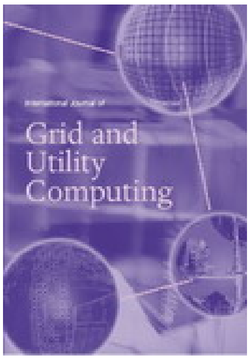

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Experimental evaluation of downlink communication performance of IEEE 802.11ax wireless LAN: OFDM vs. OFDMA

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Abstract: Although Orthogonal Frequency Division Multiple Access (OFDMA), adopted in IEEE 802.11ax, allows an Access Point (AP) to communicate with multiple stations (STAs) simultaneously, the bandwidth of the Resource Unit allocated to each STA is inversely proportional to the number of STAs. In contrast, Orthogonal Frequency Division Multiplexing (OFDM) allows an AP/STA pair, determined by carrier-sense multiple access with collision avoidance, to dominate the entire bandwidth. However, the latency before packet transmission increases with the number of STAs. The number of STAs that want to communicate with an AP thus significantly impacts throughput under OFDM and OFDMA. Therefore, this study evaluates the communication performance for rich content and voice data when multiple STAs (up to five) are connected to an AP with OFDM or OFDMA by lab experiments. Through experimental results, we clarified which is more suitable, either OFDM or OFDMA, to improve the Quality of Experience (QoE) and throughput with the change in the number of STAs and application types of traffic.

Keywords: IEEE 802.11ax; channel bonding; resource unit; OFDM; OFDMA.

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1 Introduction

The number of Wi-Fi devices and users has drastically increased due to the widespread use of laptop computers, tablets and smartphones (Ministry of Internal Affairs and Communications, 2021; Cisco Systems, 2020a, 2020b). To supply rich content, such as high-quality videos and music, Wireless Local Area Networks (WLANs) need to provide high throughput for many Wi-Fi users simultaneously, and thus, efficient data transmission through mechanisms such as modulation, Media Access Control (MAC), channel bonding and frame aggregation, has become important (Rochim and Sari, 2016). Furthermore, a massive number of Internet of Things (IoT) devices have been newly connected to the Internet via WLAN, and it was clear that they had different traffic characteristics with the traditional rich content in WLAN (Iori et al., 2023). Thus, various types of applications through WLAN require a diverse Quality of Experience (QoE). Therefore, WLAN Access Points (APs) must provide not only high throughput for rich content but also high QoE performance for voice data even when many stations (STAs) are communicating simultaneously.

IEEE 802.11ax (11ax) introduces Orthogonal Frequency Division Multiple Access (OFDMA), which enables simultaneous communication between an AP and multiple STAs, as a solution to throughput degradation due to Head-Of-Line (HOL) blocking of simultaneous communication with multiple users via the Carrier-Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism.

When many STAs communicate with an AP, the allocated bandwidth to each STA becomes small with OFDMA, whereas it remains constant with Orthogonal Frequency Division Multiplexing (OFDM); however, for the latter, some STAs must wait for a long time before getting channel access via CSMA/CA. The number of STAs that want to communicate with an AP could thus significantly impact on throughput under OFDM or OFDMA. Many studies have evaluated 11ax performance using simulations (Adian et al., 2020; Qiao et al., 2019; Islam and Kashem, 2022; Zined and Abdellah, 2018). However, there has been no quantitative investigation on the impact of modulation, the MAC mechanism, and the use of OFDM or OFDMA on performance for various numbers of STAs connected to an AP. Therefore, in this research, we experimentally compare the throughput of two types of applications (rich content and voice data) when multiple STAs retrieve application data via an 11ax AP with downlink OFDM or OFDMA. Furthermore, we investigate the impact of the number of STAs connected to an AP, channel bonding and traffic characteristics for each STA on throughput for rich contents and QoE for voice data by lab experiments. Through our experiments, we also aim to determine the most suitable network environments for OFDM and OFDMA with the change in the number of STAs and application types of traffic.

The major contributions of this paper are summarised as follows:

- We provide the downlink throughput performance in the actual IEEE 802.11ax WLAN with commercially available equipment.
- We reveal the appropriate transmission method (OFDM or OFDMA) when the number of STAs and the types of applications are varied.

The rest of this paper is organised as follows: Section 2 reviews channel bonding, OFDM and OFDMA and the MAC control of 11ax channel bonding. Section 3 describes our experimental environment and performance measures. Section 4 presents the experimental results. Section 5 discusses the adaptability of OFDM and OFDMA, considering the number of STAs connected to an AP and traffic characteristics. Finally, Section 6 summarises the results.

