COMPARATIVE PERFORMANCE ANALYSIS OF THE IEEE802.11AX AND 802.11AC MIMOLINK FOR WLANS

Md. Delowar Hossain[1], Sumon Kumar Debnath[1], Iffat Ara Badhan[1],
Md. Monirul Islam[1], Ad. Ahsan Habib[1], Md. Sharif Uddin[1], Md. Abul Munjer[1],
Prodip Kumar Sarker[2], Ileas Pramanik[2], and Mutia Afroze Alin[1]

[1]Dept. of Electrical and Electronic Eng., Begum Rokeya University,
Rangpur, Bangladesh
[2]Dept. of Computer Science Eng., Begum Rokeya University,
Rangpur, Bangladesh

ABSTRACT

The escalating demand for swift and dependable wireless internet access has spurred the development of various protocols within 802.11 WLANs. Among them, the 802.11ac protocols have gained widespread acceptance over the past few years, offering enhanced data transfer rates compared to the 802.11n standard. However, the persistent congestion of wireless IoT devices, particularly in densely populated areas, remains a significant challenge. To tackle this issue, IEEE 802.11 has advanced IEEE 802.11ax as the successor to 802.11ac, introducing critical enhancements at the PHY/MAC layers to improve throughput in dense scenarios. Additionally, modelling and simulating these protocols are vital for WLAN researchers and designers to anticipate link characteristics effectively, fostering high-performance WLAN design. The need for such tools led to the creation of diverse network simulation programs, and NS-2 is widely accepted as an open-source program that has achieved remarkable success in research. In this paper, we focus on various connection properties of 802.11ax WLANs through NS-3 simulations, including MCSs, bonded channels, GI, data encoding, antennas, data rates, link distance, Tx/Rx power, gain, and payload size. We also compare their performance against 802.11ac, which demonstrates that NS-3 accurately supports most 802.11ax capabilities and outperforms 802.11ac in various scenarios.

KEYWORDS

WLANs, IEEE 802.11ac, IEEE 802.11ax, MIMO, NS-3 simulator.

1. INTRODUCTION

In response to the growing demand for faster and more robust wireless communication, the IEEE 802.11 wireless networking standards were developed. Over the past 20 years or so, there has been a significant increase in the use of wireless networks, especially wireless local area networks (WLANs). In 2021, there will be over 14 billion mobile devices available worldwide. It was expected to surpass 15 billion by 2021 and 18.22 billion by 2025, a 4.2 billion device increase from the previous year. Furthermore, it is predicted that there will be 5.3 billion Internet users globally by 2023, with a compound annual growth rate (CAGR) of 6%, compared to the estimated 3.9 billion Internet users in 2018. In 2018, 51% of the world's population used the Internet, and by 2023, it will reach up to 66% [1]–[5].

DOI:10.5121/ijans.2023.13401

The network design is critical for meeting all the requirements of client users, including the upward mobility issue and impacting distributed system characteristics like message speed, routing complexity, fault tolerance, and cost. Designing an optimal topology is challenging due to conflicting requirements' fault tolerance, suitable topological properties, efficient routing, and scalability with various system size choices [6]. The next generation of WLANs faces challenges with dense scenarios and rising throughput requirements due to real-time and high-definition contents [7]. Several prominent IEEE 802.11 standards, including 802.11n/ac/ax/be, are widely used in consumer products for their low cost, flexibility, and high-performance internet access services [8]. To meet rising wireless demand, IEEE 802.11n is widely used in WLANs, supporting technologies like MIMO, 40 MHz bonded channels, frame aggregation, and block acknowledgment, boosting data transfer rates up to 600 Mbps [8], [9]. IEEE 802.11ac offers faster and more adaptable performance, reaching 6.9Gbps with 160MHz channels and 8X8 MIMO, linking users' devices to the Internet [10]. Congestion on wireless IoT devices arises due to limited spectrum resources. This can lead to missed updates and wastage of channel resources, especially in densely populated areas [11]. These problems especially occur in densely populated spaces like classrooms, shopping malls, bus or train stations, offices, airports, stadiums, cafes, hotels, restaurants, and other public and private spaces [12], [13]. The IEEE 802.11 standard underwent a transformation, leading to the emergence of IEEE 802.11ax, aimed at resolving the specified concerns through enhancements in throughput and raw bit rate capabilities. The IEEE 802.11ax protocol significantly improves network performance and efficiency, accommodating modern communication systems [14], [16]. It introduces measures like expanded QAM constellation sizes (up to 1024) and essential MAC layer mechanisms such as OFDMA, MU-MAC, downlink and uplink MU-MIMO, OBSS-PD, TWT, and MCS 10 and MCS 11 [4], [14], [15], [17]-[22]. These advancements promise to greatly enhance wireless network effectiveness and efficiency.

Before deploying any algorithm, protocol, or standard in the real world, WLAN researchers and engineers should often use simulation tools or testing modules to evaluate the connection properties of 802.11n/ac/ax or future protocols, the functionality of their proposed hardware, and scenarios. The accurate representation of connection characteristics for IEEE 802.11n/ac/ax or forthcoming protocols holds significant importance when devising new models or algorithms for WLAN [23]–[25], mobile ad hoc networks (MANET) [26], or vehicular ad hoc networks

(VANET) [27]. Former to practical deployment, improving the system design of IEEE 802.11 WLANs can be cost-effectively and efficiently accomplished by iterative modeling and simulating future algorithms with a network simulator. Many other network simulators have been suggested as potential solutions to this problem. They are the WIMNET simulator [28], the NS-2 simulator [29], the NS-3 simulator [30], the Qual-Net simulator [31], and the OPNET simulator [32]. In the realm of evaluating novel protocols and approaches for WLANs, the NS-3 realistic non-proprietary software platform among this software has garnered widespread usage in academic institutions. Hence, it becomes crucial to delve into the multitude of link characteristics of the 802.11ax protocol through NS-3 simulations. This investigation aims to assess how their efficiency and accuracy fluctuate based on different operational settings.

This research aims to evaluate the effectiveness of various link features in 802.11ax WLANs and conduct a comparative performance analysis with 802.11ac using NS-3 simulation. In this comprehensive study, we extensively examine essential parameters, including throughput and maximum achievable distance, emphasizing their connection to modulation and coding schemes (MCSs), guard intervals (GI), channel aggregation, link distance performance, and the influence of the quantity of antennas in single input single output (SISO) or multiple input multiple output (MIMO) configurations, along with the corresponding data rates. To achieve this, we employ NS3 simulations, specifically targeting scenarios where a solitary client user engages in packet transmission or reception with a single access point (AP). Our focus will be on highlighting the distinctions between these two protocols. Specifically, we will analyse their effects on throughput and determine which protocol better fulfils consumer demands by identifying the one that offers the highest throughput capabilities.

To measure throughput performance, we used the NS-3 simulator as our core method. The paper's structure is displayed. The introduction outlines the study's purpose and methodology, underscoring the research's credibility and soundness. In the 2nd section, we explored the relevant research and studies. The 3dr section provided an overview of the IEEE 802.11ac and IEEE 802.11ax technologies. Subsequently, the 4th section detailed the simulation environment and methodology employed in our study. The 5th section presented the simulation outcomes, and comprehensive discussions were conducted in this section as well. Finally, the key conclusions were summarized in the 6th section.

2. RELATED RESEARCH WORKS

At present-day, there is a substantial amount of scholarly research dedicated to exploring various performance aspects of the 802.11 protocol in wireless local area networks (WLANs) through simulation techniques. In this section, we provide a summary of significant prior research that is relevant to our topic.

