Throughput-maximizing OFDMA Scheduler for IEEE 802.11ax Networks

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***Abstract*—In this paper, we develop a novel throughput-maximizing OFDMA scheduler for the multi-user MAC framework for the IEEE 802.11ax networks. The scheduler works both in the downlink and uplink directions and assigns resource units to stations using a linear programming technique considering load of each client, possible resource unit configurations, modulation-coding scheme of each client, and ageing factor of each client's load. The performance of the proposed scheduler has been evaluated using the NS3 simulator and compared against the legacy MAC layer mechanism of IEEE 802.11 protocol (i.e., DCF/EDCA). Simulation results show that our proposed throughput-maximizing scheduler increases the total throughput in the network as well as decrease the average end-to-end delay regardless of the number of stations connected to the access point by prioritizing the traffic of clients connected via high modulation-coding schemes.**

***Index Terms*—WiFi, 802.11ax, OFDMA, scheduler, throughput**

I. Introduction

Over the last decade based on the ever-increasing demand for higher throughput in WiFi networks, the two core IEEE 802.11 standards: IEEE 802.11n and IEEE 802.11ac, focused mainly on throughput-increasing mechanisms and pushed the network throughput over the gigabit barrier. This increase further pushed up the pervasiveness of WiFi and resulted in many overlapping dense WiFi networks with higher numbers of user devices (i.e., stations (STA)) per network. With time, in such dense environments, the key bottleneck metric became the throughput density instead of aggregate throughput [1].

In order to address this new requirement the next generation of the IEEE 802.11 standard family, namely the IEEE 802.11ax, is geared towards increasing the efficiency of the network(s) in a given area [2]. In this direction, IEEE 802.11ax (or in other words WiFi6[1]) offers several key medium access control (MAC) layer mechanisms such as orthogonal frequency division multiple access (OFDMA) scheduled access via the multi-user MAC framework (MU-MAC), MU-MIMO, overlapping basic service set packet detect (OBSS-PD), and target wake timer (TWT) [3]. Among these new features, OFDMA enables the division of the channel into smaller parts called resource units (RUs) each corresponding to a set of subcarriers of the available channel bandwidth. Then, using the MU-MAC framework, the access point (AP) is able to schedule the access of STAs to these RUs at the same time over the same WiFi channel. This mechanism is fundamentally different from the classical random access method of WiFi by practically giving the control of the medium access to the AP. Such a controlled access is expected to mitigate the impact of common performance-limiting cases such as the bad apple scenario, where a single STA having a low modulation and coding scheme (MCS) level significantly diminishes the overall performance of the whole WiFi network.

Obviously, the performance of this MU-MAC framework hinges on the AP knowing the queue information regarding all its associated STAs. Although this information is readily available for the downlink (DL) traffic, in the current WiFi standard, the AP does not have any mechanism to gather this information for the uplink (UL) traffic. To this end, IEEE 802.11ax also introduces a buffer status report (BSR) mechanism via which the AP is able to gather this information from the STAs. In case the AP does not know this information, it also has the option of allocating some (or all) of these RUs as random access RUs, which is called the Uplink OFDMA Random Access (UORA) mechanism.

Although the MU-MAC framework has been explained in detail in the upcoming IEEE 802.11ax standard, the scheduling mechanism on the RU assignment is intentionally left unstandardized. In [4], Wang et al. propose a scheduler that aims to maximize the user sum rate by defining an optimization problem for the RU allocation. The problem is simplified by allowing multiple STAs to be allocated to a given RU, which is not compliant with the MU-MAC framework of IEEE 802.11ax. The study offers multiple solutions on reducing the time complexity of solving the problem and note that in case only a single STA should be allocated to a given RU, this problem can only be solved by an exhaustive search. Bankov et al. propose an MU-MAC framework compliant scheduler for UL traffic that works in two levels, one for selecting the appropriate RU configuration and MCS level to be used, another for assigning RUs to STAs by using a Hungarian algorithm [5]. They offer three variants of the same scheduler

[1]Name of the Wi-Fi Alliance certification program for IEEE 802.11ax standard compliance.

having different goals: maximizing the rate, being proportionally fair to STAs, and minimizing the remaining processing time. Finally, Wu et al. propose a throughput maximizing scheduler for UL traffic (HiTRAS) that also considers the overhead of the BSR mechanism [6].

Another group of works focuses on analyzing the performance of the UORA mechanism based on the well-known Bianchi model [7]. Considering the MU-MAC framework, these works focus on choosing the optimal number of RUs allocated for UORA among the total number of available RUs as well as selecting ideal UORA contention window values [8]–[10].

