BIDIRECTIONAL SCHEDULING FOR Wi-Fi 6 (IEEE 802.11ax) NETWORKS

by

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ABSTRACT

BIDIRECTIONAL SCHEDULING FOR Wi-Fi 6 (IEEE 802.11ax) NETWORKS

In recent years, Wi-Fi, along with Broadband Wireless, has been at the center of wireless communication. End-users owning laptops, tablets, and mobile phones enjoyed connected mobility. This massive adaptation brought more bandwidth demands. Consecutive IEEE 802.11 standard amendments were developed to overcome these requirements. Since hitting the gigabit barrier in IEEE 802.11ac, the main focus has shifted to increasing efficiency and reducing power consumption. Motivated by this, the latest amendment, IEEE 802.11ax, aims to minimize channel contention among network devices due to the very nature of random access, especially in dense areas. In this respect, IEEE 802.11ax, or Wi-Fi 6, brings several improvements focusing on these demands for better user experience and environment protection. In this regard, it introduces Target Wake Time (TWT) to make certain nodes sleep a definite amount of time to preserve power, Overlapping Basic Service Set Preamble Detection (OBSS/PD) to exploit co-existence better, and finally, Orthogonal Frequency Division Multiple Access (OFDMA) based scheduled access to abandon previously used random access mechanisms by replacing it with scheduled access that allows an Access Point (AP) to schedule and manage traffic by making use of resource level parallelism and multiple spatial streams.

This thesis investigates proper scheduling mechanisms and develops novel scheduler that work downlink and uplink directions. Our scheduler ensures maximum throughput delay. We tested our scheduler on state-of-the-art NS-3 network simulator and doubled the performance, leading to better power saving and greener Wi-Fi.

ÖZET

IEEE 802.11ax (Wi-Fi 6) İÇİN ÇİFT YÖNLÜ ZAMANLAMA

Son yıllarda geniş bant kablosuzla birlikte Wi-Fi, kablosuz iletişimin merkezinde oldu. Mobil bağlantılar dizüstü bilgisayar, tablet ve cep telefonu sahibi son kullanıcıların hayatını kolaylaştırdı. Mobil cihazlara olan bu uyum artan miktarlarda bant genişliği ihtiyacını beraberinde getirdi. Bu beklentiyi karşılamak amacıyla IEEE 802.11 standardına zaman içinde yenilikler getirildi. IEEE 802.11ac versiyonuyla beraber gigabit bariyerinin aşılmasıyla ana odak Wi-Fi'ın verimliliğini arttırma ve enerji tüketimini azaltma üzerine kaydı. Son Wi-Fi versiyonu olan IEEE 802.11ax, özellikle kalabalık bölgelerdeki plansız erişimden kaynaklanan sinyal çakışmalarını azaltmayı hedefliyor. Bu sayede kullanıcılara daha iyi bir deneyim ve çevre koruması sunmaya odaklanan Wi-Fi 6, bu amaçla belirli cihazların antenlerini belirlenmiş bir süre boyunca uyutmayı hedefleyen Hedef Uyandırma Zamanı (TWT), sinyallerin bir arada var olmasını daha iyi değerlendiren Kesişen Basit Servis Seti Başlangıç Tespiti (OBSS/PD) ve Dikey Frekans Bölümlemeli Çoklu Erişim (OFDMA) temelli planlı erişim ile plansız erişimin terki ve kaynak birimi düzeyinde paralelizm ve çoklu erişim yöntemleriyle erişim noktası cihazının (modem) ağ trafiğini yönetmesini sağlayan mekanizmaları getiriyor.

Çalışmamız uygun zamanlama mekanizmalarını araştırmakta ve geliştirdiğimiz yeni zamanlayıcıyı önermektedir. Zamanlayıcılarımız çift yönlü çalışmakta ve maksimum internet hızı sağlamaktadır. Gelişmiş NS-3 ağ simülatörü ile yapılan testlerde iki kata varan performans artışı sağlanmış ve bu sayede daha az enerji tüketen ve daha yeşil bir Wi-Fi elde edilmiştir.

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LIST OF SYMBOLS

A_i	Age value at time i
A_{initial}	Initial age value
$D_{i,j,k}$	Delay of STA i for allocated j^{th} RU of RUC_k
d_{TXOP}	TXOP duration
F	Aging factor
$\mathbf{I_{bw}}$	Index set for RUCs in $\mathbf{R_{bw}}$
$\mathbf{I}_{\text{RUC}_\mathbf{k}}$	Index set for RUs in RUC_k
L_i	Queue length of STA_i
L_i^*	Historic weighted average of queue lengths of STA_i
m	RU index
MCS_i	Modulation and coding index (MCS) of STA_i
$\mathbf{R_{bw}}$	Set of all possible RU distributions (RUCs) given the channel bandwidth **bw**
$\text{RUC}_\mathbf{k}$	k^{th} RUC distribution
$RUV_{j,k}$	Number of subcarriers in the j^{th} RU of RUC_k
$\mathbf{S}$	Set of connected STAs to an AP
T_k	Binary optimization variable having 1 if RUC_k is selected
$Tr_{MCS_i,\, RUV_{j,k}}$	Transmission rate of STA_i, given MCS index and RU
w	Window length
$X_{i,j,k}$	Binary optimization variable having 1 if STA i is allocated j^{th} RU of RUC_k
$Y_{i,j,k}$	Non-negative floats optimization variable of transmission rate allocated to STA i for j^{th} RU of RUC_k
δ	Aging delta
ε	Very small value, i.e., 10^{-7}
$\varphi\,(k, j)$	Function returning the unique index of an RU given RUC_k
$\varphi^{-1}\,(m)$	Function returning RU and RUC_k given the unique index m

LIST OF ACRONYMS/ABBREVIATIONS

A-MSDU	Aggregated MAC Service Data Unit
A-MPDU	Aggregated MAC Protocol Data Unit
ACK	Acknowledgement
AP	Access Point (Router, Modem)
bps	Bits per second
BPSK	Binary Phase Shift Keying
BSR	Buffer Status Report
BSRP	Buffer Status Report Poll
BSS	Basic Service Set
CTS	Clear To Send
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
DCF	Distributed Coordination Function
DCM	Dual Subcarrier Modulation
DIFS	Distributed Inter-Frame Space
DL	Downlink
DL-MU	Downlink Multi User
EDCA	Enhanced Distributed Channel Access
FCC	Federal Communications Commission
Gbps	Gigabits per second
GHz	Gigahertz (frequency)
HE-PPDU	High Efficiency Protocol Data Unit
HE-LTF	High Efficiency Long Training Field
HE-SIG-A	High Efficiency Signal A
HE-SIG-B	High Efficiency Signal B
HE-STF	High Efficiency Short Training Field
HSPA+	Evolved High Speed Packet Access
IEEE	Institute of Electrical and Electronics Engineers

IEEE 802.11	IEEE Wireless Local Area Network (WLAN) Computer Communication
IoT	Internet of Things
kHz	Kilohertz (frequency)
L-LTF	Legacy Long Training Field
L-SIG	Legacy Signal Field
L-STF	Legacy Short Training Field
LAN	Local Area Network
LTE	Long-Term Evolution
Mbps	Megabits per second
MAC	Medium Access Control
Mbit	Megabit
MCS	Modulation and Coding Scheme
MHz	Megahertz (frequency)
MIMO	Multiple Input Multiple Output
MU-MAC	Multi User Medium Access Control
MU-MIMO	Multi User Multiple Input Multiple Output
NAV	Network Allocation Vector
NS-3	Network Simulator 3 todo ref
OBSS/PD	Overlapping BSS Preamble Detection
ODFM	Orthogonal Frequency Division Multiplexing
ODFMA	Orthogonal Frequency Division Multiple Access
PC	Point Coordinator
PCAP	Packet Capture
PCF	Point Coordination Function
PE	Packet Extension
PHY	Physical Layer
PIFS	PCF Inter-Frame Space
PIMRC	International Symposium on Personal, Indoor and Mobile Radio Communications
PPDU	Protocol Data Unit

RA	Random Access
RL-SIG	Repeated Legacy Signal Field
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RU	Resource Unit
RTS	Request To Send
SA	Scheduled Access
SIFS	Short Inter-Frame Space
SNR	Signal Noise Ratio
SR	Spatial Reuse
STA	Station
TCP	Transfer Control Protocol
TF	Trigger Frame
TP	Throughput
TXOP	Transmission Opportunity
UDP	User Datagram Protocol
UL	Uplink
UL-MU	Uplink Multi User
UORA	Uplink OFDMA Random Access
Wi-Fi	Wireless Fidelity
WLAN	Wireless Local Area Network

1. INTRODUCTION

Wireless Local Area Network (WLAN) has played a key role in the mobile internet era. Since the massive speed increase with IEEE 802.11n standard and the adoption of mobile devices, including mobile phones, tablets, and laptops, Wi-Fi technology has been embraced at a vast scale. Until passing the gigabit barrier with IEEE 802.11ac, the central focus has been increasing the total throughput of a network. This increase in throughput further extended the use of Wi-Fi including public spaces [1], like metro stations [2], sport stadiums [2], conference halls [3], large hotels [4], educational institutions [5] [6] and more. The outcome of this major adoption has become a higher number of devices in these dense environments.