Rochim et al. (2020) in [33], this research paper highlights the performance of the IEEE 802.11ax and IEEE 802.11ac protocols, which is evaluated by various link features such as modulation and coding schemes, guard intervals, number of spatial steams, and simulation time. The primary focus is on throughput for both IEEE 802.11ax with a higher MCS-11 and IEEE 802.11ac with a higher MCS-9, all while maintaining a fixed payload size. However, the paper lacks an analysis of the coverage provided by these protocols, the effects of Tx/Rx power and gain, and how changing payload size impacts throughput. Debnath et al. (2018) in [34], the author focuses on estimating throughput in IEEE 802.11n with MIMO technology. It investigates the influence of transmission rates and data capacity on multiple streams using the NS-3 environment. The findings highlight substantial improvements in throughput, along with enhanced delay and jitter performance when higher bandwidths are utilized. These results underscore MIMO's potential to enhance wireless network performance in the context of the IEEE 802.11n framework. Rochim et al. (2016) in [35], aim to compare throughput using a range of spatial streams (SS), data rates, and client counts between IEEE 802.11n and IEEE 802.11ac. Changes in attributes, including client quantity, the MCS index, data rates, and spatial streams (SS) in the context of 802.11n and 802.11ac, are examined. The results demonstrate that, with a client and one to four spatial streams, the throughput of IEEE 802.11n is equivalent to that of IEEE 802.11ac with a bandwidth of 40 MHz’s. Sharon et al. (2017) in [36], the IEEE 802.11ax standard, the following generation of WLAN, is described in this document along with some novel characteristics. It contrasts the top throughput rates of IEEE 802.11ax and IEEE 802.11ac for the situation where the AP constantly broadcasts to a single station in single-user mode. In addition to two levels of frame aggregation in IEEE 802.11ax, the comparison takes modulation and coding methods into account. These findings contribute to assessing the evaluation and enhancement of network performance, advancing our insight into next-generation WLAN technology. Khalil et al. (2020) in [37], by using the NS-3 simulator, this study examines the performance of 802.11ac while highlighting characteristics including channel bonding, MCS, guard intervals, and frame aggregation. It also investigates the impact of differences in the space between STAs and APs on network throughput. This study aims to offer relevant details for configuring 802.11ac networks for various scenarios. According to Amewuda et al. (2018) in [38], the implementation of a wireless LAN system based on 802.11ac in a residential context relies on the guidelines outlined in the 802.11ax task group scenario document. Under various operating settings, they assess how well the 802.11ac protocol performs. They looked at important aspects like frame aggregation, MIMO, and modulation coding set (MCS). Additionally, they assess the network's average throughput, delay, jitter, optimal range for goodput, and impact of station (STA) density per AP. The simulation was carried out using NS-3, an open-source network simulator that includes 802.11ac functionality. Khairy et al. (2017) in [39], this paper focuses on establishing an analytical framework for multi-channel bonding within IEEE 802.11ac WLANs, considering the presence of legacy users. It analyzes the impact of channel bonding on data transfer rates and introduces a channel selection approach to optimize network efficiency. Through this investigation, the paper intends to clarify the significant improvements brought about by IEEE 802.11ac. Milos et al. (2017) in [19], the performance of IEEE 802.11ac and IEEE 802.11ax standards at the PHY level is investigated. MATLAB-based simulation models are employed to compare these two WLAN systems. Additionally, the study explores the effects of carrier frequency offset (CFO) on performance degradation. The findings of this research enhance our understanding of the challenges and provide insights for optimizing future wireless networks. Natkaniec et al. (2023) in [40], focus on optimizing IEEE 802.11ax dense networks. The utilization of the NS-3 simulator is for the analysis and comparison of diverse network topologies. The results highlight the advantages of employing MSDU and MPDU aggregations in dense network environments. These findings contribute to enhancing IEEE 802.11ax networks in dense deployments.

Based on our upstairs discussion, it is apparent that most prior studies do not consider all comprehensive performance metrics for both the IEEE 802.11ax and IEEE 802.11ac protocols. However, in this study, we assess the performance of the IEEE 802.11ax protocol across various link features and compare it to its predecessor, the IEEE 802.11ac protocol, while focusing on single-user communication. To address network performance scenarios in this research paper, we investigate how the newly introduced IEEE 802.11ax standard outperforms the former protocols, making it a superior choice for real-life WLAN installations.

3. Overview Of The Ieee802.11ax and its Predecessor Technology

The IEEE 802.11 standard, commonly known as Wi-Fi, has undergone several iterations to improve wireless communication performance and address the ever-increasing demand for faster and more reliable connections. Two significant advancements in this realm are the predecessor technology IEEE 802.11ac and its successor IEEE 802.11ax, which have revolutionized wireless networks. This section aims to provide a comprehensive overview of these technologies, highlighting their key features, differences, and benefits.

The IEEE 802.11ac protocol, commonly referred to as Wi-Fi 5, emerged as a progression beyond 802.11n, satisfying the need for higher data rates and enhanced network performance. Operating exclusively in the 5 GHz frequency band, it introduced wider channel bandwidths of 80 MHz and 160 MHz, enabling better data speeds and increased capacity. MU-MIMO technology improved efficiency in crowded conditions, while MIMO technology and spatial stream configurations from 1x1 to 8x8 allowed flexible stream combinations. Beamforming enhanced signal strength and coverage, and OFDM increased reliability by transferring data over multiple subcarriers. Various Modulation and Coding Schemes (MCS) accommodated diverse channel conditions, with coding rates for 256-QAM responding to changing scenarios.

Meanwhile, IEEE 802.11ax, or Wi-Fi 6, emerged as the latest iteration, addressing the challenges of connected devices, faster data rates, and network performance. Operating in both the 2.4 GHz and 5 GHz bands, it introduced OFDMA to optimize spectrum utilization. The "number of spatial streams," which could involve up to 12 streams, denoted data streams between access points and devices, while Multi-User Multiple Input, Multiple Output (MU-MIMO) and 1024-QAM increased communication efficiency and data throughput. Wi-Fi 6's Modulation and Coding Schemes (MCS) were adapted to diverse channel scenarios, with coding rates for 1024-QAM responding to changing conditions. Target Wake Time (TWT) optimizes power usage, making it suitable for contemporary high-speed, densely connected networks. Finally, IEEE 802.11ax extended upon the foundation established by 802.11ac and introduced features like OFDMA and 1024-QAM, which in turn led to higher data rates, enhanced network efficiency, and improved power management, effectively addressing the ever-growing demands of wireless communication.

4. Simulation Environment and Proposed Methods

In order to assess the IEEE 802.11 WLAN MIMO/SISO protocol, the NS-3 network simulator, a tool that is frequently used in academics, is used. Under the collective acronym "ns" (from network simulator), a group of discrete-event computer network simulators, includingNS-1, NS-2 [29], and NS-3[30], find common use in academic settings for simulating computer networks. The initial version, NS-1, was developed by Lawrence Berkeley National Laboratory (LBNL) in the mid-1990s. Subsequently, with funding from DARPA and NSS, ns-2 emerged as a modification of NS-1 in 1997 [41]. Later, in 2003, NSF provided funding for NS-3's development as a replacement for NS2. Full backward compatibility with NS-2 was eventually abandoned after the team collaborated with the Planate project of INRIA. The development of NS-3 commenced in July 2006, utilizing the C++ programming language [30]. It incorporates crucial IEEE 802.11n/ac/ax components like MIMO, channel bonding, and various guard intervals, and it offers insightful information on a variety of WLAN algorithms operating at 2.4, 5, and 6 GHz frequencies. A scenario involving WLAN formation with communication between a single host and the AP is used to evaluate performance while looking at elements including MCS choice, bandwidth, antenna configurations, and frame size. The following settings were used for conducting the simulation, and table 1 shows the hardware used for the simulation.

- Network Simulator, NS-3.37.
- Operating system: Linux (Ubuntu 20.04.5LTS).
- Hardware specifications:

Table 1. The hardware parameter utilized in estimating the results.