All these works on developing a scheduler for the MU-MAC framework focus on the UL traffic only and more importantly the behavior of the scheduler is stateless in terms of time. Therefore, the same RU allocation schedule shall be repeated in each time slot, which leads to the starvation of some STAs. In this work, we develop a throughput maximizing OFDMA scheduler for the MU-MAC framework of IEEE 802.11ax, considering both the UL and the DL traffic. The proposed scheduler is designed to work repeatedly at the start of each OFDMA opportunity by utilizing an aging mechanism to provide some level of fairness and avoid starvation of STAs whose traffics are low compared to others. We develop a detailed simulator by extending the WiFi module of the NS3 simulator to evaluate the performance of the proposed scheduler. The main contributions of our paper are as follows:

- First, we develop a throughput maximizing scheduler for the MU-MAC framework of the IEEE 802.11ax standard considering channel bandwidth, STA traffic queues, and STA MCS levels.
- Next, we present an aging mechanism to be used within the scheduler so that in each subsequent run of the optimization problem, the scheduler acts by considering the allocations to each STA in the previous schedules.
- Finally, we evaluate the performance of the proposed scheduler in both UL and DL directions as well as UDP and TCP traffics by simulating its behavior over the NS3 simulator.

II. MU-MAC Framework of IEEE 802.11ax and OFDMA Access

At its core, the MU-MAC framework of IEEE 802.11ax is responsible for allocating channel resources (i.e., frequency and time slots) to the AP and connected STAs while also being compliant to the legacy random channel access mechanism of IEEE 802.11. In the frequency dimension, the channel is divided into so-called RUs, each of which can be allocated to different devices. In the time dimension similar to legacy IEEE 802.11, time is divided into fixed slots called transmission opportunities (TXOP). At the MAC layer, the MU-MAC framework of IEEE 802.11ax introduces four different mechanisms for different use-cases: DL-MU access, UL-MU access, Cascading UL & DL-MU access, and UORA. While the first three mechanisms are scheduled access mechanisms where the whole channel access is managed by the AP, in the fourth mechanism, the RUs are allocated to devices with a DCF/EDCA-like random access mechanism. Since we focus on the core scheduled access mechanism of IEEE 802.11ax, both the cascading UL DL-MU access and UORA mechanisms are out of the scope of this work.

A. Subcarrier Division in IEEE 802.11ax: Resource Units

Traditionally the OFDM PHY layer of IEEE 802.11 divides the wireless channel into 312.5 kHz subcarriers (or tones). In order to allocate the subcarriers into devices in a more efficient manner and increase the spectral efficiency, IEEE 802.11ax utilizes four times smaller subcarriers, each with a bandwidth of 78.125 kHz. These subcarriers are bundled together to form RUs, each of which can be allocated to devices in an atomic manner. The standard sets the sizes of all possible RUs as well as how to divide a channel with a certain bandwidth into a set of RUs. Seven different RU sizes are defined in the standard as 26-tone, 52-tone, 106-tone, 242-tone, 484-tone, 996-tone, and 2x996-tone. Considering these RU sizes, a 20 MHz channel can be divided in a variety of ways ranging between a single 242-tone RU to nine 26-tone RUs as depicted in the RU configuration tree (Figure 1). Note that, each node of the tree can be divided into smaller parts independently. An RU configuration, denoted by RUC, consists of selected nodes of the tree, but if a node is selected, all of its descendants cannot be selected in the same RUC (e.g., for a channel bandwidth of 20 MHz, (106, 26, 106) or (106, 26, 52, 52) are possible RUCs).

An important issue with this different RUCs is the fact that the more the number of RUs in an allocation, the smaller the total number of data subcarriers that can be used. Therefore, in addition to deciding on the RU size allocated to each device, the selected RUC is also critical for the performance of the network.