2 IEEE 802.11ax

11ax introduced OFDMA (IEEE SA Standard Board, 2021) for dense Wi-Fi deployment. OFDMA enables simultaneous communication for multiple users. In this section, we describe the channel bonding and OFDMA used in our experiments and the communication procedures for downlink communication using these technologies.

2.1 Channel bonding

Channel bonding enables wider bandwidth via the use of multiple adjacent channels as shown in Figure 1 (Cisco Systems, 2018; National Instruments, 2023). A communication band consists of one primary channel (20 MHz) and one or more secondary channels, as shown in Figure 2 (Hitomi et al., 2021). The 11ax AP used in this study operates with static channel bonding, where the AP communicates only when all channels, that are preliminarily set in the AP, are clear simultaneously and the Request-To-Send/Clear-To-Send (RTS/CTS) function is applied for channel access (shown in Figure 3) (Erfan et al., 2022). In response to CTS is generated as the response to RTS across the entire channels, the sender can send its data frame to its destination using the second modulation method such as OFDM or OFDMA. If other WLAN communication is detected, the sender must wait until the channel is cleared. As the second modulation method, OFDM was applied for communication standards before 11ac, whereas OFDMA is applied for 11ax. Furthermore, a data frame is sent at a physical rate, represented by the Modulation and Coding Scheme (MCS) index. The MCS index is defined by the first and second modulation methods. The two sorts of second modulation schemes are described in Sub-sections 2.2 and 2.3. The MCS index is described in Sub-section 2.4.

The 11ax standard also employs Enhanced Distributed Channel Access (EDCA) (Kong et al., 2004) to support service differentiation with four traffic classes. EDCA defines four Access Categories (ACs), namely Voice, Video, Best Effort and Background, each of which is queued in four different queues at an AP. Each access category has its own interframe space and contention window. Data frames are transmitted in priority order according to traffic quality of service requirements.

We cannot confirm whether the 11ax AP used in our experiments supported EDCA. In our experiments, traffic of the same class was transmitted between an AP to some STAs for each experimental setting. That is, we did not employ any priority control for practicality in real-world environment. Therefore, we can regard the channel access method of the 11ax AP which we used as general CSMA/CA in our experiments.

2.2 OFDM

OFDM divides incoming signals into multiple low-bandwidth, low-rate carrier waves (sub-carriers) and orthogonalises them for simultaneous transmission without interference (Cisco Systems, 2018). Figure 4 shows an example of communication with multiple STAs using OFDM. When STA1 transmits a data frame, the entire bandwidth should be used for data transmission. Since the available bandwidth of each STA is constant, the frame transmission rate at the PHY layer is constant. However, other STAs must wait to transmit data. For communication using OFDM, the waiting time for a transmission opportunity caused by CSMA/CA increases with the increasing number of STAs connected to the AP.

Figure 1 Channel allocation at 5GHz-band channel bonding (see online version for colours)

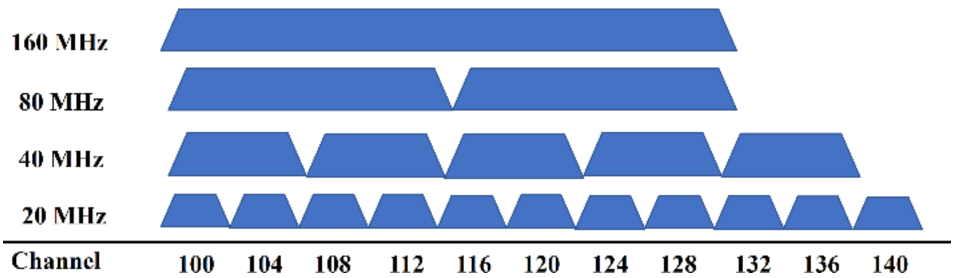


Figure 2 Channel configuration for channel bonding at 80 MHz (see online version for colours)

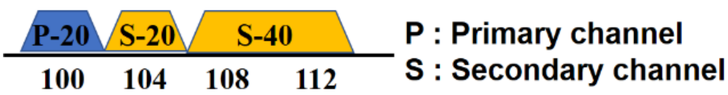


Figure 3 Static channel bonding using CSMA/CA with RTS/CTS (P: Primary, S: Secondary) (see online version for colours)

