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Next-Generation Indoor Wireless Systems: Compatibility and Migration Case Study

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ABSTRACT The indoor connected environment has witnessed significant research and development attention from industries and academia due to the growing number of smaller smart indoor devices around us. Developing an effective and efficient wireless access standard is one of the challenging tasks to enable the next generation indoor connected environment. The technical characteristics of existing wireless access standards, including IEEE 802.11a, 802.11n, and 802.11ac, are considerably limited for realizing indoor connected environments, particularly with a growing number of smaller intelligent devices. Moreover, their backward compatibility and migration strategies are significant for developing the next-generation wireless access standard for the indoor Internet of Things environment. In this context, this paper presents an indoor environmental experimental study focusing on the backward compatibility and migration-centric performance analysis of existing wireless access standards. Three wireless access standards that operate in the 5 GHz frequency spectrum are evaluated considering the metrics, including throughput, range, efficiency, and backward compatibility in an indoor environment. The experimental results are also compared with the analytical path loss model to observe the attributes for next-generation wireless access between the observed and analytical models. The evaluation can attest to the suitable migration strategy for stable next-generation wireless access development and deployment for an indoor smart Internet of Things environment.

INDEX TERMS Next-generation wireless, indoor wireless access, Internet of Things, compatibility, migration.

I. INTRODUCTION

Smart indoor devices are significantly growing day by day around us. According to a recent report by Statista [1], the UK's smart home revenue is expected to grow at the annual rate of 14.3% between 2020-24, and the project value of the market is \$7423 million by 2024. The market penetration rate of smart indoor devices is 16.4% in 2020, and it is expected to hit 44.8% by 2024. Towards realizing the indoor Internet of Things (IoT), some critical scientific-technological developments lead the way forward in embedded hardware and software research themes [2]. It includes advanced embedded systems, edge and green computing, low power transmission, physical layer security, and ultra-channel access [3], [4]. Wireless channel access is one of the key technologies in smart indoor IoT environment development, considering the expected growth in smart indoor devices. The indoor wireless access is exceptionally challenging for sensor-enabled small smart devices considering the constraints, including dynamic channel fading, ultra-bandwidth sharing, and power and security-centric physical layer signal transmissions [5].

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Existing wireless access schemes are incredibly vulnerable to the realistic implementation of indoor IoT networking. For example, IEEE 802.11ac is more scalable, faster, and an improved version of IEEE 802.11n with broader bandwidth and Gigabit Ethernet capabilities; however, the realistic implementation approach for both the technologies requires an entirely different direction. The IEEE 802.11n and 802.11ac amendments are known as High Throughput Wireless Local Area Networks (HT-WLANs). In IEEE 802.11 standards, 802.11a specifications deliver up to 54 Mbps of theoretical data rates [6]. However, the recorded practical throughput of IEEE 802.11a is 25 Mbps [7]. The physical (PHY) layer enhancement is implemented by using spatial diversity in IEEE 802.11n standard, which enabled at least a four-fold throughput improvement over legacy protocols [8]. In addition, many complex features developed to improve physical layer throughput, Quality of Service (QoS), signal coverage, and reliability are included in the IEEE 802.11ac standard [9]. Wider frequency channels (up to 160 MHz), improved spectral efficiency, high-density modulation (up to 256-QAM), MIMO (up to 8), and Multi-User MIMO scheme are among the advancements that will enhance the user experience, and overall performance [10]. The MIMO system consists of a transmitter and a receiver having multiple antennas to transmit and receive a wireless signal simultaneously [11].

However, in the next generation indoor IoT environment, the performance of the aforementioned wireless access standards would be minimal, considering the congestion and interference among neighboring smart products [12]. These 5 GHz centric wireless access technologies suffer from signal attenuation at higher frequencies resulting in a diminished communication range. Furthermore, the 802.11 WLAN is hindered by inefficiency due to the interference caused by other Wireless LAN technologies employed in the same environment. This adversely impacts the data throughput and overall efficiency, QoS of the indoor wireless network [13]. Towards enabling the existing wireless access standards for the next generation indoor IoT environment, compatibility in interoperability and roaming, and suitable migration strategies are the primary scientific way forwards to validate the performance in a realistic indoor environment [14]. This paper extends our previous conference paper focusing on the throughput and range of the IEEE wireless standards as mentioned earlier [15]. This paper extends our previous work to consider the interference factors in a heterogeneous wireless environment. Moreover, all these tests are performed between the IEEE wireless standards to check their backward compatibility in real-time, which is necessary to evaluate their operational requirements and implementation during deployment in an enterprise network. The path loss model is incorporated into this analysis to evaluate the experimental results and verify signal attenuation considering propagation losses due to wireless signals' free space, absorption, and diffraction characteristics. Moreover, the path losses are calculated for the individual devices (Cisco AIR-AP-1242AGE-K9, Cisco AIR-AP-1262N-E-K9, and Asus RT-AC66U) and protocols (IEEE 802.11a/n/ac in 5 GHz) used for the experiment in this study.

In this context, this research sets out to use an experimental methodology to evaluate IEEE 802.11ac in terms of throughput, range, efficiency, and backward compatibility to compare it with previous protocols such as IEEE 802.11a/n in a typical heterogeneous wireless environment. In addition, we will propose a suitable migration strategy that would enable legacy protocols to co-exist with IEEE 802.11ac in an enterprise network deployment. The four significant contributions of this paper can be summarised as follows:

- Firstly, an experimental testbed methodology is presented, focusing on devices, software, and test environment for examining the realistic efficiency of IEEE 802.11 wireless standards in an indoor heterogeneous wireless access setting.
- Secondly, each test scenario is detailed, considering test cases and actual execution steps for throughput, range, and compatibility centric experiments.
- Thirdly, analytical path loss models are utilized for a comparative investigation of the experimental testbed results to validate the technical significance and determine threshold parameters for roaming and migration scenarios.
- Finally, an extensive analysis of results is presented considering the number of metrics to deploy a heterogeneous indoor wireless environment consists of multiple wireless access technologies.

The rest of this paper is organized as follows. First, as related work, Section II provides a concise overview of the specifics and challenges for IEEE 802.11 standards operating in a heterogeneous setting. Next, section III goes over the testbed experiment's detailed conception and configuration. Finally, section IV discusses the reliability of the findings and results, while Section V contains the conclusion and future directions.

II. RELATED WORK

The 2.4 GHz frequency band spectrum has been excessively used with IEEE 802.11b/g/n and alternative forms of wireless technology such as Bluetooth and microwaves. The congestion in the spectrum leads to an interference and interoperability issue between different protocols operating in the same heterogeneous environment. Hence, alternative frequency band spectrum and protocols with band steering are required to accommodate the growing number of wireless devices, which can operate at their total capacity without interoperability and interference issues [16]. The band steering was initially introduced in the 802.11n standard, allowing specific protocols and devices to operate simultaneously in 2.4 and 5 GHz frequency bands. Therefore, 802.11n can operate in both the frequency band spectrum, 2.4 and 5 GHz, unlike other protocols like IEEE 802.11a/b/g/ac, which are limited to the single frequency spectrum for their operation [17].

In [18], performance estimation of two access points operating in an indoor setting and configured with 802.11n and 802.11ac, respectively, have been evaluated. It was observed that the signal transmitted by 802.11ac overlaps with the one sent by 802.11n, which results in narrow channel bandwidth and recorded loss in data throughput. In addition, the accuracy and stability of the Time Difference of Arrival (TDOA) of a signal were affected at reduced Signal-to-Noise Ratio (SNR) values for 802.11ac when operating in an indoor setting with 802.11n [19]. The results concluded that utilizing a broader bandwidth in 802.11ac could enhance the precision and dependability of TDOA at lower SNR values.

A measurement-based study was proposed in [20] to evaluate the data throughput of IEEE 802.11n and 802.11ac on various channel bandwidths. A client-server configuration has been designed to transmit multiple IPv4 User Datagram Protocol (UDP) traffic within a range of different packet sizes, such as 128 Bytes to 512 Kilobyte (KB). Numerous tests for 802.11n at 2.4 GHz with 20 MHz bandwidth, 802.11n at 5 GHz with 40 MHz bandwidth, and 802.11ac with 80 MHz bandwidth have been proposed. The results conclude that the 802.11ac delivers greater throughput than 802.11n at all the proposed test cases.