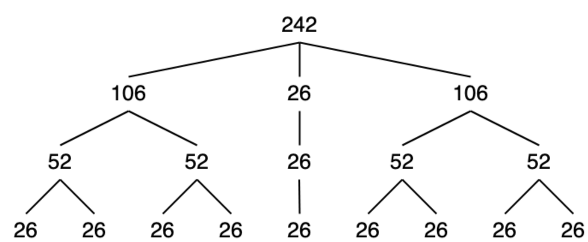


Fig. 1: RU configuration tree for 20 MHz

B. Downlink Multi-user Access (DL-MU access)

The DL-MU access is used when the AP is sending frames to its associated STAs using the OFDMA mechanism (Figure 2). First of all, the AP contends with its STAs to get access to the channel using the classical DCF/EDCA mechanism. After winning the contention, the AP sends the data frame with a legacy PHY header as well as an IEEE 802.11ax specific header named HE-SIG-B. While the legacy PHY header is used by all STAs (legacy or not) to set their network allocation vectors (NAVs) accordingly, it is the HE-SIG-B header where the DL OFDMA schedule resides. In this header, the AP declares the RUC to be used in the subsequent transmission as well as which RU is allocated for the communication with which STA. Upon the reception of this HE-SIG-B header, the STAs learn which RU to listen to, if there is a transmission destined for them, or not to listen to any RUs at all.

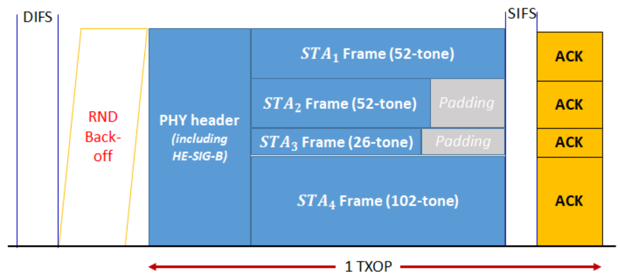


Fig. 2: DL-MU access example for 20 MHz channel bandwidth with 52, 52, 26, and 106 RUC

Subsequently, the AP sends its data frames to the destined STAs in the allocated RUs. This communication lasts for up to the duration of a TXOP, which is predetermined as in legacy IEEE 802.11 behavior. Lastly, the STAs wait for a SIFS duration at the end of the data transmission and participate in the MU-ACK action based on their ACK policy. In the MU-ACK action, each STA that is required to send an ACK frame sends the ACK frame through the RU allocated for its ACK frame transmission in the UL direction. This second RU allocation may or may not be the same allocation of the actual DL direction of the data frame transmission.

C. Uplink Multi-user Access (UL-MU access)

In the reverse direction, the STAs use the UL-MU access to send their frames to the AP (Figure 3). Although this is an UL transmission, similar to DL-MU access, it is again managed by the AP via deciding on the RUC as well as RU-to-STA allocation. After this allocation, the AP contends with its STAs to get access to the channel as usual. Upon winning the contention, the AP sends a special control frame, called trigger frame, that is destined to all of its associated STAs, which describes the RU configuration to be used as well as the RU to STA allocation. This trigger frame also defines the MCS level that will be used by each STA in this allocation. Afterwards, STAs wait for a SIFS duration and start sending their frames to the AP according to the resource allocation information given in the most recent trigger frame. Again similar to DL-MU access, this transmission lasts up to a TXOP duration. Finally, the AP waits for a SIFS duration and according to its own ACK policy, sends an ACK frame to each STA that has successfully sent data frames to itself using the same RUC and RU-to-STA allocation.

Although conceptually very similar to the DL-MU access, a key difference in the UL-MU access is the fact that, before the mechanism starts working, the AP should know the amount of UL frames in each of its associated STAs' queues to allocate

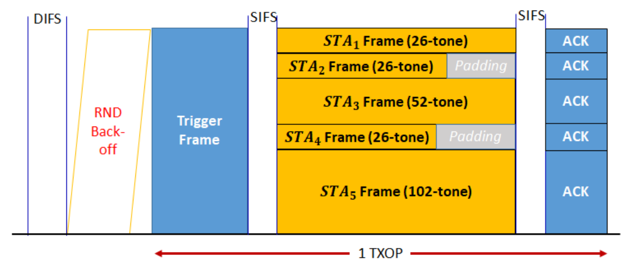


Fig. 3: UL-MU access example for 20 MHz channel bandwidth with 26, 26, 52, 26, and 106 RUC

the resources accordingly. IEEE 802.11ax standard suggests two alternatives in relaying this queue length information to the AP: explicit BSR and implicit BSR. In the explicit BSR, upon the request of the AP via a buffer status report poll (BSRP) trigger frame, each STA sends a BSR frame containing the queue length information of each of its queues (AC_BE, AC_BK, AC_VI, and AC_VO). In the implicit BSR, the same information is sent to the AP but it is piggybacked to a previous UL data or ACK frame. Both alternatives can also be sent in a periodic fashion to the AP without an explicit BSRP frame sent by the AP.

