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Multi-channel Bonding Effects of the IEEE 802.11ac on the WLAN Performance

Abstract. *The IEEE802.11ac standard of wireless networking operates in the 5GHz frequency range and offers higher data rates and improved performance compared to earlier standards. One of the key features of 802.11ac is channel bonding, which allows for the use of multiple channels simultaneously to increase the available bandwidth. In the 5GHz frequency range, channel bonding is typically achieved by combining adjacent 20 MHz channels into wider channels of up to 160 MHz. This provides a significant increase in available bandwidth, which can lead to faster data rates and improved overall network performance. As a result, channel bonding is an important technology for improving wireless network performance, and it is widely used in many applications, including video streaming, online gaming, and enterprise networks. In this research paper, multiple scenarios are examined, with different channel bandwidth configurations including (8x20, 4x40, 2x80, & 1x160 MHz), as well as (4x20, 2x40, & 1x80 MHz), and (2x20 & 1x40 MHz). The scenarios also vary in terms of MIMO spatial streams, with options for (1x1, 2x2, 4x4, and 8x8 SS). To simulate these scenarios, the network simulator (NS-3) version 3.37 is utilized. The simulation results show that when bonding (8x20, 4x20, and 2x20 MHz) is considered, the highest throughput and least amount of delay values are acquired. Specifically, for MIMO (8x8) SS and with respect to the Static Channel Bonding (SCB) (1x160, 1x80, and 1x40 MHz), the effect of DCB is more clarified specially when high number of nodes scenario (48) is used. The throughput values for the bondings (8x20, 4x20, & 2x20 MHz) are (4365, 1840, & 720 Mbps) respectively, compared to (3055, 982.4, and 378.5 Mbps) for 1x160, 1x80, and 1x40 MHz, and the delay values for (8x20, 4x20, & 2x20 MHz) are (0.0019, 0.0046, & 0.0117 Sec), compared to (0.0028, 0.0085, and 0.0222 Sec) for 1x160, 1x80, and 1x40 MHz.*

Streszczenie. *Standard sieci bezprzewodowych IEEE802.11ac działa w zakresie częstotliwości 5 GHz i zapewnia wyższą szybkość transmisji danych oraz lepszą wydajność w porównaniu z wcześniejszymi standardami. Jedną z kluczowych cech standardu 802.11ac jest łączenie kanałów, które umożliwia jednoczesne korzystanie z wielu kanałów w celu zwiększenia dostępnej przepustowości. W zakresie częstotliwości 5 GHz łączenie kanałów jest zwykle osiągane poprzez łączenie sąsiednich kanałów 20 MHz w szersze kanały o szerokości do 160 MHz. Zapewnia to znaczny wzrost dostępnej przepustowości, co może prowadzić do wyższych szybkości przesyłania danych i poprawy ogólnej wydajności sieci. W rezultacie łączenie kanałów jest ważną technologią poprawiającą wydajność sieci bezprzewodowej i jest szeroko stosowane w wielu aplikacjach, w tym w strumieniowym przesyłaniu wideo, grach online i sieciach korporacyjnych. W tym artykule badawczym zbadano wiele scenariuszy z różnymi konfiguracjami przepustowości kanału, w tym (8x20, 4x40, 2x80, & 1x160 MHz), a także (4x20, 2x40, & 1x80 MHz) i (2x20 & 1x40 MHz)). Scenariusze różnią się również pod względem strumieni przestrzennych MIMO, z opcjami dla (1x1, 2x2, 4x4 i 8x8 SS). Do symulacji tych scenariuszy wykorzystywany jest symulator sieci (NS-3) w wersji 3.37. Wyniki symulacji pokazują, że przy uwzględnieniu łączenia (8x20, 4x20 i 2x20 MHz) uzyskuje się najwyższą przepustowość i najmniejsze wartości opóźnień. W szczególności dla MIMO (8x8) SS i w odniesieniu do Static Channel Bonding (SCB) (1x160, 1x80 i 1x40 MHz), efekt DCB jest bardziej klarowny, zwłaszcza gdy stosowany jest scenariusz dużej liczby węzłów (48). Wartości przepustowości dla wiązań (8x20, 4x20, & 2x20 MHz) wynoszą odpowiednio (4365, 1840, & 720 Mb/s) w porównaniu z (3055, 982.4 i 378.5 Mb/s) dla 1x160, 1x80 i 1x40 MHz oraz wartości opóźnienia dla (8x20, 4x20, & 2x20 MHz) wynoszą (0.0019, 0.0046, & 0.0117 s), w porównaniu do (0.0028, 0.0085 i 0.0222 s) dla 1x160, 1x80 i 1x40 MHz.* ***(Multi-channel Bonding Wpływ standardu IEEE 802.11ac na wydajność sieci WLAN)***

Keywords: WLAN, Multi-channel bonding, DCB, MIMO
Słowa kluczowe: WLAN, DCB, MIMO

Introduction

Over the last few years, the use of IEEE802.11 networks has become widespread, offering easy Internet access and various other services. These networks are compatible with most modern technological devices, including laptops, cameras, smartphones, and HDTVs [1]. In order to meet the needs of growing numbers of users and to support new applications such as video streaming and online gaming, which require high data transfer rates (throughput), the standard has introduced new amendments such as standards 802.11ad/n & ac, which provide faster data transfer rates [2, 3]. In fact, 802.11n is a widely used standard that offers data speeds of up to 600Mbps (throughput) in both the (2.4GHz & 5GHz) frequency bands [4, 5]. IEEE802.11ad is designed for the (60GHz) frequency band, with transmission speeds of 6.8 Gbps but a relatively limited range of only 10 meters [6]. The IEEE802.11ac standard works in the 5GHz band and can achieve throughput of up to 6.9 Gbps [7]. 802.11ac can transfer data at very high speeds by using multiple techniques, such as new modulation and coding schemes (256-QAM), MIMO Spatial streams with up to eight SS, and different channel bandwidths 20,40,80, and 160 MHz [2, 7]. Also, 802.11ac uses frame aggregation to improve the performance of the media access control (MAC) layer [8].

Channel bonding is a technique used in wireless networks to improve available bandwidth by connecting multiple neighboring channels. Channel bonding in 802.11n allows two neighboring (20MHz) basic channels to be combined to form a single (one) 40MHz channel [9]. The IEEE802.11ac, which is adopted in this paper, supports channel bonding with a wider channel of up to 40,80, and 160MHz, by combining two, four, or eight neighboring (20MHz) basic channels into a single (one) channel [3, 10].