In [21], another analysis on the effect of broader channel bandwidths on energy efficiency and interference for 802.11ac has been proposed. A Client-Server framework is proposed, where Access Point (AP) moves away from the fixed client device in an open parking lot using the Iperf tool [22] to generate UDP data traffic with maximum possible data rates. The tests were performed for ten repetitions to get an accurate reading, and the average values were recorded. The results show that the wider channel bandwidth significantly improves data throughput with high power expenditure. It was further observed that the multiple spatial streams improve the throughput performance by consuming less power when compared with a wider channel bandwidth. The authors use an 80 MHz channel with 1-2 spatial streams for the above experimental setup.

In [23], another study on the performance and energy efficiency of IEEE 802.11ac over legacy protocols in an indoor enterprise network setting has been conducted. The experiments are conducted in 2.4 and 5 GHz frequency spectrum on 40 MHz channel width, and UDP traffic is generated between client and server for the tests. The results suggest that migrating to the 5 GHz frequency spectrum from 2.4 GHz brings valuable benefits. It increases the range of non-overlapping channels that can be used, minimizing interference and offering greater data throughput. The boost in data throughput helps to achieve a substantial improvement in QoS. In addition, an improvement of 10-30% in energy efficiency and 8% gain in throughput is achieved.

It is evident from the above research work; the authors have provided beneficial information with several comprehensive analyses. However, these studies have not examined the behavior of TCP and UDP protocols in terms of theoretical data rates, range, signal strength, experimental data rates, efficiency, backward compatibility, and roaming behavior while operating in an indoor and diverse wireless environment. Moreover, the features like band steering, channel bonding, MIMO, SGI, and path loss are not considered. In contrast to the theoretical studies, which are always presented with the best possible scenarios, such as testing in anechoic chambers, they do not provide these protocols' real-world performance statistics. The compatibility between different vendor-specific devices and wireless standards is a very well-known issue. Therefore, addressing the compatibility issue in an enterprise or indoor heterogeneous environment needs extensive experimental testing. Consequently, we proposed a novel approach by constructing a testbed using off-the-shelf equipment and defining several test scenarios to evaluate every protocol's (IEEE 802.11a/n/ac) efficiency and interoperability in indoor settings.

III. METHODOLOGY OF THE TESTBED DEVELOPMENT

A. DEVICES AND SOFTWARE USED FOR DEVELOPING TEST BED

The network diagram is shown in Figure 1, where two Cisco 3560 switches are utilized at the distribution and access layers, respectively [24]. These switches contain 12 gigabit Ethernet ports on fibre and 2 gigabit Ethernet ports on copper. Furthermore, these switches' 1000 Mbps gigabit Ethernet ports are utilised to deliver greater bandwidth in order to adapt to changing network requirements by reducing congestion and increasing system performance for hardware-based IP routing. Cisco's Fast Ether Channel technology is also included in these switches, which enhances fault tolerance and offers high-speed aggregated bandwidth between switches and routers, including individual servers. Furthermore, during transmission, these switches employ Layer 2 trace-route capabilities to troubleshoot the packet's physical path from source to destination. The server is configured with an IP traffic generator that functions as a host and is linked to a gigabit port on the distribution switch. For high-speed data transfer via 802.11n (600 Mbps) and 802.11ac, a fibre optic port is installed for the downlink from the distribution switch to the access layer switch (1300 Mbps). All connections are terminated at the access layer switch to fulfil our testing criteria.

Three Wireless Access Points (WAPs) have been installed for testing. For 802.11a testing, use Cisco AIR-AP-1242AG-E-K9, and for 802.11n testing, use Cisco AIR-AP-1262N-E-K9 [25], [26]. These access points have channel bandwidths of 20 and 40 MHz, utilise 2 × 3 MIMO with two spatial streams, and can deliver data speeds of up to 300 Mbps with beam-forming capabilities. Furthermore, these access points offer 1000BASE-T interfaces, which are Gigabit Ethernet compatible. To deliver ultra-fast data rates, the Asus RT-AC66U [27] access point employs dual-band technology and operates at 2.4 and 5 GHz. This access point has 3 × 3 MIMO and multiple streams, resulting in data rates ranging from 450 to 1300 Mbps for 802.11n and 802.11ac,

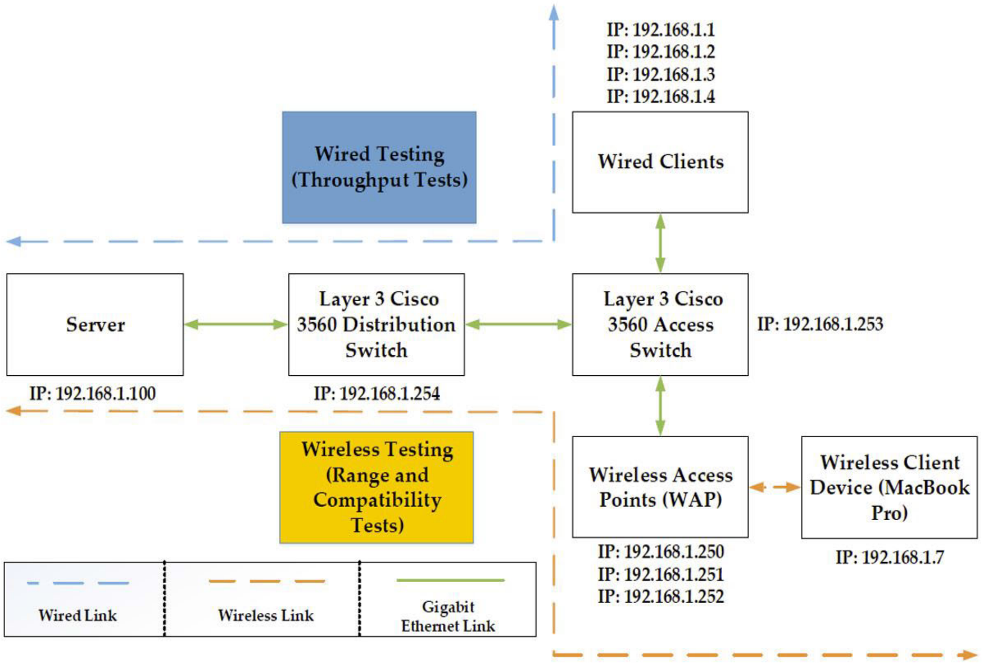


FIGURE 1. The primary network architecture of the experiments.

respectively. Jperf (a software application) was also utilised to calculate data throughput and network performance as parameter values were modified.

A host computer with AMD Athlon dual-core CPU operating at 2.20 GHz and 8 GB of RAM running Windows 7 Service Pack 1 (64-bit) is utilised as both a client and a server for computing purposes. Both host PCs have two network adapters that enable wireless and wired network access. For wireless protocol throughput, range, and compatibility testing, a MacBook Pro with a 2.5 GHz Intel i5 processor and 4 GB of RAM is used. The external wireless adapters such as Cisco-Linksys WUSB600N [28] and ASUS dual-band USB-AC56 [29] are used for wireless connectivity as they provide multiple simultaneous streams of data over the wireless channel for IEEE 802.11 amendments [30]. The Cisco-Linksys WUSB600N is used for testing 802.11a/n protocols as it supports dual-band operation and has two internal omnidirectional antennas which facilitate beam-forming and MIMO functionality.