Hardware part for the PC	
Model Name	Lenovo ThinkPad P14s Gen 2
Processor Brand	Intel
Processor Model	Core i7-1165G7
Generation	11th Gen
Frequency	2.80 GHz up to 4.70 GHz
Processor Core	4
Processor Thread	8
CPU Cache	12B

4.1. Methodological Framework

The provided techniques are used to simulate and test an 802.11ac and 802.11ax-based WLAN. The installation process for the NS-3.37 version is launched using Linux terminal commands.

Certain code files are accessed and modified after installation. A simulation is created for a WLAN with a single host, an AP, and support for 802.11ac and 802.11ax. A number of performance factors, including data throughput, transmission range, MCSs, connection distance features, and antenna layouts, are the main subjects of the inquiry. Increases in guard interval and channel bandwidth are considered. To determine throughput, a flow meter and a predetermined equation are utilized.

Follow these steps:

A. Install the NS-3.37 version with the help of the Linux terminal procedures listed on https://www.nsnam.org/.

B. After the installation process is finished, navigate to the installation directory on your PC. Open the wifi-vht-network.cc and wifi-he-network.cc files by going to the ns-allinone-3.37/NS-3.37/examples/wireless folder.

C. To perform the required code adjustments, copy these files to the scratch folder and then open them in an editor program. The section of the code that we modified can be found in the appendix.

D. Use the Linux Terminal to launch the changed code, then type the following command in the directory containing the code file: ./ns3 run scratch/filename, where "filename" denotes the name of the modified code file you want to execute.
E. Create a simulation of an 802.11ac and 802.11ax-based WLAN formed by a single host and an AP.
F. Analyze the effects of various factors on the network's performance, including data throughput, transmission range, different MCSs (802.11ac supports MCS-0 to MCS-9 and 802.11ax supports MCS-0 to MCS-11), link distance features by rate adaptation, and the number of antennas used at both ends of the link (802.11ac/ax permits 1×1 to 4×4 antennas).

G. The impacts of increasing the channel bandwidth for 802.11ac and 802.11ax (both standards support 20 MHz, 40 MHz, 80 MHz, and 160 MHz or 80+80 MHz bonded channels) and the Guard Interval (GI) (3200ns, 1600ns, and 800ns for 802.11ax and 800ns(long) or 400ns(short) for 802.11ac) are taken into consideration.

H. Determine the throughput for each VHT and HE bit rate value using the flow monitor and Equation (1):

$$\text{Throughput} = \frac{\text{rxBytes} * 8}{\text{TimeLastRxpkt} - \text{TimeFirstRxpkt}} \quad (1)$$

where rxBytes represents the total number of packets received, TimeLastRxPacket represents the time at which the final packet was received, and TimeFirstRxPacket represents the time at which the flow monitor first began receiving packets.

5. Discussion and Observation of Simulation Results

In this section, we showcase various simulation outcomes depicting communication between a specific host and an access point (AP).

5.1. Evaluating the Average Throughput and the Maximum Range for Various MCS

In this section, we evaluate the relationships between variables, focusing on the impact of varying MCSs and physical distances between the AP and STA on maximum throughput and transmission range. Figure 1 and Table 2 display the results, showing a noteworthy finding: increasing the MCS value improved peak throughput due to higher RSS but reduced communication range. This trade-off was due to the need for higher SNRs at higher MCSs for accurate signal decoding, leading to signal attenuation and interference at extended distances, limiting the range.

To provide an equitable comparison between the IEEE 802.11ax and 802.11ac standards, it's important to note that both standards offer MCS values ranging from 0 to 9. However, IEEE 802.11ax introduces two additional MCS options, MCS 10 and MCS 11, which contribute to enhanced performance. To facilitate a fair comparison, we focus exclusively on the common MCS values (0 to 9) shared by both standards. Additionally, we include the performance of MCS 11 for IEEE 802.11ax, which enhances its superiority over the previous IEEE 802.11ac standard.
As the distance between the AP and the STA increases, RSS levels align with the adoption of higher MCSs, especially at shorter distances with optimal signal strength, thereby enhancing throughput. Conversely, lower RSS values necessitate the use of lower MCSs. This adjustment involves a trade-off: throughput decreases, but communication ranges significantly expand, which is shown in Figure 1 for lower MCS 1 we get a higher distance, approximately 70 meters for IEEE 802.11ax, and approximately 60 meters for IEEE 802.11ac. In both communication range and throughput, IEEE 802.11ax outperforms IEEE 802.11ac. To optimize throughput with higher MCS values, strategic STA positioning near the AP becomes imperative. These insights are invaluable for designing and optimizing wireless networks across diverse conditions, offering crucial guidance for network professionals and administrators.

Table 2. IEEE 802.11 WLAN's range simulation measurement parameter.

Parameter	Value for IEEE 802.11ac	Value for IEEE 802.11ax
Propagation Model	LogDistancePropagationLossModel	LogDistancePropagationLossModel
Mobility Model	ConstantPositionMobilityModel	ConstantPositionMobilityModel
Remote Station Manager	ConstantRateWifiManager	ConstantRateWifiManager
Packet Size	TCP,1472bytes[8]	TCP,1472bytes[8]
Spatial Stream	2×2	2×2
Tx/Rx Power	17dBm	17dBm
Mode	80MHz	80MHz
MCS	1,3,5,7 & 9	1,3,5,7, 9 & 11
Guard Interval (GI)	800ns	800ns

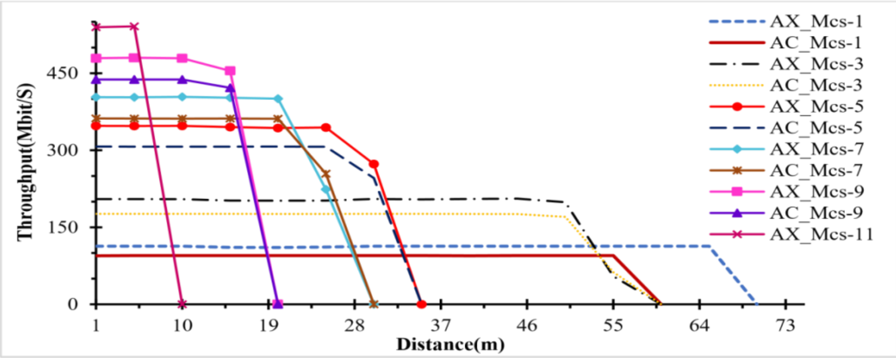


Figure 1. Link distance vs. throughput with respect to different MCSs.

5.2. Investigating the Impact of Number of Spatial Streams (NSS) on Throughput

In this section, we investigate the impact of different NSS settings on data performance for a fixed MCS in the context of IEEE 802.11ax and 802.11ac standards. The simulation scenario aims to analyze the effects of varying NSS on data throughput and assess the performance of different NSS values. The incorporation of Figure 2, displaying the simulation outcomes, and Table 3, illustrating the parameters used in the simulation, enhances the clarity of the research setup. These graphical representations offer readers analytical insights and a comprehensive overview of the simulation design, allowing them to quickly grasp the key concepts to the study.

Figure 2 presents the average throughput estimation for various NSS values when a single STA is connected to the AP to generate traffic. Particularly, we observe that altering the NSS has no discernible impact on distances, aligning with the IEEE 802.11ax and 802.11ac standards. However, WLAN performance does depend on NSS variations. The results demonstrate that increasing the number of spatial streams enhances throughput for both standards. Specifically, at NSS 2×2, IEEE 802.11ax achieves higher throughput, reaching 454.54 Mbps, compared to IEEE 802.11ac, which achieves 410.813 Mbps. When we increase the NSS to 3×3, we observe throughput of 545.736 Mbps for IEEE 802.11ax and 512.517 Mbps for IEEE 802.11ac. Further increasing the NSS value to 4×4 results in throughput of 620.466 Mbps for IEEE 802.11ax and 596.388 Mbps for IEEE 802.11ac standards. These findings highlight the significance of NSS settings in influencing throughput performance in wireless networks.