Since legacy Wi-Fi is based on random access mechanism and requires colliding devices to wait for an increasingly randomized amount of time, the performance of Wi-Fi in dense and crowded areas is sub-optimal. This sub-optimality also raises environmental concerns: Too many packet collisions mean increasing backoffs in at least several devices [7], leading to an accumulated increase in cumulative power consumption. Considering that most wireless devices have limited battery power, some advancements are needed in Wi-Fi or, as the name of the standards family, IEEE 802.11.

To meet the demands of the new mobile era, the new standard IEEE 802.11ax (or Wi-Fi 6) is determined to increase the efficiency of a selected area. To this end, several improvements over the existing medium access protocol are presented [8]. The first is Multi-User Multiple Input Multiple Output (MU-MIMO) scheduled access over the Orthogonal Frequency Division Multiple Access (OFDMA) mechanism. The others are Overlapping Basic Service Set (BSS) Preamble Detection (OBSS/PD), and Target Wake Time (TWT). OBSS/PD aims to increase Spatial Reuse by allowing concurrent transmissions in a given area [9]. TWT makes the IoT devices sleep for a predefined amount of time by the Access Point (AP) [10] [11]. Finally, our center of focus, OFDMA, facilitates the division of transmission channels into small pieces named Resource Units (RUs). The AP can allocate each RU to a different subcarrier using the novel Multi-User Medium Access Control (MU-MAC) mechanism [12]. This RU division has its rules, but they are not limited to one fixed distribution. The AP has a core role in this scheduling process. In contrast with random access, central scheduling of channel resources is expected to mitigate a set of throughput performance restricting problems: Preventing channel collisions, avoiding one bad STA having a low MCS rate to limit all channel performance, and so on.

For an AP to schedule network traffic, the number of network packets to send and the signal quality of connected STAs need to be known. For DL traffic, an AP has this information inherently. In this case, the AP schedules the traffic, informs the connected STAs to listed their allocated RU frequencies, and send data frames. On the other hand, for UL traffic, the AP has no information about traffic queues of connected STAs. In this regard, the AP can schedule UL traffic using the Uplink OFDMA Random Access (UORA) procedure [13]. Alternatively, it can request queue size data by requesting a Buffer Status Report (BSR) and then schedule and let which STAs use which specific RU for any given Transmission Opportunity (TXOP).

There are a set of schedulers designed for IEEE 802.11ax standard to address a variety of optimizations. These schedulers will be discussed in Chapter 2.

1.1. Contributions of This Thesis

In this thesis, we develop a throughput maximizing scheduler: The properties of the scheduler and the contributions of this thesis are summarized below:

- We model and implement the scheduler. Unlike many others, our modelling is direction agnostic and work in both downlink (DL) and uplink (UL) directions.
- Our scheduler exploit IEEE 802.11ax capabilities: Queue lengths of STAs, link quality of each STAs to the AP.

- Then, we develop an aging mechanism, which allows weak nodes to send their packages by allowing their starvation. Weak nodes are the nodes with low MCS levels, either far from the AP or close to a powerful interference source.
- For performance evaluation, we implement IEEE 802.11ax in robust Network Simulator-3 (NS-3) [14] [15] and our scheduler using Google-OR Tools [16]. We test our scheduler in both DL and UL directions.

2. RELATED WORK

Possible scheduling strategies with IEEE801.11ax enables features are thoroughly discussed in [17] and [18]. The authors of [17] explain what IEEE 802.11ax brings in detail, derive a traffic pattern, and compare it to the previous standard, IEEE 802.11ax. [18] does the same explanations and presents detailed charts.

One well-accepted paper for the scheduling problem is [19]. The authors define a simple MU-MAC framework compatible algorithm and two more with different objectives and solve the problem with the Hungarian algorithm.

There are also many approaches to the problem. A model named Efficient Resource Allocation is developed in [20]. They split STAs into three load groups: High load (HL), medium load (ML), and low load (LL). Thresholds between these are dynamically set. They also define an algorithm that we can implement and compare. An analytical model is provided as well.

In [21], the solution inspired by LTE scheduling relaxes the problem by allowing users to be allocated multiple resource units (RUs). Then, a divide & conquer algorithm is applied. The authors propose another algorithm that is greedy and near-optimal. However, these relaxations are not soft limits of IEEE 802.11ax, and hence the applicability of these schedulers can be a problem. [22] also proposes an OFDMA-based scheduling algorithm, but for broadband wireless networks. Their method is Quality of Service (QoS) adaptive and aims for fairness.

A joint optimization that considers scheduling problems and Target Wake Time (TWT), especially for low-power IoT devices, is studied in [23]. The author approaches the problem scheduling with IoT devices by enabling TWT for them. They develop a Lyapunov optimization algorithm aiming to reduce energy usage. Their algorithm is close to the optimal but with a drawback of increased queue sizes.

A model named MMRU-ALLOC (Min-Max Resource Allocation) is discussed in [24], proposing a bipartite matching algorithm tested on NS-3. Their cost function is on minimizing data transmission rate and minimizing padding length of packages. However, this requires changing the size of transmission durations, which adds a new dimension to the problem.

Another model called SCAT (Scheduling Channel Acces with TWT), which makes unused STAs sleep until some time and reduces the number of STAs scheduled at a time, is proposed in [11]. They solve this issue by using genetic algorithms and caring for energy efficiency.

An esoteric approach is presented in [25]. The authors do not propose scheduling but better utilization of queues, making them smart queues. Their proposed queues are interference-aware, meaning that the following network packet to be sent is selected by interference level. This method works only in the downlink direction.

Another perspective is presented in [26]. The authors propose TCP-aware scheduling. It uses Acknowledgement (ACK) packets for scheduling mechanisms and aims to improve OFDMA performance, especially in unreliable environments.

IEEE 801.11ax also enables non-scheduling for random access, named UORA. Such probabilistic models are discussed in [27] and [28]. [29] proposes Cycling Resource Allocation Algorithm over random access. [30] does performance evaluation for UORA and comes up with an UORA-based UL scheduler. However, we will not be focusing on random access, and UORA is out of the scope of this thesis.

There are more schedulers based on different objectives, too. For example, [31] tries to minimize packet drop. STAs are divided into two groups, emergency, and non-emergency in [32], and then scheduled with a simple algorithm. A cluster and schedule algorithm for STAs is also attempted in [33]. The clusters are formed by grouping STAs that require transmission times closer together. [34] proposes a UL-only algorithm along with IEEE 802.11 performance evaluations. A UL OFDMA performance evaluation for throughput and Buffer Status Report (BSR) Delivery Rate is provided in [35].

And finally, our previous work and the basis of this thesis on throughput maximizing scheduler is published on IEEE PIMRC 2020 [36]. It uses queue lengths and link qualities and provides an aging mechanism to prevent starvation.

Table 2.1 summarizes the related work: Whether a work utilizes Scheduled Access (SA) or OFDMA Random Access (RA), the use of UORA, whether a scheduler is designed, the method of scheduling, what the scheduler optimizes and the language or framework used.

Table 2.1. Comparison of the related work.

Work	**SA/RA**	**UORA**	**Scheduler**	**Analytical / Algorithmic**	**Optimizes**	**Language Framework**
[18]	Both	✓	✓	Algorithmic	TP	C++
[19]	SA	✗	✓	Algorithmic	TP, fairness, upload time	Unknown
[20]	SA	✗	✓	Analytical	TP	NS-3 [14]
[21]	SA	✗	✓	Divide & Conquer Algorithm	TP	-
[22]	SA	✗	✓	Algorithmic	QoS	Unknown
[23]	SA	✗	✓	Lyapunov Optimization	TWT	Unknown
[24]	SA	✗	✓	Bipartite Matching Algorithm	Maximum cost of resource allocation	NS-3 [14]

Table 2.1. Comparison of the related work. (cont.)