One criticism of the UL-MU access mechanism is the fact that after the UL-MU access is finished, all the STAs -whether given RU allocations in the previous UL-MU access or not and whether they have the IEEE 802.11ax support or not- have the same chance of winning the contention. This may lead to pretty unfair UL performances among the STAs of the same AP. In order to remedy this potential issue, IEEE 802.11ax standard utilizes a second set of EDCA parameters in addition to the classical EDCA parameter set [11]. This second set of EDCA parameters, which are envisioned to have higher values than the classical EDCA parameter set, is to be used only by STAs which have been given RU allocation in the previous UL-MU access opportunity. Therefore, probabilistically these STAs will have a much lower chance of winning the contention right after the UL-MU access opportunity. After a certain period from the UL-MU access opportunity, these STAs revert to using the classical EDCA parameter set. Note that, the AP can set the second EDCA parameter values to zero, which means these STAs cannot even contend for channel access for a certain period. By utilizing this flexibility, in a WLAN with all 802.11ax capable STAs, the AP can guarantee that it can win the contention right after the UL-MU access opportunity, greatly increasing the control of the AP over the medium access.

D. Multi-user Multiple Input Multiple Output (MU-MIMO)

In addition to allocating channel resources to devices, IEEE 802.11ax also includes utilizing the MU-MIMO scheme where a particular STA can communicate (or be communicated with) at a RU within a TXOP on an allocated spatial stream both in the DL and UL directions. The MU-MIMO capability is actually not new to the IEEE 802.11 protocol family. The previous major WiFi standard, IEEE 802.11ac, also had MU-MIMO capability in the DL direction. However, this feature has been relegated to the wave 2 products and has only been implemented by some products. In IEEE 802.11ax, coupled with the OFDMA access technique, MU-MIMO is expected to increase the efficiency of the network where the STAs are considerably away from each other and individual spatial streams can be allocated to them at the same RU at the same time while keeping the interlink interference between the different spatial streams within an acceptable limit (Figure 4).

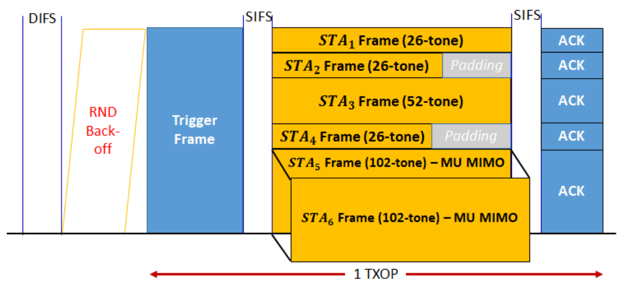


Fig. 4: UL-MU access with MU-MIMO example for 20 MHz channel bandwidth with 26, 26, 52, 26, and 106 RUC, where the 106 RU is allocated to two STAs on different spatial streams

E. Scheduling mechanism

Similar to any resource allocation framework, the MU-MAC framework of the IEEE 802.11ax standard also requires a resource allocation/scheduling mechanism in order to utilize the benefits of this framework to its intended efficiency. Due to the possible RUCs that are available, the resource allocation in the IEEE 802.11ax OFDMA scheduling becomes a three-dimensional problem (i.e., allocation of RUC, allocation of RUs, allocation of the time slots), or a four-dimensional problem when MU-MIMO is also considered. Furthermore, at any given TXOP, the transmission can either be in the DL or UL direction. Therefore, based on the characteristics of the network traffic, the AP should also decide on the direction of the MU access at any given time. Lastly, considering the fact that legacy STAs will not be able to utilize the OFDMA access, the AP should also allocate some TXOPs for classical random access in which legacy devices can send their frames as well as the AP sending them frames.

III. Optimization Problem

Considering this OFDMA scheduling problem, we have developed an OFDMA scheduler, which focuses on maximizing the throughput of the WiFi network while avoiding any starvation issues. We formulate the problem as an optimization problem that runs at the start of each TXOP and calculates the ideal resource allocation considering the queue lengths and link qualities of each STA, in both DL and UL directions. Note that the proposed scheduler works either in DL mode or UL mode. Although, the dynamic selection of the transmission direction based on the DL and UL traffic rates is an important issue and constitutes a problem on its own, here we focus on single direction traffics. Therefore, dynamic transmission direction selection is not covered in this paper and left out-of-scope.