Table 3. IEEE 802.11 WLAN's spatial streams simulation parameter.

Parameter	Value for IEEE 802.11ac	Value for IEEE 802.11ax
Propagation Model	LogDistancePropagationLossModel	LogDistancePropagationLossModel
Mobility Model	ConstantPositionMobilityModel	ConstantPositionMobilityModel
Remote Station Manager	ConstantRateWifiManager	ConstantRateWifiManager
Packet Size	TCP,1472bytes[8]	TCP,1472bytes[8]
Spatial Stream	2×2, 3×3, 4×4	2×2, 3×3, 4×4
Tx/Rx Power	17dBm	17dBm
Mode	80MHz	80MHz
MCS	8	8
Guard Interval (GI)	800ns	800ns

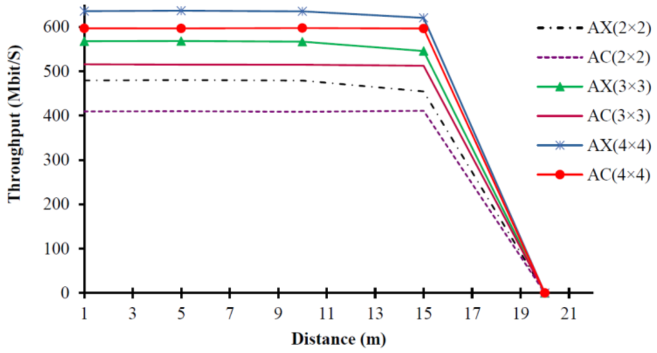


Figure 2. MIMO's throughput enhancement impact.

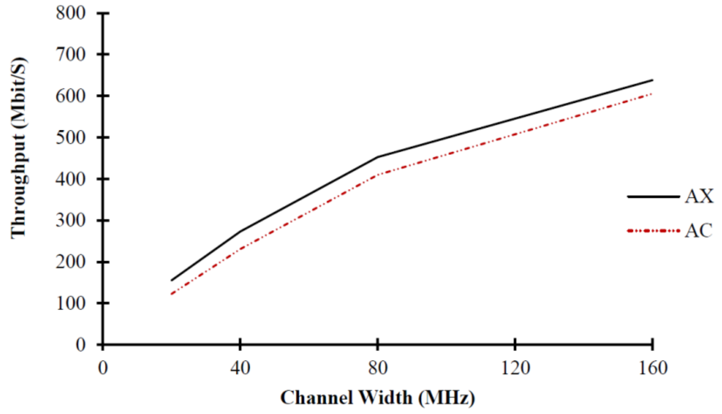
The results indicate that improving the NSS for a constant MCS values lead to enhanced performance in both IEEE 802.11ax and 802.11ac standards. Significantly, IEEE 802.11ax demonstrates a more significant performance boost, offering faster data throughput of approximately 17% for each increase in NSS, on average, and better spectral efficiency than IEEE 802.11ac. Optimal performance requires careful selection of MCS and NSS settings between the AP and end nodes, as these parameters have a substantial impact on achievable throughput.

5.3. Analysing the Influence of Channel Width on Throughput

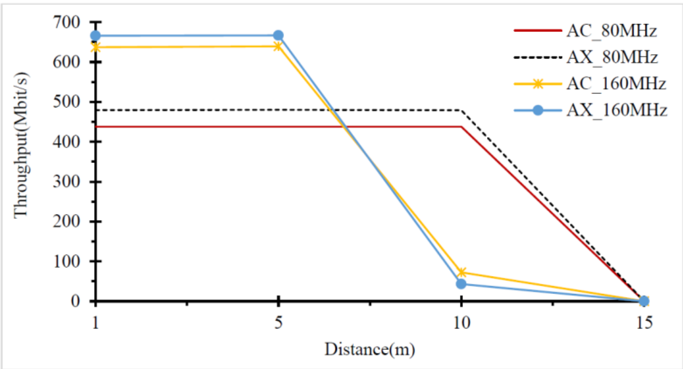
In this section, we investigate how channel width influences the throughput of IEEE 802.11ax and 802.11ac wireless network. To facilitate a deeper understanding of the simulation setup, we incorporate Figure 3, which displays the simulation outcomes, and Table 4, illustrating the simulation parameters. These visual aids enhance comprehension and provide valuable context for our investigation.

Table 4. IEEE 802.11 WLAN's channel width simulation parameter.

Parameter	Value for IEEE 802.11ac	Value for IEEE 802.11ax
Propagation Model	LogDistancePropagationLossModel	LogDistancePropagationLossModel
Mobility Model	ConstantPositionMobilityModel	ConstantPositionMobilityModel
Error Rate Model	Nist Error Rate Model	Nist Error Rate Model
Remote Station Manager	ConstantRateWifiManager	ConstantRateWifiManager
Packet Size	TCP,1472bytes[8]	TCP,1472bytes[8]
Spatial Stream	2×2	2×2
Tx/Rx Power	17dBm &16dBm[8]	17dBm & 16dBm[8]
Channel Width	80 MHz/160 MHz	80 MHz/160 MHz
MCS	8 & 9	8 & 9
Guard Interval (GI)	800ns	800ns
Distance(m)	5	5



(a) Channel width vs. throughput at fixed distance.



(b) Channel width vs. throughput at different distances.

Figure 3. Effect of wider channels on throughput.

In our investigation (Figure 3(a)), we assess the impact of doubling the channel width for both IEEE 802.11ax and IEEE 802.11ac at MCS 8, maintaining a constant distance of 5 meters, Tx/Rx power is 17dBm and other parameters are remains same for this simulation setup. For IEEE 802.11ax, when we double the channel width from 20 MHz to 40 MHz, we observe a significant increase in average throughput, approximately 76%. However, for the higher bonded channels, we observe a decrease in average throughput. Specifically, for the 40 MHz to 80 MHz bonded channel, there is a decrease of approximately 67%, and for the 80 MHz to 160 MHz bonded channel, the decrease is approximately 41%. Due to better signal quality, less interference, and more effective modulation, the smaller (20+20) bonded channel 40 MHz increases throughput. These variations underscore the significance of channel width selection in optimizing wireless communication performance.

Furthermore, in Figure 3(b), we explore the effects of doubling the channel width on available bandwidth at MCS 9 and Tx/Rx power is 16dBm, resulting in a substantial 39% increase in data transmission rates for IEEE 802.11ax, leading to higher throughput. Faster data rates are achieved by wider channels, which allow the wireless signal to carry more data simultaneously. However, wider channels might lead to trade-offs, such as reduced coverage area or increased interference. For instance, when transitioning from an 80 MHz channel width to a broader 160 MHz channel, which necessitates a higher SNR, we observe a significant decrease in throughput as distances extend. Interestingly, amid these adjustments, the coverage range remains remarkably stable. The study's key finding underscores that progressively doubling the channel width at each stage is the most effective strategy for achieving the highest throughput in the wireless communication system by efficiently harnessing the available bandwidth.

5.4. Assessing MCS Impact on Throughput with Different NSS Configurations

In this section, we assess a comprehensive exploration of the influence of MCS on the typical throughput of wireless networks, following the esteemed IEEE 802.11ax and IEEE 802.11ac standards. Through extensive simulations, we investigate both 2x2 and 4x4 spatial streams, providing valuable insights into the impact of MCS variations on system performance and overall wireless communication. The results, depicted in Figure 4 and summarized in Table 5, offer clear information about the simulation setup.