Work	**SA/RA**	**UORA**	**Scheduler**	**Analytical / Algorithmic**	**Optimizes**	**Language Framework**
[11]	SA	✗	✓	Genetic Algorithm	Energy efficiency	Matlab [37]
[25]	SA	✗	✗	Analytical	MAC queue	-
[27]	Both	✓	✓	Utility Maximization Algorithm	Overall satisfaction	Matlab [37]
[28]	RA	✓	✓	Both	TP	Matlab [37]
[29]	RA	✓	✓	Algorithmic	Real time delay	Unknown
[30]	RA	✓	✓	Both	TP	Unknown
[31]	SA	✗	✓	Analytical	Package drop	Unknown
[32]	SA	✗	✓	Algorithmic	Deadline	Matlab [37]
[33]	SA	✗	✓	Analytical	TP	Matlab [37]
[34]	SA	✗	✓	Both	TP	NS-3 [14]
[36]	SA	✗	✓	Analytical	TP	NS-3 [14]

3. MECHANICS: IEEE 802.11AX MU-MAC FRAMEWORK AND OFDMA

3.1. Former Versions of IEEE 802.11

The specifications for IEEE 802.11 standard were first set in the 1990s. There are six versions under consideration now: IEEE 802.11a/b/g/n/ac/ax. As marketing names, they are named from Wi-Fi 1 to Wi-Fi 6. These are the most widely implemented and conventional ones operating on mostly adopted 2.4 GHz and 5 GHz frequency bands. Other versions are associated with local regulation requirements, like IEEE 802.11h for the EU regulations on 5 GHz, IEEE 802.11j for Japan's on the same frequency, and IEEE 802.11y for the USA's FCC regulations [38]. Not all IEEE 802.11 versions are major; some define security enhancements, amendments, and new features. For instance, IEEE 802.11e introduces Quality of Service (QoS), where traffic is classified into four categories based on EDCA: Video, voice, best-effort, and background traffic [39]. IEEE 802.11i provides security advancements after the previous encryption mechanism, since WAP was broken [40] [41] [42]. IEEE 802.11aa improves video/audio streaming efficiency by enabling frame differentiation and graceful reduction of the quality [38].

The initial goal of the first set of versions was to increase the transmission rate. This increase was primarily achieved by employing faster modulation techniques, better coding schemes, wider communication channels, and several other mechanisms. At first, the earliest version had a data rate of 1-2 Mbps. Later, it increased to 11 Mbps with version IEEE 802.11b. Consequent two versions IEEE 802.11a and IEEE 802.11g, introduced Orthogonal Frequency Division Multiplexing (OFDM), and both reached a transmission rate of 54 Mbps. The first one was on a different frequency band of 5 GHz. In contrast, the lack of interoperability of IEEE 802.11a led the same OFDM improvement to be made in the 2.4 GHz frequency band, which is named IEEE 802.11g.

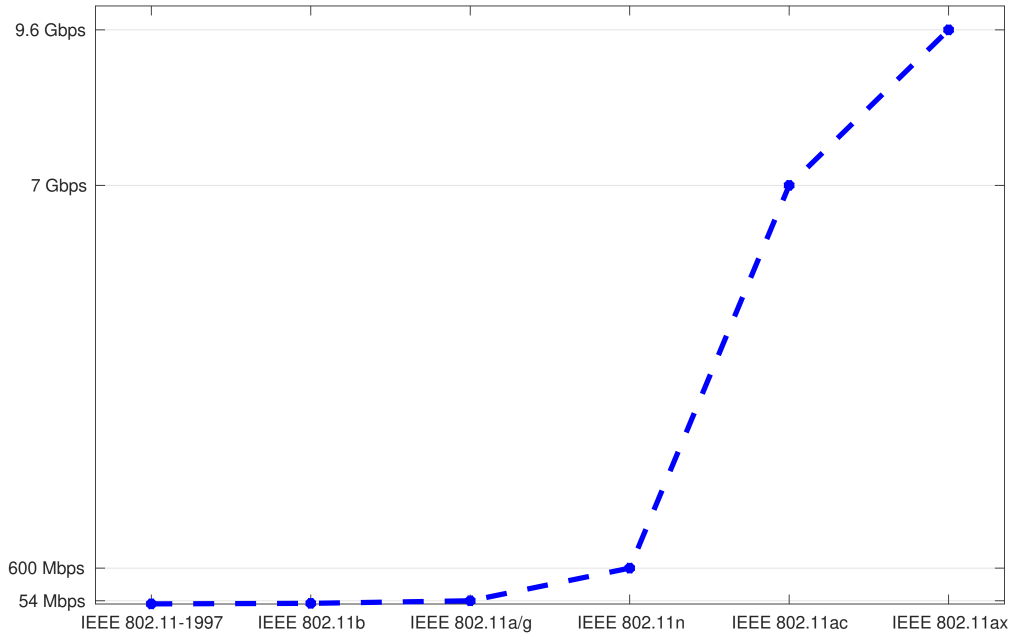

Figure 3.1. Comparison of ideal peak data transmission rates of major Wi-Fi versions for IEEE 802.11-1007/b/a/g/n/ac/ax.

IEEE 802.11n portrays the most significant jump in IEEE 802.11's history in 2009, utilizing transmission rate and newly used techniques. With the introduction of up to four multiple antennas, Multiple Input Multiple Output (MIMO) made simultaneous spatial streams attainable. It also expanded channel width to 40 MHz, compared to 20 MHz of former versions, and uses a coding rate of 5/6 against the former rate of 3/4. With these enhancements, the transmission rate hit up to 600 Mbps.

Along with these plain increases, IEEE 802.11n also improves the MAC layer by decreasing the overhead caused by repeated control frame information. Therefore, two aggregation techniques were implemented: Aggregated MAC Service Data Unit (A-MSDU) and Aggregated MAC Protocol Data Unit (A-MPDU).

IEEE 802.11ac further extended channel width up to 160 MHz for a further boost in transmission rate. It introduced Multi-User - Multiple Input Multiple Output (MU-MIMO) scheme. Contrary to the former MIMO mechanism used in IEEE 802.11, this approach enables APs to communicate with different STAs simultaneously, creating synchronization problems. Thus, IEEE 802.11ac also brings some mechanisms like Transmission Opportunity (TXOP). These improvements enabled a 10-fold increase in transmission rate, i.e., up to 7 Gbps, the first commercially used IEEE 802.11 version to reach a Gbps level, as can be seen on Figure 3.1.

3.2. IEEE 802.11ax and OFDMA

Apart from mainly focusing on increasing throughput (a.k.a transmission data rate), the 802.11ax standard's core priority is to enhance its efficiency [12] [43]. The primary method to achieve this goal is providing a new key medium access mechanism, Orthogonal Frequency Division Multiple Access (OFDMA), based on scheduled access [44]. This enables the division of the communication channel into smaller pieces called RUs. Each RU at a given point in time can connect to different subcarriers. By utilizing the MU-MAC framework of IEEE 802.11ax, the access point (AP) can schedule the allocation of resource units (RUs) to stations (STAs) on a single channel. Unlike the random access mechanism used in IEEE 802.11 versions, this mechanism is essentially different by positioning the access point (AP) as an authority of STAs. This controlled access is expected to reduce channel collisions, especially in crowded areas, and reduce antenna power wasted. There is also a new mechanism called Target Wake-up Time (TWT), that the access point (AP) commands several STAs to sleep for some predefined amount of time. However, TWT and its efficient implementation techniques are out of the scope of this thesis.

For an AP to effectively schedule traffic of STAs, an AP needs to know the queue information of STAs. This information is available in downlink (DL) traffic in AP's queue. Nevertheless, uplink (UL) queue information is hidden from an AP and exists in each STA. IEEE 802.11ax develops a Buffer Status Report (BSR) mechanism in this regard. With BSR, an AP can request queue size information from a set (or all) of STAs and retrieve them once. As an alternative to BSR, an AP can randomly allocate some or all of us to STAs. This mechanism is named UORA. In our thesis, we are only concerned with scheduled access; thus, UORA is out of the scope of this thesis.

Table 3.1. Notable changes from IEEE 802.11ac to IEEE 802.11ax.

Parameter	**IEEE 802.11ac**	**IEEE 802.11ax**
Modulation	BPSK - 256 QAM	BPSK - 1024 QAM
Bandwidth	20 MHz - 160 MHz	20 MHz - 160 MHz
Subcarrier Spacing	312.5 kHz	78.125 kHz
Compatibility for Former Versions	IEEE 802.11a/n	IEEE 802.11a/b/g/n/ac
MIMO	Only in DL	DL and UL
Medium Access Control (MAC)	DCF	OFDMA
Maximum Data Rate	7 Gbps	9.6 Gbps
MU Methods	MU-MIMO	MU-MIMO, OFDMA
MU Direction	DL only	DL & UL

The IEEE 802.11ax specification document details the MU-MAC framework of IEEE 802.11ax [8]. Although this framework is elaborative, no scheduling algorithm or method is defined. This scheduling task is left to hardware developers or Wi-Fi vendors to put their efforts into implementing their goal-oriented schedulers. To this end, a set of schedulers are being developed and implemented, as explained in Related Work.

