Scheduling Problem for OFDMA Uplink in IEEE 802.11ax Networks

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Abstract—In order to . The new standard has the challenging goal of improving some performance indicators such as throughput per user
necessity
It takes the best of Wi-Fi and adds technology from LTE, hence the mastery of both technologies will be key in developing best performing .11ax solutions.

Index Terms—Wi-Fi, IEEE 802.11ax, High Effiency WLAN, OFDMA, Scheduling

I. Introduction

Беспроводные сети стали незаменимой везью в нашем мире. Nowadays, Wireless Local Area Network (WLAN) is believed to be the most popular technology for information transmission. It s not surprising.

Люди могут выходить в интернет буквально везде в современном мире - в ресторане, кафе, торговом центре, парки, общественный транспорт, аэропорту, на работе и конечно же, дома. Главное быть в зоне действия точки доступа. Такая популярность данной технологии привела к проблеме перегруженности Wi-Fi сетей, когда одна сеть перебивает сигнал другой. Чтобы справляться с этим и многими другими обстоятельствами, IEEE 802 LAN/MAN Standard committee is developing a new amelioration for Wi-Fi standard: IEEE 802.11ax (further in the paper we call it 11ax).

This amendment provides various ways to improve the efficiency of Wi-Fi, some of them are borrowed from 4G cellular technology. Nevertheless, one of the most significant technological enhancements of 11ax is the usage of Orthogonal Frequency-Division Multiple Access (OFDMA). It allows the Wi-Fi Access Point to service several stations simultaneously, to better cope with fading and, in case of uplink transmission, to improve the spectral power density.

II. OFDMA features in 11ax

A. Random Access

III. Related Works

IV. Network Scenario and Problem Statement

The considered Wi-Fi network scenario is shown in Fig 2. A group of station (STA) is connected to the Access point (AP). Stations are transmitting data in uplink using OFDMA.

можно делать. разные метрики , функции. как адаптировать известные планировщики в 11аикс в офдма. сртф мин задержку а едругие уделывают потому что используют задержку.

V. Scheduling in 11ax

VI. Ax-adaptations of Known Schedulers

VII. Numerical Results

VIII. Conclusion

In the paper, we have studied scheduling problem in 11ax networks, the standard of which is currently under development. We show that because of 11ax OFDMA peculiarities the existing schedulers cannot be directly applied to the new technology.

Specifically, in the paper we have considered the problem of uplink scheduling which aims to minimize average upload time in a scenario with high number of active users.

We showed that depending on the scenario sometimes it is worth to use classic SRTF scheduler, while in other cases the channel should be split between several STAs in order to minimize upload time. We develop a novel scheduler, called MUTAX, which adaptively chooses the best strategy and significantly outperforms existing popular solutions.
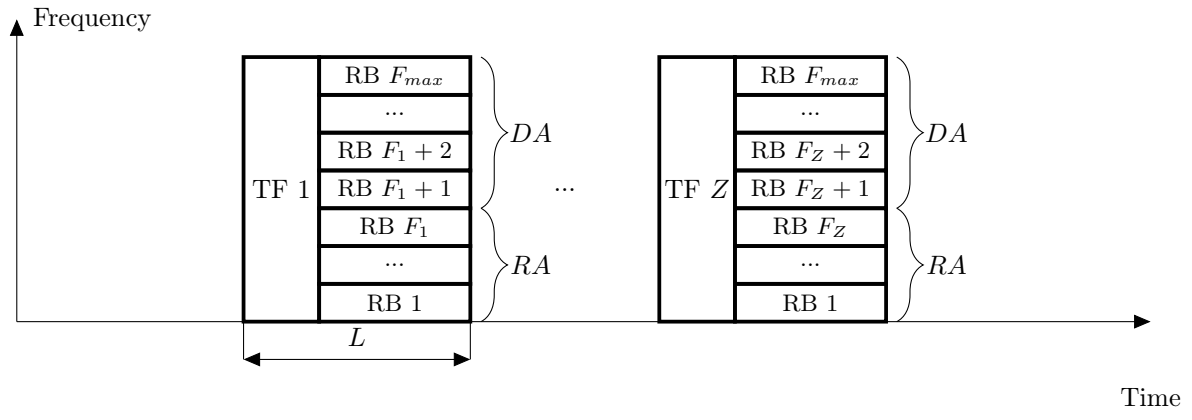
We can get gain due to division of channel.

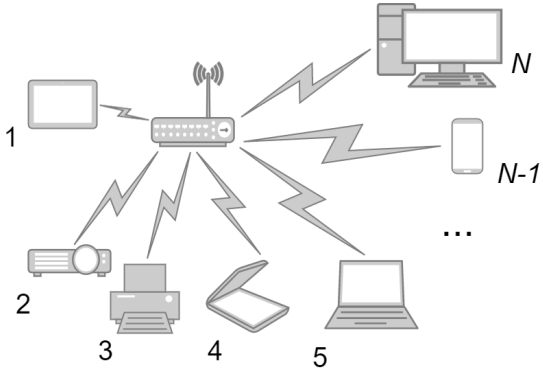Figure 1: Data transmission process from the AP's point