In the optimization problem, each parameter and variable is defined over the following sets: 1) $\mathbf{S}$, the set of STAs connected to the AP in the network; 2) $\mathbf{R_{bw}}$, the set of available RUCs given the channel bandwidth (an example of this set considering 20 MHz channel bandwidth is as given in (2)); 3) $\mathbf{I_{bw}}$, the index set for RUCs in $\mathbf{R_{bw}}$; 4) $\mathbf{I}_{\mathrm{RUC}_\mathbf{k}}$, the index set for RUs in RUC_k. $\varphi(k, j)$ gives the unique index of each possible RU within each possible RUC given a channel bandwidth. It is a map from the index of a RUC (k, $\forall k \in \mathbf{I_{bw}}$) and the index of an RU within that RUC (j, $\forall j \in \mathbf{I}_{\mathrm{RUC}_\mathbf{k}}$) to a set of integer numbers between 1 and m_{max} for the given channel bandwidth, following the function in Eq.1. Please note that $\varphi^{-1}(m) = (k, j)$ is its inverse function.

Three parameters are defined over the set $\mathbf{S}$: the modulation and coding rate of each STA (MCS_i, $\forall i \in \mathbf{S}$), queue length of each STA (L_i, $\forall i \in \mathbf{S}$), and the aging factor of each STA (A_i, $\forall i \in \mathbf{S}$). $RUV_{j,k}$ is defined as the value (i.e., number of subcarriers) of the j^{th} RU of RUC_k. Finally, $Tr_{MCS_i,RUV_{j,k}}$ is defined as the data transmission rate of the i^{th} STA given its MCS level, MCS_i, and j^{th} RU of RUC_k. An example of these transmission rates considering 20 MHz channel bandwidth, one spatial stream, and 3.2 µs guard interval are as given in (Table I).

$$\varphi(k, j) = j + \sum_{l=1}^{k-1} |\mathbf{I}_{\mathrm{RUC}_l}| \tag{1}$$

TABLE I: Data transmission rates considering 20 MHz channel bandwidth, one spatial stream, and 3.2 µs guard interval

MCS_i	MCS Level	$Tr_{MCS_i,RUV_{j,k}}$ (in Mbits)			
		26	52	106	242
0	BPSK, 1/2 - DCM0	0.8	1.5	3.2	7.3
1	QPSK, 1/2 - DCM0	1.5	3.0	6.4	14.6
2	QPSK, 3/4	2.3	4.5	9.6	21.9
3	16-QAM, 1/2 - DCM0	3.0	6.0	12.8	29.3
4	16-QAM, 3/4 - DCM0	4.5	9.0	19.1	43.9
5	64-QAM, 2/3	6.0	12.0	25.5	58.5
6	64-QAM, 3/4	6.8	13.5	28.7	65.8
7	64-QAM, 5/6	7.5	15.0	31.9	73.1
8	256-QAM, 3/4	9.0	18.0	38.3	87.8
9	256-QAM, 5/6	10.0	20.0	42.5	97.5
10	1024-QAM, 3/4	11.3	22.5	47.8	109.7
11	1024-QAM, 5/6	12.5	25.0	53.1	121.9

There are three variables in the optimization problem: T_k, binary variables whose value is 1 if RUC_k is selected, and 0 otherwise; $X_{i,j,k}$, binary variables whose value is 1 if STA i is allocated the j^{th} RU of RUC_k, 0 otherwise; lastly $Y_{i,j,k}$, refers to the allocated transmission rate of the i^{th} STA at the j^{th} RU of RUC_k in bits.

$$
\begin{aligned}
\mathbf{R_{bw}} &= \{\mathrm{RUC}_1, \mathrm{RUC}_2, ..., \mathrm{RUC}_{13}\} \\
&= \{(26, 26, 26, 26, 26, 26, 26, 26, 26), \\
&\quad (52, 26, 26, 26, 26, 26, 26, 26), \\
&\quad (52, 52, 26, 26, 26, 26, 26), \\
&\quad (52, 52, 52, 26, 26, 26), \\
&\quad (52, 52, 52, 52, 26), \\
&\quad (106, 26, 26, 26, 26, 26), \\
&\quad (106, 52, 26, 26, 26), \\
&\quad (106, 52, 52, 26), \\
&\quad (106, 106, 26), \\
&\quad (242)\} \qquad (2)
\end{aligned}
$$

$$
\underset{X_{i,j,k}}{\text{maximize}} \sum_{i \in \mathbf{S}} \sum_{k=1}^{|\mathbf{R_{bw}}|} \sum_{j \in \mathbf{I}_{\mathrm{RUC}_\mathbf{k}}} Y_{i,j,k} AF^{A_i} \qquad (3)
$$