Figure 4 illustrates the impact of channel width and spatial streams on data rates within the context of IEEE 802.11ax and IEEE 802.11ac. When employing an 80 MHz bonded channel width paired with a 2×2 spatial stream configuration, peak physical data rates reach 541.22 Mbps for IEEE 802.11ax and 437.73 Mbps for IEEE 802.11ac. Especially, maintaining the same channel width while increasing spatial streams to 4×4 results in a significant data rate boost, with speeds reaching 660.188Mbps for IEEE 802.11ax and 622.711 Mbps for IEEE 802.11ac. These observations underline the substantial influence of spatial streams on overall wireless performance.

Examining IEEE 802.11ax performance at a 5-meter distance reveals remarkable results from MCS 0 to MCS 6. However, a subtle performance drop occurs from MCS 7 to MCS 11, especially with 160 MHz channel and a 4x4 spatial stream configuration. Evidently, in these specific scenarios, IEEE 802.11ac offers slightly better performance than IEEE 802.11ax. This comprehensive understanding highlights the significance of optimizing system configurations and strategically managing trade-offs to attain exceptional wireless communication performance across varying distances. It offers valuable guidance for researchers and practitioners looking to enhance network efficiency and reliability in real-world applications.

Table 5. MCS impact on WLAN throughput simulation measurement parameter.

Parameter	Value for IEEE 802.11ac	Value for IEEE 802.11ax
Propagation Model	LogDistancePropagationLossModel	LogDistancePropagationLossModel
Mobility Model	ConstantPositionMobilityModel	ConstantPositionMobilityModel
Remote Station Manager	ConstantRateWifiManager	ConstantRateWifiManager
Packet Size	TCP,1472bytes[8]	TCP,1472bytes[8]
Spatial Stream	2×2, 4×4	2×2, 4×4
Tx/Rx Power	17dBm	17dBm
Channel Mode	80MHz	80MHz
Guard Interval (GI)	800ns	800ns
Distance(m)	5	5

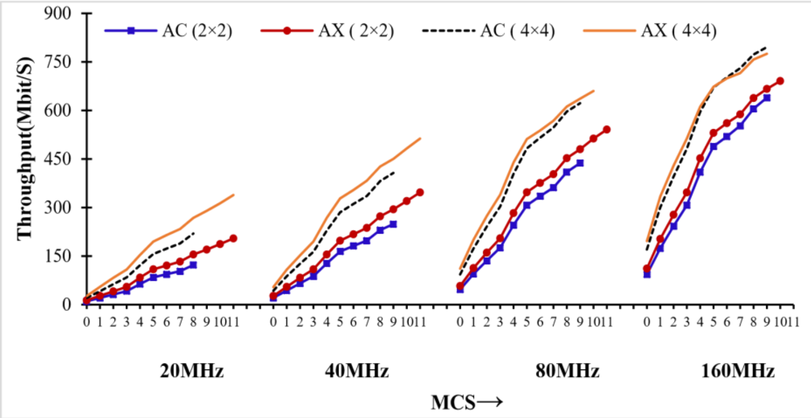


Figure 4. Assessing throughput using MCS over various channel widths.

5.5. Tx/Rx Power Impact on Throughput

In this section, we examine the influence of Tx/Rx power variation on throughput coverage within the context of IEEE 802.11ax and IEEE 802.11ac standards. The Tx/Rx power in WLAN significantly impacts network performance and coverage. Higher Tx/Rx power extends coverage and strengthens the signal, leading to better throughput and signal quality. However, it may increase the risk of interference and affect client device battery life. Optimizing Tx/Rx power involves finding a balance between coverage, signal strength, and regulatory compliance. Finetuning power settings enhances WLAN performance, coverage, and the overall user experience. The aim is to understand how adjustments in Tx and Rx power levels impact the extent of data transmission coverage in the network. Through a series of systematic tests and simulations, we analyze the performance outcomes of both 802.11ax and 802.11ac protocols under varying Tx/Rx power settings. Figure 5 showcases the simulation results, providing a clear visualization of the relationship between Tx/Rx power and throughput coverage. Table 6, presenting the parameters used in the simulation, enhances the clarity and comprehensibility of the research setup.

Table 6. IEEE 802.11 WLAN Tx/Rx Power simulation parameter.

Parameter	Value for IEEE 802.11ac	Value for IEEE 802.11ax
Propagation Model	LogDistancePropagationLossModel	LogDistancePropagationLossModel
Mobility Model	ConstantPositionMobilityModel	ConstantPositionMobilityModel
Error Rate Model	Nist Error Rate Model	Nist Error Rate Model
Remote Station Manager	ConstantRateWifiManager	ConstantRateWifiManager
Packet Size	TCP,1472bytes[8]	TCP,1472bytes[8]
Spatial Stream	2×2	2×2
Tx /Rx Power	17dBm,25dBm,30dBm	17dBm,25dBm,30dBm
Tx/Rx Gain	1dBi[42]	1dBi[42]
Channel Width	80MHz	80MHz
Guard Interval (GI)	800ns	800ns
MCS	7	7

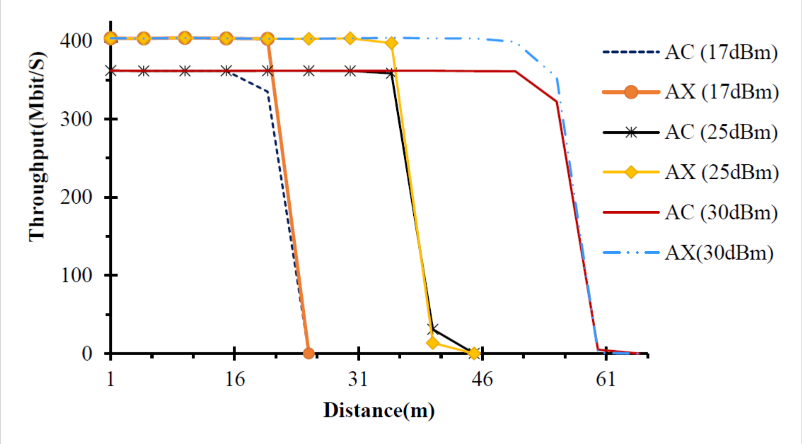


Figure 5. Analysing Tx/Rx power's effect on throughput-distance relationship.

The investigation sheds light on the pivotal role of Tx/Rx power levels in shaping signal propagation, range, and SNR in wireless communication. By examining performance across various power settings, ranging from 17 dBm to 30 dBm for both standards, we observed an average coverage increase of approximately 3 meters when raising the power level by 1 dBm. This analysis allows us to identify the optimal power levels that enhance overall throughput coverage while maintaining signal integrity and minimizing interference.

One remarkable finding is that the IEEE 802.11ax standard, known for its efficiency and improved capabilities, exhibits more robust throughput coverage compared to IEEE 802.11ac under varying Tx/Rx power levels. This insight highlights the advancements of 802.11ax in managing and optimizing throughput coverage, making it a compelling choice for modern wireless networks.

5.6. Analysis of Performance for UDP and TCP Traffic

This section analyzes UDP and TCP transport layer protocol behavior and effectiveness in relation to IEEE 802.11ax and IEEE 802.11ac standards. The inclusion of Figure 6, which presents the simulation outcomes, and Table 7, which illustrates the parameters utilized in the simulation, provides a clearer understanding of the research setup. Overall, it provides a clear introduction to the section's content and research focus. In Wi-Fi 5 (802.11ac) and Wi-Fi 6 (802.11ax), TCP maintains its connection-oriented nature, ensuring reliable and ordered data delivery. However, Wi-Fi 6's improved features may enhance TCP's throughput and latency performance compared to Wi-Fi 5. Meanwhile, UDP remains connectionless in both standards, providing fast data delivery but without guaranteed reliability.