The MU-MAC framework of IEEE 802.11ax is expected to ensure two goals: First, to provide a scheduling mechanism by allowing an AP to distribute channel resources (RUs and time slots) to connected STAs at a particular point in time and second, compliance with former versions of IEEE 802.11 that are random access instead of scheduled access.

3.2.1. Division over Frequency: Resource Units (RUs)

Compared to legacy IEEE 802.11 ODFM, the IEEE 802.11ax PHY layer divides the wireless channel into 78.125 kHz subcarriers. At a definite time, these subcarriers form Resource Units (RUs). An RU is the atomic unit of a wireless channel. Resource Units can be of variable size, yet they must be in predefined sizes, as the standard document states. These sizes are 26-tone, 52-tone, 106-tone, 242-tone, 484-tone, 996-tone, and 2x996-tone. A 20 MHz channel can be 242-tone at maximum. In the same way, 484-tone corresponds to 40 MHz and 996-tone to 80 MHz.

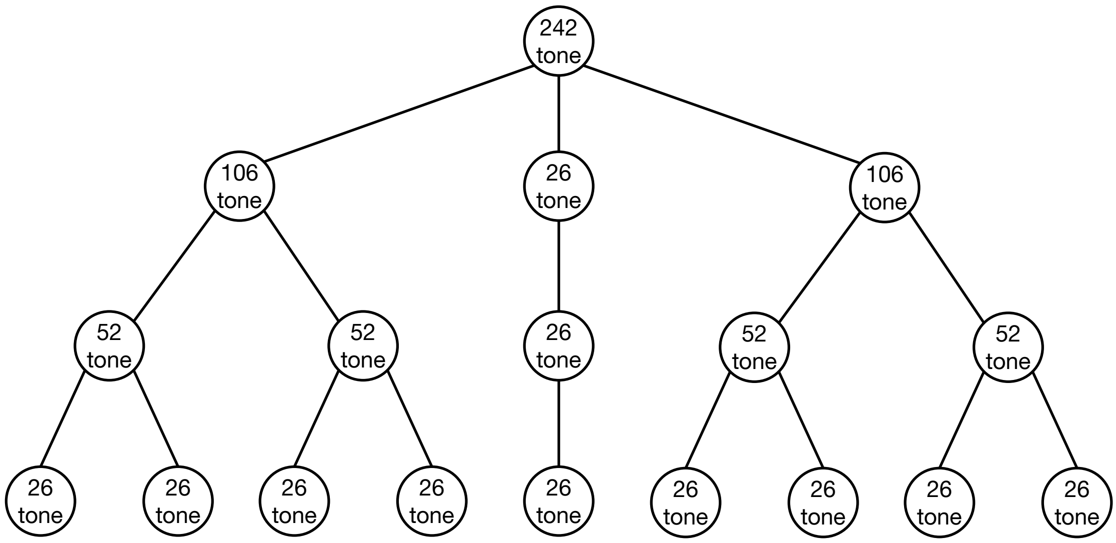

Figure 3.2. RU allocation configuration tree for 20 MHz channel.

The selection of 242-tone RU for a 20 MHz means the whole channel is allocated to only one RU. A 242-tone further can be divided by keeping the tree structure, as seen in Figure 3.2. At most, a 242-tone RU can consist of 9 different 26-tone RUs, each belonging to different subcarriers. Another example of separation is to divide a 242-tone RU into (106-tone, 26-tone, 106-tone) triplets. Here the sum of tone values does not match 242. The reason for this is to leave margins among adjacent RUs. A 106-tone RU can further be divided into (52-tone, 52-tone) pairs. So does a 52-tone to double 26-tones. While making divisions to RUs, the tree structure of Figure 3.2 must be preserved; a selected note cancels the division of all child notes. For a 20 MHz channel, (242), (106, 26, 106), (52, 52, 26, 106), (52, 52, 26, 52, 52) and (26, 26, 26, 26, 26, 26, 26, 26, 26) are examples of valid RU divisions.

3.2.2. Multi User (MU) Access

3.2.2.1. Downlink MU Access (DL-MU). In Downlink MU Access, the AP sends data using the OFDMA mechanism to a set of connected STAs. Since the AP needs to be backward compatible, it first needs to win the contention of the random access mechanism of DCF/EDCA. After winning channel access, the AP sends a data frame having a legacy PHY header, so all the STAs, including legacy ones, become aware of ongoing traffic information, including Network Allocation Vectors (NAV). In that legacy header, a HE-SIG-B header is attached at the end, which is unique to the 802.11ax standard. HE-SIG-B header contains information regarding downlink OFDMA scheduling and explained in 3.2.5. An IEEE 802.11ax-enabled STA can acquire information on whether to listen to the AP and to listen to which allocated RU to them. IEEE 802.11ax incompatible legacy STAs cannot interpret this header and skip.

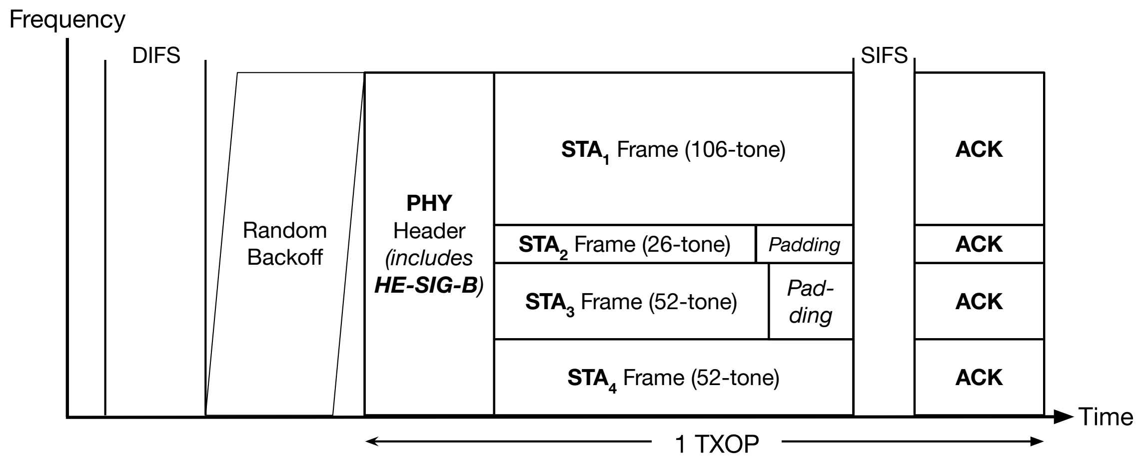

Figure 3.3. An example of IEEE 802.11ax DL-MU access for 20 MHz channel bandwidth with (106, 26, 52, 52) subcarrier allocations.

Following the PHY header, the AP sends the information in data frames to STAs over scheduled RUs. As defined by legacy IEEE 802.11, the duration is at its maximum one TXOP time. The subsequent step is to wait for a SIFS period and get acknowledgment (ACK) as compatible with the legacy standard. However, since the data is sent multi-user, the AP must also get the ACK simultaneously. For this objective, an

MU-ACK policy is presented. It is similar to ACK, but the STAs get data frames using their corresponding RUs to send their ACKs.

After getting MU-ACK from STAs, the AP may release the channel for other network edges. In IEEE 802.11ax, scheduling is done in every TXOP. This situation means STAs must listen and consider RU allocations for every PHY header at the start of each TXOP.

3.2.2.2. Uplink MU Access (UL-MU). Uplink (UL) Multi User Access is more complex than downlink (DL) transmission. The main reason is that the AP still has to manage the scheduling and allocate RUs to STAs, but does not inherently know the queue lengths of connected STAs. Thus, a new mechanism named BSR is proposed in IEEE 802.11ax [33]. In this regard, the AP gets the information it needs. BSR has two types: Explicit and implicit. In explicit BSR, the AP sends Buffer Status Report Poll frame and triggers STAs to send their queue information. In explicit BSR, this information is supplied to the AP without requiring BSRP. The information is added to previous UL data headers or ACK frames.