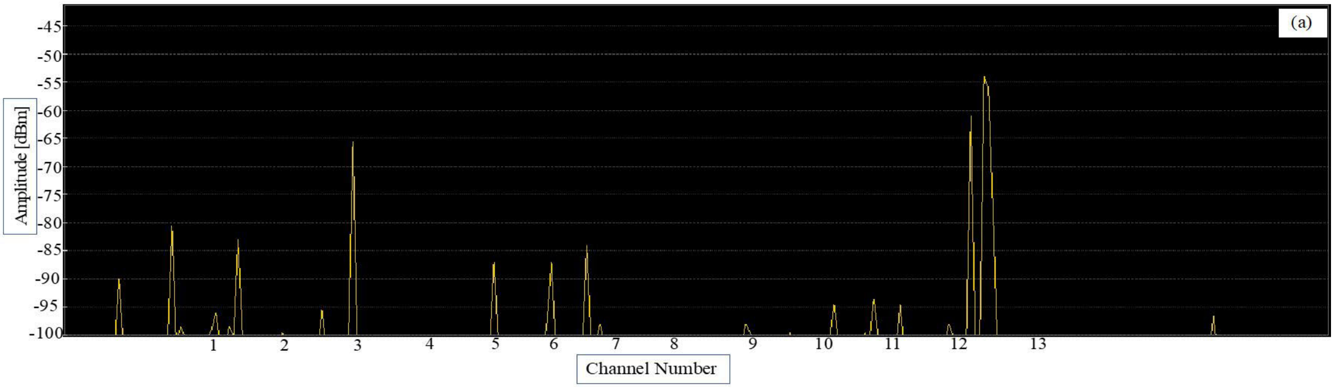
Moreover, ASUS USB-AC56 is used for testing the 802.11ac protocol since it also supports dual-band channel operation with multiple antennas to facilitate MU-MIMO. For collecting transmission and navigational data such as signal strength, noise, SNR and reasonable data rates, a Wi-Fi scanner is utilized on MacBook [31]. The values of transmission power and data rates configured on AP, and network adapters are listed in Table 3. The peaks around channels 12 and 13 in the spectrum are automatically selected using the Least Congested Frequency (LCF) settings on access points operating on 802.11n at 2.4 GHz frequency. Figure 2 (b) shows the 5 GHz frequency spectrum before testing. Comparing Figure 2 (a) and (b), it is evident that the spectrum in 5 GHz is much less congested than the spectrum in 2.4 GHz; consequently, a free spectrum indicates fewer hosts, reduced interference, improved performance and throughput. The Channel bonding can be seen in Figure 2(c), where Channel 112 was selected by the Dynamic Frequency Selection (DFS) algorithm for this test. Due to this, we observe a broader concentration of traffic around channels 108 and 112.

B. THROUGHPUT TEST

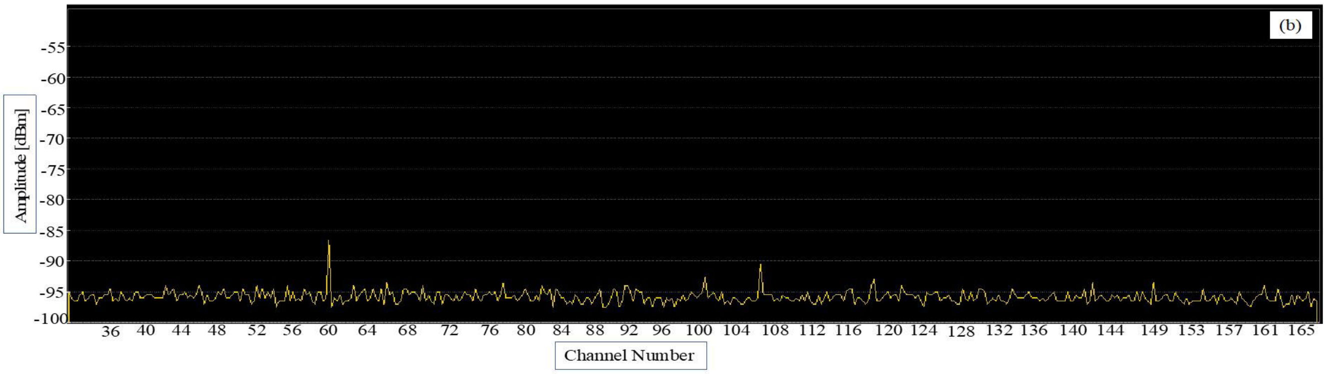
This benchmarking test intends to assess the potential of 802.11ac versus 802.11a/n and a wired network. This test will determine the relative throughput of gigabit Ethernet (wired), 802.11ac, and 802.11a/n in a heterogeneous environment. Moreover, this test will assist in determining the performance advancement offered by channel bonding, short guard interval, and multiple streams features. All the variations of protocols were tested on the transport layer using TCP and UDP.

1) TEST METHODOLOGY

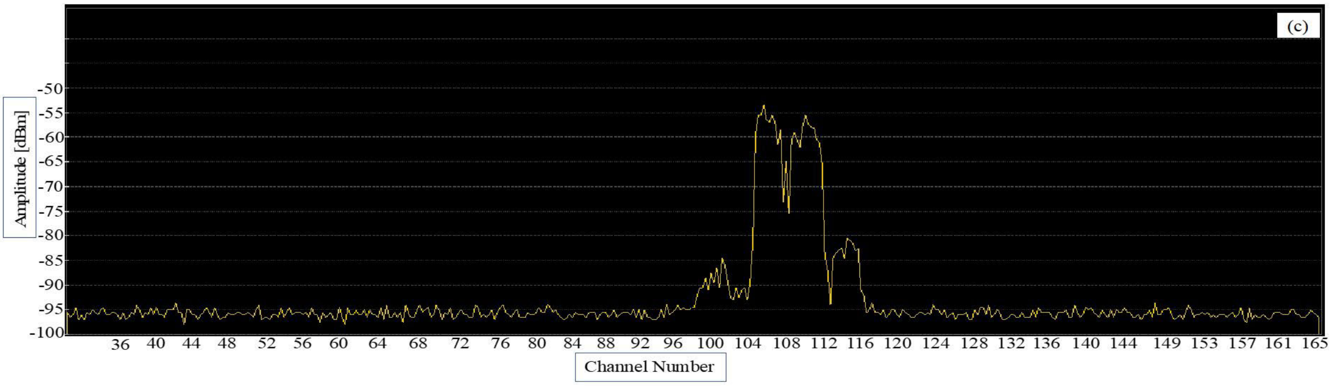
The test cases 1-9 in Table 1 gives a summary of the test cases used in a throughput test. The cases have been designed with numerous settings, including short guard interval, channel bonding, frequency spectrum, and multiple streams. Practical throughput is obtained and compared with advertised data rates by transmitting continuous data streams by several hosts to the server and vice-versa. The hosts send a constant data stream for a fixed period of 10 seconds to a server, and the throughput is recoded at the receiving host. However, only



(a) shows the 2.4 GHz Spectrum before the test.



(b) offers the 5 GHz Spectrum before the test.



(c) shows the channel-bonding feature during testing.

FIGURE 2. **The spectrum analysis of an indoor environment before and during testing.**

one host transmitting a single stream of data does not reach the link saturation; hence multiple data streams by many hosts are sent to the server, all at the same time. The obtained results show the maximum practical throughput achieved by each protocol tested on TCP and UDP. Ten runs are recorded to get more accurate results, and the averages of those runs are used as the final result.

C. RANGE TEST

The purpose of the range test is to examine how data rates curtail over a distance in an indoor setting. The result of this test will be a practical reference point for the 802.11ac presence in conjunction with 802.11a/n.

1) TEST METHODOLOGY

For this test, a 65-meter-long passageway is used, and it can be seen in Fig. 3. As mentioned in Section 3.1, a MacBook Pro connects the access points and an external USB network adapter. The access points are configured and placed at either end of the corridor, and the test cases 10-17 are used as in Table 1. The passageway is divided into 5-meter segments, where the measurements are taken. For range test, transmission power and data rates on AP and network adapter are