In this paper, we investigated and analyzed the effect of multichannel bonding on 802.11ac network performance using Network Simulator (NS-3). As well as and with respect to the SCB, the effect of the different channels bonding configuration on the WLAN performance is clarified specially when large number of network users (heavy loaded) with high MIMO spatial streams are considered.

Related work

The authors in [11], proposed aggregation with channel bonding to increase the performance of wireless local area networks, and show that channel bonding with aggregation outperforms by 15% and 20%.

In [12], the authors presented an On-Demand Channel Bonding technique that utilizes Deep Reinforcement Learning for diverse WLANs to decrease transmission delay, where the APs possess various channel bonding properties, the results of the simulation reveal their algorithm outperforms with lower delay time compared to other algorithms.

The authors in [13], developed mathematical model to investigate the channel bonding performance, their results showed that channel bonding provides efficiency when the secondary channels are free, however when the contention from other legacy users reaches a specified when in the secondary channel, then bonding should be disabled.

The authors in [14], proposed the channel allocation technique, and their simulation results of scenarios (enterprise and residential) indicate a gain 46% increase in throughput compared to the baseline approach.

In [15], the authors developed an analytical model to investigate the performance of multi-channel bonding, their results indicate that channel bonding improves the WLAN throughput when the secondary channels are idle.

The authors of reference [16], presented analytical system based on continuous-time-Markov-networks (CTMNs) to evaluate the DCB performance in high-density 802.11ac/ax. Their results showed the widest available channel selection increases throughput. Also, they show the DCB with random channel width selection improves the throughput and fairness.

In [17], the authors proposed dynamic-bandwidth-selection (DBS) for 802.11ac WLANs to prevent collisions. Their simulation results show the DBS can improve the WLAN performance in addition to prevent carrier-sensing-decreasing (CSD) and outside-warning-range (OWR) problems.

The authors in [18], proposed and evaluated the performance of dynamic channel bonding (DyB), and their simulation results show that dynamic channel bonding improves the throughput by 20%.

In [19], the authors proposed an algorithm that dynamically disables/enables dynamic bandwidth operation (DBO) and investigated the (DCA and DBO) performance in IEEE 802.11ac. They demonstrated the DCA can improve channel utilization. Also, they show their algorithm outperforms up to 2x compared to the baseline 802.11ac.

The structure of this paper is as follows: the introduction in first section; related works in second section; method and materials in third section; The results and analysis in fourth section; and finally, The conclusions.

Method and Material

A. IEEE 802.11ac main features

A.1. *MIMO technique*

802.11ac introduced MIMO (Multiple Input Multiple Output) technique in the Physical layer to increase wireless network channel capacity and (as a result throughput), the MIMO uses different spatial stream (or antennas) combinations (2x2 SS to 8x8 SS) to increase data streams and network performance [20]. The IEEE802.11ac PHY layer utilizes three processing techniques in MIMO systems to enhance WLAN performance: a) Spatial Division Multiplexing (SDM), as shown in figure (1) which is used in this paper to increase data rate; b) Space Time Block Coding (STBC) to increase reliability; and c) Low Density Parity Check (LDPC) channel coding to increase security & combat noise[21, 22, 23].

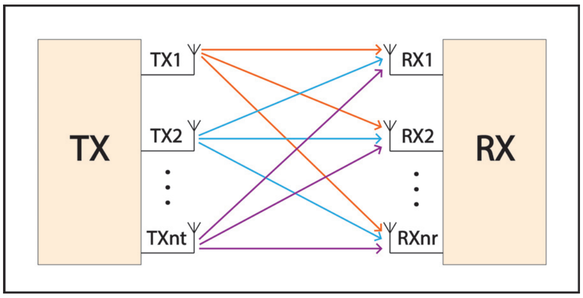


Fig. 1. The implementation of (SDM) MIMO system

A.2. *Frame Aggregation and Block acknowledgment*

Frame aggregation is a MAC feature of the IEEE802.11ac wireless network standard to improve network efficiency and throughput. It allows multiple smaller data frames to be combined into a single larger frame, which is transmitted as a single unit. This reduces the amount of overhead required for each frame, as well as the amount of time required for each transmission [24]. 802.11ac introduces two types of frame aggregation: a) MAC Service Data Unit (MSDU) aggregation and MAC Protocol Data Unit (MPDU) aggregation. MSDU aggregation combines multiple MSDUs from a single higher-layer protocol data unit (PDU), while MPDU aggregation combines multiple MAC frames into a single MPDU, with a maximum PSDU size of 1048575 bytes, as shown in figure (2) [25]. In 802.11 wireless networks, Block Acknowledgement (Block ACK) is a mechanism used to acknowledge multiple received data frames with a single frame transmission. It reduces the overhead of transmitting individual acknowledgments for each received data frame and improves the efficiency of the wireless network, all the frames sent are acknowledged by a unique Block Acknowledgement (BA) instead of an ACK frame for each frame transmitted [26, 2].

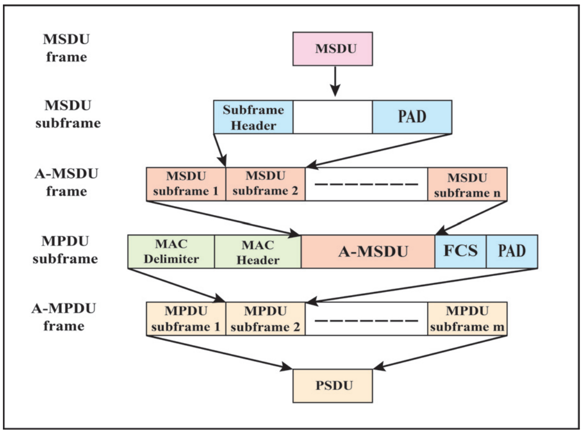
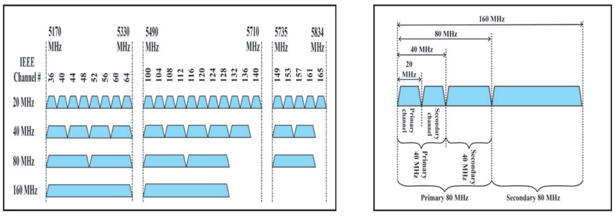


Fig. 2. The levels of frame aggregation in 802.11ac standard

A.3. *Channel bonding*

Channel bonding (CB) is reduces the non-overlapping channels number. In fact, the standard 802.11ac is intended for use in the 5GHz band. There are 19 (20MHz) non-overlapping channels used for channel bonding from (36 to 140), as shown in figure (3a). 802.11ac enables networks to utilize channels wider than the standard 20MHz width by combining two, four, or eight various 20MHz channels to form (primary (main channel) and secondary channels), relying on the width achieved, as shown in figure (3b) [3, 10].