Figure 2: The network scenario

Abstract—**Apart from obvious advantages, such as decreasing overhead for short packet transmission at high rates and improving robustness to frequency selective interference, being used for uplink transmission, OFDMA can increase power spectral density and, consequently, user data rates. However, the gain of OFDMA mainly depends on the resource scheduling between users. It allows the Wi-Fi Access Point to service several stations simultaneously, to better cope with fading and, in case of uplink transmission, to improve the spectral power density. The peculiarities of OFDMA implementation in Wi-Fi completely change properties of classic schedulers used in other OFDMA systems, e.g. LTE. In the paper, we consider the usage of OFDMA in Wi-Fi for uplink transmission. We study peculiarities of OFDMA in Wi-Fi, adapt classic schedulers to Wi-Fi, explaining why they do not perform well. Finally we develop a novel scheduler, MUTAX, and evaluate its performance with simulation.**

Abstract—**We study the usage of OFDMA in Wi-Fi for uplink transmission and consider ways to minimize the data delivery time for typical traffic patterns. Firstly, we investigate the impact of the new random access scheme used for request of channel resources on the delay and download rate. Secondly, we develop a scheduler which takes into account the peculiarities of resource allocation in IEEE 802.11ax and aims at minimizing the data delivery time for stations.**

IX. INTRODUCTION

Nowadays, Wi-Fi has become the main technology for wireless local area networks. High number of Wi-Fi devices, as well as the number of deployed networks, leads to huge interference. To improve efficiency of Wi-Fi networks in existing and emerging indoor and outdoor scenarios, Wi-Fi community is currently developing a new standard, namely IEEE 802.11ax. In contrast to 11ac, PHY layer data rate of which tenfold excels the one of the preceding technology (namely 11n), the expected quadruple growth of user throughput in 11ax networks will be caused mostly by advanced channel access techniques, rather than by PHY data rates increased by just 37%.

The main feature of 11ax is Orthogonal Frequency Division Multiple Access (OFDMA), which extends the legacy Wi-Fi Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) by introducing a possibility to divide channel resources in frequency domain. Since 11a, Wi-Fi has been using Orthogonal Frequency Division Multiplexing (OFDM). However, with OFDM, at any time instant all tones (also referred to as subcarriers) are used to transmit data for one user, while OFDMA allows assigning various tones to different users. The efficiency of OFDMA significantly depends on how the tones are scheduled between users. However the 11ax standard will provide only a flexible framework, without any predefined scheduling algorithms.

Fortunately, scheduling problem has been carefully investigated in cellular networks, like LTE, where OFDMA has appeared much earlier. So at first sight, it is worth to use one of the existing cellular schedulers and adapt it

to Wi-Fi peculiarities. This work itself is not easy, since OFDMA fundamentals in Wi-Fi differ from that in LTE. Moreover, the features of 11ax break assumptions used to derive schedulers for LTE. Thus, nobody can guarantee that being applied to 11ax networks the LTE scheduler remain the best one.

In this paper, we compare OFDMA schemes in IEEE 802.11ax and LTE, and analyze problems that arise while developing the schedulers for 11ax networks. We also make the first step in this direction and consider a problem of minimizing the average delivery time for uplink transmission. Then we show why well-known schedulers designed for a similar problem are not optimal for 11ax networks and develop a new scheduler that outperforms them.

The rest of the paper is organized as follows. Section XI briefly describes the main features of OFDMA in 802.11ax, reviews literature and states the problem. In Section XVIII we design a brand new scheduler for 11ax networks. We prove its high efficiency in Section XIX. Section XX concludes the paper.

X. OFDMA SLAVA

One of the most important technological enhancements of IEEE 802.11ax is the usage of OFDMA. For an OFDMA transmission, the AP can split the whole bandwidth into several resource units (RUs). An RU can contain 26, 52, 106, 242, 484 or 996 tones (including service ones). The whole 20 MHz band, 40 MHz band, 80 MHz band and 160 (80+80) MHz band correspond to a 242-tone RU, 484-tone RU, 996-tone RU and two 996-tone RUs, respectively. Every RU can be split into two approximately twice-narrower RUs. In turn, each of them can be split again, separately from another one, with the following exception. A 996-tone RU can be split into two 484-tone RUs and one 26-tone RU, while a 242 RU can be split into two 106-tone RUs and one 26-tone RU. Thus, RUs can be very flexibly allocated, and the AP should try to serve simultaneously as many STAs as it has. Though OFDMA can be used for both UL and DL, UL transmissions and DL transmissions cannot overlap. For DL OFDMA transmission, the AP just sends a packet with a common preamble and RU-dependent payload. The information about addresses and allocation of the RUs is indicated at the beginning of the frame. UL OFDMA transmission is more challenging, since OFDMA transmissions of each STAs shall start and end simultaneously. That is why it starts with a trigger frame in which the AP allocates RUs to each STA and informs the STAs about the transmission parameters, e.g. MCS, transmission duration. Being polled with the trigger frame, each STA immediately replies with a data frame. The amendment describes several ways how to meet the requirement on the transmission duration. For example, advanced aggregation and fragmentation methods, as well as padding, can be used. After the UL transmission, the AP replies with a modified ACK frame, in which the AP acknowledges successfully received packets or frag-

| 26 | 26 | 26 | 26 | 26 | 26 | 26 | 26 | 26 | 26 | 26 | 26 | 26 | 26 | 26 | 26 | 26 | 26 |

| 52 | 52 | 26 | 52 | 52 | 52 | 52 | 26 | 52 | 52 |

| 106 | 26 | 106 | 106 | 26 | 106 |

| 242 | 242 |

| 484 tones |

Figure 3: RU locations in 40 MHz channel

Frequency

TF		STA x
		...
		STA 2
		STA 1

| | $SIFS$ | | $SIFS$ | MSBA |

Time

Figure 4: Frame handshake for UL OFDMA transmission.

ments. To notify the AP that the STA has some data for transmission, it can send a buffer status report with the legacy channel access method, or as a part of the described UL OFDMA transmission, or using ALOHA-like Random OFDMA channel access, which is efficient only for short transmissions and is not considered in the paper.