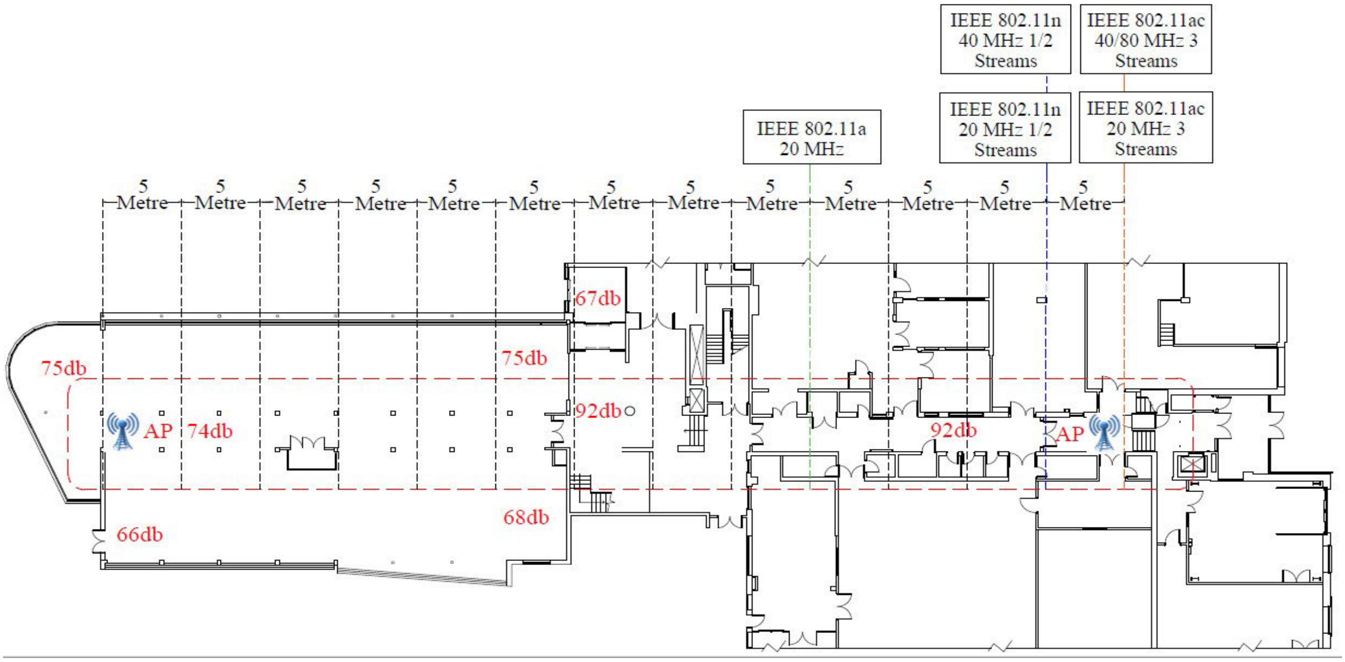


FIGURE 3. Building architecture of the Northumbria University Ellison Building D and E Block where tests are executed.

TABLE 1. Test cases used testbed testing.

Test No	Throughput Test cases
1	With Wired setup
2	With 802.11a 5GHz 20MHz
3	With 802.11n SGI=ON, 1 stream 5GHz 20MHz
4	With 802.11n SGI=ON, 2 stream 5GHz 20MHz
5	With 802.11n SGI=ON, 1 Stream 5GHz 40MHz
6	With 802.11n SGI=ON, 2 Stream 5GHz 40MHz
7	With 802.11ac SGI=ON, 3 stream 5GHz 20MHz
8	With 802.11ac SGI=ON, 3 Stream 5GHz 40MHz
9	With 802.11ac SGI=ON, 3 Stream 5GHz 80MHz
-	**Range Test cases**
10	With 802.11a Channel width 5GHz 20MHz
11	With 802.11n 1 stream Channel width 5GHz 20MHz
12	With 802.11n 2 stream Channel width 5GHz 20MHz
13	With 802.11n 1 stream Channel width 5GHz 40MHz
14	With 802.11n 2 stream Channel width 5GHz 40MHz
15	With 802.11ac 3 stream Channel width 5GHz 20MHz
16	With 802.11ac 3 stream Channel width 5GHz 40MHz
17	With 802.11ac 3 stream Channel width 5GHz 80MHz
-	**Compatibility Test cases**
18	5GHz 20MHz 802.11a vs SGI=ON 5GHz 20MHz 802.11n
19	5GHz 20MHz 802.11a vs SGI=ON 5GHz 40MHz 802.11n
20	5GHz 20MHz 802.11a vs SGI=ON 5GHz 20MHz 802.11ac
21	5GHz 20MHz 802.11a vs SGI=ON 5GHz 40MHz 802.11ac

configured with the highest values, as depicted in Table 4. To get complete readings, the measurements were obtained while traveling in the direction of and away from the access points. The tests were run for ten iterations in each sequence, with the averages utilized to obtain the precise set of findings.

D. COMPATIBILITY TEST

The principle intention behind this test is to gain a deeper understanding of the roaming behavior of the client device while access points operating with multiple protocols in an indoor heterogeneous enterprise network. It is essential to learn the functionality of client roaming from 802.11a to 802.11n/ac and vice-versa. In addition, it is critical to determine whether the client remains connected to 802.11ac regardless of signal strength and data rates offered by other legacy protocols operating on the access points to try and validate the hypothesis. The communication delay of IEEE 802.11 protocols used for testing is not evaluated in this paper as it is out of scope in our work. The switchover/roaming time is very insignificant and therefore not considered for this work. However, the signal strengths of radiofrequency signals are considered, mainly responsible for the user equipment switching from one network to another. All the experiments were performed in a passageway depicted in Figure 3, with hosts and access points are configured with 802.11a/n/ac. The length of the passageway is 65 meters, and it is clear from Figure 2a and Figure 2b that there is interference present due to other wireless networks present in an environment. Therefore it cannot be considered an interference-free indoor environment. All test hosts in any location have a direct line-of-sight (LOS) with an access point. In addition, this framework is designed only with the access point without a centralized wireless controller; therefore, hosts themselves make the roaming decisions independently.

1) TEST METHODOLOGY

For this test, a 65-meter-long passageway is used, and it can be seen in Figure 3. As mentioned in Section III-A, a MacBook Pro connects the access points and an external USB network adapter. The access points are configured and placed at either end of the corridor, and the test cases 18-21 are used as in Table 1. The passageway is divided into 5-meter segments, where the measurements are taken. For range test, transmission power and data rates on AP and network adapter are configured with the highest values, as depicted in Table 3. The measurements were taken while moving in the direction of and away from the access points to get the comprehensive readings. Tests were conducted for ten iterations in each order, and their averages are used to get the precise set of results.

These test cases 18-21 in Table 1 are designed to recognize the parameters affecting client roaming from one access point to another and keep track of and store those parameter values when roaming is detected. Because different test cases have various roaming points, we took readings every 5 meters where results could be noted and subsequently analyzed. In all of these points, Received Signal Strength Indication (RSSI) readings from both the access points are indicated along with the distance and assessed if the client roamed from one access point to another. For example, in Figure 3, AP1 and AP2 refer to the access points configured with 802.11a and 802.11n/ac, respectively. Again, the range (distance) measurements are in meters, and the hand-off (roaming) procedure was closely monitored.

2) TEST METHODOLOGY

The access points are configured with 802.11a and 802.11n and are spaced 65 meters apart. The client first connects to one of these access points, and the readings were taken while moving in the direction of the other access point until roaming is observed. The tests consider all the possible permutations of 802.11a compared with 802.11n/ac in the 5 GHz frequency spectrum. The pilot tests are designed to understand the client's navigation process from one protocol to another and vice versa. For this, access points are configured with different data rates and transmission power. The proposed test cases for the first pilot test are as follows:

- Dissimilar Service Set Identifier (SSID) with a different authentication process.
- Same SSID with the same authentication process.

The outcome of the previous pilot test has determined the creation of additional pilot tests. These further pilot tests are designed to establish whether client roaming is observed or not, and they are described thus:

- Maximum data rate and transmission power are activated for 802.11a with a similar SSID and authentication process compared to all the variants of 802.11n/ac.
- Maximum data rate and lower transmission power are enabled with the same SSID and same authentication scheme for IEEE 802.11a versus all the variants of IEEE 802.11n/ac.

The extended pilot tests provided many vital and decisive conclusions, and the output of these tests is kept in consideration, and the final examinations are designed according to it. Table 1 test cases 18-21 depicts the handover testing between IEEE 802.11 protocols, and final examinations are designed considering the following factors:

TABLE 2. Notations along with description.

Symbol	Description
γ	Path loss exponent
d	Distance transmitter and receiver
	Wavelength in free space
f	carrier frequency
c	Velocity of radio signal
P_t	Transmitted power
G_t	Antenna gain at transmitter
G_r	Antenna gain at receiver
N_{power}	Noise power
I_m	Implementation noise
N_{power}	Aditional power attenuation per meter
K	Boltzmann constant
T	Noise temperature
B	Bandwidth
N_{Figure}	Noise figure
T_{10}	Ten iterations average
D_R	Highest data rate

- Minimum power and maximum data rates are enabled on both access points.
- The transmitting power for IEEE 802.11a is kept at two mW, while IEEE 802.11n and 802.11ac are held at one mW.
- Maximum data rates enabled on all the access points for IEEE 802.11a/n/ac.