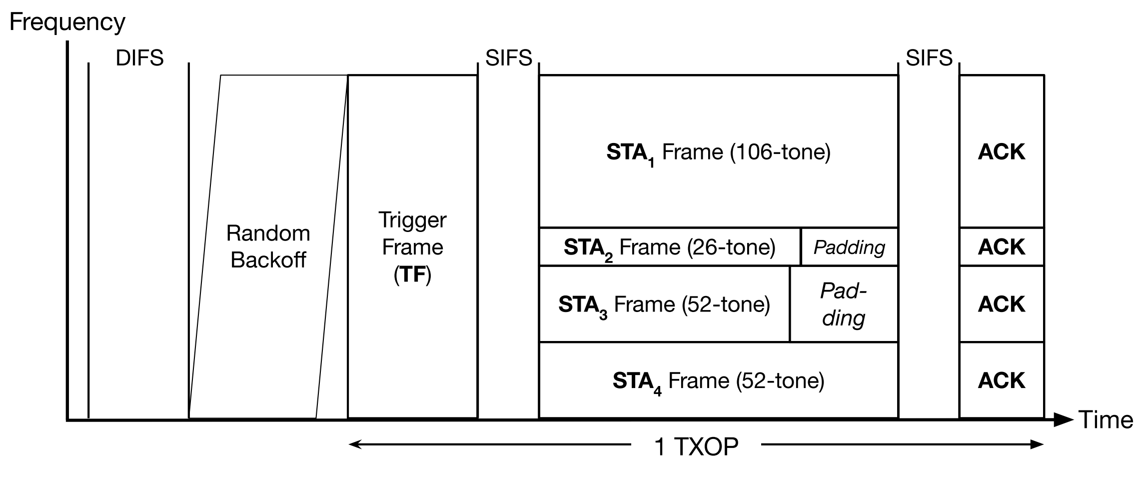

Figure 3.4. An example of IEEE 802.11ax UL-MU access for 20 MHz channel bandwidth with (106, 26, 52, 52) subcarrier allocations.

Before beginning a UL transmission and having queue information available to the AP, it must win the contention in a legacy IEEE 802.11 random access channel. After having the channel, the AP sends a Trigger Frame (TF) to all connected STAs. This Trigger Frame has the RU allocation configuration and MCS level information for each STA. Then all the STAs wait for a Short Inter-Frame Space (SIFS) duration and simultaneously send their data in their allocated RUs. Again this process takes a TXOP time. Like DL access, the AP waits for a SIFT duration and sends ACK packages this time.

3.2.3. Multi User Multiple Input Multiple Output (MU-MIMO)

MU-MIMO defines employing more than one antenna, and thus spatial streams, to make simultaneous parallel connections possible. Although MU-MIMO exists in the IEEE 802.11ac standard in the downlink direction, it was not widely adopted and was only implemented in some products. The new IEEE 802.11ax standard also utilizes MU-MIMO. Along with OFDMA, IEEE 802.11ax is expected to exploit MU-MIMO capabilities better.

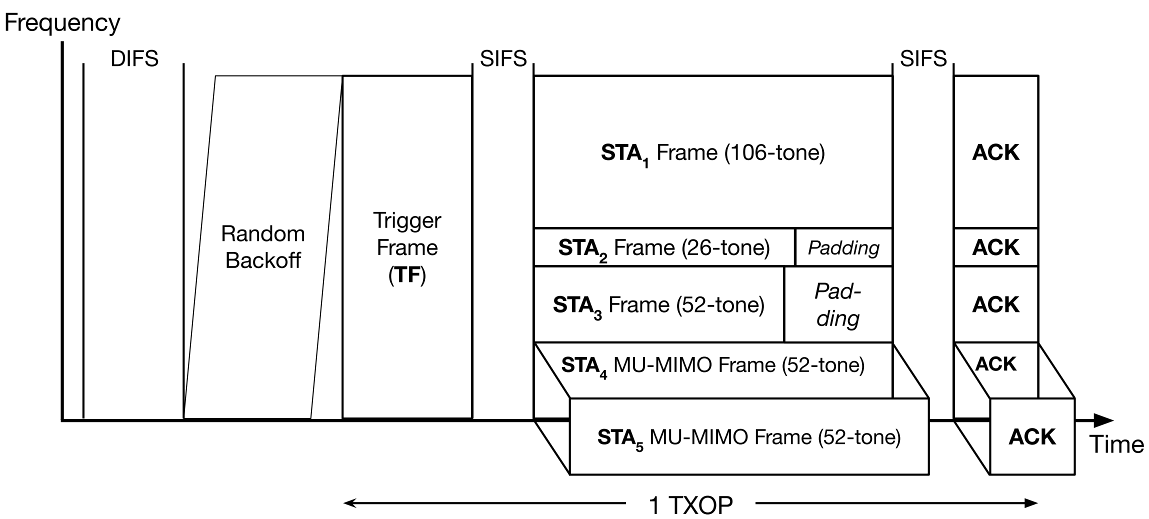

Figure 3.5. An example of IEEE 802.11ax UL-MU MIMO access for 20 MHz channel bandwidth. Here STA_5 is served on a different spatial stream.

3.2.4. Modulation and Coding Scheme (MCS)

Table 3.2. MCS values and their corresponding modulation methods, coding rates, and the existence of dual subcarrier modulation.

MCS Index	Modulation	Coding Rate	DCM
0	BPSK	1/2	DCM0
1	QPSK	1/2	DCM0
2	QPSK	3/4	-
3	16-QAM	1/2	DCM0
4	16-QAM	3/4	DCM0
5	64-QAM	2/3	-
6	64-QAM	3/4	-
7	64-QAM	5/6	-
9	256-QAM	5/6	-
10	1024-QAM	3/4	-
11	1024-QAM	5/6	-

IEEE 802.11ax introduces two new MCS levels: MCS 10 and MCS 11, as depicted in Table 3.2. These two levels utilize 1024-QAM, which means sending 1024 bits at once. The difference between MCS level 10 and 11 is that MCS 10 uses a 3/4 coding rate, whereas MCS 11 does 5/6.

Dual Subcarrier Modulation (DCM) is also introduced in IEEE 802.11ax, which increases the robustness of transmission, especially in low SNR conditions. Note that DCM is only applied to MCS 0, MCS 1, MCS 3, and MCS 4 [8].

3.2.5. High-Efficiency Protocol Data Unit (HE-PPDU) Formats

IEEE 802.11ax introduces four new High Efficiency (HE) PPPU formats, as seen in Figure 3.6 [8]. To ensure the coexistence of new IEEE 802.11ax and legacy devices, all PPDUs start with a legacy preamble. This legacy preamble is shown in yellow in Figure 3.6.

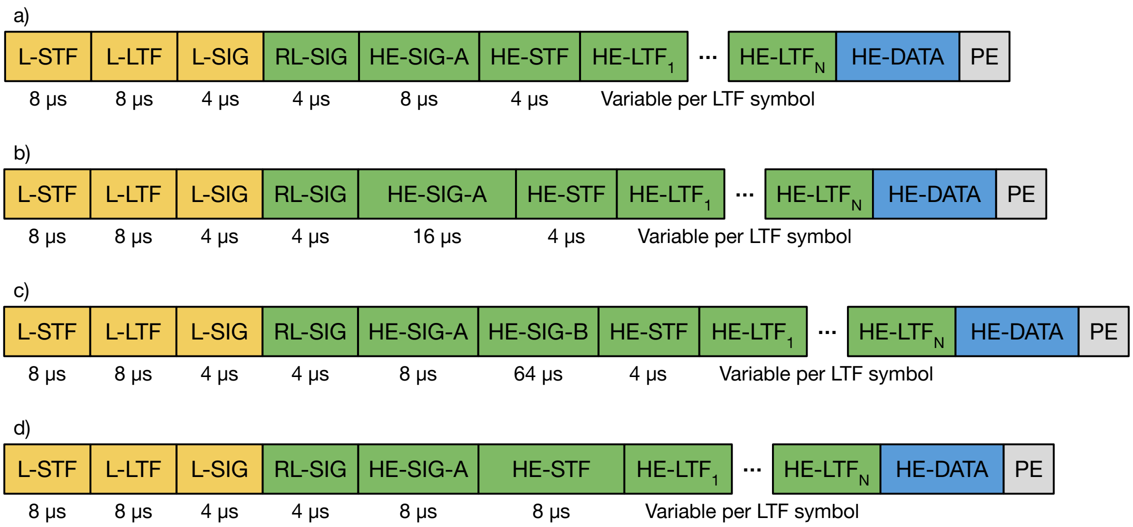

Figure 3.6. IEEE 802.11ax High Efficiency (HE) PPDU formats. a) HE Single User (SU) PPDU, b) HE Extended Range (ER) Single User (SU) PPDU, c) HE Multi-User (MU) PPDU, d) HE Trigger-based PPDU. Yellow ones (left) are legacy preamble, green ones are high-efficiency preamble, blue is data, and gray is packet extension.

The legacy preamble has three fields in it: L-STF (Legacy Short Training Field), L-LTF (Legacy Long Training Field), and L-SIG (Legacy Signal Field) fields. L-SIG contains transfer rate and length information. RL-SIG is not in the legacy preamble but is a repetition of the L-SIG field and server for detection.

