well as the BER is changed. The obtained results show the effective throughput and packet arrival rate for each scenario.

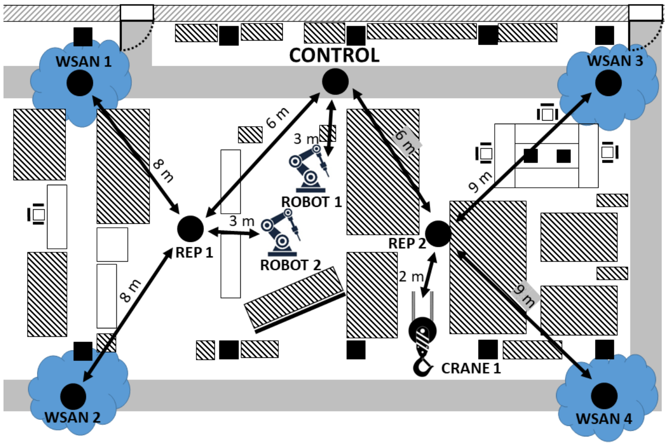


Fig. 1: Simulated 802.11ad network

The OPNET simulation environment is employed in [12] with a custom 802.11ad model. Three different scenarios are tested under this simulator, from where the throughput and delay metrics are obtained for small networks.

The conference room model presented in [15] is used in [13] in order to evaluate the performance of various configurations that the 802.11ad physical (PHY) layer offers. Here, the throughput, as well as the error rate in the form of BER/PER are analysed for a single data link. The results show the error rate under several Signal to Noise Ratio (SNR) values, and the achievable throughput under different MCSs, SNRs and distances.

Most of the existing works are oriented to test the achievable data rate of the 802.11ad standard, as it is one of the most appealing features of this technology. Some works include reliability related results as well, but these come from simulations that represent generic indoor scenarios as a conference room. The 802.11ad standard can be useful for industrial use cases as well, as its huge available bandwidth can be the key to provide the necessary performance to cope with Factory Automation (FA) like applications [16]. However, none of the analysed works provide an insight about the performance within this kind of scenario, which can be particularly challenging due to the harsh nature of factory environments. The lack of a proper research of the reliability and time-critical aspects of the 802.11ad for this particular use case is the main motivation behind this work.

III. SIMULATION SETUP

The scenario shown in Figure 1 has been elaborated to simulate an 802.11ad based backhaul network of a workshop. This network is composed of a centralized controller (CONTROL) which manages some devices along two repeaters (REP1, REP2) that are employed to increase the range of the network. Three kind of devices are connected to the network: four Wireless Sensors and Actuators Network (WSAN) managers (WSAN1-4), two robotic arms (ROBOT1, ROBOT2) and a crane (CRANE1). All these devices are assumed to perform

TABLE I: Comparison of existing 802.11ad characterization works

Ref.	Equipment		Traffic	Scenario	Results
[6]	HW - Panasonic IEEE 802.11ad radio		Iperf3 - TCP/UDP	Office - Link	Throughput, interference
[7]	HW	- Wilocity wil6210 802.11 radio - Dell Wireless Dock D5000	Iperf3 - TCP/UDP	University building - Link	Throughput
[8]	HW	- TP-Link Talon AD7200 - Netgear Nighthawk X10 - Acer Travelmate P446-M	Iperf2 - TCP/UDP	Office - Network	Throughput, delay (RTT)
[9]	HW - Asus ROG Phone		Iperf3 - TCP	Lobby, corridor - Link	Throughput, range, mobility
[10]	Simulator - TGad		4000 Byte packets	Conference room - Link	BER, PER
[11]	Simulator - Matlab Custom		7500 Byte packets	Not specified - Network	Throughput, arrival rate, service time
[12]	Simulator - OPNET		Video stream	Living, conference room - Network	Throughput, delay
[13]	Simulator - Matlab 802.11ad PHY		1000 Byte packets	Conference room - Link	Throughput vs (SNR, Distance, BER)

their internal communications successfully, and use the backhaul network to send the collected data to the CONTROL node and receive commands from it.

Three main aspects of this network were analysed before performing the simulations: the requirements of the applications, the selected equipment to simulate 802.11ad communications (which can help to achieve realistic simulations) and the available tools that can be found to perform 802.11ad network simulations. These are briefly discussed next.