E. ANALYTICAL PATH LOSS MODEL

The analytical channel estimation model compares the experimental results with the path loss model. The comparison is made for the range and backward compatibility tests. The path loss model considers the path loss of the wireless signal during transmission from the transmitter (AP) to the receiver (MacBook Pro). The model calculates the SNR and RSSI at the receiver concerning the distance while comparing with the experimental model, which affects the fading signal strength over the distance. The majority of the symbols considered for analytical modeling are described in Table 2.

The attenuation of radio signal during propagation is termed path loss, and it includes the propagation losses due to the free space, absorption, and diffraction [24]. Path loss is a widely adopted statistical channel metric and is considered the most significant quantity for any wireless channel. The path loss is determined by the surrounding environment and the distance between the transmitter and receiver(d), where γ is the path loss exponent. An increase in path loss leads to SNR attenuation, limiting the transmission range and data rates of the wireless channel between the receiver and the transmitter [25]. Therefore, in our model, the path loss will determine the transmission range of the APs. We estimate the path loss using the free-space path loss model [26], described as:

$$PL(d) = 20 * log_{10}\frac{4\pi}{\lambda} + 10\gamma log_{10}d \tag{1}$$

where $PL(d)$ is the Path Loss at a distance d and λ is the free space wavelength defined as the ratio of the velocity of radio signal c to the carrier frequency f of the radio signal. Without considering fading, the SNR can be calculated using the following equation [26], [27].

$$SNR = P_t + G_t + G_r - PL(d) - N_{Power} - I_m \qquad (2)$$

where P_t is the transmitted power, G_t is the antenna gain at the transmitter, G_r is the antenna gain at receiver, N_{power} is the noise power and, I_m is the implementation noise. N_{power} is the additional power attenuation per meter and is given by:

$$N_{Power} = 10 * log_{10}(KTB) + N_{Figure} \qquad (3)$$

where K is the Boltzmann constant, T is the noise temperature, B is the bandwidth and, N_{Figure} is the noise figure. Our model predicts that an SNR of 15 dB is obtained at the maximum distance between the transmitter and receiver at which transmission occurs. Therefore, the transmission range of the APs is evaluated from equations (1) and (2) for a threshold SNR of 15 dB. In addition, equations (1) and (2) are used to obtain the SNR at each distance d from the transmitter. Table 2 details the values of all the parameters used to calculate the path loss and SNR at a certain distance for a wireless channel in an indoor environment [28], [29].

TABLE 3. Range and compatibility test parameter setting.

Parameters	802.11a	802.11n	802.11ac
Implementation Margin	5 dB	5 dB	5 dB
Bandwidth	20 MHz	20/40 MHz	20/40/80 MHz
Antenna Gain receiver	4 dBi	4 dBi	4 dBi
Noise Power	10 dB	10 dB	10 dB
Antenna Gain transmitter	3.5 dBi	3.5 dBi	5 dBi
Path Loss Exponents	3.6	3.6	3.6
Transmission Power	17/2 dBm	20/1 dBm	20/1 dBm
Centre Frequency	5 GHz	5 GHz	5 GHz

IV. RESULT ANALYSIS AND DISCUSSION

A. THROUGHPUT TEST

Table 4 summarises the experiment's findings, and test cases 1-9 are adapted from Table 1. The wired test, also known as Ethernet, demonstrates the highest throughput over the number of hosts and provides a greater degree of data throughput for all the hosts operating on TCP and UDP than any wireless protocols used in the experiment [30], [31]. However, 802.11a's performance degraded with the increase in the number of hosts transmitting data over the same link. The maximum throughput logged by 802.11a With four hosts communicating simultaneously over TCP and UDP utilizing an 80 MHz channel bandwidth, the greatest on TCP and UDP is 23.25 and 26.61 Mbps, respectively. The performance of 802.11n with 20 and 40 MHz channel bandwidth with data transmitting simultaneously over TCP using one and two streams shows maximum throughput of 52.6 and 91.7 Mbps. However, the performance of 802.11ac for 20, 40, and 80 MHz channel bandwidth with multiple streams show decrements in throughput when all four hosts are transmitting data simultaneously. The maximum average throughput achieved over TCP and UDP for some of the test cases from Table 1 are shown in Figure 4 and Figure 5, respectively.

The throughput obtained on a single stream using 802.11n with 40 MHz channel bandwidth (Test Case 5 in Table 1) is nearly twice as high as the throughput obtained using 802.11n with 20 MHz channel bandwidth (Test Case 3 in Table 1). For example, the maximum-recorded TCP throughput on 802.11n with a single stream at 40 MHz is 91.41 Mbps, while 802.11n with a single stream at 20 MHz provides 52.6 Mbps. Using TCP and UDP, similar results were obtained with 802.11ac channel bandwidths of 20, 40, and 80 MHz. As a result, we can assert that the channel bonding (i.e., 40 MHz and 80 MHz) features of 802.11n and 802.11ac improve data throughput even when new hosts join the network and the throughput is recorded on 802.11ac is 217.38 and 223.54 Mbps. In addition, a throughput of 170.1 Mbps was generated by four hosts transmitting simultaneously over 802.11ac with 80 MHz bandwidth in which 40 MHz channel bandwidth is on TCP. The system recorded a throughput of 217.38 Mbps. The test results presented in Figure 5 show that an increase in hosts leads to throughput degradation, impacting the entire network's overall performance. As a result, several streams outperform a single stream in terms of throughput. Channel bonding provides twice the throughput compared to the same number of data streams used in the other 802.11n and ac variations.

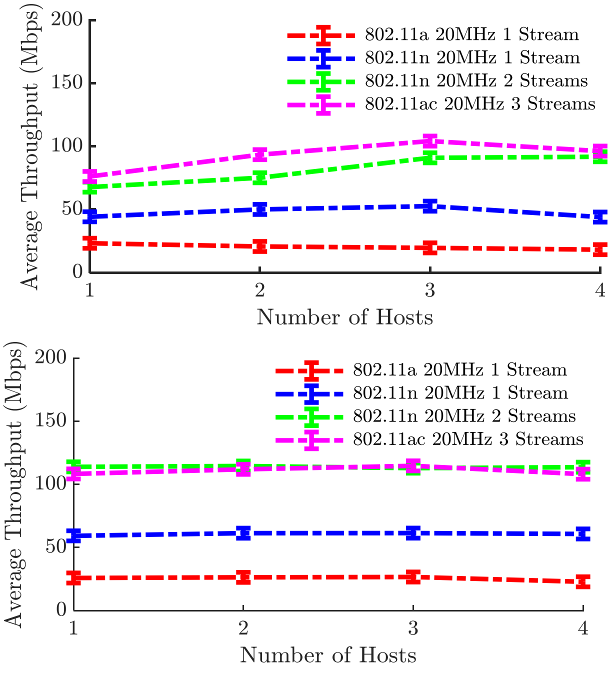


FIGURE 4. (a) TCP and (b) UDP throughput without channel bond.

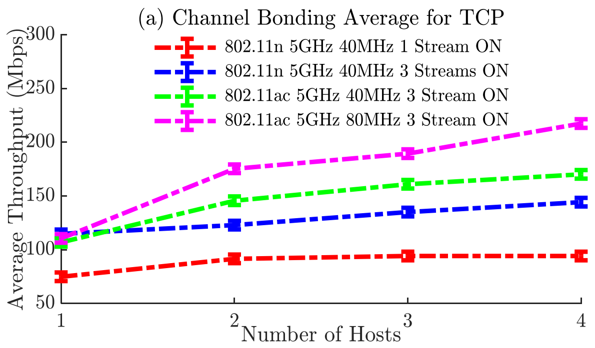
B. EFFICIENCY OF PROTOCOLS

The results from Section IV-A are analyzed for the 802.11 protocols throughput efficiency in this section of the article. Protocols used in these tests offer different data rates; therefore, to evaluate their efficiency on the same scale by comparing the data rate and throughput efficiency, we used the following equation to calculate the overall efficiency, E, as follows:

$$E = \frac{T_{10}}{D_R} * 100 \qquad (4)$$

TABLE 4. Throughput comparison of TCP-UDP test cases from Table 1.