High Efficiency (HE) fields have HE-SIG-A, HE-SIG-B, HE-STF, and HE-LTF fields. HE-SIG-A (HE Signal A) field exists in all PPDUs. HE-SIG-B is only present in Multi-User mode PPDU and carries resource allocation information. HE-STF is High-Efficiency Short Training Field, and HE-LTF is High-Efficiency Short Training Field. HE-LTFs can be variable durations of at most eight adjacent frames. Finally, HE-DATA carries transmitted information and optional Packet Extension (PE) as a processing delay time for the recipient.

Among four newly introduced PPDUs, Figure 3.6a HE-SU-PPDU has attached on a single user communication both in DL and UL direction. The frame in Figure 3.6b

HE-SU Extended Range PPDU is used for long-range transmissions. The only difference is that HE-SIG-A is twice the size since it is repeated to ensure its delivery. Figure 3.6c HE-MU-PPDU has an exclusive HE-SIG-B frame for MU transmissions. Figure 3.6d HE Trigger-based PPDU is used only in the UL direction, and response to the Trigger Frame sent by the AP [45].

4. METHODOLOGY

We model the aforementioned OFDMA scheduling problem as an optimization problem. Our scheduler is based on consecutive independent runs to solve these optimization problems with an LP solver. Our model that is going to be explained here has linear solution space. Thus, our scheduler works considerably fast.

IEEE 802.11ax MU-MAC framework makes it possible to schedule traffic for every TXOP. Thus, our scheduler is designed to run at each TXOP to meet changing demands from both the AP and STAs. Although DL and UL scheduling are different in the MU-MAC framework, we designed our scheduler to be direction agnostic. It works in DL and UL directions and considers queue lengths and data link qualities.

One aspect to note is that our scheduler does not decide the direction of the next step, i.e., TXOP. Because the dynamic selection of traffic direction between DL and UL embodies another problem statement and requires different solutions on its own, we leave this out of the scope of our work. Therefore, all of our traffic experiments are only in a single direction: Either only DL or only UL transmissions.

To fully exploit IEEE 802.11ax's scheduling capabilities, our scheduler takes not only queue lengths of the AP and STAs into consideration but also reflects their link qualities. To this end, we consider Modulation and Coding Scheme (MCS) levels of connected STAs. Table 4.1 displays possible bandwidth values in Mbits for any given MCS levels and possible RU tone allocations. Note that MCS levels are predefined and have two variables: Phase Shift Keying mechanism and coding rates. 3/4 means for every 3 bits of information, 4 bit is sent, and the remaining 1 bit is an error coding bit.

According to Table 4.1, an STA with MCS level 11 can transmit 121.9 Mbit if it is allocated a 242-tone RU slot and 12.5 if 26-tone. However, an STA with a lower MCS level, for example, MCS level 1, can transmit 14.6 Mbit at maximum even if it is allocated to transmit over 242-tone. There are two aspects of this effect: The first is independent of RU allocation; if an STA has a low MCS value, it cannot have high transmit rates. Second, for a scheduler having maximum throughput as a goal, STAs with higher MCS levels are always chosen. Although we solve the bad apple scenario by utilizing OFDMA, where an STA having a low MCS level slows down the entire network, those STAs are left starvation without a proper aging mechanism.

Table 4.1. Data transmission rates for 20 MHz channel bandwidth in one spatial stream with 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
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

For our optimization problem, we define four sets:

(i) $\mathbf{S}$, the set of connected STAs to the AP in the network area. The number of STAs should satisfy $0 \leq |\mathbf{S}|$; therefore, we do not set an upper limit.

(ii) $\mathbf{R_{bw}}$, the set of all possible RU distributions (RUCs) given the channel bandwidth $\mathbf{bw}$. RUC denotes an RU division set. The possible values for bandwidth $\mathbf{bw}$ are 20 MHz, 40 MHz, and 80 MHz according to the IEEE 802.11ax standard.

A possible set of $\mathbf{R_{20\ MHz}}$ is presented in Equation 4.1. In this case, $\mathbf{R_{20\ MHz}}$ set holds 13 different possible distributions. Set (242) allocates whole channel to only one STA, whereas $(26, 26, 26, 26, 26, 26, 26, 26, 26)$ splits the channel into 9 same sizes.

(iii) $\mathbf{I_{bw}}$, the index set for RUCs in $\mathbf{R_{bw}}$, having the same number of elements as $\mathbf{R_{bw}}$ has.

(iv) $\mathbf{I}_{\mathrm{RUC}_\mathbf{k}}$, the index set for RUs in RUC_k.

$$
\begin{aligned}
\mathbf{R_{bw}} &= \{\mathrm{RUC}_1, \mathrm{RUC}_2, ..., \mathrm{RUC}_n\} \\
\mathbf{R_{20\ MHz}} &= \{\mathrm{RUC}_1, \mathrm{RUC}_2, ..., \mathrm{RUC}_{13}\} \\
&= \{(26, 26, 26, 26, 26, 26, 26, 26, 26), \\
&\quad (52, 26, 26, 26, 26, 26, 26, 26), \\
&\quad (52, 52, 26, 26, 26, 26, 26), \\
&\quad (52, 52, 52, 26, 26, 26), \\
&\quad (52, 52, 52, 52, 26), \\
&\quad (106, 26, 26, 26, 26, 26), \\
&\quad (106, 52, 26, 26, 26), \\
&\quad (106, 52, 52, 26), \\
&\quad (106, 106, 26), \\
&\quad (242)\}
\end{aligned}
\tag{4.1}
$$

We can further simplify and state that our problem is a three-dimensional constrained allocation problem, as depicted in Figure 4.1 for a 20 MHz channel. Since this representation contains plenty of zeroes, instead of a matrix, a set of tuples representing this schema preferred as explained in Equation 4.1 is an example for a 20 MHz channel.

We define the $\varphi(k, j)$ function that gives the unique index of an RU in a given RUC_k. More specifically, it maps the index of an RUC $(k, \forall k \in \mathbf{I_{bw}})$ and the index of RU in given RUC_k $(j, \forall j \in \text{RUC}_k)$ to a unique value of m where $1 \leq m \leq m_{max}$. The value of m_{max} depends on channel size. $\varphi^{-1}(m) = (k, j)$ function does the inverse:

$$\varphi(k, j) = j + \sum_{l=1}^{k-1} |\mathbf{I}_{\text{RUC}_l}| \,. \tag{4.2}$$

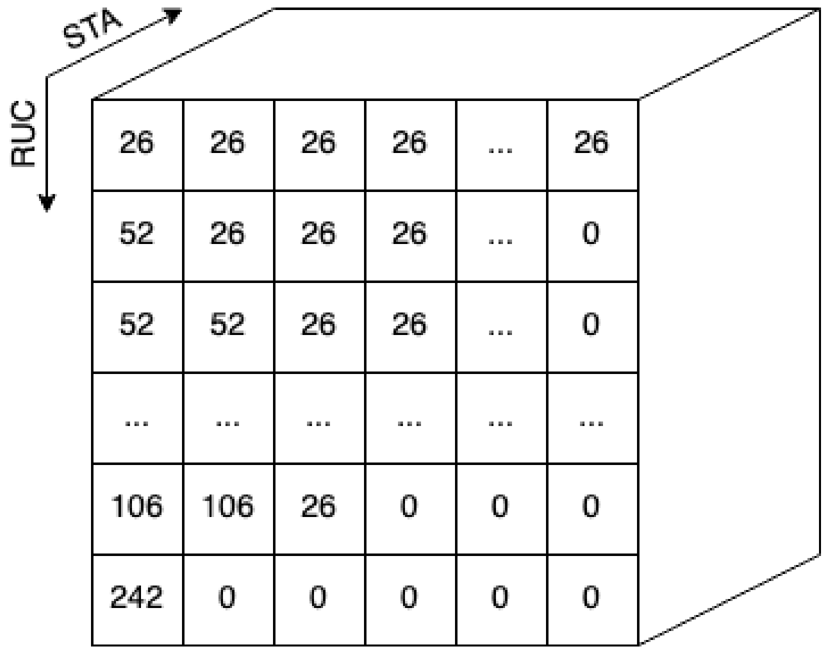

Figure 4.1. 3-dimensional depiction of the scheduling problem: Stations (STAs), RU configurations (RUCs), and Resource Units (RUs).

There are three optimization variables:

(i) $X_{i,j,k}$, having binary values. It gets 1 if STA i is allocated j^{th} RU of RUC_k and 0 if otherwise.

(ii) $Y_{i,j,k}$ values are non-negative floats, denoting the transmission rate allocated to STA i for j^{th} RU of RUC_k.

(iii) T_k is 1 if RUC_k is selected, 0 if otherwise.

Four parameters are defined over $\mathbf{S}$:

(i) L_i, $\forall i \in \mathbf{S}$ is the queue length of each STA, either DL or UL queue, given the direction of the current simulation.

(ii) MCS_i, $\forall i \in \mathbf{S}$ is modulation and coding method index.