(a) (b)

Fig. 3. (a)- Channel allocation of 802.11ac in 5GHz band. (b)- The primary & secondary channel association

The wide channel only operation on the primary channel. The node (station) operating on 40 MHz channel BW will compete for access on its primary channel BW (20MHz). If the primary is active during the PIFS duration, the node will defer sending. but if the primary was idle, the transmission will depend on secondary, if the secondary was busy, the node will send 20 MHz frame through the primary, or will send 40 MHz frame by using (primary & secondary) if the secondary was idle, as shown in figure 4 [10]. Depending on the width of the channel, a station should follow one of the following procedures [10]:

- Transmit 160 MHz mask PPDU if all the non-primary channels (80 MHz, 40 MHz, and 20 MHz) were inactive during an interval of PIFS.

- Transmit 80 MHz mask PPDU if the non-primary channels (40 MHz and 20 MHz) were inactive during an interval of PIFS.
- Transmit 40 MHz mask PPDU if the non-primary channel (20 MHz) was inactive during an interval of PIFS.
- Transmit 20 MHz mask PPDU on the primary channel (20 MHz).
- Restart the attempted channel access by the backoff process.

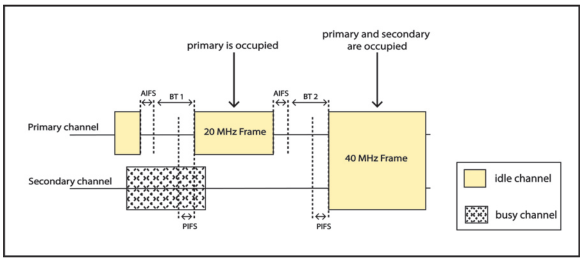


Fig. 4. Channel access transmission through primary and secondary

B. IEEE 802.11 ac theoretical throughput and delay performance

Based on the analysis provided by [27, 28], the maximum data rate (throughput) and latency (delay) at the MAC layer can be determined as (1) and (2):

$$(1)\quad Throughput_{(bit/sec)} = \frac{N_{DS} * N_{SS} * N_{BPS} * CR}{T_{OFDM}},$$

$$(2)\quad Delay_{(sec)} = \frac{MaxA-MPDULength}{MaxDR},$$

where N_{DS} is Data subcarriers number (468,234,108 & 52 for 160,80,40 & 20MHz), N_{SS} is MIMO number (1 to 8), N_{BPS} is bits per symbol (8 for 256-QAM), CR is code rate (3/4), T_{OFDM} is OFDM symbol time (3.6 μs), $MaxA-MPDU$ is second level of aggregation (1048575 bytes), $MaxDR$ is Max data rate.

Table 1: Theoretical data rate (throughput) and latency (delay) values of IEEE 802.11ac standard for different 20,40,80 and 160MHz channel BW

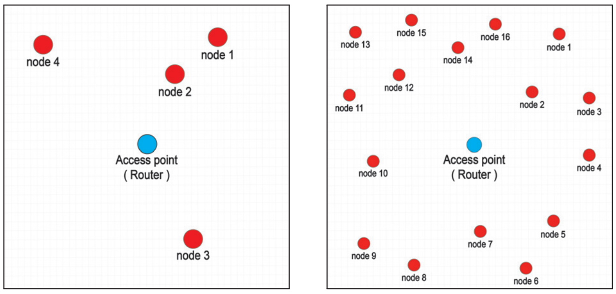
ss	20MHz		40MHz	
	Throughput (Mbps)	Delay (Sec)	Throughput (Mbps)	Delay (Sec)
1x1	86.7	0.0967	180	0.0466
2x2	173.3	0.0484	360	0.0233
4x4	346.7	0.02419	720	0.01165
8x8	693.3	0.01209	1440	0.00582
ss	80MHz		160MHz	
	Throughput (Mbps)	Delay (Sec)	Throughput (Mbps)	Delay (Sec)
1x1	390	0.0215	780	0.01075
2x2	780	0.01075	1560	0.00537
4x4	1560	0.00537	3120	0.00268
8x8	3120	0.00268	6240	0.00134

C. Modeled network scenarios with assumptions

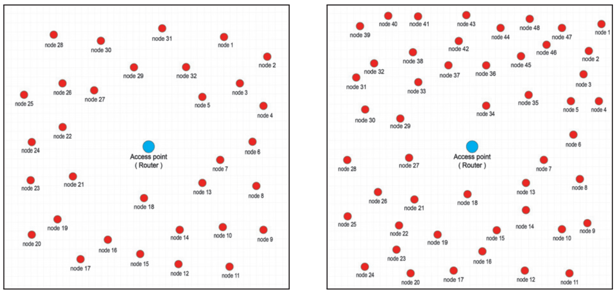
The proposed WLAN-based IEEE 802.11ac scenarios are simulated and a spectrum of (160, 80 and 40 MHz) BW is considered and organized into one of the following configurations assumptions:

- (8x20, 4x20, and 2x20 MHz) channels,
- (4x40 and 2x40MHz) channels.
- 2x80 MHz channels.
- (1x160, 1x80, and 1x40 MHz) channels.

The discrete event network simulator (NS-3) version 3.37 is used to simulate the proposed scenarios of the WLAN. The performance of a WLAN based on the IEEE802.11ac standard is investigated by considering various numbers of node scenarios (from 1 node to 48 nodes) with single-hop random topology for SCB, as shown in Figure 5.



(a) $4nodes$ (b) $16nodes$



(c) $32nodes$ (d) $48nodes$

Fig. 5. Simulation scenarios

In order to assess the effectiveness of the IEEE 802.11ac WLAN in the proposed scenarios, two metrics are analyzed: throughput and delay. The simulation processes are carried out for the various scenarios, with simulation parameters as indicated in Table 2.