Test Cases	Sys 1 TCP (Mbps)	Sys 2 TCP (Mbps)	Sys 3 TCP (Mbps)	Sys 4 TCP (Mbps)	Sys 1 UDP (Mbps)	Sys 2 UDP (Mbps)	Sys 3 UDP (Mbps)	Sys 4 UDP (Mbps)
1	687.8	850.8	855	837.5	131.5	244.5	421.9	532.1
2	23.25	20.7	19.5	18.17	25.83	26.33	26.61	22.81
3	44.2	50	52.6	44	59.22	61.33	61.39	60.73
4	67.7	75.1	90.9	91.7	113.9	114.5	112.8	113.6
5	74.7	91.4	94.09	94.41	116.5	117.5	117.5	117.1
6	114.7	122.8	134.9	144.2	180.6	196.7	192.8	188.5
7	76.1	93.4	104.2	96.27	108.2	111.9	114.6	108
8	106.8	145.5	160.8	170.1	125.5	201.5	209.1	215.5
9	110.4	175.2	189.3	217.3	117.6	199.2	215.9	223.5



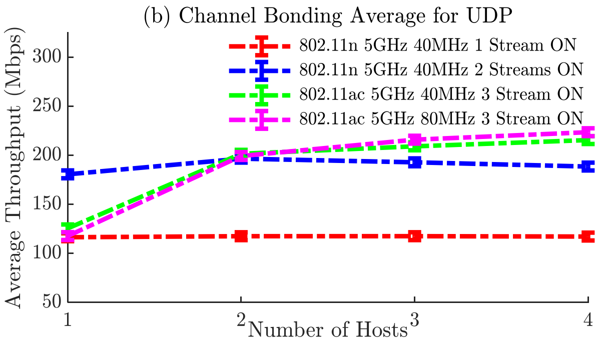


FIGURE 5. (a) TCP and (b) UDP throughput without channel bond.

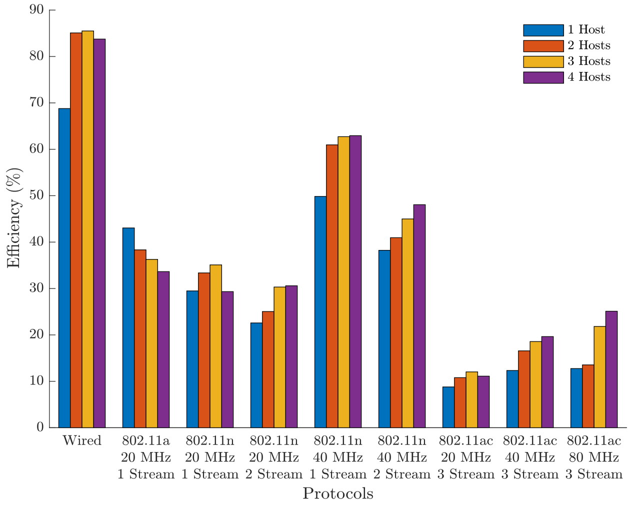


FIGURE 6. The efficiency of IEEE protocols over TCP.

where T_{10} is the ten iterations average. The highest possible data rate that the protocol can provide is represented by D_R. Figure 6 and Figure 7 show the efficiency of TCP and UDP on wired and wireless networks. Since the wireless network is half-duplex, it is more susceptible to collisions compared to a wired network. Therefore, the efficiency of the wireless network degrades as the load on the network increases. It can be seen from Figure 6; 802.11a achieves the throughput efficiency of 43.055% for a single host, compared to 33.648% with multiple hosts transmitting simultaneously over TCP. However, increased throughput efficiency is observed for 802.11n and ac over TCP VOLUME XX, 2017, as the new host joins the network. Although 802.11n with 20 MHz channel bandwidth, transmitting one stream achieves the maximum TCP throughput efficiency of 35.09%, compared to 30.59% with two streams. We expected to see better throughput efficiency with multiple streams than single streams; however, the test results show that the multiple streams are less efficient than single streams.

Similarly, with one and two streams in 802.11n with 40 MHz channel bandwidth, TCP throughput efficiency is 62.94 percent and 48.06 percent, respectively. In addition, the 802.11ac with 20 MHz channel bandwidth over three streams achieves a 12.03% throughput efficiency, while other variants with channel bonding feature of 40 and 80 MHz shows 19.64% and 25.10% of throughput efficiency, respectively. Thus, the data rates demonstrated by 802.11ac and all their variants outperform 802.11n. However, regarding TCP throughput efficiency, 802.11ac is not able to match that of 802.11n. The 802.11n and 802.11ac performed somewhat similar to a wired network concerning throughput due to the MIMO and MU-MIMO features, respectively.

These features brought into wireless protocols have significantly enhanced their throughput and range performance. Also, the channel bonding feature with multiple data streams fully exploits the potential offered by 802.11n and 802.11ac and improves their ability to achieve higher data rates. However, the TCP throughput efficiency is adversely affected by not making use of the whole spectrum, and this, in turn, means that a single stream outperforms multiple streams. Similar studies using UDP for all wireless protocols and their variants reveal that UDP has a higher throughput efficiency than TCP since it can establish a connection without any overheads and does not require any acknowledgment. Furthermore, UDP is a "best-effort delivery protocol," making it faster than TCP, even though both TCP and UDP exhibit similar behavior traits.

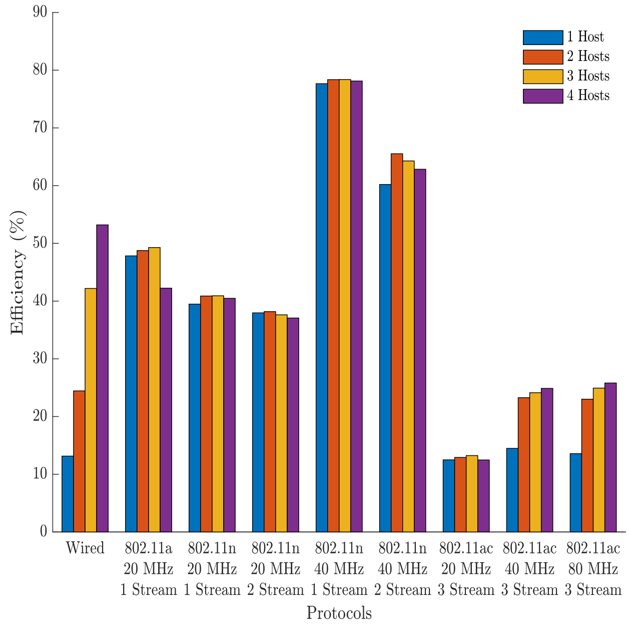


FIGURE 7. Efficiency of IEEE protocols over UDP.

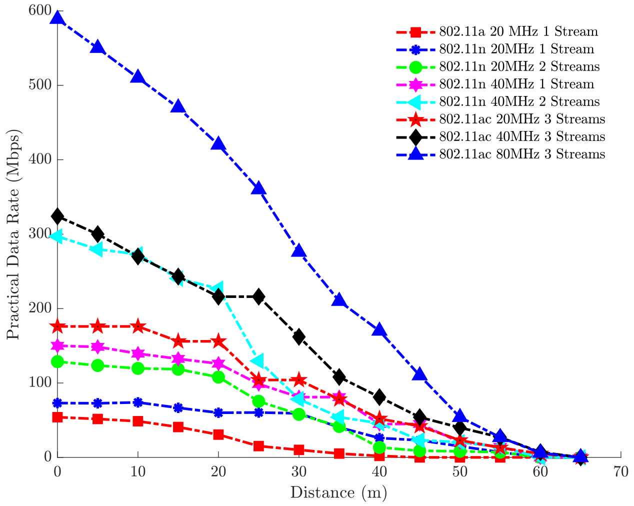


FIGURE 8. Data Rate of IEEE Access protocols with respect to the distance.

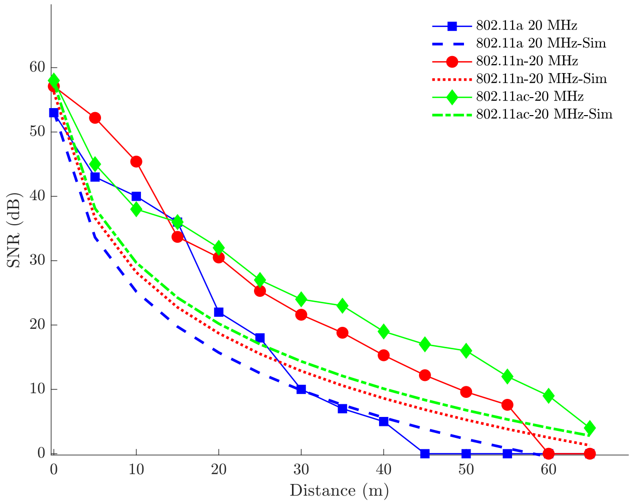


FIGURE 9. SNR of protocols at a distance with a practical and analytical measure.