XI. OFDMA IN IEEE 802.11AX NETWORKS

A. Main Features

In contrast to LTE with a rigid traffic-independent time-frequency numerology, in 11ax networks, OFDMA works at the per-frame basis upon native to Wi-Fi Enhanced Distributed Channel Access (EDCA), a sort of decentralized CSMA/CA joint with automatic repeat request. OFDMA frames start with a common preamble, which can be decoded by legacy devices. Having received the preamble, a station (STA) learns the duration of the frame and considers the medium as busy till the end of the frame. The rest of the frame is understandable only by 11ax STAs and can be formed according to OFDMA concept, i.e. various tones of the frame can be assigned to different STAs.

In 11ax networks, a group of tones assigned to a STA is called Resource Unit (RU). The IEEE 802.11ax defines RUs that consist of 26, 52, 106, 242, 484, 996 and 2×996 OFDM tones. The set of available RUs depends on the channel width, e.g., in a 40 MHz channel, the STAs can use RUs of up to 484 tones. A wide RU can be split into approximately twice narrower RUs *independently from others*. The two exceptions are as follows. 1) A 996-tone RU can be split into two 484-tone RU and one 26-tone RU. 2) A 242-tone RU can be split into two 106-tone RU and one 26 tone RU, see Fig. 3.

In LTE networks, a scheduler can allocate an arbitrary subset of downlink (DL) RUs for a user or an arbitrary *interval* of UL RUs for a user. 11ax imposes much stricter constrains on RU selection, since both in DL and UL, a STA cannot be assigned to more than one RU.

Another set of constraints limits the maximal MCS that can be used in narrow RUs and the usage of MU MIMO. Specifically, MU MIMO is only available in 106-tone and greater RUs, while the novel 1024QAM can be used only in 242-tone and greater RUs. Such constraints complicate scheduling problem in 11ax networks.
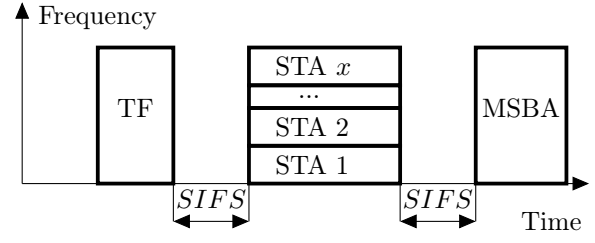
An OFDMA frame may contain RUs with different number of tones, however all RUs inside the frame must have the same duration. For that, the STAs may use novel flexible fragmentation or padding.

All transmissions inside one OFDMA frame must be synchronized, i.e. start and finish at the same time instants. This can be easily done in DL, where an OFDMA frame is generated by the Access Point (AP). However, to provide synchronization for uplink, the AP can use novel Trigger Frame (TF). SIFS after TF reception, the STAs transmit their parts of UL OFDMA frame. If needed, the AP acknowledges reception of each part by sending a set of ACKs inside an OFDMA frame or by sending Multi-STA Block Acknowledgment (MSBA).

It is the AP which, for both DL and UL transmissions, determines modulation and coding scheme (MCS), duration, RU assignment and other OFDMA parameters. Such information can be transmitted in frame headers (for DL) and in the Trigger frame (for UL). An example of UL OFDMA transmission is shown in Fig. 6.

As mentioned above, 11ax moves decision making logic from the STAs to the AP that determines which STA transmits, when, in which RU, how much data it transmits, etc. To make a correct decision, the AP needs to be aware of STAs' buffered traffic and channel conditions. This information can be periodically requested by the AP. Moreover, to notify the AP about arrived packets, a STA can proactively send so-called Buffer Status Report (BSR). For that, it can aggregate BSR with a data frame sent in the dedicated RU. Another option is legacy EDCA. Thanks to the recent change in the 11ax draft standard, the AP can separately tune EDCA parameters of scheduled STAs in such a way, that they do not contend for the channel with unscheduled STAs. It means that if a STA does not obtain UL RUs, it likely delivers a BSR at the first transmission attempt because of the extremely low contention. The third approach to send a BSR is using OFDMA Random Access. For that, the AP can allocate one or several RUs for random access and the contending STAs will randomly choose one of such RUs. Anyway, thanks to these methods, the AP can quickly obtain information about new frames buffered at the associated STAs and waiting for UL RUs.