subject to

$$
\sum_m X_{i,\varphi^{-1}(m)} \leq 1 \qquad \forall i \in \mathbf{S} \qquad (4)
$$

$$
\sum_i X_{i,\varphi^{-1}(m)} \leq 1 \qquad \forall m = 1..m_{max} \qquad (5)
$$

$$
\sum_i \sum_j X_{i,j,k} \leq |\mathrm{RUC}_\mathbf{k}| \, T_k \qquad \forall k \in \mathbf{I_{bw}} \qquad (6)
$$

$$
\sum_k T_k = 1 \qquad (7)
$$

$$
Y_{i,j,k} \leq L_i X_{i,j,k} \qquad \forall i \in \mathbf{S}, \ \forall j \in \mathrm{RUC}_\mathbf{k}, \ \forall k \in \mathbf{I_{bw}} \qquad (8)
$$

$$
Y_{i,j,k} \leq \sum_j \sum_k Tr_{MCS_i, RUV_{j,k}} d_{TXOP} \qquad \forall i \in \mathbf{S} \qquad (9)
$$

Considering these parameters and variables, the goal can be reached by giving as much allocated transmission rate as possible to all STAs with an aging mechanism (i.e. a fixed Base Aging Factor (AF), and an aging value, A_i, for each STA) while adhering to the STA-to-RU, RU-to-STA, RU limit, RU configuration, queue length, and MCS level constraints. The first four constraints reflect the RU allocation rules and limitations of the IEEE 802.11ax OFDMA scheduling. The STA-to-RU constraint (Eq. 4) states that in an OFDMA schedule, a given STA can only be allocated a single RU. In the other direction, the RU-to-STA constraint (Eq. 5) states that a given RU can only be allocated to a single STA. Given an RU configuration, the number of RUs allocated to different STAs cannot exceed the RU count of the selected RUC, or in other words cannot exceed the cardinality of the selected item of $\mathbf{R_{bw}}$ (Eq. 6). Lastly, only a single RUC can be selected at any given time (Eq. 7).

The last two constraints deal with limitations over the allocated transmission rate. Queue length constraint (Eq. 8) states that each STA cannot be allocated transmission rate more than its queue length, whether it is allocated this RU or not. The MCS level constraint on the other hand (Eq. 9) states that the allocated transmission rate cannot exceed the transmission rate of the RU given the MCS level of the STA for a specific WiFi TXOP duration (d_{TXOP}), i.e., even if a STA has many frames at its queue, if the link between itself and the AP has very low RSSI values, it will have much lower maximum allocated transmission rate than STAs whose link to the AP is higher.

As explained in the previous section, the IEEE 802.11ax standard dictates that in terms of time, the OFDMA resource allocation is active for only the next TXOP duration. Therefore, in a real implementation, this scheduler should work in rounds, once at the start of each TXOP.

Since the optimization problem is trying to maximize the total amount of data that has been transmitted, the STAs whose MCS levels or $L_i[t]$ values are low will be at a disadvantage and will be given RUs last, if available. Although this behavior increases the airtime efficiency of the network, if left unchecked, it leads to starvation of the traffics of STAs with low MCS values. In order to avoid this behavior, at the end of each optimization round, the aging values of each STA, A_i, are recalculated based on the previous $Y_{i,j,k}$ values and current L_i values. For a given STA i, if there are unsent frames in the queue of the STA (i.e., $L_i[t] > 0$),

$$
A_i[t] = \begin{cases} \min(1, A_i[t-1] - \delta), & Y_{i,j,k}[t-1] > 0 \\ \max(MI, A_i[t-1] + \delta), & Y_{i,j,k}[t-1] = 0 \end{cases} \qquad (10)
$$

where MI is the maximum aging value for a given STA. On the other hand, if there are no leftover frames in the queue (i.e., $L_i[t] = 0$),

$$
A_i[t] = A_{initial}. \qquad (11)
$$

Note that, this aging mechanism can be disabled by setting AF as 1.

IV. Performance evaluation

The performance of the proposed maximum throughput OFDMA scheduler is evaluated via simulations using the NS3 simulator coupled with Google OR-tools software suite for solving the optimization problem [12], [13]. As a reference point, we also evaluate the performance of the legacy random access performance of WiFi (i.e., DCF/EDCA) under the same parameters. NS3 IEEE 802.11 codebase rigorously implements the inner workings of MAC layer mechanisms of IEEE 802.11. We have extended this code base by adding the OFDMA DL-MU and UL-MU access mechanisms as explained in Section 2 as well as the proposed maximum throughput scheduler as explained in Section 3.