Table 2: Simulation parameters

Parameter	Values
PHY and Band	802.11ac, 5GHz
MCS	8 (256–QAM) (3/4)
Data rate (Mbps)	6240,3120, 1440 & 693.3
Bandwidth (MHz)	160,80,40 & 20
Packet size (bytes)	2048
A-MSDU aggregation (bytes)	11454
A-MPDU aggregation (bytes)	1048575
Spatial streams (SS)	1x1, 2x2, 4x4 & 8x8
Guard interval (ns)	400
CWmax, CWmin	1023, 15
Slot time, SIFS, DIFS (μs)	9, 16, 34
Transmit power (Watt)	0.1
Simulation time (sec)	10

Simulation results and analysis

The performance of the modeled WLAN is investigated using the NS-3 simulator based on the (Throughput) and (Delay) metrics, and the results are shown in Figures (6,7,8) and (9,10,11) respectively. For the different number of nodes topologies, the investigation considers various configurations of MIMO (1x1, 2x2, 4x4, and 8x8) with different bonding channel bandwidths:

A. Throughput

The figures 6(a-d), 7(a-d), and 8(a-d) depict the variations in throughput between various MIMO (1x1, 2x2, 4x4,

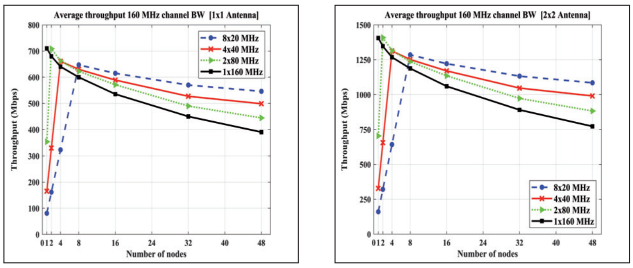
& 8x8) antenna systems for different channels BW (160, 80, and 40 MHz) respectively. It is clear that the throughput increases (due to capacity increase) as the number of spatial streams (SS) increases. However, the rate of data transfer decreases with an increase in the number of nodes, and the reason for this is that more packets of data are passing through the access point (router), which increases the probability contention, collision and as a result packet drop. The performance of throughput for various channels bandwidth can be described as follows:

1x1 MIMO spatial stream throughput performance:

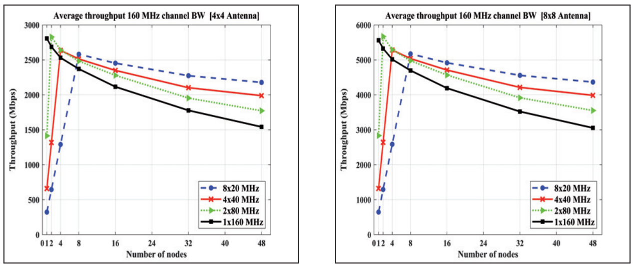
- For 160 MHz, figure 6(a) shows that when only one node is present, a spectrum of channels (8x20, 4x40, and 2x80 MHz) are partially utilized, with only one (20, 40, and 80 MHz) channels being used. The WLAN provides a throughput of (80.88, 165.2, and 354.5 Mbps) in this configuration, while a spectrum of 1x160 MHz channel BW achieves a much higher throughput of 710.1 Mbps. In contrast, when all (20, 40, and 80 MHz) channels in the spectrum are used with (8, 4, and 2 nodes), the WLAN outperforms the configuration with a single 1x160 MHz channel. For example, with (8, 4, and 2) contending nodes, the throughput values are (647, 660.8, and 709.1 Mbps) for (8x20, 4x40, and 2x80 MHz) channel spectrum, compared to (599.8, 640.4, and 680.1 Mbps) for 8,4,2 nodes number respectively of the single 1x160 MHz channel BW,
- For 80 MHz, figure 7(a) shows that when only one node is present, a spectrum of channels (4x20 and 2x40 MHz) are partially utilized, with only one (20 and 40 MHz) channels being used. The WLAN provides a throughput of (80.88 and 165.2 Mbps) in this configuration, while a spectrum of 1x80 MHz channel BW achieves a much higher throughput of 354.5 Mbps. In contrast, when all (20 and 40 MHz) channels in the spectrum are used with (4 and 2 nodes), the WLAN outperforms the configuration with a single 1x80 MHz channel. For example, with (4 and 2) contending nodes, the throughput values are (323.5 and 330.4 Mbps) for (4x20 and 2x40 MHz) channel spectrum, compared to (310.2 and 327 Mbps) for 4, 2 nodes number respectively of the single 1x80 MHz channel BW.
- For 40 MHz, figure 8(a) shows that when only one node is present, a spectrum of channels 2x20 MHz are partially utilized, with only one 20MHz channel being used. The WLAN provides a throughput of 80.88 Mbps in this configuration, while a spectrum of 1x40 MHz channel BW achieves a much higher throughput of 165.2 Mbps. In contrast, when all 20 MHz channels in the spectrum are used (with 2 nodes), the WLAN outperforms the configuration with a single 1x40 MHz channel. For example, with 2 contending nodes, the throughput achieved with the 2x20 MHz channel spectrum is 161.8 Mbps, compared to 157.5 Mbps for the single 1x40 MHz channel BW.

The throughput performance of the other considered SS are summarized as shown in figures 6,7,8 and tables 3,4,5.

For all channels BW scenarios and when DCB is considered, the best achieved throughput values are acquired for the highest nodes number (48 nodes) scenario with (8x8SS), and these values (for 8x20, 4x20, & 2x20 MHz) are (4365, 1840, & 720 Mbps) compared to SCB values (3055, 982.4, and 378.5 Mbps) for 1x160, 1x80, and 1x40 MHz.