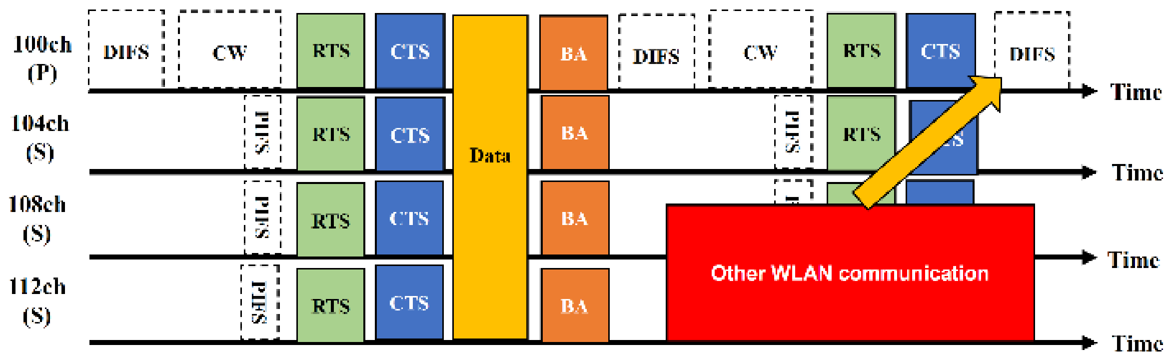
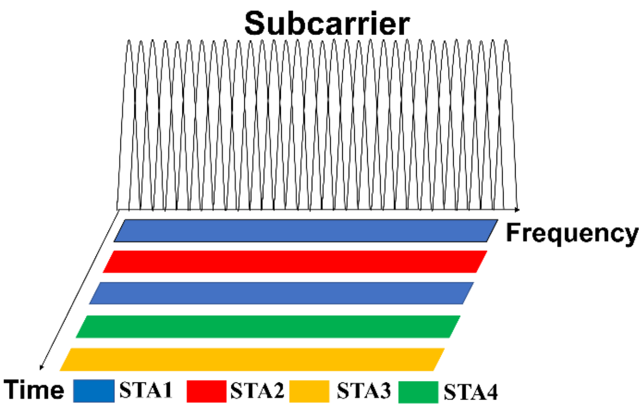


Figure 4 Example of time sequence of frequency use in OFDM (see online version for colours)



2.3 OFDMA

OFDMA aggregates multiple neighbouring sub-carriers into Resource Units (RUs) and provides RUs to multiple STAs. Since OFDMA assigns an RU to each STA, an AP can communicate with multiple STAs simultaneously (Cisco Systems, 2020). The size of an RU depends on the number of sub-carriers. For a single channel without channel bonding (i.e., 20 MHz), four types of RU, namely RU-26 (26 sub-carriers), RU-52 (52 sub-carriers), RU-106 (106 sub-carriers) and RU-242 (242 sub-carriers) are available. They allow 9, 4, 2 and 1 STA to communicate simultaneously, respectively. Moreover, RU-484 and RU-996 are available for 40/80 MHz and 80 MHz bonding channels, respectively (Aruba Networks, 2019). Figure 5 shows an example of communicating with multiple STAs using OFDMA at 20 MHz. If each STA uses RU-52, the AP can communicate with at most 4 STAs simultaneously. If each STA uses RU-26, the AP can communicate with at most 9 STAs simultaneously. The simultaneous communication provided by OFDMA significantly reduces the waiting time caused by CSMA/CA. However, the bandwidth of each STA is reduced to as low as one-ninth for OFDM. The allocation of RUs in OFDMA decreases the bandwidth and thus may lead to degrade throughput for each STA. The timing and method for allocating RUs to STAs are not specified in the 11ax standard and thus depend on the vendor implementation. Furthermore, considering the improvement in QoE when multiple STAs transmit traffic with different characteristics simultaneously, it is necessary to understand the relationship between the traffic characteristics and the communication performance of OFDMA.

2.4 MCS index

The theoretical maximum physical transmission rate in a WLAN can be calculated from the first modulation scheme (e.g., QPSK, 16 QAM, 256 QAM), the number of Spatial Streams (SS), the channel bonding width (20, 40, 80), the Guard Interval (GI), and the number of subcarriers. The MCS index is defined based on combinations of these parameters. In 11ax, the MCS index ranges from 0 to 11. Table 1 shows some MCS index values (Francois, 2019) for OFDM with SS=2, bonding width=20 MHz and GI=0.8 µs. For OFDMA, the maximum physical rate depends on the number of allocated RU tones.