OFDMA brings many benefits to 11ax networks. First it makes transmission more reliable to frequency selec-

tive interference and fading. This is especially important for wide 160 MHz channels introduced in 11ac. Second, with OFDMA we can glue short packets destined for or originated from various STAs, which significantly reduces overhead caused by PHY headers and channel access time and interframe spaces. Third, for UL transmissions by edge STAs it makes sense to use narrow channels instead of wide ones. Indeed, since the STAs are spatially separated they can simultaneously transmit at the maximal allowed power without breaking legal limitations on the emitted energy. Thus, by reducing RU width, we increase power spectral density received from the STAs and can use higher MCS. In other words, by allowing numerous spatially separated STAs to transmit in parallel, we increase the cumulative received power in comparison to the case when only one STA transmits. For edge STAs, increasing power spectral density leads to a higher MCS, so the average amount of data received from an OFDMA frame is higher than that from a legacy. Thus in contrast to LTE, in 802.11ax networks the rates in UL RUs are non-additive, i.e. if a STA transmits in twice wider RU, it is not guaranteed that it transmits twice more data. This effect will be carefully investigated in the paper.

B. Related Works

Despite the fact that 802.11ax amendment is expected to be finished by 2019, it has been already studied in the literature [1]–[5].

In [2], authors study the performance of the network consisting of the legacy and 802.11ax STAs. Authors propose an approach for optimal channel access parameter values selection, which guarantees fairness between legacy and 802.11ax and significantly increases the number of the OFDMA transmissions for 802.11ax STAs. However, the model developed in [2] allows only estimating the number of the OFDMA transmissions in the network, but not the achievable data rate.

Many studies on 802.11ax performance were presented at the meetings of the 802.11ax Task Group (TGax), e.g. [4], [5]. However, although many network topologies have been already studied, the only considered scheduler in TGax has been the random scheduler with a static RU configuration.

The problem of scheduling in 11ax uplink has been considered in [3], which focuses on selection of the RU duration. The authors initially assume that the AP does not know the amount of data the STAs have and thus does not know the correct duration of RUs that should be allocated. They propose a scheme that can be used by the AP to obtain this information and derive the best way to select the duration of STAs' transmission in terms of throughput and energy consumption. However, they do not consider any specific way to divide the channel into RUs and to assign the RUs to the STAs. Neither do they consider random access and the possibility of STAs to deliver BSRs by aggregating them to the transmitted data.

Random access for UL OFDMA in 802.11ax has been studied in [6]. The authors consider a scenario, when STAs transmit saturated data flows and use only random access for transmission. They describe a mathematical model of transmission with OFDMA random access and use it for analysis and optimization of the network performance in terms of throughput and percentage of successful RUs. The methodology introduced in the paper might be used to tune the random access for OFDMA UL, however, usage of deterministic access is more feasible in terms of channel efficiency for the studied scenario.

The problem of resource allocation in cellular networks is widely studied in literature. In many papers, it is formulated as the following optimization problem. Consider a network with a base station (BS) and N associated users. Each time unit, the BS runs scheduler which allocates M RUs to some STAs in order to maximize some network-wide utility function. The most widely used utility functions and corresponding schedulers are listed below.

To maximize cumulative throughput $S = \sum_{i=1}^{N} S_i(t)$ at time instant t, the BS uses the Max Rate (MR) scheduler, which considers RUs one by one and assigns each RU to a user with the highest nominal data rate in this RU (data rate of user i in RU j is hereinafter denoted as r_i^j). However, as shown in many papers (e.g. [7]), under high load the MR scheduler blocks users with low instant rates.

To avoid this problem, the Proportional Fair (PF) scheduler has been proposed. It maximizes $\sum_{i=1}^{N} \log S_i(t)$. For that, RU j shall be allocated to user $\hat{i}_{PF} = \arg\max_i \frac{r_i^j(t)}{S_i(t-1)}$. Authors of [8] show that in long term the PF scheduler gives the same amount of channel time for all users, therefore resulting in fair resource allocation.

Both MR and PF have been designed for saturated (infinite) flows. From the practical point of view, it is worth to consider unsaturated scenario with finite flows of given length. Such flows can represent HTTP requests or files transmitted in a wireless network. For such traffic, it is worth to consider upload time which affects user perceived quality of experience (QoE). If the channel properties do not change with time, the rate in different RUs is the same and additive, the Shortest Remaining Time First (SRTF) scheduler is proven to provide minimal average upload time. Simplistically, SRTF allocates all RUs to a user for which $\frac{D_i(t)}{r_i}$ is the minimal one, where $D_i(t)$ is the remaining amount of data of user i and r_i is its rate in the whole channel. As explained in Section XI-A, the assumptions made to derive such a scheduler are not met for UL OFDMA transmission in 11ax networks, which brings us to the following problem statement.

XII. Related Papers

Reviews: [1], [13]. Performance improvement for random access: [2]. Dense deployment interference improvement: [14]. Something about OFDMA: [15].

A. Problem Statement

Consider a scenario with an AP and a group of STAs associated to it. From time to time, STAs generate finite data flows to be delivered to the AP. To notify the AP about new flow, the STAs use EDCA to transmit BSR. Thus the whole channel can be allocated to those STAs, which are known by the AP as having traffic.