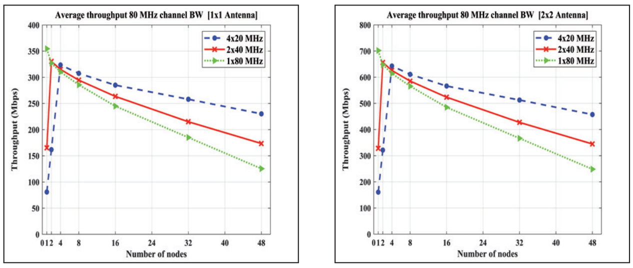


(a) 1x1SS (b) 2x2SS

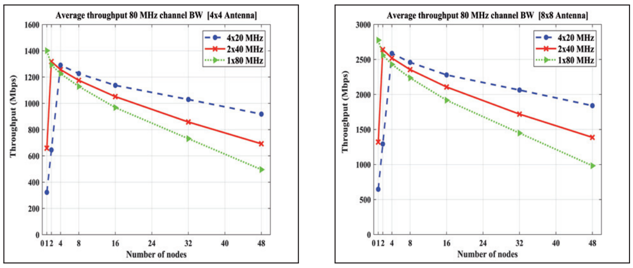


(c) 4x4SS (d) 8x8SS

Fig. 6. Throughput performance for multi-channel bonding 160MHz

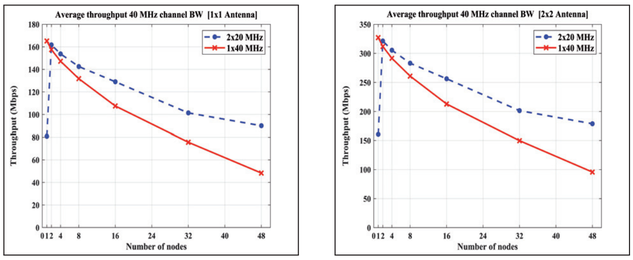


(a) 1x1SS (b) 2x2SS

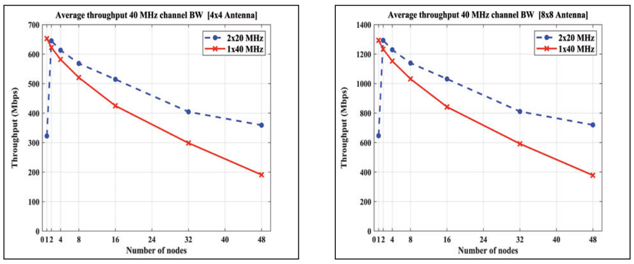


(c) 4x4SS (d) 8x8SS

Fig. 7. Throughput performance for multi-channel bonding 80MHz



(a) 1x1SS (b) 2x2SS



(c) 4x4SS (d) 8x8SS

Fig. 8. Throughput performance for multi-channel bonding 40MHz

Tables 3, 4, and 5 show the channel bandwidth (160, 80, and 40 MHz) throughput values for various spatial stream and node number scenarios.

Table 3: Throughput performance for multi-channel bonding 160MHz

Nodes	1x1SS				2x2SS			
	8x20 (MHz)	4x40 MHz	2x80 MHz	1x160 MHz	8x20 MHz	4x40 MHz	2x80 MHz	1x160 MHz
1	80.88	165.2	354.5	710.1	160.7	328.2	704.3	1406
2	161.8	330.4	709.1	680.1	321.3	656.4	1409	1347
4	323.5	660.8	660.8	640.4	642.7	1313	1313	1268
8	647	630.1	630.1	599.8	1285	1252	1252	1188
16	615	589	571.2	535.3	1222	1170	1135	1060
32	570	527	489.8	449.9	1132	1047	973.1	890.7
48	546	498.6	444.3	390.1	1085	990.5	882.7	772.4
Nodes	4x4SS				8x8SS			
	8x20 MHz	4x40 MHz	2x80 MHz	1x160 MHz	8x20 MHz	4x40 MHz	2x80 MHz	1x160 MHz
1	322.6	659	1414	2806	646.6	1321	2834	5560
2	645.2	1318	2828	2688	1293	2642	5669	5325
4	1290	2636	2636	2531	2586	5283	5283	5015
8	2581	2513	2513	2371	5173	5038	5038	4697
16	2453	2350	2279	2116	4917	4709	4567	4192
32	2274	2102	1954	1778	4557	4213	3916	3522
48	2178	1989	1772	1542	4365	3986	3552	3055

Table 4: Throughput performance for multi-channel bonding 80MHz

Nodes	1x1SS			2x2SS		
	4x20 MHz	2x40 MHz	1x80 MHz	4x20 MHz	2x40 MHz	1x80 MHz
1	80.88	165.2	354.5	160.7	328.2	702
2	161.8	330.4	327	321.3	656.4	647.5
4	323.5	315	310.2	642.7	625.9	614.3
8	307.5	294.5	285.6	610.9	585.1	565.5
16	285	263.5	244.9	566.2	523.5	484.9
32	258	215.1	185	512.6	427.2	366.4
48	230.2	173.5	125.5	457.2	344.7	248.4
Nodes	4x4SS			8x8SS		
	4x20 MHz	2x40 MHz	1x80 MHz	4x20 MHz	2x40 MHz	1x80 MHz
1	322.6	659	1401	646.6	1321	2776
2	645.2	1318	1292	1293	2642	2561
4	1290	1257	1226	2586	2519	2429
8	1227	1175	1129	2458	2355	2236
16	1137	1051	967.9	2279	2107	1918
32	1029	857.9	731.2	2063	1719	1449
48	918.1	692.1	495.9	1840	1387	982.4

Table 5: Throughput performance for multi-channel bonding 40MHz

Nodes	1x1SS		2x2SS		4x4SS		8x8SS	
	2x20 MHz	1x40 MHz	2x20 MHz	1x40 MHz	2x20 MHz	1x40 MHz	2x20 MHz	1x40 MHz
1	80.88	165.2	160.7	327.1	322.6	652.9	646.6	1294
2	161.8	157.5	321.3	311.9	645.2	622.5	1293	1233
4	153.8	147.3	305.4	291.6	613.3	581.9	1229	1153
8	142.5	131.8	283.1	260.9	568.5	520.7	1139	1032
16	129	107.5	256.3	212.9	514.7	425	1032	842
32	101.4	75.61	201.5	149.7	404.5	298.8	810.8	592
48	90.05	48.34	178.9	95.72	359.2	191	720	378.5

B. Delay

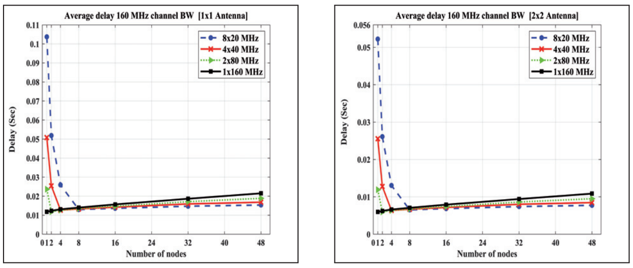
The figures 9(a-d), 10(a-d), and 11(a-d) depict the variations in delay between various MIMO (1x1, 2x2, 4x4, & 8x8) antenna systems for different channels BW (160, 80, and 40 MHz) respectively. It is clear that the delay decreases as the number of spatial streams (SS) increases. However, the delay increase (i.e longer time) with an increase in the number of nodes, and the reason for this is that more packets of data are passing through the access point (router), which increases the probability contention, collision and as a result packet drop. The performance of delay for various channels bandwidth can be described as follows:

1x1 MIMO spatial stream delay performance:

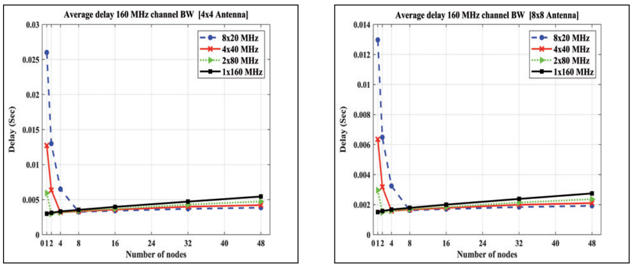
- For 160 MHz, figure 9(a) shows that when only one node is present, a spectrum of channels (8x20, 4x40, and 2x80MHz) are partially utilized, with only one (20, 40, and 80MHz) channels being used. The WLAN provides a delay of (0.1037, 0.0508, and 0.0237 sec) in this configuration, while a spectrum of 1x160 MHz channel BW achieves a much lower delay time of 0.0118 Sec. In contrast, when all (20, 40, and 80 MHz) channels in the spectrum are used with (8, 4, and 2 nodes), the WLAN outperforms the configuration with a single 1x160 MHz channel. For example, with (8, 4, and 2) contending nodes, the delay values are (0.013, 0.0127, and 0.0118 Sec) for (8x20, 4x40, and 2x80 MHz) channel spectrum, compared to (0.014, 0.0131, and 0.0123 Sec) for 8,4,2 nodes number respectively of the single 1x160 MHz channel BW.
- For 80 MHz, figure 10(a) shows that when only one node is present, a spectrum of channels (4x20 and 2x40 MHz) are partially utilized, with only one (20 and 40 MHz) channels being used. The WLAN provides a delay of (0.1037 and 0.0508 Sec) in this configuration, while a spectrum of 1x80 MHz channel BW achieves a much lower delay time of 0.0237 Sec. In contrast, when all (20 and 40 MHz) channels in the spectrum are used with (4 and 2 nodes), the WLAN outperforms the configuration with a single 1x80 MHz channel. For example, with (4 and 2) contending nodes, the delay values are (0.0259 and 0.0254 Sec) for (4x20 and 2x40 MHz) channel spectrum, compared to (0.027 and 0.0257 Sec) for 4, 2 nodes number respectively of the single 1x80 MHz channel BW.
- For 40 MHz, figure 11(a) shows that when only one node is present, a spectrum of channels 2x20 MHz are partially utilized, with only one 20 MHz channel being used. The WLAN provides a delay of 0.1037 Sec in this configuration, while a spectrum of 1x40 MHz channel BW achieves a much lower delay time of 0.0508 Sec. In contrast, when all 20 MHz channels in the spectrum are used (with 2 nodes), the WLAN outperforms the configuration with a single 1x40 MHz channel. For example, with 2 contending nodes, the delay achieved with the 2x20 MHz channel spectrum is 0.0519 Sec, compared to 0.0533 Sec for the single 1x40 MHz channel BW.

The delay performance of the other considered SS are summarized as shown in in figures 9,10,11 and tables 6,7,8.

For all channel BWs scenarios and when DCB is considered, the best achieved delay values are acquired for the highest nodes number (48 nodes) scenario with (8x8 SS), and these values (for 8x20, 4x20, & 2x20 MHz) are (0.0019, 0.0046, & 0.0117 Sec), compared to SCB values (0.0028, 0.0085, and 0.0222 Sec) for 1x160, 1x80, and 1x40 MHz.

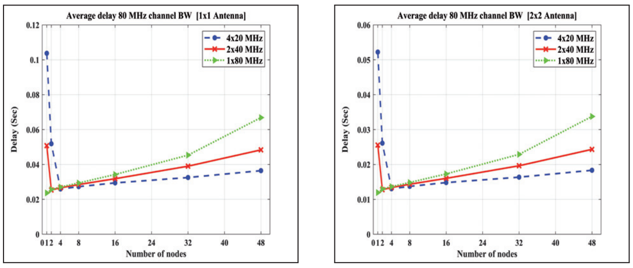


(a) 1x1SS (b) 2x2SS

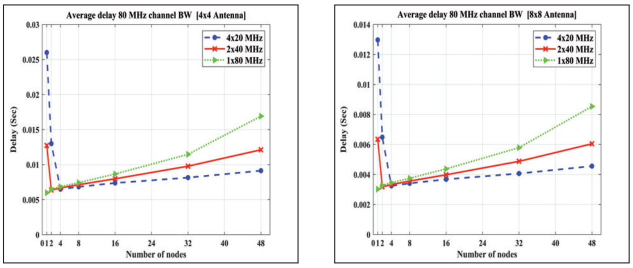


(c) 4x4SS (d) 8x8SS

Fig. 9. Delay performance for multi-channel bonding 160MHz

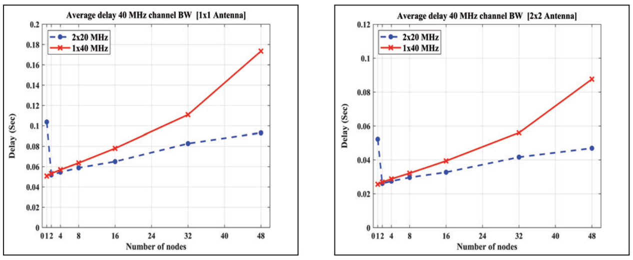


(a) 1x1SS (b) 2x2SS

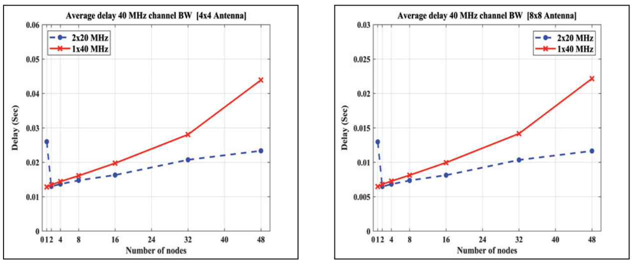


(c) 4x4SS (d) 8x8SS

Fig. 10. Delay performance for multi-channel bonding 80MHz



(a) 1x1SS (b) 2x2SS



(c) 4x4SS (d) 8x8SS

Fig. 11. Delay performance for multi-channel bonding 40MHz

Tables 6, 7, and 8 show the channel bandwidth (160, 80, and 40 MHz) throughput values for various spatial stream and node number scenarios.