Figure 5 Example of time sequence of frequency use in OFDMA (see online version for colours)

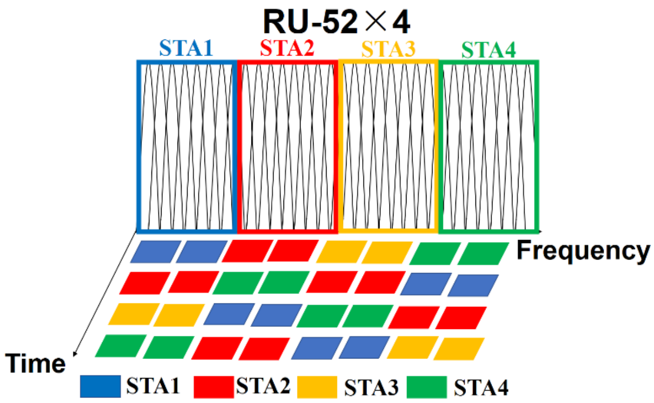


Table 1 IEEE 802.11ax MCS index values (SS=2, 20 MHz, GI=0.8=00 µs)

MCS index	*OFDMA[Mb/s]*			
	RU-26	*RU-52*	*RU-106*	*RU-242 (OFDM)*
5	14.1	28.2	60	137.6
6	15.9	31.8	67.5	154.9
7	17.6	35.3	75	172.1
8	21.2	42.4	90	206.5
9	23.5	47.1	100	229.4
10	26.5	52.90	112.5	258.1
11	29.4	58.8	125	286.8

3 Experimental environment

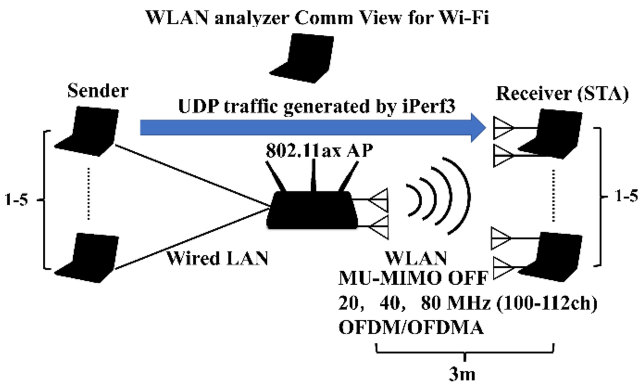
3.1 Experimental setup

We evaluated and compared the throughput of downlink communication from an 11ax-compliant WLAN AP to multiple STAs using OFDM or OFDMA. Figure 6 shows the experimental setup. The number of STAs, *n*, was varied from 1 to 5, and the channel bonding width was set to 20 MHz, 40 MHz or 80 MHz. The channels used for the performance evaluation of channel bonding were 100 to 104 ch (primary channel is 100 ch) at 40 MHz and 100 to 112 ch at 80 MHz in the 5 GHz band. In addition, Multi-User Multiple-Input Multiple-Output (MU-MIMO) was turned off, and thus, the AP and each STA communicated with two antennas. The use of OFDM or OFDMA was set in the AP configuration in advance. The sender PCs were connected to the AP via a wired local area network, and the receiver PCs (STAs) were connected to the AP via a WLAN. The sender PCs sent the same traffic to all STAs simultaneously using iPerf3 (iPerf3, 2016) for 40 seconds. In this experiment, we used two types of traffic with different characteristics, namely (1) rich content (large frame size, high rate) and (2) voice data (small frame size, low rate), and the parameters of iPerf3 are shown in Table 2. For rich content, the parameters for traffic generation in iPerf3 were set to exceed the PHY rate to evaluate the maximum transfer performance. We conducted five experiments for each setting. We then used TamoSoft CommView for Wi-Fi (TamoSoft, 2023) to analyse frames in the WLAN for each experiment. The experiments were conducted in an electromagnetic anechoic chamber or the basement hall of Building C at the Fukuoka Institute of Technology, and thus, there were no extraneous radio waves from 100 to 112 ch.

Table 2 Parameters of iPerf3 in our experiments and R_{phy} for various channel bonding widths

Channel bonding width [MHz]	*PHY rate R_{phy} [Mbps]*	*Parameters for iPerf3 (Packet size, Packet generation rate)*
20	286.8	(1)1470 Byte, 300 Mb/s (2)160 Byte,128 kb/s
40	573.5	(1)1470 Byte, 610 Mb/s (2)160 Byte, 128 kb/s
80	1201	(1)1470 Byte, 1210 Mb/s (2)160 Byte, 128 kb/s

Figure 6 Experimental configuration (see online version for colours)



3.2 *Performance measures*

We evaluated performance using throughput $Th(x)_i$, which was obtained from the iperf3 command for each STA (x=1, 2, 3, 4, 5) in the i-th experiment. The average and normalised throughput are respectively expressed as where R_{phy} is the PHY rate and n is the number of STAs connected to the AP. Th_{ave_n} is the average throughput for each STA, and $Th^*_{ave_n}$ is the ratio of the throughput to the maximum physical transmission bandwidth. If a normalised throughput is close to 1, then the throughput is close to the PHY rate.

$$Th_{ave_n} = \left(\frac{1}{5n}\right)\sum_{i=1}^{5}\sum_{x=1}^{n} Th(x)_i \tag{1}$$

$$Th^*_{ave_n} = \frac{\left(n * Th_{ave_n}\right)}{R_{phy}} \tag{2}$$

4 Experimental results

We conducted the experiments using two traffic patterns (rich content and voice data) to investigate how traffic characteristics impact on the throughput of OFDM and OFDMA. We mainly evaluated the throughput for rich content and the stability of voice data.