In the paper, we consider the following problem: *to design a scheduler for UL OFDMA data transmission in 11ax networks that minimizes the average upload time.*

XIII. Network scenario

XIV. Network Scenario and Problem Statement

We consider a scenario with an AP and a group of STAs connected to it. From time to time STAs generate data streams that have to be transmitted to the AP. The data stream length in bytes and the interval between two stream generation times are random and are described by a given distribution. In the considered scenario devices use only OFDMA for data transmission, i.e., traditional Wi-Fi random access (EDCA) is not used.

When a STA generates a stream, it requests channel resources from the AP. For this purpose it uses the OFDMA random access to send a buffer status report (BSR) to the AP. Having received a BSR, the AP learns that it has to allocate an RU for the STA, and also it learns the amount of resources that the STA intends to transmit.

We consider a typical scenario for uplink data transmission in Wi-Fi network, when the STAs send small streams, such as HTML requests or any other data related to Web browsing. In such scenario, it is critical to minimize the data delivery time for the STAs. The data delivery time for the STAs depends on two summands: the time spent in random access and the time spent actually transmitting data. Both of these summands are, in fact, determined by the scheduling algorithm used at the AP.

The IEEE 802.11ax standard does not specify a scheduler. It does not state the number of RUs that should be allocated for random access, neither does it define an algorithm to select the RU sizes for different STAs.

So we state the following problem in the paper: *to design a scheduler for Wi-Fi OFDMA uplink data transmission that minimizes data delivery time.*

Information transmission process is divided into two phases in OFDMA IEEE 802.11ax. First one is channel access phase, where stations should request a frequency band with a short request frames. The second one is directly about transmitting data. In this way from the point of packet delivery time consists of two summands: requesting time and transmission time:

$$T_{delivery} = T_{request} + T_{transmission},$$

where each summand is corresponding for each of the aforementioned phases. We want to minimize $T_{delivery}$.

Access Point is allocating Resource Units every time slot (further in the article we'll call it trigger-interval) for both processes simultaneously. It means that in one moment there could be stations which using resources for requesting phase and some other stations for transmitting phase. Obviously, the more resource blocks allocated for certain phase, the less corresponding summand is in a cost of fact that another summand's value increases respectively. Thus, in this paper we try to optimize resource block allocation process with finding the minimum amount of resource units allocated for requesting channel resource for further data transmission.

We assume the bandwidth requests to be short so that one 26-tone RB is enough for its transmission. Due to this it doesn't make sense to allocate RB larger than 26-tone for request phase. In this paper we assume that each time slot the Access Point allocates F 26-tones RBs for request phrase.

Also it's worth mentioning that if AP decides to allocate K 26-tones RBs for requesting channel phrase than the scheduler can dispose of the remaining tones. In the case when the scheduler doesn't use all the remaining tones, we assume that these unused tones are given to request phase as some number of 26-tone RBs. For example, if there are 8 stations in transmission phase and $K = 0$ then RR-scheduler gives 106-tone RB (approximately 4 times bigger than 26-tone RB) to each station (i.e. 32 out of 37 RBs are occupied now by these stations) then 5 remaining 26-tones can be used for request phrase as well. This's why next in this paper we will call K *minimum* number of resource blocks allocated for request phrase and write K_{min} for clearness. Note that in this example in trigger-frame AP will indicate that $F = 5$, where F — number of resource blocks allocated for request phrase.

Then, there is a not mentioned feature about slot duration in OFDMA. The more stations are in transmission phrase and the more RBs are allocated for request phrase, the longer the duration of the slot is.

XV. Considered process

The considered process from the point of the access point's view is shown in Fig 1. The AP is broadcasting beacons periodically with a period *beacon-interval* BI. Also during beacon-interval the AP is broadcasting trigger-frames periodically with a period *trigger-interval* TI. As said, each OFDMA RB can be used for one of two phases: for performing requests or transmitting data. Those trigger-frames contain information about block allocation. It's about set of RBs, their sizes and function of each RB for the current trigger-interval: channel access phase or transmission phase. We consider random access (RA) method for channel access phase and deterministic access methods (DA) for transmission phase. Deterministic access methods suppose presence of a scheduler, which can distribute resource blocks between stations. In this
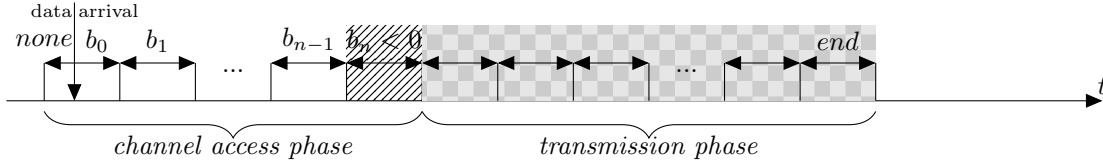
Figure 5: Data transmission process from the STA point

paper we consider interpretations of known Round Robin (RR) and Proportional Fair (PF) scheduler.

We consider following random access method shown in Fig 5. When data arrives to the transmission queue of a station, it cock random backoff counter b chosen from $[0, CW_{min} - 1]$. CW is competitive window and value of CW_{min} is indicated in beacons.