(iii) $RUV_{j,k}$ is the number of subcarriers in the j^{th} RU of RUC$_k$.

(iv) $Tr_{MCS_i,RUV_{j,k}}$ is the transmission rate of STA for given modulation and coding index and RU value. An example for this is given in Table 4.1.

4.1. Throughput Maximizing Scheduler

We design a throughput maximizing scheduler that needs to both make use of the channel resources as much as possible and avoid possible starvation while doing so. Our scheduler is stateless, meaning it has independent runs for each turn, i.e., TXOP.

Having explained common sets, optimization variables, and parameters, we can now write our objective function along with a list of our constraints:

$$\underset{X_{i,j,k}}{\text{maximize}} \sum_{i \in \mathbf{S}} \sum_{k=1}^{|\mathbf{R_{bw}}|} \sum_{j \in \mathbf{I}_{\mathrm{RUC}_\mathbf{k}}} Y_{i,j,k} F^{A_i} \ . \tag{4.3}$$

Our objective function is subject to:

$$\sum_m X_{i,\varphi^{-1}(m)} \leq 1 \qquad \forall i \in \mathbf{S} \tag{4.4}$$

$$\sum_i X_{i,\varphi^{-1}(m)} \leq 1 \quad \forall m = 1..m_{max} \tag{4.5}$$

$$\sum_i \sum_j X_{i,j,k} \leq |\mathrm{RUC}_\mathbf{k}|\, T_k \qquad \forall k \in \mathbf{I_{bw}} \tag{4.6}$$

$$\sum_k T_k = 1 \tag{4.7}$$

$$Y_{i,j,k} \leq L_i X_{i,j,k} \qquad \forall i \in \mathbf{S}, \ \forall j \in \mathbf{RUC_k}, \ \forall k \in \mathbf{I_{bw}} \tag{4.8}$$

$$Y_{i,j,k} \leq Tr_{MCS_i,\, RUV_{j,k}}\, d_{\mathrm{TXOP}} \qquad \forall i \in \mathbf{S}. \tag{4.9}$$

The first four constraints account for RU allocation rules and limitations by the IEEE 802.11ax standard. Constraint 4.4 restricts any STA from being allocated only a single RU. Constraint 4.5 does the opposite and limits an RU only to be allocated a single STA. For a chosen RUC_k, the total number of chosen RUs cannot surpass the count of RUs in chosen RUC_k. Finally, constraint 4.7 ensures that only one RUC_k can be selected.

The following two constraints limit transmission rates. Queue length constraint (4.8) determines the allocated transmission rate for each STA to be at most the queue length, in case it gets any. Equation 4.9 is an MCS level constraint and states that any STA cannot get more than the maximum transmission rate of its MCS level for a given TXOP duration. STAs with lower MCS levels have lower bandwidth due to their signal quality.

Having defined transmission rate on $Y_{i,j,k}$ variable and limited it with various required constraints, maximizing for it gets maximum throughput. However, an aging mechanism is added to avoid starvation of STAs with lower queue lengths.

The aging mechanism defines $A_{initial}$ to each STA at the initialization time, which is the minimum age. If an STA is not allocated to an RU at a TXOP, its age value is increased by δ, decreased by the same amount otherwise. Age value cannot exceed A_{max}. In case an STA consumes their queue and leaves with a queue length of 0, its aging value is returned to the initial age value:

$$A_i[t] = A_{\text{initial}}. \tag{4.10}$$

Age value is used as an exponent of the aging factor F. It is possible to disable the aging mechanism by setting $F = 1$.

Values for aging parameters $F = 1.15$, $A_{initial} = 1.15$ and $\delta = 0.4$ worked quite well. This scheduler is published on [36].

5. EXPERIMENTS AND RESULTS

Table 5.1. Simulation parameters.

Parameter	Value
Channel frequency	2.4 GHz
Channel bandwidth	20 MHz
Guard interval	3.2 µs
Number 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
Wi-Fi ACK policy	Block ACK
RTS/CTS	Enabled
AP buffer size (DL only)	500 frame/STA
STA buffer size (UL only)	500 frame
Number of STAs	$\{5, 10, 15, 20, 25\}$
MCS level of STA	$\{3, 11\}$
d_{TXOP}	4.6 ms
$A_{initial}$	1.15
F	1.15
δ	0.4

For performance evaluation, we employed NS-3 for simulations. When we initiated research studies on IEEE 802.11ax, NS-3 did not have a complete toolset for IEEE 802.11ax and OFDMA. Therefore, we developed novel `OFDMA Manager` module in sophisticated NS-3 simulator [36]. Our simulator can export PCAP output files for further investigation, such as Wireshark [46].

We developed our scheduler in Google Operations Research (Google-OR) Tools [16]. Both NS-3 and Google-OR Tools use C++ language, make use of parallelism, and they work considerably fast.

We evaluate our scheduler and legacy IEEE 802.11 MAC random access performance. Table 5.1 lists parameters we used.

Our simulations incorporate single AP and multiple connected STAs, on 2.4 GHz with 20 MHz bandwidth over only one single spatial stream. A remark is that no STA is hidden from any others to avoid side effects and complications. Our PHY layer is in free space path loss propagation and validated [47].

We grouped our STAs into two types of MCS levels: High link STAs have MCS level 11, and low ones have MCS level 3. We did not change network topology during simulations and kept both the AP and STAs stationary. We also did not model any outside noise from weather conditions or external devices. In this regard, we did not change the MCS levels of our scheduler.

We ran tests for 10 seconds and replicated each test ten times. Compared to the TXOP duration of 4.6 ms, this is quite long enough to extract the results. We both set frame lengths of STAs and the AP to 500 frames. Finally, we have RTS/CTS defined.

5.1. Throughput Maximizing Scheduler

When we first look at Figure 5.1, using Transfer Control Protocol (TCP) mechanism, we can state that our maximum throughput scheduler outperformed the legacy DCF/EDCA mechanism. The gap increases as the number of STAs increase, and DCF/EDCA even performs worse. The reason is that as the number of STA increases, the effect of channel contention becomes much more prominent, whereas our scheduled access provides contention-free access.

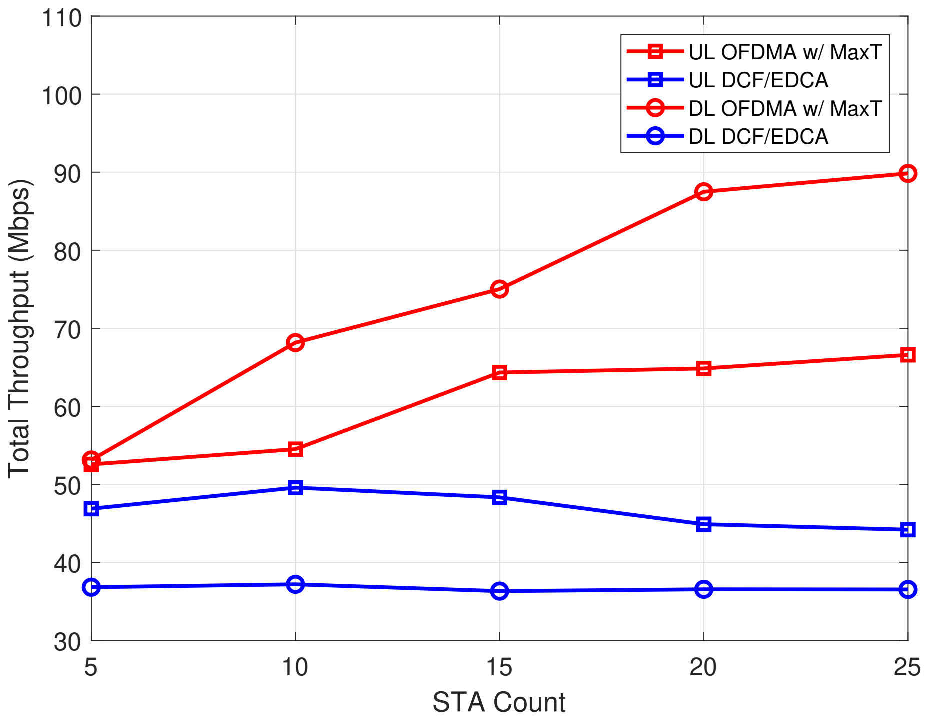

Figure 5.1. Comparison of the total throughput of our OFDMA-based MaxT scheduler and legacy DCF/EDCA, both are in TCP.