4.1 *Rich content*

We evaluated how the number of STAs and bonding width impact on the normalised throughput of OFDM and OFDMA in an 11ax WLAN when all STAs receive rich content.

4.1.1 *Impact of number of STAs on throughput at 20 MHz*

First, we investigate the impact of the number of STAs on the throughput of OFDM and OFDMA without channel bonding. Figure 7 shows the average throughput per STA calculated by equation (1) as a function of the number of STAs (n) results. The error bars indicate the standard deviation of throughput obtained by each STA in one experiment. From Figure 7, the average throughput per STA in OFDMA decreases as the number of STAs increases, which is not entirely different from OFDM. When the number of STAs is 2 and 3, the average throughput of OFDMA is slightly higher than that of OFDM. Furthermore, the standard deviation of throughput in OFDMA is larger than in OFDM except for the number of STA is 2. From the standard deviation, OFDMA leads to more unstable throughput than OFDM. We expected that uneven RU tones might be allocated to each STA in OFDMA; however, we could not validate the number of tones. We discussed the details of the throughput performance; thus, we derived the normalised throughput by equation (2), investigated the throughput performance degradation from the ideal throughput, and found the reason for performance degradation in OFDM and OFDMA.

Figure 7 Impact of the number of STAs on average throughput and standard deviation (20 MHz) (see online version for colours)

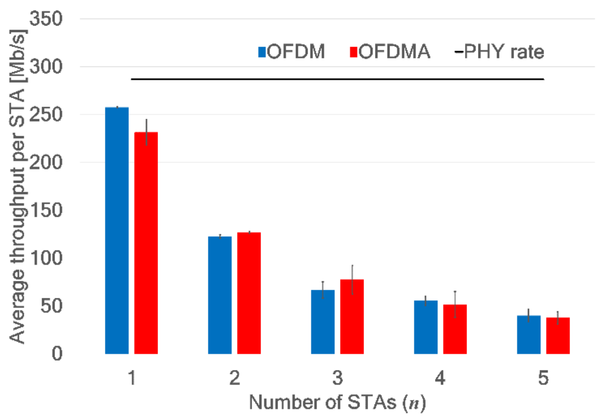
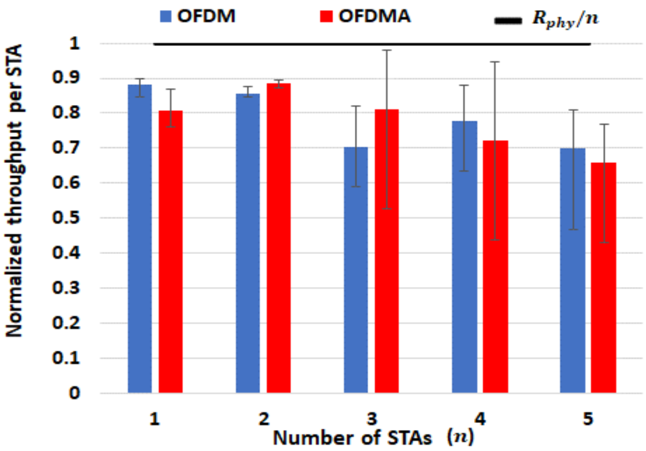


Figure 8 shows the normalised throughput per STA calculated by equation (2). The error bars indicate the maximum and minimum values of the normalised throughput in the five experiments. In Figure 8, the normalised throughput of OFDMA is slightly higher than that of OFDM when n =2 or 3; the normalised throughput of OFDM is higher than that of OFDMA when n =1, 4 or 5. In OFDM, an STA that gets channel access can transmit data frames using the entire bandwidth. The other STAs must wait until they get channel access due to CSMA/CA procedures. As the number of STAs increases, the waiting time for getting channel access increases. In OFDMA, the overhead due to CSMA/CA can be minimised when the number of STAs, n , does not exceed 9; however, the bandwidth per STA becomes $1/n$.