In each trigger frame number of resource blocks F allocated for RA is indicated. Each time a station receives a trigger frame, it decreases its backoff counter b by the received value of F. When the backoff becomes less than or equal to zero, the station transmits request-frame in one of the randomly selected resource blocks allocated for RA. If at least two stations have chosen the same resource block, a collision occurs, and their transmissions are considered as unsuccessful. Then the stations again throw out the random backoff counter again according to the following rule. In advance, a certain threshold is selected, let $W = CW_{min}$. With each collision happened, CW is doubled until it reaches a certain predetermined $CW_{max} = 2^S W$ and each time backoff counter is chosen from $[0, CW - 1]$. We call *backoff stage* s the number of repeated face-offs of the counter b. Then, when the station receives the packet, s equals zero, and the number S is *the maximum backoff stage*. Packets are not thrown out of the queue after the maximum backoff stage. In this case the upper CW limit does not grow. For convenience, we denote $W_i = 2^i W$, where $i \in \overline{0, S}$.

If request for the packet transmission was successful the AP includes this STA in a list of stations in DA and in the next trigger frames scheduler will take this station into account when allocating RBs.

XVI. MAIN FEATURES OF OFDMA IN 802.11AX

Data transmission in Wi-Fi with OFDMA has a number of peculiarities which make it different from data transmission in LTE, although it also uses OFDMA.

A. Channelization in 802.11ax

The available channel can be split into sets of OFDMA subcarriers called resource units (RUs). The IEEE 802.11ax defines RUs that consist of 26, 52, 106, 242, 484, 996 and 2×996 OFDM tones. The set of available RUs depends on the channel width, e.g., in a 40 MHz channel the STAs can use RUs with up to 484 tones. Wide RUs can be split into narrower RUs: 52-tone, 106-tone RU and 484-tone RUs can be split in two, while 242-tone and 996-tone RUs are split into two approximately twice-narrower

RUs (from the available set) and one 26-tone RU between them (see Fig. 3). The scheduler can allocate only one RU to a station, but it can vary the RU size for each station according to the aforementioned limitations. In other words we have 37 26-tone resource units and certain groups of 2, 4, 9, 18 or all 37 of them can be united in order to obtain larger RUs. According to the standard, such a limitation appears because of the need to have service tones next to each allocated RU of any size.

The size of an RU determines the set of modulation-coding schemes (MCSs) that can be used for transmission in the RU. For example, the standard prohibits the usage of high-speed MCSs in small RUs. At the same time, for each RU width, the standard defines the minimal receiver sensitivity to signal transmitted with a specific MCS, and the faster the MCS, the higher is the sensitivity threshold. As the result, a STA cannot use high-speed MCSs if it has poor channel conditions.

A wider RU does not necessarily mean that the STA transmits at greater speed. A STA uses the same transmission power both for wide and narrow RUs, which results in greater signal-to-noise ratio (SNR) values for narrow RUs. As the result, in a narrow RU it can use higher MCSs which can yield greater transmission rate.

B. Data Transmission Sequence

To organize data transmission process with OFDMA, the AP transmits Trigger Frames, in which it includes the scheduling information (see Fig. 6). Specifically, for each allocated RU it adds a User Info element that indicates the RU, the MCS that should be used in that RU and the AID of the designated STA. If the AID is 0, then the RU is allocated for random access, which can be used by STAs to request channel resources from the AP.

Having received a Trigger Frame, STAs transmit their data frames in designated RUs or in RUs allocated for random access. The inter-frame space between the STAs' frames and the Trigger Frame is $SIFS$. The STAs pad their frames, so that they end at the same time. To acknowledge the STA transmissions, the AP can either send multiple BlockAcks in each RU to the respective STAs, or send a single Multi-STA BlockAck which acknowledges the frames from all STAs. In any case, the inter-frame space used is $SIFS$

C. Random Access with Wi-Fi OFDMA

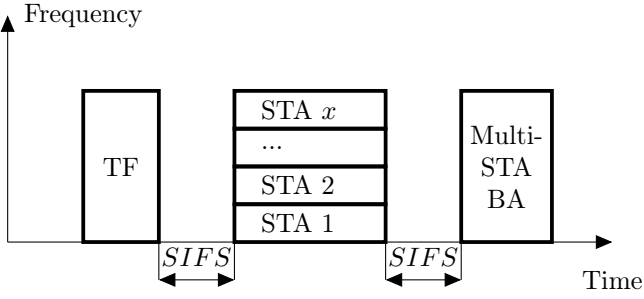The AP includes in beacons an OFDMA-based Random Access Parameter Set element, which contains the

Figure 6: Data transmission process

OFDMA contention window (OCW) parameters, specifically, its minimal (OCW_{min}) and maximal (OCW_{max}) values.

To transmit a frame in random access, a STA maintains an OFDMA backoff (OBO) counter and an OFDMA contention window, initially equal to $OCWmin$. For a frame transmission, the STA draws its OBO counter equiprobably in the range from 0 to OCW. Every time a STA receives a Trigger Frame, it decrements the OBO counter by the number of RUs assigned for random access. If the OBO counter becomes less then or equal to zero, the STA randomly selects one of the RUs assigned for random access and transmits its frame in this RU. If the frame is successfully transmitted (i.e., the STA has received an acknowledgement for its frame), the STA sets its OCW to $OCWmin$. Otherwise, the STA updates its OCW to $2 \times OCW + 1$, if the new OCW does not exceed $OCWmax$.

XVII. Scheduler

Dynamic programming algorithm to solve the problem: [9].