A. Requirements of the network

The work presented in [16] provides a thorough analysis of the existing communication types and requirements in industrial settings. This study separates industrial communications in different classes based on how demanding the use cases are. In this paper, class 1 communications have been considered since these define closed loop regulatory control applications that have the strictest demands, which are the following ones:

- **Reliability:** Maximum PER of 10^{-7}.
- **Update rate:** 0.5 to 8 ms.
- **Payload:** 8 to 64 Bytes.

B. Selected equipment for simulation

As for the simulated equipment, a COTS device is used as a reference in order to keep the environment under test as realistic as possible. The Talon AD7200 router from TP-Link has been selected for the task, as an extensive analysis of this equipment is carried out in [17] and the available radiation patterns are provided as well. In this regard, two sectors have been selected: sector 27 to represent a pattern with no predominant component and sector 63, which contains a very strong main lobe. These can be found in Figure 2. The main motivation behind this selection is to be able to compare both radiation pattern edges in the simulations, since they approach the isotropic and directional cases.

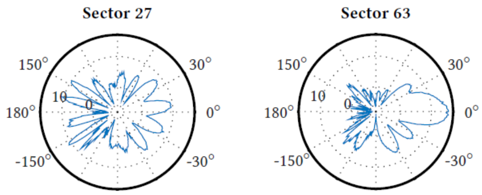


Fig. 2: Sectors 27 and 63 of Talon AD7200 [17]

C. Simulation tools

The selected tool for the simulation is NS-3, as the work presented in [18] is the only available implementation that allows to represent the 802.11ad protocol stack. As NS-3 is a discrete event based simulator, the only channel effects that can be introduced are fading and delay, and more complex scenarios as multipath or doppler cannot be completely represented. The abundance of reflective surfaces in factory environments makes the multipath analysis essential, and for this reason this work has performed an independent simulation in Matlab first with the aim of testing more complex channels for a single link. The idea of this simulation is to work with the PHY layer under different conditions as LoS/Non Line of Sight (NLoS), various distances or radiation patterns, and obtain the expected PER for each circumstance in order to use it in NS-3 later. Each simulation type and their corresponding results are discussed in the next sections.

IV. LINK LEVEL SIMULATION

The link level simulation has the aim of obtaining the statistics of the PER of a link under various circumstances. To achieve this, Monte Carlo (MC) simulations [19] have been carried out using the WLAN toolbox from Matlab [20], which allows to work with Directional Multi-Gigabit (DMG) frames. The selected channel model is the millimeter Industrial Channel Model (mmICM), which was developed by the authors of this article. This model is publicly available in the *Measurements in a University Workshop with Industrial Equipment* dataset in [21].

All the configuration parameters of this simulation are summarized in Table II. As for the scenario, the Vertical Machining Center (VMC) from the mmICM model has been considered for the testing, and all the expected SNRs and distances have been tested for the LoS and NLoS cases. The DMG frame is set to operate in SC mode, because the implementation of OFDM is not supported by all COTS equipment. Regarding the MCS, the option 1 is selected because it is the most robust option. A total payload of 156 Bytes is chosen for the packets, since this is the required PHY layer length to encapsulate 64 data Bytes (the largest payload defined in [16]) using UDP and IPv4. At last, the transmitted power is selected in accordance with the information provided by the vendor.

TABLE II: Link level simulation configuration

	Parameter	Value
Environment	Scenario	VMC (LoS, NLoS)
	Distance (m)	2:2:10
	SNR (dB)	0:2:40
DMG Frame	MCS	1
	Payload (Byte)	156
Talon	Tx Power (dBm)	10
	Sector	27, 63
Monte Carlo	Iterations	1E6

The amount of required MC iterations was estimated first for a confidence interval of 1E-7, since it is the maximum PER defined in [16]. A formula provided in [19] was used for this task, where a total amount of over 3E14 iterations were required for the desired confidence interval. After analysing the available computational capabilities, it was concluded that the estimated amount was not viable, and performing 1E6 MC iterations per configuration was proposed as a more realistic approach. Here, each result can be obtained in approximately one day with a confidence interval of ±1E-3, which, even if it is far from the desired interval of 1E-7, it is considered to be sufficient to perform an initial assessment.