Figure 8 Impact of the number of STAs on normalised throughput with the maximum and the minimum normalised throughput of 20 MHz channel bonding (see online version for colours)



Thus, the airtime for data frame transmission increases as n increases. In our experimental environment, the overhead of the narrower bandwidth in OFDMA was more significant than the waiting time for getting channel access via CSMA/CA in OFDM when n was more than 4.

Furthermore, for $n \geq 3$, there was a difference between the maximum and minimum normalised throughput increases in OFDMA; that is, the normalised throughput for each STA was imbalanced. This was in part caused by the heterogeneous number of sub-carriers for the RU of each STA.

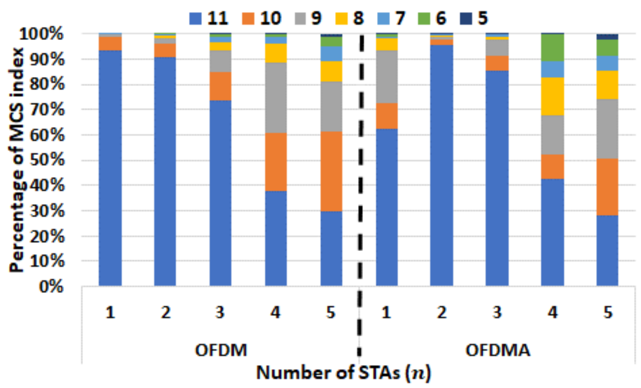
4.1.2 *Relationship between throughput and selected MCS index values*

The rate control also contributed to the difference between the maximum and minimum normalised throughput in OFDMA. Since the WLAN analyser used in this study cannot detect the number of subcarriers bonded in each RU, we investigated the selected MCS index value per data frame transmission. Figures 9 and 10 show the ratio of selected MCS index values in the frame header captured by the WLAN analyser in the experiments. From these figures, the ratio of MCS 5 to 10 increases with the increase in the number of STAs. Therefore, the number of STAs affects the transmission rate per frame. In addition, the MCS index varies depending on the RUs allocated by OFDMA (see Table 1). We calculated the expected value of the MCS index for each number of STAs from the data in Figure 9. The expected values of the MCS index are shown in Table 3. For OFDMA, when the number of STAs is 2 or 3, the expected value of the MCS index in case of OFDMA is higher than that for OFDM. However, when the number of STAs is more than 4, the expected value of the MCS index for OFDMA is lower than that for OFDM. The trend of the expected value of the MCS index is correlated with the normalised throughput. When the number of STAs is 4 or 5 for OFDMA, the allocated bandwidth for each STA becomes small due to the RU allocation procedure. Even if the MCS indexes for OFDMA and OFDM are the same, the PHY rate for OFDMA is narrower than that for OFDM. Thus, the normalised throughput of OFDMA degrades more than that of OFDM. These results indicate that the selected MCS index value per frame significantly impacts the throughput. Therefore, a rate selection scheme for each frame transmission is necessary to improve throughput.

Table 3 Expected values of MCS index

Number of STAs	*The expected value of the MCS index in OFDM*	*The expected value of the MCS index in OFDMA*
1	10.92095	10.2513
2	10.83804	10.91251
3	10.47499	10.72834
4	9.812112	9.339107
5	9.541203	9.265387

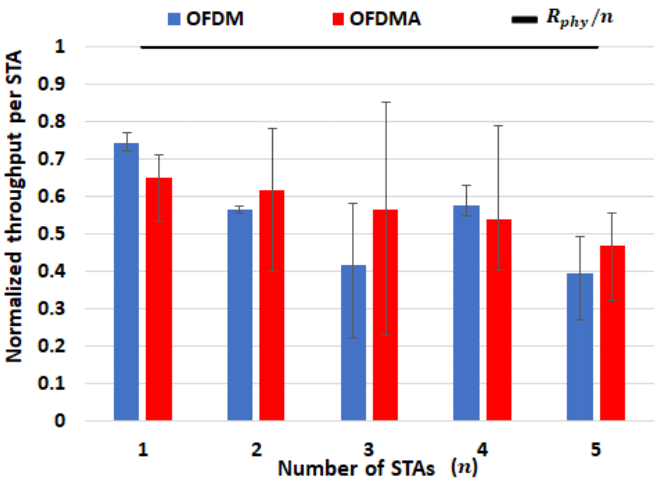
Figure 9 Ratio of MCS index values used in frame transmission for OFDM and OFDMA (see online version for colours)



4.1.3 *Impact of channel bonding*

We investigated the impact of channel bonding width on the normalised throughput. Figure 10 shows the experimental results for rich content when the bonding width is set to 80 MHz. When the channel bonding width is 40 MHz, the normalised throughput is almost the same as that for 20 MHz. In contrast, for OFDMA, when the channel bonding width is 80 MHz, the bandwidth of RUs allocated to each STA is doubled compared to the channel bonding width is 40 MHz. OFDMA thus achieves better throughput even for five STAs.