XVIII. Design of the Scheduler

In this section, we design a novel scheduler called MUTAX, Minimizing Upload Time in 11AX networks. While deriving formulae we neglect the effects related to packetization (including aggregation and fragmentation) overhead. Apart from that, for shortness we consider only n STAs with flows and assume that each STA has only one flow. Both STA and flow are denoted as $i, i = 1, ..., n$.

Let slot be a time interval between two consequent TFs. It should be noted that slots may have different duration. The maximal one is related to the standard limit of 5484 μs for the physical protocol data unit (PPDU) duration. A slot can be shorter, if all STAs that transmit in this slot have no more data.

The MUTAX algorithm has two steps. At the first step, we order existing flows and calculate the sum upload time of the flows, as if we used exhaustive service. At the second stage, we try to improve the sum upload time by serving some flows in parallel. Let us consider the steps in detail.

At the first step, we serve each flow exhaustively. Except for waiting, the time needed to upload flow i equals $t_i = $ $\frac{D_i}{r_i}$. The first STA finishes delivering its flow by time t_1. The second STA starts right after the first one and delivers its flow by time $t_2 + t_1$, etc. As the result, the total upload time for existing flows is

$$T_{step1} = \sum_{i=1}^{n} (n - i) \, t_i. \tag{1}$$

Obviously, to minimize the sum upload time we have to sort the STAs in the ascending order by t_i.

At the second step, we divide the channel into several RUs. Let m be the number of RUs and $j, 1 \le j \le m$ be the index of RU in the considered RU configuration. x_i^j is an indicator which equals 1 if STA i is assigned to RU j, and 0, otherwise. For shortness, X is the two dimensional matrix of $\left\{ x_i^j \right\}$ representing RU assignment to the STAs.

With defined notation, the total upload time $T(X)$ of existing flows differs from T_{step1} in the following way. First, the upload time of each of n flows increases by the current slot duration τ. Second, if $x_i^j = 1$, the remaining amount of data of flow i decreases by the amount of data the STA transmits in RU j of the current slot: $\Delta D_i^j = \min \left\{ D_i, \tau \times r_i^j \right\}$. Thus

$$T(X) = n\tau + \sum_{i=1}^{n} (n - i) \frac{D_i - \sum_{k=1}^{m} x_i^j \Delta D_i^j}{r_i}. \tag{2}$$

Since both τ and ΔD_i^j depend on the resource allocation X, minimization of $T(X)$ requires exhaustive search by possible ways to allocate the RUs to the STAs, and to simplify the task we propose an heuristic approach based on two assumptions. Firstly, we neglect the change of $n\tau$ for different allocations, as a slot cannot be too long due to standard limitations. Secondly, we sort the STAs in the ascending order by t_n only once, before considering different ways to assign RUs to the STAs. Under these assumptions, to minimize $T(X)$, we have to maximize the following expression $\sum_{k=1}^{m} \sum_{i=1}^{n} (n - i) \frac{x_i^j \Delta D_i^j}{r_i}$.

Let us denote $\lambda_i^j = (n - i) \frac{\Delta D_i^j}{r_i}$ and define the following optimization problem:

$$\max \sum_i \sum_j x_i^j \lambda_i^j \tag{3}$$

$$\text{subject to} \sum_i x_i^j \le 1, \quad \forall j \tag{4}$$

$$\sum_j x_i^j \le 1, \quad \forall i \tag{5}$$

$$\sum_i \sum_j x_i^j \le m \tag{6}$$

This problem[1] is known as the assignment problem which can be solved in polynomial time using the Kuhn-Munkres

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[1]If we define $\lambda_i^j = \frac{r_i^j}{S_i}$, where S_i is the amount of data transmitted by STA i, we obtain the optimization problem for the adaptation of the PF scheduler to 11ax.

algorithm [9]. Its solution is the assignment $\hat{X}$ that yields minimal $T(X)$.

Note that assignment $\hat{X}$ is found for a specific configuration of RUs. To minimize upload time, we consider different ways to split the channel into RUs. For each configuration of RUs we solve the optimization problem and thus find the best assignment of the channel resources. The examination of RU configuration can be hastened by excluding configurations that are obviously worse than the known alternatives, e.g., if we have two STAs and a 20 MHz channel, we consider configuration with one 106-tone, one 52-tone and three 26-tone RUs, but exclude configuration with one 106-tone RU and five 26-tone RUs.

XIX. NUMERICAL RESULTS

To evaluate the developed scheduler, we use the well-known NS-3 simulator [10]. We have implemented the MUTAX scheduler, as well as 11ax adaptations of PF, MR and SRTF. Since the performance of PF significantly depends on how the channel is divided into RUs, we find the best RU configuration with exhaustive search.

We run simulation in a scenario described in Section XII-A. The network operates in a 40 MHz channel at 5 GHz. The flow sizes are drawn from truncated lognormal distribution with minimal, average and maximal values of 1 KB, 500 KB, and 5 MB, respectively. When a flow is delivered, the next flow is generated after a random delay drawn from truncated exponential distribution with minimal, average and maximal values of 0.1 s, 0.3 s and 0.6 s, respectively. We consider channel with no fading and the 802.11ax path-loss model for the residential scenario [11]. All STAs transmit with power of 15 dBm. The AP has a set of bounds on receive power for each MCS, and assigns each STA the maximal MCS that fits the specified bounds. As mentioned in Section XI-A, the MCS assigned to a STA can differ depending on the RU width.