The simulation topology consists of a single AP operating at a 20 MHz 2.4 GHz IEEE 802.11 channel over a single spatial stream and multiple STAs, all of which have been associated with this AP. All STAs are in range of each other, so there are no hidden nodes. As for the physical layer, free space path loss propagation with NIST WiFi channel error rate model has been used without any external interference sources [14]. We group the STAs in two categories based on their link quality to the AP: STAs with high link quality (i.e., MCS 11) and STAs with low link quality (i.e., MCS 3). These MCS levels are constant and do not change throughout the simulation [2]. The RTS/CTS mechanism has been turned on with block ACK policy. We utilize both TCP and UDP traffic in both DL and UL directions in four different scenarios. Simulation parameters are as given in Table II.

TABLE II: Simulation parameters

Parameter	Value
Channel frequency	2.4 GHz
Channel bandwidth	20 MHz
Guard interval	3.2 µs
# of spatial streams	1
Traffic rate/STA (MCS_3 STA)	10 Mbps
Traffic rate/STA (MCS_{11} STA)	25 Mbps
Traffic transport layer protocol	TCP, UDP
Simulation duration	10 s
Simulation replication count	10
WiFi ACK policy	Block ACK
RTS/CTS enabled?	Yes
AP buffer size (DL only)	500 frame/STA
STA buffer size (UL only)	500 frame
# of STA	$\{5, 10, 15, 20, 25\}$
MCS level of STA	$\{3, 11\}$
d_{TXOP}	4.6 ms
$A_{initial}$	1.15
AF	1.15
δ	0.4

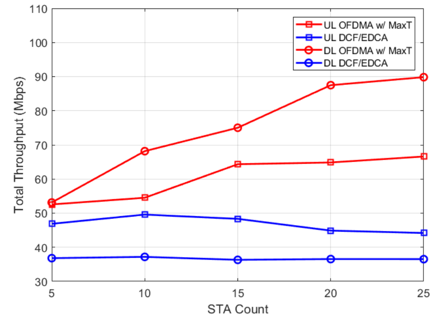


Fig. 5: Total throughput under TCP traffic considering the proposed OFDMA MaxT scheduler and DCF/EDCA

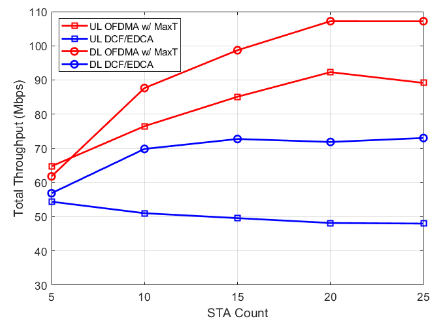


Fig. 6: Total throughput under UDP traffic considering the proposed OFDMA MaxT scheduler and DCF/EDCA

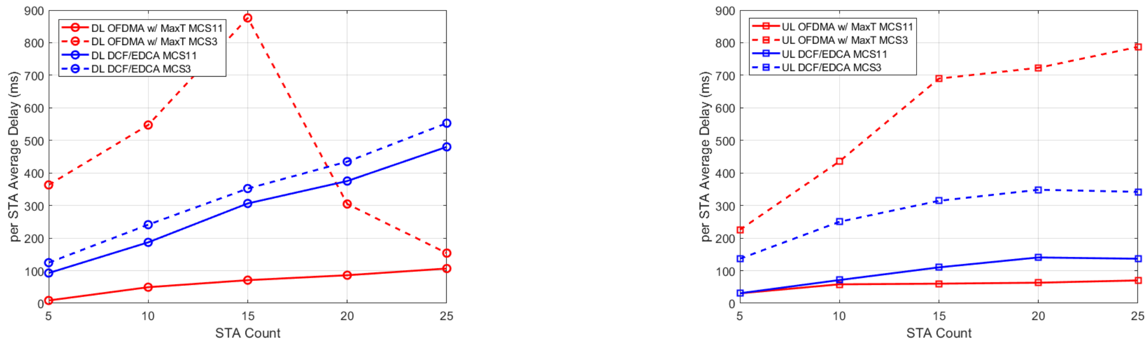
The simulation is conducted for 10 seconds over rounds of TXOP duration, d_{TXOP}, which has been selected as $4.6\,\text{ms}$. The optimization function works at the start of each TXOP, after which the transmission is conducted and finally the aging mechanism works as explained in Eq. 10. In the case where the $A_i[t]$ value for a given STA i reaches the maximum age value, MI, for the aging mechanism to continue working as intended we have halved $A_i[t]$ values for all STAs in the network.