The results of all the tested setups are shown in Tables V to VIII. The first observation that can be made to this data is that, independently of the selected sector, the LoS scenarios always provide a significantly better performance. It can be seen that an error-free communication can be achieved when a sufficient SNR value is reached, unlike the case of NLoS, where an error floor is present. This indicates that, in order to achieve reliable communications over the mmWave spectrum, visibility between stations must be guaranteed. Apart from this, sector 63 shows a slightly better performance in all the evaluated scenarios. The improvement is more significant in the NLoS case, where the error floor is an order of magnitude lower. This could happen because the directive radiation pattern focuses on the strongest detected multipath component and amplifies it as much as possible whereas the omnidirectional-like pattern amplifies directions that may contain just noise. With these results in mind, it was concluded that the backhaul network must guarantee visibility between stations and that the directive radiation pattern can be helpful to increase the reliability.

V. NETWORK LEVEL SIMULATION

The network level simulation is carried out in this section. This simulation has the objective of testing the network detailed in Figure 1 with the NS-3 tool using the metrics generated in the previous section to represent the channel. A summary of all the parameters that have been used in this simulation can be found in Table III.

As it can be seen, the simulation is configured to last 1024 seconds, which corresponds to 1E6 Beacon Intervals (BIs). This metric is selected following the previous MC simulations, where the same amount of iterations are employed to estimate the PER of the links. The individual BIs are configured to have the shortest possible duration. To do so, a BI of 1 Time Unit (TU) (or 1024 μs) and service periods of 15 μs each have been defined. Apart from this, a limited beamforming configuration is set, where 8 sectors are defined around each device and a BI is capable of aggregating just one new device. Since the network will be composed of very few nodes that are static and previously known, this can be an assumable configuration. As for the payload, a size of 64 data Bytes has been selected following the maximum length defined [16]. At last, a SNR value has been assigned to each link defined in Figure 1. To estimate these values, the difference between the noise floor that can be appreciated in the measurements the mmICM is elaborated with [21] and the power that would arrive at each distance is used, considering the power of the simulated COTS device and antenna gain.

TABLE III: Network level simulation configuration

		Parameter	Value
Timing		Duration (s)	1024
		BI (μs)	1024
		SP (μs)	15
Beamforming		Sectors	8
		SSSlots	1
Data		Payload (Byte)	64
		Protocol	IPv4 + UDP
SNR	CONTROL -	REP1, REP2 (dB)	10
		ROBOT1 (dB)	16
	REP1 -	WSAN1, WSAN2 (dB)	8
		ROBOT2 (dB)	16
	REP2 -	WSAN3, WSAN4 (dB)	6
		CRANE1 (dB)	20

In order to include the previously computed PERs in NS-3, a simple channel model has been created for this simulation tool. This model computes if a packet has an error based on a probability that can be assigned to each link, and since the previous simulation concluded that LoS links with directive antenna radiation patterns are preferable, the error probabilities defined in Table VII have been used for this channel model.

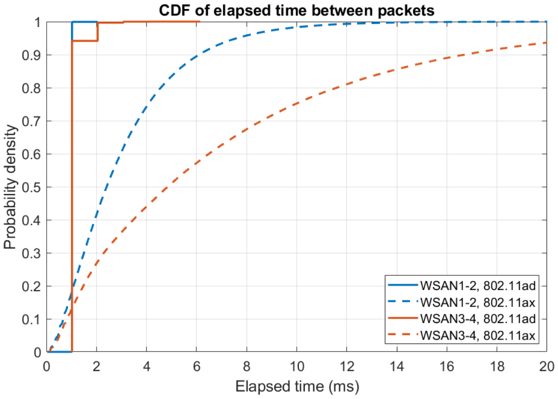
The performance provided by the 802.11ad standard needs to be compared to a reference in order to determine if there is an improvement. To achieve this, the same network has been simulated using 802.11ax compliant nodes, and the amount of exchanged packets, as well as their timestamps, have been recorded to generate the mentioned reference. This network has been configured to operate with the MCS 4 and a bandwidth of 160 MHz to achieve a throughput of 408 Mbps, which is close to the 802.11ad network where the throughput is of 385 Mbps. Apart from this, the elaborated channel model cannot be used in this test, since the 802.11ax network uses the 5 GHz frequency band and the PERs have been estimated for the 60 GHz spectrum. Instead, the *LogDistancePropagationModel* from NS-3 has been selected, using the path loss exponent measured in the VMC scenario from the workshop the mmICM has been elaborated with.