Figure 10 Impact of the number of STAs on normalised throughput with the maximum and the minimum normalised throughput of 80 MHz channel bonding (see online version for colours)



A comparison of Figures 8 and 10 indicate that the normalised throughput decreased by about 20% as the bonding width doubled, regardless of the number of STAs.

The normalised throughput might degrade due to the waiting time caused by the control overhead to confirm that multiple channels are clear for static channel bonding.

4.1.4 Overhead caused by control frames

One of the reasons for the decrease in the normalised throughput with channel bonding is the overhead of exchanging RTS and CTS over all the channels used, as described in Sub-section 2.1.

Since the WLAN AP used in this experiment employs static channel bonding using the communication procedure shown in Figure 3, we investigated the relationship between the channel bonding width and the number of RTS/CTS frames. The number of CTS frames increased with bonding width. We checked the destination MAC addresses of the CTS frames and found that the AP transmitted these frames to itself. Since the CTS frame is sent after the transmission of a Block ACK (BA), which is sent as an acknowledgment of a frame, it was determined that this CTS was a CTS-to-self sent by the AP. Table 4 shows the number of CTS-to-self frames generated by the AP for OFDM and OFDMA, respectively, when the number of STAs is 4. For the normal RTS/CTS and BA, CTS-to-self is transmitted when there are frame loss and frame retransmission. Table 4 shows that the number of CTS-to-self frames increases as the bonding width increases for OFDMA. This might be caused by frame retransmission or bit error; we could not clarify the reason due to the limitations of the Wi-Fi analyser. In any case, the experimental results show that as the channel bonding width increases, the number of CTS-to-self frames increases. Frame retransmission and the overhead caused by CTS-to-self frames degrade the normalised throughput.

Table 4 Impact of channel bonding width on the number of CTS-to-self frames (n=4)

	20 MHz	*40 MHz*	*80 MHz*
OFDM	86	67	345
OFDMA	1486	2960	6403

With current Wi-Fi hardware, channel bonding leads to unstable communication and applying OFDMA might lead to even more instability. Therefore, for OFDMA in an 11ax AP, channel bonding should be disabled.

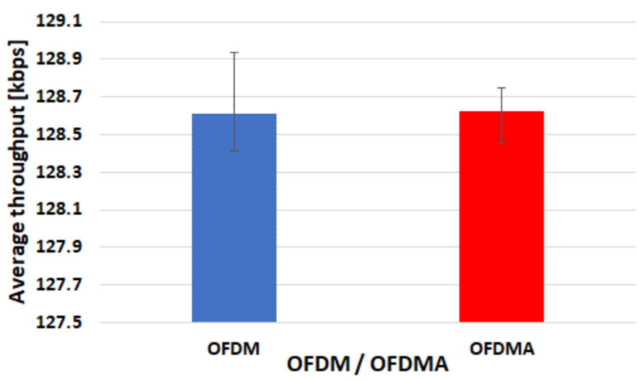
4.2 Voice data

We also investigated the performance of OFDM and OFDMA for voice data in terms of the average throughput and jitter. For voice data, a wide bandwidth is not needed. Therefore, we did not use channel bonding; the channel width was fixed at 20 MHz.

4.2.1 Impact on average throughput

Figure 11 shows the average throughput for five STAs. The error bars indicate the maximum and minimum values of normalised throughput in five experiments. As shown, there is no significant difference in the average throughput between OFDM and OFDMA. The difference between the maximum and minimum throughput was lower for OFDMA than for OFDM (0.04 kb/s vs. 0.13 kb/s). Even when the generated traffic has a small packet size and a low rate, OFDMA provides stable communication quality because the bandwidth allocated to each STA is generally higher than the traffic rate. In contrast, for OFDM, each STA randomly accesses a channel even when the packet size is small, and thus the wait time until the start of communication varies. Therefore, the difference between the maximum and minimum throughput becomes wider.