In first set of experiments, the STAs are located uniformly within a small circle of radius $R = 5$ m around the AP. In such a case, the channel quality is so high that in any RU the STAs use the maximal permitted MCS. Obviously, in this case OFDMA cannot bring any profit against SRTF, as the division of the channel without changing the MCS cannot increase the data rate, provided that the MCS can cope with the noise. This result is supported by simulation, see Fig 7, which shows that if the channel for all STAs is perfect, MUTAX yields the same upload time, as SRTF, and they both outperform the PF and MR schedulers by up to 30%. As we consider traffic model of a closed loop system, along with the reduction of upload time MUTAX provides the increase of goodput compared to the other schedulers.

The second set of experiments corresponds to the case when STAs are located in a larger circle of radius $R = 20$ m. Such conditions provide variety of MCSs among STAs and among RU widths, so it becomes feasible to split the channel between different users. According to

simulation results, see Fig. 8, in this case designed to minimize upload time the classic SRTF works much worse than even 11ax adaptation of PF. At the same time, MUTAX shows 20% lower upload time than PF. The results show that in this case the schedulers based on the exhaustive service (MR and SRTF) are much less efficient than channel-splitting schedulers (MUTAX and PF) and the gap between them increases with the number of client STAs. In a large circle scenario the gain in goodput of MUTAX against SRTF and MR is almost 100%.

XX. CONCLUSION

In the paper, we have studied scheduling problem in IEEE 802.11ax networks, the standard of which is currently under development. We show that because of 11ax OFDMA peculiarities the existing schedulers cannot be directly applied to the new technology. Specifically, in the paper we have considered the problem of uplink scheduling which aims to minimize average upload time in a scenario with high number of active users. We showed that depending on the scenario sometimes it is worth to use classic SRTF scheduler, while in other cases the channel should be split between several STAs in order to minimize upload time. We develop a novel scheduler, called MUTAX, which adaptively chooses the best strategy and significantly outperforms existing popular solutions.

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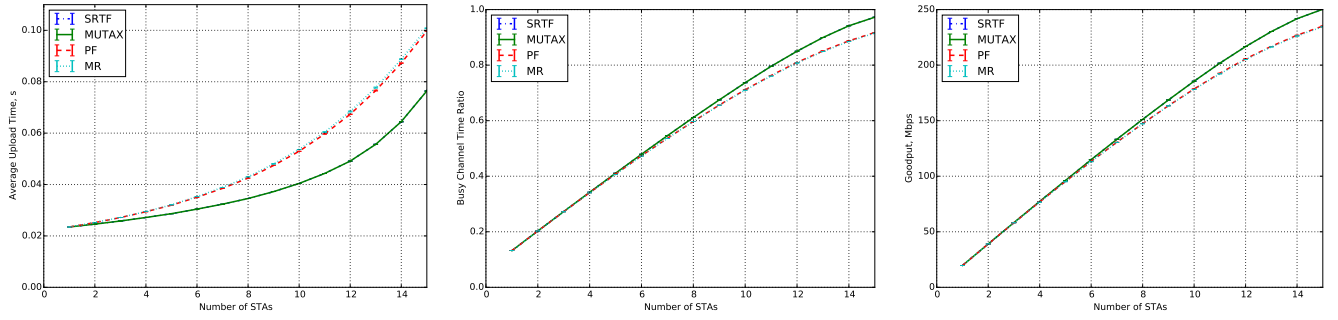
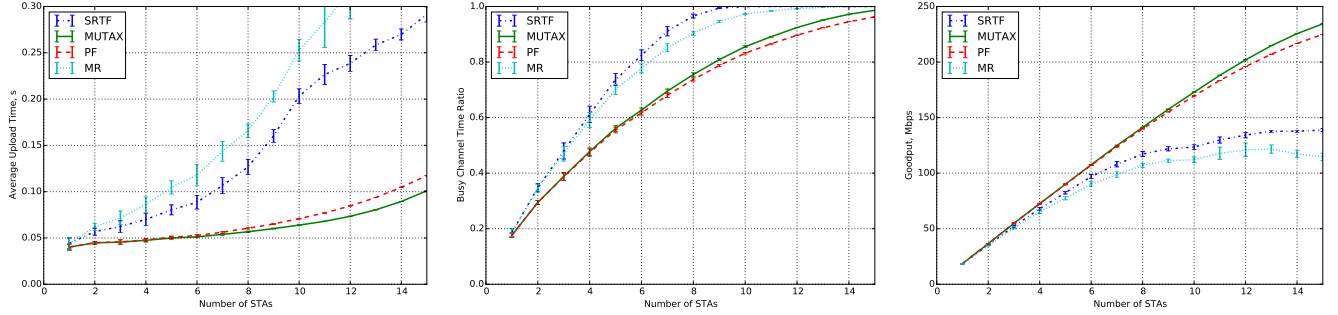Figure 7: Upload time, busy channel time ratio and goodput vs the number of STAs in the small circle.

Figure 8: Upload time, busy channel time ratio and goodput vs the number of STAs in the large circle.

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