Table 6: Delay performance for multi-channel bonding 160MHz

Nodes	**1x1SS**				**2x2SS**			
	8x20 MHz	**4x40 MHz**	**2x80 MHz**	**1x160 MHz**	**8x20 MHz**	**4x40 MHz**	**2x80 MHz**	**1x160 MHz**
1	0.1037	0.0508	0.0237	0.0118	0.0522	0.0256	0.0119	0.006
2	0.0519	0.0254	0.0118	0.0123	0.0261	0.0128	0.006	0.0062
4	0.0259	0.0127	0.0127	0.0131	0.0131	0.0064	0.0064	0.0066
8	0.013	0.0133	0.0133	0.014	0.0065	0.0067	0.0067	0.0071
16	0.0136	0.0142	0.0147	0.0157	0.0069	0.0072	0.0074	0.0079
32	0.0147	0.0159	0.0171	0.0187	0.0074	0.008	0.0086	0.0094
48	0.0154	0.0168	0.0189	0.0215	0.0077	0.0085	0.0095	0.0109
Nodes	**4x4SS**				**8x8SS**			
	8x20 MHz	**4x40 MHz**	**2x80 MHz**	**1x160 MHz**	**8x20 MHz**	**4x40 MHz**	**2x80 MHz**	**1x160 MHz**
1	0.026	0.0127	0.0059	0.003	0.013	0.0064	0.003	0.0015
2	0.013	0.0064	0.003	0.0031	0.0065	0.0032	0.0015	0.0016
4	0.0065	0.0032	0.0032	0.0033	0.0032	0.0016	0.0016	0.0017
8	0.0033	0.0033	0.0033	0.0035	0.0016	0.0017	0.0017	0.0018
16	0.0034	0.0036	0.0037	0.004	0.0017	0.0018	0.0018	0.002
32	0.0037	0.004	0.0043	0.0047	0.0018	0.002	0.0021	0.0024
48	0.0039	0.0042	0.0047	0.0054	0.0019	0.0021	0.0024	0.0028

Table 7: Delay performance for multi-channel bonding 80MHz

Nodes	**1x1SS**			**2x2SS**		
	4x20 MHz	**2x40 MHz**	**1x80 MHz**	**4x20 MHz**	**2x40 MHz**	**1x80 MHz**
1	0.1037	0.0508	0.0237	0.0522	0.0256	0.012
2	0.0519	0.0254	0.0257	0.0261	0.0128	0.013
4	0.0259	0.0266	0.027	0.0131	0.0134	0.0137
8	0.0273	0.0285	0.0294	0.0137	0.0143	0.0148
16	0.0294	0.0318	0.0343	0.0148	0.016	0.0173
32	0.0325	0.039	0.0453	0.0164	0.0196	0.0229
48	0.0365	0.0484	0.0669	0.0184	0.0243	0.0338
Nodes	**4x4SS**			**8x8SS**		
	4x20 MHz	**2x40 MHz**	**1x80 MHz**	**4x20 MHz**	**2x40 MHz**	**1x80 MHz**
1	0.026	0.0127	0.006	0.013	0.0064	0.003
2	0.013	0.0064	0.0065	0.0065	0.0032	0.0033
4	0.0065	0.0067	0.0068	0.0032	0.0033	0.0035
8	0.0068	0.0071	0.0074	0.0034	0.0036	0.0038
16	0.0074	0.008	0.0087	0.0037	0.004	0.0044
32	0.0082	0.0098	0.0115	0.0041	0.0049	0.0058
48	0.0091	0.0121	0.0169	0.0046	0.0061	0.0085

Table 8: Delay performance for multi-channel bonding 40MHz

Nodes	**1x1SS**		**2x2SS**		**4x4SS**		**8x8SS**	
	2x20 MHz	**1x40 MHz**	**2x20 MHz**	**1x40 MHz**	**2x20 MHz**	**1x40 MHz**	**2x20 MHz**	**1x40 MHz**
1	0.1037	0.0508	0.0522	0.0257	0.026	0.0129	0.013	0.0065
2	0.0519	0.0533	0.0261	0.0269	0.013	0.0135	0.0065	0.0068
4	0.0546	0.057	0.0275	0.0288	0.0137	0.0144	0.0068	0.0073
8	0.0589	0.0637	0.0296	0.0322	0.0148	0.0161	0.0074	0.0081
16	0.065	0.078	0.0327	0.0394	0.0163	0.0197	0.0081	0.01
32	0.0827	0.1109	0.0416	0.056	0.0207	0.0281	0.0104	0.0142
48	0.0932	0.1735	0.0469	0.0876	0.0234	0.0439	0.0117	0.0222

Conclusion

In this paper, various (from 1 to 48) node number scenarios are proposed for simulating WLANs that are compatible with the IEEE 802.11ac standard. Network simulator (NS-3) version 3.37 is used to analyze and investigate the performance of IEEE 802.11ac standard based WLANs for various multi-channel bonding. Extensive simulation procedures are used for these scenarios to enhance the performance of networks. The simulation results show that when dynamic bonding (8x20, 4x20, and 2x20 MHz) is considered, the highest throughput and least amount of delay values are acquired. Specifically, for MIMO (8x8) SS and with respect to the Static Channel Bonding (SCB) (1x160, 1x80, and 1x40 MHz), the best achieved values of throughput and delay are obtained in the highest (48 node number) scenario. The throughput values for (8x20, 4x20, & 2x20 MHz) are (4365, 1840, & 720 Mbps), compared to (3055, 982.4, and 378.5 Mbps) for 1x160, 1x80, and 1x40 MHz, and the delay values for (8x20, 4x20, & 2x20 MHz) are (0.0019, 0.0046, & 0.0117 Sec), compared to (0.0028, 0.0085, and 0.0222 Sec) for 1x160, 1x80, and 1x40 MHz. These results (and for equal nodes load) indicate that bandwidth efficiency rises when separated into several narrow channels rather than fewer large channels.

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REFERENCES

[1] Cisco, “ Cisco Annual Internet Report (2018–2023) White Paper,"*Cisco*. 2020.

[2] R. Karmakar, S. Chattopadhyay, and S. Chakraborty, “Impact of IEEE 802.11n/ac PHY/MAC high Throughput Enhancements on Transport and Application Protocols—A Survey,” *IEEE Communications Surveys & Tutorials*, vol. 19, no. 4, pp. 2050–2091, 2017.