C. RANGE TEST

The range test is designed to compare advertised data rates faired concerning distance and derive the SNR at a given distance. In this test, the theoretical throughput is considered over the practical throughput. It can be seen from Figure 8, the advertised data rates by a client operating at a shorter distance from the APs provide higher data rates. In contrast, lower data rates are recorded due to deterioration of the signal strength as the client moves further away from the access points. The results show that 802.11a starts at the bottom of the curve compared to other 802.11n and 802.11ac. This is because, within a five-meter range of the AP, 802.11a gives the highest feasible data rate. The client, however, is unable to connect to the AP as it approaches the 40-meter mark.

Due to channel bonding, MIMO, and MU-MIMO, 802.11n and 802.11ac give better data throughput during the test. Two 802.11n streams with channel bonding generate a maximum data rate of 279 Mbps, compared to half of that for one stream. While considering the data rates in the close range of 0-25 meters, two streams provide the best data rates compared to one stream. However, one stream offers better data rates in the range of 25-35 meters. The test shows that the maximum data rate of 54 Mbps for 802.11a is only achieved at the distance of the first 5 meters, while all the variants of 802.11n offer better data rates even at a distance beyond 30 meters. As demonstrated in Figure 3, the 802.11ac protocol, which was also evaluated in this experiment, has superior signal strength across a greater distance than any other protocol examined in this investigation. When compared 802.11n single stream with channel bonding to both are more suited to longer distance 802.11ac without channel bonding, the data rates offered by communication than 802.11a.

However, the client could not connect to 802.11n after 60 meters but stayed connected to 802.11ac at the same distance. The test results show that 802.11ac with channel bonding surpasses all other protocols examined in the trial in terms of range (both close and long) and signal strength.

Figure 9 compares the SNR ratio with distance, and Table 5 shows the measurements of the recorded data during experimental evaluation and analytical model. It shows that their data rates and SNR deteriorate whenever a client moves away from the access point, resulting in poor connectivity. Here, we also compared the experimental test results with the path loss model to observe the behavior of the protocols in an indoor heterogeneous environment. The results show that the client cannot connect 802.11a AP after the 40-meter mark; however, it can connect 802.11n and 802.11ac AP even at a distance beyond 60 meters.

Thus, in line with the best industrial practice of the 20 dB rule for SNR, 802.11a will not be efficiently operable beyond 20 meters. At the same time, 802.11n and 802.11ac can still perform efficiently even after the 30-35 meters range.

TABLE 5. SNR fading versus distance for experimental and analytical.

Distance (Meters)	SNR-exp(dB) 802.11a-20M	SNR-exp(dB) 802.11n-20M	SNR-exp(dB) 802.11ac-20M	Distance (Meters)	SNR-sim(dB) 802.11a-20M	SNR-sim (dB) 802.11n-20M	SNR-sim(dB) 802.11ac-20M
0	53.00	57.10	57.10	2	53.20	56.20	57.71
5	43.00	52.20	52.20	7	33.60	36.60	38.12
10	40.00	45.40	45.40	12	25.50	28.20	29.12
15	36.00	33.70	33.70	17	19.70	22.70	24.25
20	22.00	30.50	30.50	22	15.70	18.70	20.22
25	18.00	25.30	25.30	27	12.50	15.50	17.01
30	10.00	21.60	21.60	32	9.86	12.90	14.36
35	7.00	18.80	18.80	37	7.59	10.60	12.09
40	5.00	15.30	15.30	42	5.61	8.61	10.11
45	0	12.20	12.20	47	3.85	6.85	8.35
50	0	9.60	9.60	52	2.27	5.27	6.77
55	0	7.60	7.60	57	0.83	3.83	5.33
60	0	0	0	62	0	2.52	4.02
65	0	0	0	67v 0	1.30v 2.80		

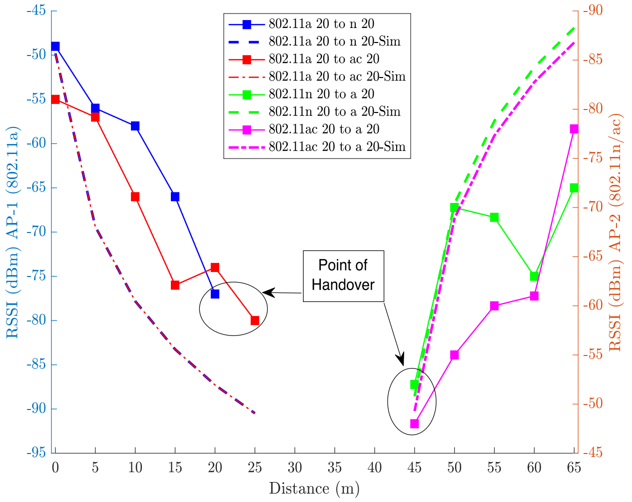


FIGURE 10. 802.11a to 802.11n/ac handover at distance-practical and analytical.

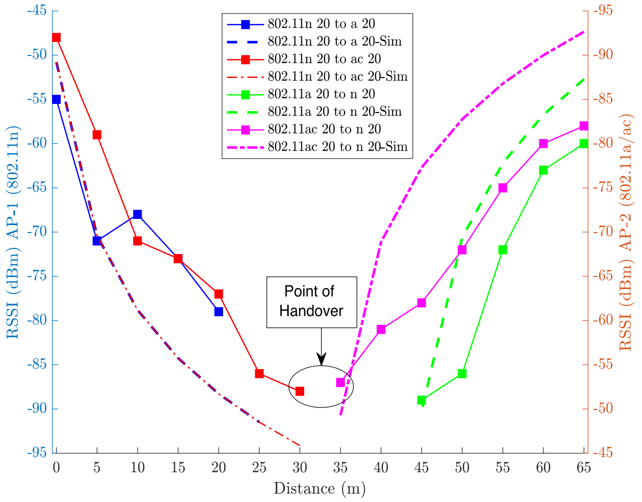


FIGURE 11. 802.11n to 802.11a/ac handover at distance-practical and analytical.

D. COMPATIBILITY TEST

This section investigates the test methodology from Section III-D and III-E, followed by test cases 18-21 from Table 1. In Figure 10, AP-1 is configured with 802.11a with a transmission power of 2 mW, whereas AP-2 is set with 802.11n and 802.11ac with a transmission power of 1 mW. For the first ten runs, the client (MacBook) is linked to AP-1, and the RSSI values are recorded while traveling in the direction of AP-2 with a resolution distance of 5 meters. A similar approach is adopted for roaming from AP-2 to AP-1. All test results provided in this section shows the comparison of an analytical and experimental model on measurement and handover point at which client roam form one protocol to others.

Figure 10 shows the result of bi-directional roaming from IEEE 802.11a to IEEE 802.11n/ac. The results represent the client's roaming that is initially connected to 802.11a and moving towards 802.11n/ac. It can be seen that the client roams from 802.11a to 802.11n with 20 MHz bandwidth at an average difference in RSSI of −25 dBm at a distance of 22 meters. Similar results were obtained when the client roamed from 802.11a to 802.11ac with a 20 MHz bandwidth at an average difference in RSSI value of −30 dBm at a distance of 20 meters. Further, it also shows the cases where the client initially connected to 802.11n/ac and moved towards 802.11a. It is observed that the client roams from 802.11n to 802.11a with an average RSSI difference of −25 dBm and at a distance of 25 meters between them. Similar findings were observed when the client roamed from 802.11ac to 802.11a at a distance difference of 20 meters with an average difference in RSSI value of −33 dBm.