Results are discussed next. Here, two different metrics have been computed to assess the performance: the amount of received packets and the elapsed time between them.

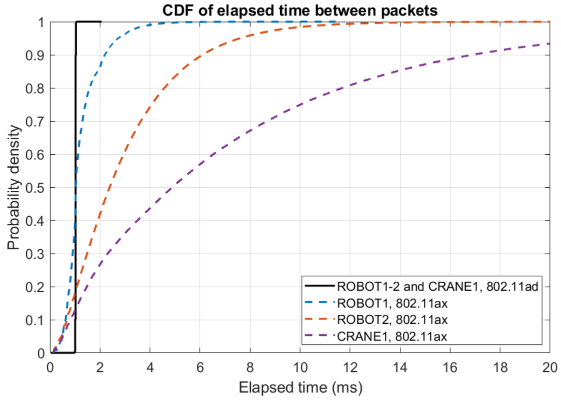
The amount of received packets can be used as an indicator of the expected reliability of the network. As a reference,

TABLE IV: Percentage of received packets in CONTROL

	Received packets (%)	
	802.11ad	**802.11ax**
WSAN 1	99.92	34.03
WSAN 2	99.91	34.02
WSAN 3	94.16	14.32
WSAN 4	94.11	14.34
ROBOT 1	99.99	81.50
ROBOT 2	99.99	34.18
CRANE 1	99.99	14.19



(a) WSAN generated packets



(b) ROBOT and CRANE generated packets

Fig. 3: CDF of time between arrived packets in CONTROL

the total percentage of successfully received messages in the CONTROL node is shown in Table IV for the 802.11ad and 802.11ax operated networks. Note that the simulation has stopped just after transmitting the last packet, meaning that all the packets that were transmitted or buffered after this instant do not form part of the statistic. Apart from this, the Medium Access Control (MAC) layer message aggregation was disabled as well, since this mechanism does not cope well with low latency applications. The results show that the 802.11ad standard clearly outperforms 802.11ax in this kind of network, and two main reasons can justify this behaviour. The first one is the use of the mmWave spectrum, where the multipath and interference levels are lower and the overall quality of the received signal is improved. The second reason is that 802.11ad uses a radio access technique that is more suitable for this use case, where each station has a pre-allocated time slot (or SP) for its transmission instead of having to compete for radio access. On the other hand, 802.11ax nodes have to request channel access before sending each message, which requires a lot of time and makes it impossible to deliver all the packets in time. This difference in the performance highlights the importance of using a radio access technique that grants exclusive access to the stations. At last, even if the 802.11ad standard shows promising results, the requirement defined in [16] cannot be met unless very short distances (up to 3 meters) are used to exchange information, which can be a challenge for the most demanding use cases.

The elapsed time between the received packets gives an insight of the expected update rate. In order to analyse this metric, the Cumulative Distribution Function (CDF) of the probability to receive a packet within a certain delay has been computed for all the nodes that send information to the CONTROL node, as shown in Figure 3. As it can be seen, the periodical structure of the 802.11ad standard makes the elapsed time acquire values that are multiples of 1024 μs, which is the transmission period. Most 802.11ad nodes show that they can maintain an update rate of 1024 μs with a probability of 0.99, unlike WSAN 3 and 4 where a probability of 0.94 can be seen. This difference is explained with the bigger separation that these nodes have, since their communication has a lower SNR. In any case, the probability is raised to 0.99 if a time window of 2048 μs is considered, and the measured worst case scenario is of 6144 μs in WSAN 3. On the other hand, 802.11ax shows a much less predictable behaviour since channel access is negotiated before each transmission. Some cases show an update rate faster than the one of 802.11ad, even if they are uncommon. However, the required time to guarantee a probability of 0.99 for an update, periods of 4, 12 and 34 ms must be defined for the ROBOT1, ROBOT2 and CRANE1 nodes, respectively. Again, this is a consequence of the radio access technique employed in 802.11ax, which is not prepared for this use case because it cannot handle large amount of short packets in a confined time interval. The overall conclusion extracted from this test is that none of the standards can provide an update rate that covers the most stringent case, where a periodicity of 0.5 ms must be maintained [16]. However, 802.11ad shows a clear advantage over its counterpart, and if the more relaxed threshold of 8 ms updates is considered, this standard could provide the required performance to cope with it.