[3] O. Bejarano, E. W. Knightly, and M. Park, “IEEE 802.11ac: From channelization to multi-user MIMO,” *IEEE Communications Magazine*, vol. 51, no. 10, pp. 84–90, 2013.

[4] B. S. Kim, H. Y. Hwang, and D. K. Sung, “Effect of frame aggregation on the throughput performance of IEEE 802.11n,” in *2008 IEEE Wireless Communications and Networking Conference*, pp. 1740–1744, 2008.

[5] Z. K. Farej and M. M. Jasim, “Investigation on the performance of the iee802.11n based wireless networks for multimedia services,” in *2018 2nd International Conference for Engineering, Technology and Sciences of Al-Kitab (ICETS)*, pp. 48–53, 2018.

[6] T. Nitsche, C. Cordeiro, A. B. Flores, E. W. Knightly, E. Perahia, and J. C. Widmer, “IEEE 802.11ad: directional 60 GHz communication for multi-Gigabit-per-second Wi-Fi [Invited Paper],” in *IEEE Communications Magazine*, vol. 52, no. 12, pp. 132–141, 2014.

[7] M. S. Gast, *802.11ac: a survival guide: Wi-Fi at gigabit and beyond*. 2013.

[8] N. Khalil and A. Najid, “Performance analysis of 802.11 ac with frame aggregation using NS3,” *International Journal of Electrical and Computer Engineering*, vol. 10, no. 5, p. 5368, 2020.

[9] M. S. Gast, *802.11n: A Survival Guide*, no. 1. 2012.

[10] IEEE Standards Association, *part 11: Wireless lan medium access control (mac) and physical layer (phy) specifications–amendment 4: Enhancements for very high throughput for operation in bands below 6 ghz*. 2013.

[11] V. Parashar, R. Kashyap, A. Rizwan, D. Karras, G. Cieza Altamirano, E. Dixit, and F. Ahmadi, “Aggregation-based dynamic channel bonding to maximise the performance of wireless local area networks (WLAN),” *Wireless Communications and Mobile Computing*, vol. 2022, 06 2022.

[12] H. Qi, H. Huang, Z. Hu, X. Wen, and Z. Lu, “On-demand channel bonding in heterogeneous WLANs: A multi-agent deep reinforcement learning approach,” *Sensors*, vol. 20, no. 10, 2020.

[13] M. Han, S. Khairy, L. X. Cai, Y. Cheng, and F. Hou, “Capacity Analysis of Opportunistic Channel Bonding Over Multi-Channel WLANs Under Unsaturated Traffic,” in *IEEE Transactions on Communications*, vol. 68, no. 3, pp. 1552–1566, 2020.

[14] A. Zakrzewska and L. Ho, “Dynamic Channel Bandwidth Use through Efficient Channel Assignment in IEEE 802.11ac Networks,” *2019 IEEE 90th Vehicular Technology Conference (VTC2019-Fall)*, pp. 1–6, 2019.

[15] S. Khairy, M. Han, L. X. Cai, Y. Cheng, and Z. Han, “Enabling efficient multi-channel bonding for IEEE 802.11ac WLANs,” in *2017 IEEE International Conference on Communications (ICC)*, pp. 1–6, 2017.

[16] S. Barrachina-Muñoz, F. Wilhelmi, and B. Bellalta, “Dynamic Channel Bonding in Spatially Distributed High-Density WLANs,” in *IEEE Transactions on Mobile Computing*, vol. 19, no. 4, pp. 821–835, 2020.

[17] Y.-D. Chen, D.-R. Wu, T.-C. Sung, and K.-P. Shih, “DBS: A dynamic bandwidth selection MAC protocol for channel bonding in IEEE 802.11ac WLANs,” *2018 IEEE Wireless Communications and Networking Conference (WCNC)*, pp. 1–6, 2018.

[18] P. Huang, X. Yang, and L. Xiao, “Dynamic Channel Bonding: Enabling Flexible Spectrum Aggregation,” in *IEEE Transactions on Mobile Computing*, vol. 15, no. 12, pp. 3042–3056, 2016.

[19] S. Byeon, C. Yang, O. Lee, K. Yoon, and S. Choi, “Enhancement of wide bandwidth operation in IEEE 802.11ac networks,” *2015 IEEE International Conference on Communications (ICC)*, pp. 1547–1552, 2015.

[20] O. Aboul-Magd, U. Kwon, Y. Kim, and C. Zhu, “Managing downlink multi-user MIMO transmission using group membership,” in *2013 IEEE 10th Consumer Communications and Networking Conference (CCNC)*, pp. 370–375, 2013.

[21] S. R. Chaudhary, A. J. Patil, and A. V. Yadao, “Wlan-ieee 802.11ac: Simulation and performance evaluation with MIMO-OFDM,” in *2016 Conference on Advances in Signal Processing (CASP)*, pp. 440–445, 2016.

[22] E. Ghayoula, M. H. Taieb, J.-Y. Chouinard, R. Ghayoula, and A. Bouallegue, “Improving MIMO systems performances by concatenating LDBC decoder to the STBC and MRC receivers,” in *2015 World Symposium on Computer Networks and Information Security (WSCNIS)*, pp. 1–6, 2015.

[23] Z. Farej and A. Al-Najafi, “Modeling of MIMO-OFDM Channel with STBC and Directivity to Combat Fading and Co-Channel Interference,” *OALib*, vol. 07, pp. 1–15, 01 2020.

[24] O. Sharon and Y. Alpert, “MAC level Throughput comparison: 802.11ac vs. 802.11n,” *Physical Communication*, vol. 12, pp. 33–49, 2014.

[25] B. T. Vijay and B. Malarkodi, “MAC improvements for very high throughput WLANs,” *International Journal of Communication Networks and Distributed Systems*, vol. 22, pp. 74–97, 01 2019.

[26] E. Charfi, L. Chaari, and L. Kamoun, “PHY/MAC Enhancements and QoS Mechanisms for Very High Throughput WLANs: A Survey,” *IEEE Communications Surveys & Tutorials*, vol. 15, no. 4, pp. 1714–1735, 2013.

[27] Z. Farej and O. Ali, “On the evaluation of the IEEE 802.11ac wlan performance with QoS deployment,” *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 24, p. 1618, 12 2021.

[28] Z. Farej and M. Jasim, “Performance evaluation of the IEEE 802.11n random topology WLAN with QoS application,” *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 10, p. 1924, 04 2020.