Figure 11 shows the results for test case 19 from Table 1 for observing bi-directional roaming from IEEE 802.11n to IEEE 802.11a/ac. The results represent the client's roaming that is initially connected to 802.11n and moving towards 802.11a/ac. It can be seen that the client roams from 802.11n with 20 MHz bandwidth to 802.11a with 20 MHz bandwidth with an average difference in RSSI of −26 dBm and at an average distance of 25 meters. Similar results were obtained when the client roamed from 802.11n to 802.11ac with 20 MHz bandwidth at an average difference in RSSI value of −33 dBm at an average distance of 32 meters. Figure 12 represents the cases where the client initially connected to IEEE 802.11a and moving towards IEEE

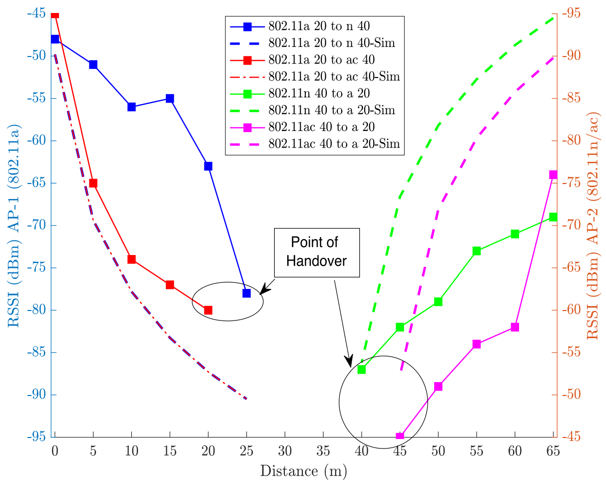


FIGURE 12. 802.11a to 802.11n/ac handover at channel bonding and distance – practical and analytical.

802.11n/ac with 40 MHz bandwidth. This test is designed to observe the roaming between protocols with 20 MHz bandwidth operating with protocols having channel bonding feature and running at 40 MHz bandwidth. It can be seen that the client roams from 802.11a with 20 MHz to 802.11n with 40 MHz with an average difference in RSSI of −26 dBm and at the difference in their distance of 20 meters. Similar results were obtained when the client roamed from 802.11ac with 40 MHz to 802.11a with 20 MHz at an average difference in RSSI values of −35 dBm at an average distance of 25 meters.

Figure 13 represents the cases where the client initially connected to IEEE 802.11n with 40 MHz channel bandwidth and moving towards IEEE 802.11ac with 40 and 80 MHz channel bandwidth. This test is designed to observe the roaming between protocols with channel bonding feature. It can be seen that the client roams from 802.11n with 40 MHz to 802.11ac with 40 MHz bandwidth at an average difference in RSSI of −29 dBm at a distance of 30 meters. Similar results were obtained when the client roamed 802.11ac with 80 MHz channel bandwidth to 802.11n with 40 MHz bandwidth at an average difference in RSSI values of −30 dBm at an average distance of 35 meters.

Here, we also compared the experimental test results with the path loss model to observe the behavior of the protocols. The test results confirm the 20 dBm rule of roaming thresholds, and clients connect to the network with a higher RSSI value. When roaming thresholds are attained, the clients start scanning for another network with greater RSSI values and associate with it. The test results show that roaming can be seen between 802.11a, 802.11n, and 802.11ac. For this, all the access points are configured with maximum data transmission rates and minimum transmission power. Consecutively, bidirectional roaming is detected. It can safely be inferred that roaming from 802.11ac to legacy protocols and vice-versa is feasible with the settings configured on access points and the client operating system. Some of the observations derived from the compatibility test are as follows:

- Roaming is not detected with distinct SSIDs and authentication schemes.
- Roaming is detected with similar SSIDs, and authentication schemes configured on the access points.
- The transmission range of the protocols is affected by transmission power.
- The roaming threshold of 20 dB does exist, and once the client has reached this roaming threshold, it commences the roaming process.
- The clients' network adapter/operating systems settings sacrifice the data throughput to save power.
- The bidirectional roaming is detected between all the tested protocols.

E. *MIGRATION STRATEGY*

There are mainly three types of migration strategies available, which are used for the successful deployment of a wireless network in an enterprise or an indoor heterogeneous wireless environment.

1) CLEAN SLATE DESIGN

The clean slate strategy can be used to migrate from legacy protocols to a newer IEEE 802.11ac. In a clean-slate design, the existing design's valuable information is considered along with the network's future aspects while building utterly new network architecture if required [32]. This strategy is the best solution but expensive. The data rate of IEEE 802.11ac is much higher than legacy protocols, and if an enterprise network is planning to migrate from IEEE 802.11a/b/g/n, then the clean slate strategy is the best suited. The IEEE 802.11ac access points come with two radios that can support the legacy protocol IEEE 802.11n and work on the 5 GHz band, which is less crowded and can gain higher data throughput [33].

2) THE RIP-AND-REPLACE

This migration can be considered replacing the existing access point one by one with the newer ones [34]. The main idea behind the rip-and-replace is to keep the old hardware and install it in an enterprise where it can still be used. This strategy is beneficial and economical but comes with some drawbacks since all the network infrastructure is designed to work with the legacy protocols. The newer IEEE 802.11ac protocols demand a completely new approach for its network infrastructure. This would affect the network coverage, range, and throughput of the latest IEEE 802.11ac protocol. Furthermore, the IEEE 802.11ac access point supports only a 5 GHz frequency spectrum, and their signals will not travel as far as the protocols operating on the 2.4 GHz frequency spectrum. The rip-and-replace migration strategy is an easy to implement and faster way to upgrade the network infrastructure.

3) PHASED MIGRATION

The phased migration is a migration technique in which all the upgrades are done in phases, and careful planning is required for the phased migration. While migrating from

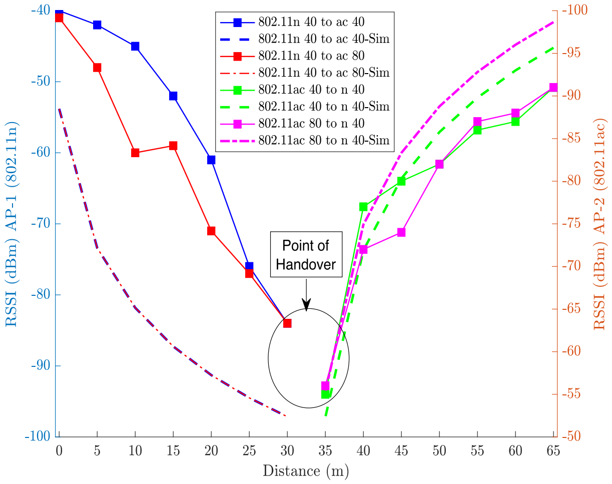


FIGURE 13. 802.11n to 802.11a/ac handover at channel bonding, distance-practical and analytical.

IEEE 802.11n to IEEE 802.11ac to meet end-user performance demands, cautious planning and implementation are required without compromising an existing network's operations. The phased migration saves the cost of upgrading the whole network infrastructure at once since it can be done in phases and would overcome the drawbacks of the clean slate and rip-and-replace migration method. The first step would be to analyze the performance of the existing system and find the coverage holes. Once it is being investigated, a new design for partial parallel deployment can be considered. Therefore, it can be cheaper than upgrading the entire network infrastructure from legacy protocols to a more recent IEEE 802.11ac while keeping the network functioning and supporting the end-user requirements.

V. CONCLUSION AND FUTURE WORK

In the paper, we have systematically investigated compatibility, migration, and the effect of test scenarios in an indoor line of sight environment for existing IEEE wireless access protocols. The data rates of 50% and 60% of the actual advertised data rates are achieved over TCPs and UDPs, respectively. Moreover, the results attest that the short-guard interval of 400 ns improves the data rate by 8-12%. The 802.11n and 802.11ac function effectively in the range of 30-35 meters and provides good signal strength up to a range of 60-65 meters for connectivity. However, the client could not establish a connection to the access point configured with 802.11a beyond 40 meters and could only achieve the data rate of 54 Mbps in the first 5 meters. Thus, the proposed hypothesis for backward compatibility is proven correct. The client connects to the access point with higher signal strength and RSSI values. We can now safely conclude that the seamless roaming is observed from legacy protocols to the 802.11ac and vice-versa. The 802.11ac has all the functionality and capability to meet the growing need of wireless culture; thus, it is helpful for IoT applications. The test results also imply that the phased migration strategy would best implement stable wireless network deployment.

In future work, IEEE 802.11 Wave 2 (802.11ad) will be investigated, considering the influence of channel bonding and multiple spatial streams in a heterogeneous indoor environment for next-generation wireless systems. Furthermore, its applicability in emerging systems will also be the quest in the future related to electric vehicle-centric indoor charging and effective data visualization and analytics of indoor network usage.

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