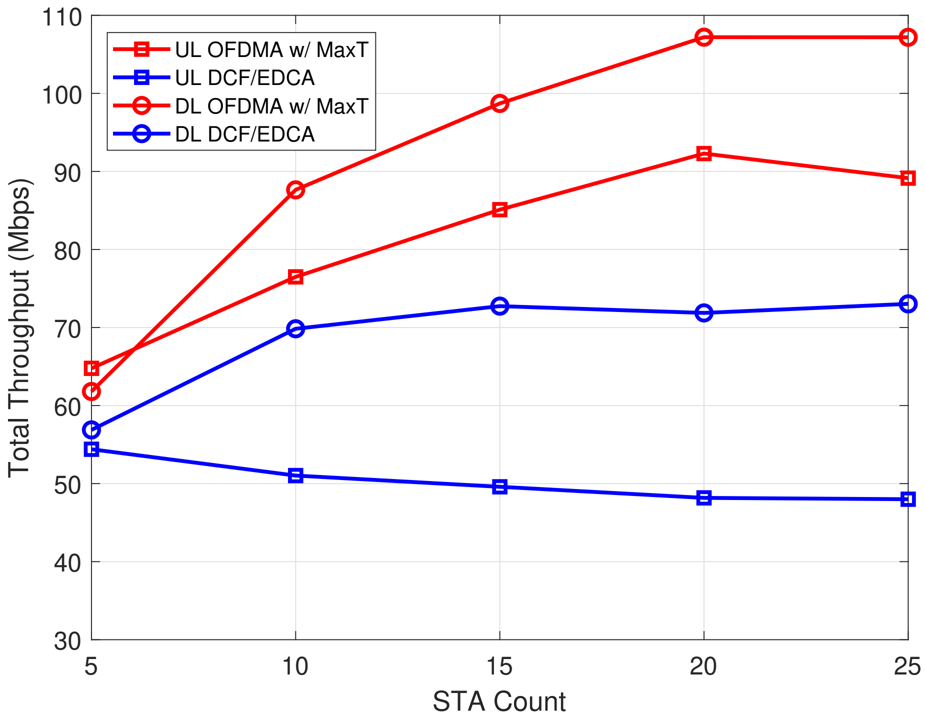

Figure 5.2. Comparison of the total throughput of our OFDMA-based MaxT scheduler and legacy DCF/EDCA, both are in UDP.

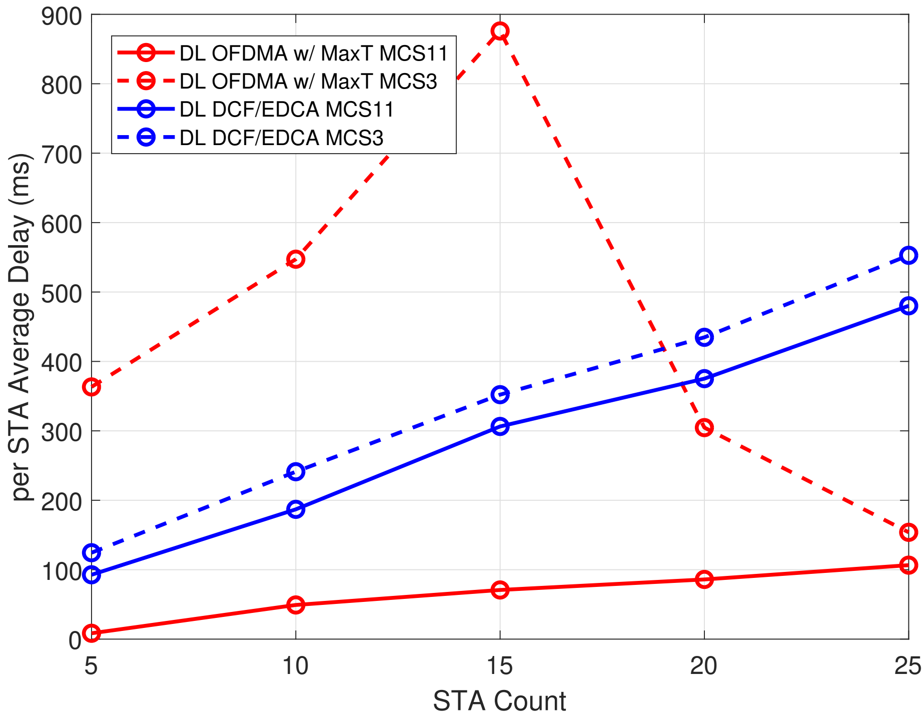

Figure 5.3. Average DL direction delay per STA under TCP.

Figure 5.2 makes the same comparison under User Datagram Protocol (UDP). UDP has no stream control mechanism compared to TCP: If a data packet is lost, it is lost, and no recovery is attempted, whereas, in TCP, both data packet arrivals and their orders are preserved by the repetition of packets in case of an unsuccessful delivery. For TCP to control the transfer order of data packets, it utilizes ACK packets sent back to the source. Our scheduler favors STAs having higher data queues for allocation. Therefore we can further improve the performance of our scheduler by adding precedence to TCP ACK packets.

The effect of UDP is higher throughputs, both in OFDMA and DCF/EDCA mechanisms. We can also state that, as the number of STA increases, collision avoidance mechanisms of DCF/EDCA, such as frame aggregation and RTS/CTS alleviate the negative impact of collisions.

We also analyze the delay effect of our maximum throughput scheduler. Looking at Figure 5.4, we can state that our scheduler favors STAs with higher MCS levels. Therefore, they have lower delays. This is due to that they can transfer more at a given TXOP. The decrease after 15 STAs in Figure 5.4 can be explained by the TCP mechanism, as it reduces the traffic flow of those STAs due to an increased number of packet losses, resulting in lower delays.

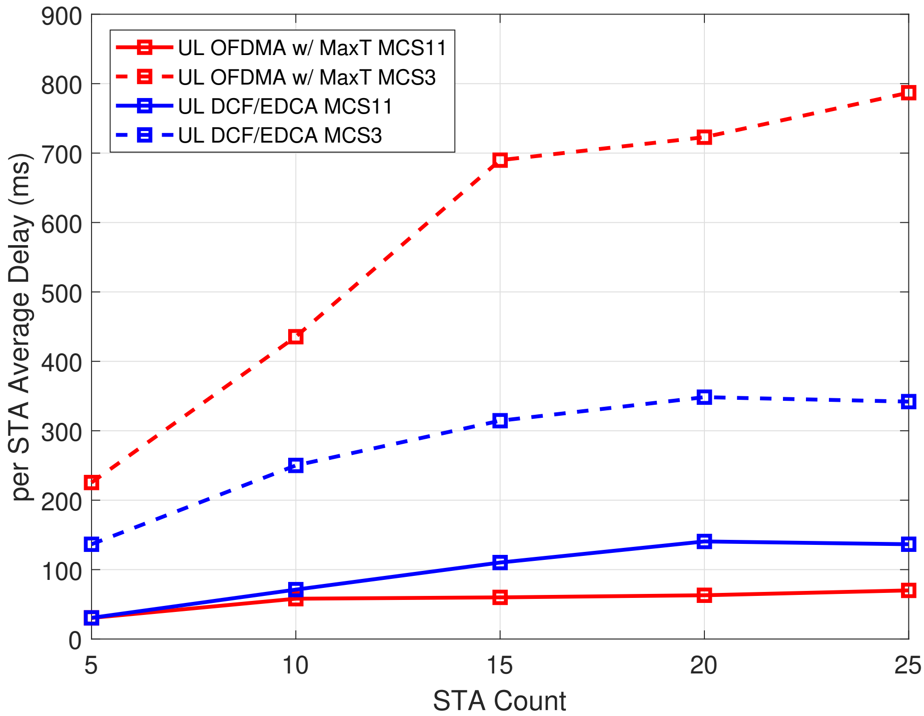

Figure 5.4. Average UL direction delay per STA under TCP.

Figure 5.4 demonstrates the average delays, but in UL direction. Here, STAs with MCS 11 levels enjoy lower delays. In contrast, STAs with MCS 3 levels suffer increasing delays as the number of STA increases.

In conclusion, our maximum throughput scheduler increases total channel throughput compared to legacy random access mechanism. Our scheduler also solves bad apple scenario and does not let low MCS levels to win the whole channel. However, STAs having higher MCS levels benefit from our model more, and low MCS levels starve more, having higher delays.

6. CONCLUSION

Introducing many new mechanisms, the latest version IEEE 802.11ax lets the AP schedule the network traffic in DL and UL directions. This controlled scheduled access aims to mitigate contention effects caused by backoffs in legacy standards, especially in dense areas with many connected devices. We designed throughput maximizing that exploit this new MU-MAC framework. Our scheduler consider queue sizes and link qualities and work dynamically at each TXOP. We modeled our scheduler with Google-OR Tools [16] and evaluated them with NS-3 [14].

We plan to add our scheduler to new abilities like satisfying QoS constraints, preserving given limits, and making them hybrid. We also plan to make a dictionary of scheduling outputs as a dictionary is less power-intensive and enables rapid access to schedule information.

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