Our analysis reveals that UDP consistently outperforms TCP in terms of network throughput, achieving 528.844 Mbps for IEEE 802.11ax and 453.562 Mbps for IEEE 802.11ac. TCP performance, as detailed in Table 7, reaches 403.43 Mbps for IEEE 802.11ax and 362.06 Mbps for IEEE 802.11ac. Distinctively, both UDP and TCP perform better in IEEE 802.11ax networks compared to IEEE 802.11ac. The choice between UDP and TCP in these networks depends on specific application requirements, considering factors such as data sensitivity, latency tolerance, and real-time communication needs.

Table 7. UDP/TCP flow simulation measurement parameter for IEEE 802.11 WLAN

Parameter	Value for IEEE 802.11ac	Value for IEEE 802.11ax
Propagation Model	LogDistancePropagationLossModel	LogDistancePropagationLossModel
Remote Station Manager	ConstantRateWifiManager	ConstantRateWifiManager
Mobility Model	ConstantPositionMobilityModel	ConstantPositionMobilityModel
Error Rate Model	Nist Error Rate Model	Nist Error Rate Model
Packet Size	UDP, TCP, 1472bytes[8]	UDP, TCP, 1472bytes[8]
Spatial Stream	2×2	2×2
Tx /Rx Power	17dBm	17dBm
Tx/Rx Gain	1dBi[42]	1dBi[42]
Channel Width	80MHz	80MHz
Guard Interval (GI)	800ns	800ns
MCS	7	7

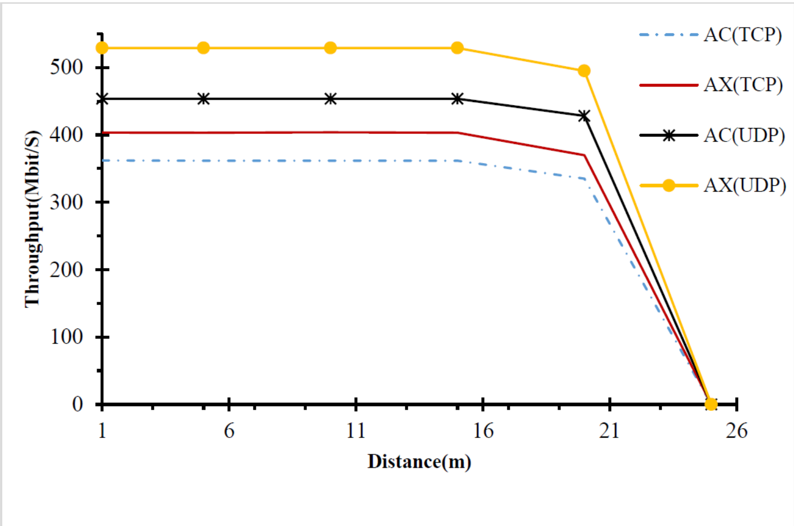


Figure 6. Comprehensive analysis of UDP and TCP flows.

5.7. Investigating Throughput Impact with Varying Payload Size

In this section, we investigate the crucial impact of varying payload sizes on throughput, particularly within the context of IEEE 802.11ax and 802.11ac protocols. In WLANs, the payload size has a significant impact on different aspects of network performance metrics. Optimizing payload size not only enhances quality of service (QoS) but also improves power efficiency in battery-powered devices. In our simulation setup, we consider line-of-sight environments to comprehensively understand the protocol behavior. Figure 7 graphically illustrates our findings, demonstrating the impact of payload size variations on throughput for both standards. Complementing this, Table 8 provides precise numerical data and relevant performance metrics, offering a comprehensive analysis of payload size's influence on throughput.

Table 8. IEEE 802.11 WLAN payload size variation simulation parameter.

Parameter	Value for IEEE 802.11ac	Value for IEEE 802.11ax
Propagation Model	LogDistancePropagationLossModel	LogDistancePropagationLossModel
Mobility Model	ConstantPositionMobilityModel	ConstantPositionMobilityModel
Remote Station Manager	ConstantRateWifiManager	ConstantRateWifiManager
Error Rate Model	Nist Error Rate Model	Nist Error Rate Model
Data Flow Type	TCP	TCP
Spatial Stream	2×2	2×2
Tx /Rx Power	17dBm	17dBm
Tx/Rx Gain	1dBi[42]	1dBi[42]
Channel Width	80MHz	80MHz
MCS	7	7
Guard Interval (GI)	800ns	800ns
Distance(m)	1	1

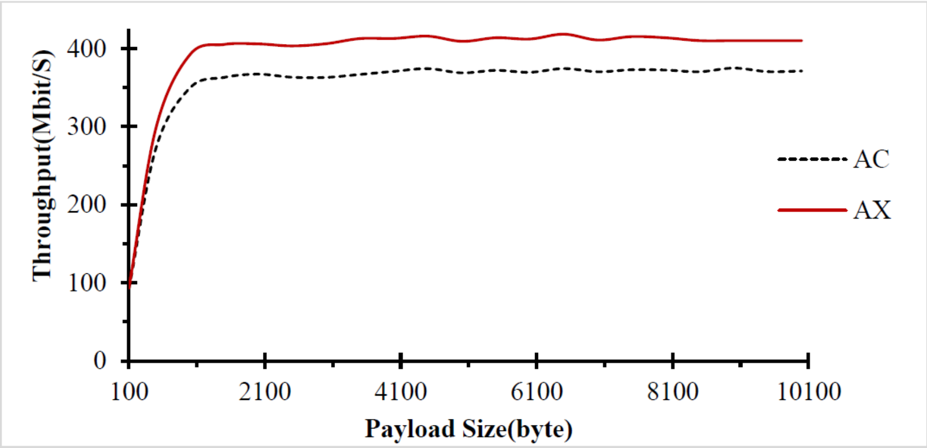


Figure 7.Analysing throughput impact on varying payload size.

Our investigation's outcomes demonstrate the impact of varying payload sizes on throughput for both IEEE 802.11ac and IEEE 802.11ax protocols. Through extensive simulations in our controlled environment, we analyze the performance of both Wi-Fi standards under different payload conditions, as illustrated in Figure 7. Conspicuously, we observe a payload size threshold—approximately 418 Mbps for IEEE 802.11ax and 374 Mbps for IEEE 802.11ac—beyond which the data rate remains unchanged, indicating a saturation point for throughput improvement. Further increasing the payload size, we observe fluctuations in throughput at a specific point. Subsequently, we notice a stabilization effect, leading to a constant throughput. This phenomenon occurs as the payload size continues to increase.

5.8. Tx/Rx Antenna Gain's Impact Assessing on Throughput

In this section, we assess the throughput coverage, specifically focusing on how varying Tx/Rx antenna gain influences performance in the context of IEEE 802.11ax and 802.11ac standards.

These cutting-edge wireless protocols have transformed networking, elevating data rates and the user experience. Tx/Rx antenna gain significantly shapes signal propagation and SNR in these protocols. Adjusting antenna gain directly impacts throughput coverage, whether it's in a specific direction or in an omni-directional manner. Figure 8 presents performance results, while Table 9 details simulation parameters.