As seen in both Fig. 5, and Fig. 6, in all scenarios the OFDMA performance with our proposed scheduler outperform the DCF/EDCA mechanism. Also in all scenarios, the discrepancy between OFDMA and DCF/EDCA becomes much more prevalent as the number of STAs increases. In most scenarios the total throughput of the DCF/EDCA mechanism only changes slightly as the number of STAs increases since the RTS/CTS, TXOP, and frame aggregation mechanisms significantly reduce the negative impact of the collisions.

Under the TCP traffic due to the transport layer flow control algorithms, DCF/EDCA mechanism behaves equally to all STAs (Fig. 5). Consequently in the DCF/EDCA mechanism, all STAs yield similar throughput values regardless of their MCS levels (hence the bad apple problem). In the case of OFDMA with our proposed scheduler, the STAs with high MCS levels are being prioritized in favor of the STAs with low MCS levels. This is due to the fact that STAs with high MCS levels utilize the air medium much more efficiently in terms of throughput. As a result, the total throughput of OFDMA with our proposed scheduler significantly (i.e., up to three times in 20 and 25 STA scenarios) increases especially in the DL scenario. Note that due to the transport layer ACK packets, TCP traffic is inherently an asymmetrical rate bidirectional traffic. Therefore, its performance greatly depends on the time allocated to ACK frames in the reverse direction. In our simulations we observed that by fine tuning this time allocated to ACK frames, the total throughput of the OFDMA with the proposed scheduler in the UL scenario can increased even further. Under UDP traffic, the UL scenario yields similar results with TCP UL scenario albeit the fact that the benefit of OFDMA is higher (Fig. 6). In the DL scenario, both the DCF/EDCA and OFDMA with our proposed scheduler yields higher throughput compared to TCP scenario. But even here the proposed scheduler yields around 50% gain over the DCF/EDCA mechanism.

While increasing the total network throughput, as shown in Fig. 7, the proposed scheduler also significantly decreases the WiFi delay of the STAs with high MCS values while increasing it for the STAs with low MCS values. Therefore, the prioritization introduced by the scheduler is also shown to affect the WiFi delay of the network traffic. Note that after a consistent increase until 15 STA scenario, the delay

[2] It can be argued that OFDMA scheduler can be designed coupled with the selection of the MCS level, in actual WiFi implementations the MCS selection is conducted via separate algorithms such as Minstrel. Therefore, the MCS selection algorithm is left out-of-scope of the paper [15].



(a) Average per STA delay with TCP traffic in DL direction

(b) Average per STA delay with TCP traffic in UL direction

Fig. 7: Average per STA delay with TCP traffic considering the proposed OFDMA MaxT scheduler and DCF/EDCA

of STAs with low MCS levels drops in 20, 25 STA scenarios. Although this low delay values seem counter-intuitive at first glance, after considering the extreme low data rates of MCS3 STAs in these scenarios (i.e., 0.05 Mbps in 20 STA and 0.001 Mbps in 25 STA) it becomes clear that this is due to the TCP flow control mechanism. In these scenarios, since the scheduled does not assign many RUs to these STAs, the TCP flow control mechanism significantly decreases the traffic rate of each one of these STAs, resulting in a very slow traffic, hence the reduced average delay values.

V. Conclusion

The upcoming WiFi standard, IEEE 802.11ax, offers many new mechanisms one of which is the OFDMA-based MU-MAC framework. In this paper, we have developed a scheduler for this MU-MAC framework that aims to maximize the overall network throughput by considering the channel bandwidth, MCS levels of STAs, and traffic loads of STAs. Based on the performance evaluations conducted over the detailed IEEE 802.11ax-compliant NS3 WiFi codebase we had developed, our proposed scheduler not only increases the overall network throughput but also considerably decreases the last-mile delay of traffics with high MCS levels. We plan to extend our work by adding a hybrid scheduler that has different utility functions based on the quality-of-service levels of each traffic. Also, by utilizing the cascading UL/DL MU access we plan to extend our work to cover transmissions where the transmission direction dynamically changes. Finally, we plan to develop a faster, real-life implementation-friendly version of the scheduler considering the time complexity aspect of the optimization problem part of the scheduler.

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