VI. CONCLUSIONS

This paper has presented a simulation based analysis of an hypothetical IEEE 802.11ad standard managed industrial network, focusing on the reliability and time-critical aspects. A backhaul network that manages different processes within a workshop was created and simulated in NS-3 to achieve this goal, where several nodes exchange information and commands with a centralized controller. Since NS-3 cannot represent realistic channels, the reliability of an individual link was modeled first under several conditions using the

Matlab tool. Here, MC tests were carried out with the mmICM, considering cases as different distances, LoS/NLoS or directional/omnidirectional antenna radiation patterns. The link level results showed a clear advantage for the LoS scenarios, where error-free communications can be achieved if a minimum SNR is guaranteed. Apart from this, directional antenna radiation patterns showed a significant improvement, where the achieved error rate was an order of magnitude lower. The complete network was simulated in NS-3 later, where two versions were tested: one managed with 802.11ad and another one with 802.11ax, which served as a comparison source. Reliability and update-rate metrics were extracted from the results, from where the 802.11ad implementation clearly outperformed its competitor. Two main reasons were attributed to these results: the use of the mmWave spectrum, which improved the quality of the signal, as well as the radio access employed by 802.11ad, which grants an exclusive channel access to the nodes in periodic intervals. Even if the performance was better, 802.11ad showed to be incapable of providing the required reliability in links with a distance of 6 meters and more. Apart from this, it was capable to cope with just the most relaxed update-rate requirement of the use case of interest, which concluded that, even if the standard has potential, the standard is not capable of meeting all the demands as it is. At last, additional aspects as the scalability, maximum number of hops or the use of mechanisms as redundant transmissions have not been included in this work and will be endorsed in future research.

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REFERENCES

[1] I. C. society, *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*. IEEE, 2002.

[2] *Talon AD7200 multi-band Wi-Fi router*. [Online]. Available: https://www.tp-link.com/us/home-networking/wifi-router/ad7200/.

[3] *Nighthawk X10 smart WiFi router (AD7200)*. [Online]. Available: https://www.netgear.com/home/wifi/routers/r9000-x10-router/.

[4] K. Sakaguchi *et al.*, "Where, when, and how mmwave is used in 5G and beyond," *IEICE Transactions on Electronics*, vol. 100, no. 10, pp. 790–808, 2017.

[5] M. Cheffena, "Industrial wireless communications over the millimeter wave spectrum: Opportunities and challenges," *IEEE Communications Magazine*, vol. 54, no. 9, pp. 66–72, 2016.

[6] K. Nguyen, M. G. Kibria, K. Ishizu, and F. Kojima, "Empirical investigation of IEEE 802.11 ad network," in *2017 IEEE International Conference on Communications Workshops (ICC Workshops)*, IEEE, 2017, pp. 192–197.

[7] S. K. Saha, V. V. Vira, A. Garg, A. Tennenbaum, and D. Koutsonikolas, "On the feasibility of indoor IEEE 802.11 ad WLANs," in *2015 IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS)*, IEEE, 2015, pp. 107–108.

[8] H. Assasa, S. K. Saha, A. Loch, D. Koutsonikolas, and J. Widmer, "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)*, IEEE, 2018, pp. 1–11.

[9] S. Aggarwal, A. Thirumurugan, and D. Koutsonikolas, "A first look at 802.11 ad performance on a smartphone," in *Proceedings of the 3rd ACM Workshop on Millimeter-wave Networks and Sensing Systems*, 2019, pp. 13–18.

[10] M. Zaaimia, R. Touhami, A. Hamza, and M. Yagoub, "Design and performance evaluation of 802.11 ad phys in 60 GHz multipath fading channel," in *2013 8th international workshop on systems, signal processing and their applications (WoSSPA)*, IEEE, 2013, pp. 521–525.

[11] C. Hemanth and T. Venkatesh, "Performance analysis of contention-based access periods and service periods of 802.11 ad hybrid medium access control," *IET Networks*, vol. 3, no. 3, pp. 193–203, 2014.

[12] C. Cordeiro, D. Akhmetov, and M. Park, "IEEE 802.11 ad: Introduction and performance evaluation of the first multi-Gbps WiFi technology," in *Proceedings of the 2010 ACM international workshop on mmWave communications: from circuits to networks*, 2010, pp. 3–8.