Table 9. Tx/Rx gain simulation measurement parameter for IEEE 802.11 WLAN

Parameter	Value for IEEE 802.11ac	Value for IEEE 802.11ax
Propagation Model	LogDistancePropagationLossMod el	LogDistancePropagationLossMo del
Mobility Model	ConstantPositionMobilityModel	ConstantPositionMobilityModel
Remote Station Manager	ConstantRateWifiManager	ConstantRateWifiManager
Error Rate Model	Nist Error Rate Model	Nist Error Rate Model
Packet Size	TCP,1472bytes[8]	TCP,1472bytes[8]
Spatial Stream	2×2	2×2
Tx /Rx Power	17dBm	17dBm
Tx/Rx Gain	1dBi[42], 6dBi[43]	1dBi[42], 6dBi[43]
Channel Width	80MHz	80MHz
Guard Interval (GI)	800ns	800ns
MCS	7	7

To ensure protocol reliability, we conducted simulations comparing IEEE 802.11

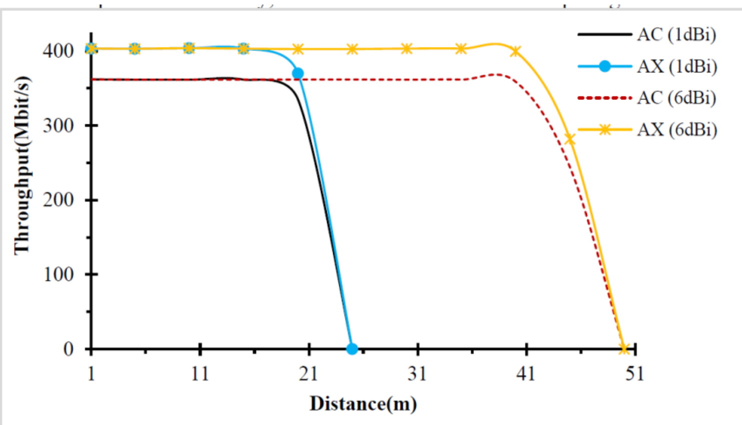


Figure 8. Evaluating throughput with varied Tx/Rx gain over distance

ax with the previous IEEE 802.11ac standard before real-world deployment. We explore the intricate relationship between antenna gain and throughput in line-of-sight settings, vital for optimizing network performance.

During our analysis of performance across a spectrum of antenna gain settings, spanning from 1 dBi to 6 dBi for both standards, we noted that increasing the gain level by 1 dBi resulted in an average coverage extension of approximately 5 meters. As the Tx/Rx gain increases, there is a corresponding expansion in the throughput coverage area, providing consistent service quality to users regardless of their distance from the AP. The comparison between IEEE 802.11ax and

802.11ac within the same simulation environment shows the superiority of 802.11ax, emphasizing its potential for enhanced efficiency and reliability in wireless communication.

5.9. Evaluating Remote Rate Adaptation's Effect on Throughput across Distances

In this section, we make use of the benefits of rate adaptation models within a wireless network, concentrating on the separation between the AP and STA in a corporate WLAN environment. The incorporation of a remote station manager into the WLAN proves highly beneficial, particularly concerning MCS. This manager centrally oversees and adjusts MCS settings, ensuring consistency and enhancing WLAN performance by aligning with Received Signal Strength (RSS) cues. Real-time monitoring allows quick adaptation to changing signals.

Our simulation includes various IEEE 802.11ac and 802.11ax configurations. Figure 9 provides an overview of performance results, while Table 10 outlines the simulation parameters in detail. For IEEE 802.11ax, we observed a remarkable data rate of 687.181 Mbps within a 1-meter distance coverage, extending up to approximately 80 meters in total coverage. In contrast, IEEE 802.11ac achieved its highest throughput at 624.298 Mbps but covered only about 65 meters. As AP-STA distance increases, there's a significant standard throughput reduction due to signal attenuation, causing increased packet loss and retransmissions. Figure 9 visualizes this decline, linked to dynamic MCS adjustments and SNR challenges.

Table 10. Rate adaptation simulation measurement parameter for IEEE 802.11 WLAN

Parameter	Value for IEEE 802.11ac	Value for IEEE 802.11ax
Propagation Model	LogDistancePropagationLossModel	LogDistancePropagationLossModel
Mobility Model	ConstantPositionMobilityModel	ConstantPositionMobilityModel
Remote Station Manager	IdealRateWifiManager	IdealRateWifiManager
Error Rate Model	Nist Error Rate Model	Nist Error Rate Model
Packet Size	TCP,1472bytes[8]	TCP,1472bytes[8]
Spatial Stream	4×4	4×4
Tx /Rx Power	17dBm	17dBm
Tx/Rx Gain	1dBi[42]	1dBi[42]
Channel Width	80MHz	80MHz
Guard Interval (GI)	800ns	800ns
Distance(m)	5	5

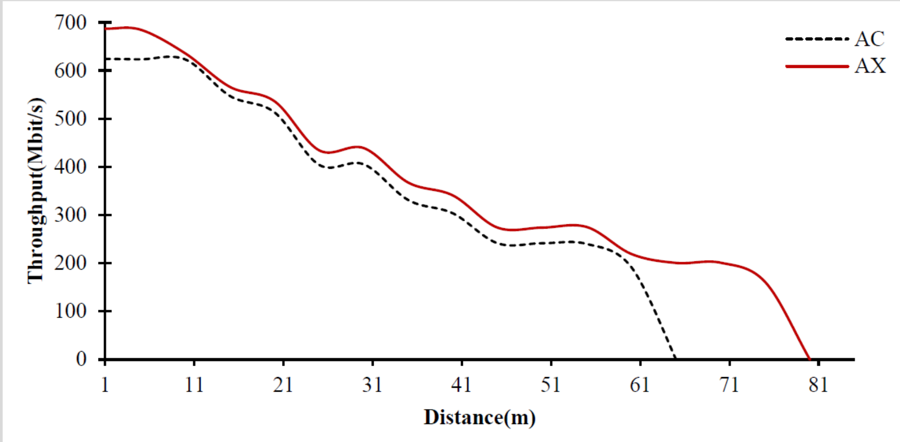


Figure 9. Assessing rate adaptation's impact on throughput vs. distance relationship.

6. Conclusions and Future Works

This paper compares the simulation performance of the IEEE 802.11ax and 802.11ac MIMO link features of WLANs, which demonstrates the major gains and benefits provided by these technologies. Our simulation results show that for a single-user scenario, both 802.11ac and 802.11ax MIMO exhibit better performance over earlier Wi-Fi protocols, with 802.11ax demonstrating considerably more improvements. Throughput, coverage, capacity, and spectral efficiency are among the factors we consider in our analyses. The results show that the 802.11ax MIMO link performs better than 802.11ac and is a great fit for next-generation wireless LANs, providing better user experiences and higher network efficiency. Our upcoming work utilizes deep learning to detect and mitigate interference in IEEE 802.11ax WLANs, enhancing network reliability and performance.

References

[1] "The Statista." https://www.statista.com/statistics/245501/multiple-mobile-device-ownershipworldwide/#:~:text=In 2021%2C the number of mobile devices operating,of 4.2 billion devices compared to 2020 levels.

[2] M. Natkaniec and N. Bieryt, "An Analysis of the Mixed IEEE 802.11ax Wireless Networks in the 5 GHz Band," Sensors, vol. 23, no. 10, 2023.

[3] T. Cisco and A. Internet, "Cisco: 2020 CISO Benchmark Report," Computer Fraud & Security, vol. 2020, no. 3, pp. 4–4, 2020.

[4] Q. Qu et al., "Survey and Performance Evaluation of the Upcoming Next Generation WLANs Standard - IEEE 802.11ax," Mobile Networks and Applications, vol. 24, no. 5, pp. 1461–1474, 2019.

[5] K. H. Lee, "Using OFDMA for MU-MIMO user selection in 802.11ax-Based Wi-Fi Networks," IEEE Access, vol. 7, pp. 186041–186055, 2019.

[6] A. Volokyta et al., "Extended DragonDeBrujin Topology Synthesis Method," International Journal of Computer Network and Information Security, vol. 14, no. 6, pp. 23–36, 2022.

[7] M. A. C. Ieee, S.- Mo, and T. Group, "Ieee 802.11," no. February 2016, pp. 38–46, 2019.

[8] S. K. Debnath, P. K. Sarker, Md. M. Islam, and I. Pramanik, "Investigation and Evaluation of IEEE 802.11n WLANs Link Features Performance Under Single Host and Concurrent Communication," International Journal on AdHoc Networking Systems, vol. 11, no. 1, pp. 1–13, Jan. 2021.