Figure 11 Average throughput with the maximum and the minimum throughput of voice traffic (n =5) (see online version for colours)



4.2.2 Impact on jitter

We finally investigated the jitter to confirm the quality and communication stability of voice traffic. In iPerf3, jitter is defined as the variance between the one-way delay of two consecutive packets (Henning et al., 1996). Figure 12 shows the change in the jitter variation in time series in OFDM and OFDMA where the number of STA was fixed to 5 and the bonding width was set to 20 MHz. As shown, the jitter obtained for OFDMA remains small, even if it takes 0.176 msec at a maximum. On the other hand, the jitter obtained for OFDM sharply increases up to 8.23 msec (maximum) for a short duration. Thus, we calculated the Mean Opinion Score (MOS) derived from equation (3) (Therdpong et al., 2021) based on the maximum value of the jitter we obtained in our experiments.

$$\text{MOS} = 2.482 * e^{-10.453 * jitter} + 1.141 \quad (3)$$

The MOS is one of the most popular measurements for QoE. As a result, we obtained that the MOS for OFDMA is 3.618 and that for OFDM is 3.418. From Table 5, which shows the relationship between MOS and QoE, we can see that the QoE for OFDMA is 'Some users dissatisfied (Fair)', whereas that for OFDM becomes 'Many users dissatisfied (Poor)'. In other words, OFDMA can improve QoE more than OFDM because OFDMA can provide stable communication due to ensure obtaining RUs for voice traffic. We thus conclude that OFDMA is suitable for transmitting traffic that has a small packet size and at low rate to multiple users simultaneously.

Figure 12 Variation of jitter at a time in OFDM and OFDMA (n =5) (see online version for colours)

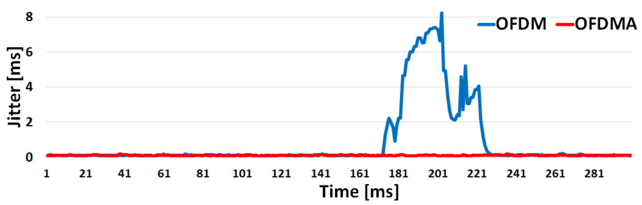


Table 5 Relationship between MOS (QoE) score and user satisfaction

MOS (QoE)	*User satisfaction*	*Meaning*
4.34–5.0	Very satisfied	Excellent
4.03–4.33	Satisfied	Good
3.60–4.02	Some users dissatisfied	Fair
3.10–3.59	Many users dissatisfied	Poor
2.58–3.09	Nearly all users dissatisfied	Bad
1–2.58	Unacceptable	Very bad

5 Discussion

Through our experimental results, we quantitatively confirmed that the number of STAs, traffic characteristics and bonding width impact on the average throughput for OFDM and OFDMA. Suitable environments, in terms of the number of STAs and the channel bonding width, for OFDMA are summarised in Table 6. For rich content (e.g., movies, music), OFDM is better than OFDMA because it provides a wider bandwidth for each STA, when the number of STAs exceeds 4 and the bonding width is lower than 40 MHz. On the other hand, OFDMA is better than OFDM when the number of STAs does not exceed 4 or the bonding width is 80 MHz. When the bandwidth of the RU assigned to each STA is relatively high, the average throughput is improved by OFDMA. However, since the wider channel bonding width for OFDMA increases frame retransmission, channel bonding should be disabled for OFDMA.

Table 6 Suitable environments for OFDMA

		Bonding width		
		20MHz	*40MHz*	*80MHz*
Number of STA	1	×	×	×
	2	○	○	○
	3	○	○	○
	4	×	×	×
	5	×	×	○

For voice data, the average throughput is almost the same for OFDM and OFDMA, but jitter is more stable for OFDMA. Therefore, we can remark that OFDMA is more suitable for the simultaneous transmission of lightweight traffic. Based on the above discussions, the QoE can be increased if an AP adaptively selects OFDM or OFDMA according to the number of STAs, bonding width and traffic characteristics.

In our experiments, we use only UDP traffic because we preliminarily investigated the throughput performance of OFDM and OFDMA; however, TCP traffic should be investigated because some network applications use TCP as a transport layer protocol. As a result of our experiments, we clarified that frame retransmission and throughput degradation could occur with the use of OFDMA and channel bonding as the number of STAs increases. Frame retransmission, end-to-end delay and the bandwidth of each flow could impact the TCP performance; we could expect that OFDM and OFDMA might impact the throughput of TCP traffic; thus, we need further investigation to clarify the influence of OFDM and OFDMA on TCP performance.

6 Conclusions

In this study, we evaluated the applicability of OFDM and OFDMA through experiments using a commercially available 11ax AP. The experimental results quantitatively confirm that the number of STAs, traffic characteristics and bonding width impact on the average throughput for rich contents and QoE for voice data of OFDM and OFDMA. Therefore, the adaptive selection of OFDM or OFDMA in 11ax depending on the number of STAs and traffic characteristics should improve the throughput and QoE.

In future research, we will investigate the impact of OFDM and OFDMA on the throughput of TCP applications. Furthermore, we will propose and evaluate an adaptive selection method for OFDM or OFDMA according to the number of STAs, channel bonding width and traffic characteristics.

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