[13] X. Zhu, A. Doufexi, and T. Kocak, "Throughput and coverage performance for IEEE 802.11 ad millimeter-wave WPANs," in *2011 IEEE 73rd vehicular technology conference (VTC Spring)*, IEEE, 2011, pp. 1–5.

[14] N. Saito *et al.*, "A fully integrated 60-GHz CMOS transceiver chipset based on WiGig/IEEE 802.11 ad with built-in self calibration for mobile usage," *IEEE Journal of Solid-State Circuits*, vol. 48, no. 12, pp. 3146–3159, 2013.

[15] A. Maltsev, R. Maslennikov, A. Sevastyanov, A. Lomayev, and A. Khoryaev, "Statistical channel model for 60 GHz WLAN systems in conference room environment," in *Proceedings of the Fourth European Conference on Antennas and Propagation*, IEEE, 2010, pp. 1–5.

[16] K. Montgomery, R. Candell, Y. Liu, and M. Hany, *Wireless user requirements for the factory workcell*. Department of Commerce, National Institute of Standards and Technology, 2020.

[17] D. Steinmetzer, D. Wegemer, M. Schulz, J. Widmer, and M. Hollick, "Compressive millimeter-wave sector selection in off-the-shelf IEEE 802.11 ad devices," in *Proceedings of the 13th International Conference on emerging Networking EXperiments and Technologies*, 2017, pp. 414–425.

[18] H. Assasa, N. Grosheva, T. Ropitault, S. Blandino, N. Golmie, and J. Widmer, "Implementation and evaluation of a WLAN IEEE 802.11 ay model in network simulator ns-3," in *Proceedings of the 2021 Workshop on ns-3*, 2021, pp. 9–16.

[19] W. Oberle, "Monte carlo simulations: Number of iterations and accuracy," Army Research Lab Aberdeen Proving Ground MD Weapons and Materials Research ..., Tech. Rep., 2015.

[20] *WLAN toolbox*, https://www.mathworks.com/products/wlan.html, Accessed: 2023-03-07.

[21] *NextG CMA — home*, https://nextg.nist.gov/, (Accessed on 2023-03-07).

TABLE V: MC results for PER in Sector 27 LoS

		SNR(dB)												
		2	**4**	**6**	**8**	**10**	**12**	**14**	**16**	**18**	**20**	**22**	**24**	**26**
Distance(m)	**2**	0.9987	0.6610	0.0638	0.0011	1.2E-5	3.0E-6	0	0	0	0	0	0	0
	3	0.9989	0.6752	0.0697	0.0015	3.9E-5	1.0E-6	0	0	1.0E-6	0	1.0E-6	1.0E-6	1.0E-6
	4	0.9990	0.6828	0.0729	0.0018	6.1E-5	4.0E-6	0	0	1.0E-6	0	1.0E-6	1.0E-6	0
	5	0.9991	0.6868	0.0749	0.0021	8.5E-5	1.1E-5	1.0E-6	2.0E-6	1.0E-6	1.0E-6	3.0E-6	3.0E-6	4.0E-6
	6	0.9991	0.6875	0.0755	0.0022	1.0E-4	1.0E-5	6.0E-6	4.0E-6	3.0E-6	3.0E-6	3.0E-6	2.0E-6	2.0E-6
	7	0.9991	0.6876	0.0755	0.0022	1.1E-4	1.9E-5	8.0E-6	5.0E-6	5.0E-6	3.0E-6	6.0E-6	8.0E-6	6.0E-6
	8	0.9992	0.6867	0.0742	0.0022	1.1E-4	2.6E-5	1.2E-5	5.0E-6	7.0E-6	4.0E-6	5.0E-6	5.0E-6	7.0E-6
	9	0.9992	0.6849	0.0735	0.0020	1.2E-4	2.1E-5	1.2E-5	8.0E-6	6.0E-6	4.0E-6	8.0E-6	5.0E-6	6.0E-6
	10	0.9991	0.6836	0.0723	0.0019	1.2E-4	3.1E-5	1.1E-5	8.0E-6	7.0E-6	9.0E-6	1.0E-5	1.1E-5	1.1E-5