[9] M. S. Gast, "802.11ac: A Survival Guide."

[10] Cisco, “802.11ac: The Fifth Generation of Wi-Fi,” Cisco.Com, no. 1, pp. 1–20, 2018, [Online]. Available: https://www.cisco.com/c/dam/en/us/products/collateral/wireless/aironet-3600series/white-paper-c11-713103.pdf

[11] L. Li, Y. Dong, C. Pan, and P. Fan, “Age of Information of CSMA/CA Based Wireless Networks,” 2022 International Wireless Communications and Mobile Computing, IWCMC 2022, pp. 530– 535, 2022.

[12] N. Shahin, R. Ali, S. W. Kim, and Y.-T. Kim, “Cognitive backoff mechanism for IEEE802.11ax high-efficiency WLANs,” Journal of Communications and Networks, vol. 21, no. 2, pp. 158–167, 2019.

[13] R. Ali, S. W. Kim, B. S. Kim, and Y. Park, “Design of MAC Layer Resource Allocation Schemes for IEEE 802.11ax: Future Directions,” IETE Technical Review (Institution of Electronics and Telecommunication Engineers, India), vol. 35, no. 1, pp. 28–52, 2018.

[14] A. Malhotra, M. Maity, and A. Dutta, “How much can we reuse? An empirical analysis of the performance benefits achieved by spatial-reuse of IEEE 802.11ax,” 2019 11th International Conference on Communication Systems and Networks, COMSNETS 2019, vol. 2061, pp. 432– 435, 2019.

[15] M. S. Kuran, A. Dilmac, O. Topal, B. Yamansavascilar, S. Avallone, and T. Tugcu, “Throughputmaximizing OFDMA Scheduler for IEEE 802.11ax Networks,” IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC, vol. 2020-Augus, 2020.

[16] A. Masiukiewicz, “Throughput comparison between the new hew 802.11ax standard and 802.11n/ac standards in selected distance windows,” International Journal of Electronics and Telecommunications, vol. 65, no. 1, pp. 79–84, 2019.

[17] G. Naik, S. Bhattarai, and J. J. Park, “Performance Analysis of Uplink Multi-User OFDMA in IEEE 802 . 11ax,” 2018 IEEE International Conference on Communications (ICC), pp. 1–6, 2018.

[18] T. Uwai, T. Miyamoto, Y. Nagao, L. Lanante, M. Kurosaki, and H. Ochi, “Performance evaluation of OFDMA random access in IEEE802.11ax,” International Symposium on Intelligent Signal Processing and Communication Systems, ISPACS 2016.

[19] J. Milos, L. Polak, and M. Slanina, “Performance Analysis of IEEE 802 . 11ac / ax WLAN Technologies under the Presence of CFO,” pp. 4–7, 2017.

[20] S. Bhattarai, G. Naik, and J. M. J. Park, “Uplink Resource Allocation in IEEE 802.11ax,” IEEE International Conference on Communications, vol. 2019-May, pp. 1–6, 2019.

[21] Y. Daldoul, D. E. Meddour, and A. Ksentini, “Performance evaluation of OFDMA and MUMIMO in 802.11ax networks,” Computer Networks, vol. 182, no. June, p. 107477, 2020.

[22] Cisco Systems Inc., “Wi-Fi 6: The Next Generation of Wireless,” no. April, 2019.

[23] S. Computing, “Enhancements of minimax access-point setup optimisation approach for IEEE 802 . 11 WLAN Kyaw Soe Lwin , Nobuo Funabiki *, Sumon Kumar Debnath , Ismael Munene Kwenga , Rahardhita Widyatra Sudibyo and Minoru Kuribayashi Wen-Chung Kao,” vol. 9, no. 1, 2019.

[24] M. Saha, N. Funabiki, S. K. Debnath, and W. C. Kao, “A Study of MIMO Host Location Optimization in Active Access-Point Configuration Algorithm for Elastic WLAN System,” 2018 IEEE International Conference on Consumer Electronics-Taiwan, ICCE-TW 2018, pp. 1–2, 2018.

[25] M. S. Al Mamun, S. K. Debnath, K. S. Lwin, and N. Funabiki, “A channel assignment extension of active access-point configuration algorithm for elastic WLAN system under limited channels,” Proceedings - 2016 4th International Symposium on Computing and Networking, CANDAR 2016, pp. 318–324, 2017.

[26] M. Muhammad, A. GidadoHalilu, and S. Mohammed Bunu, “Framework, Implementation and Algorithm for Asynchronous Power Saving of UWBMAC with Steerable Directional Antenna In MANETS,” International Journal on AdHoc Networking Systems, vol. 09, no. 02, pp. 01–11, Apr. 2019.

[27] O. Mahma and A. Korichi, “Simulation & VANET : Towards a New Reliable and Optimal Data Dissemination Model,” International Journal on AdHoc Networking Systems, vol. 6, no. 2, pp. 01–11, 2016.

[28] N. Funabiki, Ed., “Wireless Mesh Networks.” IntechOpen, Rijeka, 2011.

[29] “The network simulator-2”, [Online]. Available: https://www.isi.edu/nsnam/ns/

[30] “The Network Simulator 3”, [Online]. Available: https://www.nsnam.org/

[31] SCALABLE Networks, “QualNet Network Simulator Software,” SCALABLE Networks Technologies, pp. 1–6, 2017.

[32] W. Jiang, "OPNET-based WLAN modeling and its performance testing," Chem Eng Trans, vol. 51, pp. 361–366, 2016.

[33] A. F. Rochim, S. Fuad, B. Harijadi, Y. P. Purbanugraha, and K. A. Nugroho, "Performance comparison of wireless protocol IEEE 802.11ax vs 802.11ac," 2020.

[34] S. K. Debnath, M. Saha, N. Funabiki, and W. C. Kao, "A Throughput Estimation Model for IEEE 802.11n MIMO Link in Wireless Local-Area Networks," 2018 3rd Int. Conf. Comput. Commun. Syst. ICCCS 2018, pp. 421–425, 2018.

[35] A. F. Rochim, U. Indonesia, R. F. Sari, and U. Indonesia, "Performance Comparison of IEEE 802 . 11n and IEEE 802.11ac," pp. 54–59, 2016.

[36] O. Sharon and Y. Alpert, "Single User MAC Level Throughput Comparision: IEEE 802.11ax vs. IEEE 802.11ac," Wireless Sensor Network, vol. 09, no. 05, pp. 166–177, 2017.

[37] N. Khalil, A. Najid, and N. Khalil, "Performance analysis of 802 . 11ac with frame aggregation using NS3," vol. 10, no. 5, pp. 5368–5376, 2020.

[38] A. B. Amewuda, F. A. Katsriku, and J. D. Abdulai, "Implementation and Evaluation of WLAN 802.11ac for Residential Networks in NS-3," Journal of Computer Networks and Communications, vol. 2018, 2018.

[39] S. Khairy, M. Han, L. X. Cai, Y. Cheng, and Z. Han, "Enabling efficient multi-channel bonding for IEEE 802.11ac WLANs," IEEE Int. Conf. Commun., 2017.

[40] M. Natkaniec and M. Kras, "An Optimization of Network Performance in IEEE 802.11ax Dense Networks," International Journal of Electronics and Telecommunications, vol. 69, no. 1, pp. 169–176, 2023.

[41] "Wikipedia", [Online]. Available: https://en.wikipedia.org/wiki/Ns_(simulator)

[42] R. Albar, "Modified Rate Control for Collision-Aware in Minstrel-HT Rate Adaptation Algorithm," 2018 International Conference on Electrical Engineering and Informatics (ICELTICs)(44501), pp. 7–12, 2018.

[43] D. A. Point, "XV2-2 Wi-Fi 6 Access Point," pp. 1–8, 2023.