TABLE VI: MC results for PER in Sector 27 NLoS

		SNR(dB)												
		2	**4**	**6**	**8**	**10**	**12**	**14**	**16**	**18**	**20**	**22**	**24**	**26**
Distance(m)	**2**	1.0000	0.9744	0.6063	0.1528	0.0177	0.0016	0.0004	0.0003	0.0003	0.0003	0.0003	0.0004	0.0005
	3	1.0000	0.9632	0.5598	0.1368	0.0172	0.0024	0.0010	0.0009	0.0008	0.0009	0.0010	0.0011	0.0013
	4	1.0000	0.9437	0.4949	0.1169	0.0169	0.0038	0.0023	0.0020	0.0019	0.0020	0.0021	0.0023	0.0025
	5	0.9999	0.9192	0.4321	0.1006	0.0174	0.0055	0.0038	0.0033	0.0031	0.0032	0.0034	0.0036	0.0038
	6	0.9999	0.8991	0.3906	0.0922	0.0183	0.0070	0.0049	0.0042	0.0041	0.0041	0.0042	0.0045	0.0048
	7	0.9999	0.8869	0.3749	0.0915	0.0199	0.0081	0.0055	0.0047	0.0045	0.0045	0.0047	0.0049	0.0052
	8	0.9999	0.8790	0.3659	0.0917	0.0210	0.0087	0.0061	0.0052	0.0048	0.0048	0.0049	0.0051	0.0054
	9	0.9998	0.8693	0.3512	0.0895	0.0211	0.0088	0.0062	0.0053	0.0049	0.0049	0.0049	0.0052	0.0054
	10	0.9998	0.8549	0.3269	0.0830	0.0204	0.0087	0.0060	0.0050	0.0047	0.0045	0.0045	0.0046	0.0048

TABLE VII: MC results for PER in Sector 63 LoS

		SNR(dB)												
		2	**4**	**6**	**8**	**10**	**12**	**14**	**16**	**18**	**20**	**22**	**24**	**26**
Distance(m)	**2**	0.9986	0.6358	0.0548	0.0007	1.0E-6	0	0	0	0	0	0	0	0
	3	0.9987	0.6415	0.0559	0.0007	1.0E-6	1.0E-6	0	0	0	0	0	0	0
	4	0.9988	0.6454	0.0565	0.0007	2.0E-6	0	0	0	0	0	0	0	0
	5	0.9989	0.6485	0.0573	0.0008	0	0	0	0	0	0	0	0	0
	6	0.9990	0.6493	0.0580	0.0008	1.0E-6	0	0	0	0	0	0	0	0
	7	0.9989	0.6521	0.0585	0.0008	1.0E-6	0	0	0	0	0	0	0	0
	8	0.9990	0.6525	0.0582	0.0007	2.0E-6	0	0	0	0	0	0	0	0
	9	0.9990	0.6541	0.0587	0.0007	3.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6
	10	0.9990	0.6551	0.0591	0.0008	2.0E-6	0	0	0	0	0	0	0	0

TABLE VIII: MC results for PER in Sector 63 NLoS

		SNR(dB)												
		2	**4**	**6**	**8**	**10**	**12**	**14**	**16**	**18**	**20**	**22**	**24**	**26**
Distance(m)	**2**	0.9998	0.8395	0.2590	0.0427	0.0048	0.0005	0.0002	0.0002	0.0001	0.0001	0.0001	0.0002	0.0002
	3	0.9998	0.8194	0.2278	0.0358	0.0044	0.0006	0.0003	0.0003	0.0002	0.0002	0.0002	0.0002	0.0002
	4	0.9998	0.8010	0.2002	0.0300	0.0040	0.0008	0.0004	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003
	5	0.9997	0.7816	0.1778	0.0255	0.0036	0.0009	0.0005	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004
	6	0.9997	0.7682	0.1620	0.0225	0.0034	0.0010	0.0006	0.0005	0.0004	0.0004	0.0004	0.0004	0.0004
	7	0.9997	0.7602	0.1522	0.0207	0.0035	0.0010	0.0006	0.0005	0.0004	0.0004	0.0004	0.0004	0.0004
	8	0.9997	0.7532	0.1444	0.0190	0.0033	0.0010	0.0006	0.0005	0.0004	0.0004	0.0004	0.0003	0.0003
	9	0.9996	0.7451	0.1358	0.0174	0.0032	0.0010	0.0007	0.0005	0.0004	0.0004	0.0004	0.0003	0.0003
	10	0.9996	0.7379	0.1266	0.0156	0.0030	0.0010	0.0007	0.0005	0.0004	0.0003	0.0003	0.0003	0.0003