A2P: A Scalable OFDMA Polling Algorithm for Time-Sensitive Wi-Fi Networks

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***Abstract*—Over the years, advancements such as increased bandwidth, new modulation and coding schemes, frame aggregation, and the use of multiple antennas have been employed to enhance Wi-Fi performance. Nonetheless, as network density and the demand for low-latency applications increases, contention delays and retransmissions have become obstacles to efficient Wi-Fi deployment in modern scenarios. The introduction of Orthogonal Frequency-Division Multiple Access (OFDMA) in the IEEE 802.11 standard allows simultaneous transmissions to and from multiple users within the same transmission opportunity, thereby reducing the contention. However, the AP must efficiently manage the resource allocation, particularly in uplink scenarios where it lacks prior knowledge of users' buffer statuses, thus making polling a critical bottleneck in networks with a high number of users with sporadic traffic pattern. This paper addresses the polling problem and introduces the A2P algorithm, designed to enable scalable and efficient polling in high-density OFDMA-based time sensitive Wi-Fi networks. Simulation results show that A2P outperforms the alternative schemes by maintaining significantly lower delay and packet loss in dense time-sensitive teleconferencing scenario.**

***Index Terms*—Wi-Fi, OFDMA, polling, scalability, simulation**

I. Introduction

Historically, Wi-Fi technology standardized as IEEE 802.11 has always relied solely on random channel access procedures, Distributed Coordination Function (DCF) or Enhanced Distributed Channel Access (EDCA). One of the main advantages of such schemes is that stations can transmit data on demand, without the need for the access point (AP) to coordinate the schedule. Throughout the development of Wi-Fi, different approaches were applied to increase its performance in terms of the data rate, such as bandwidth increase, advanced modulation and coding schemes, frame aggregation, and multiple transmitting and receiving antennas. However, with increasing network density and application demands for low latency, the overhead corresponding to the contention delays and retransmissions has become a significant obstacle for applying Wi-Fi to many modern scenarios, which often encompass time sensitive traffic. In contrast, channel orchestration delays for scheduled access have become lower due to increased data rate. Hence, since the introduction of the IEEE 802.11ax standard [1], OFDMA is available as an alternative channel access method in Wi-Fi.

Although OFDMA is relatively new to Wi-Fi, it has long been used for wireless communication in cellular systems, such as 4G, 5G, and beyond. OFDMA allows simultaneous transmissions to/from multiple users in the same transmission opportunity, thus reducing the contention between them. To achieve this, the bandwidth is divided into multiple subcarriers, called Resource Units (RUs), that can be allocated by the AP to different users. Hence, the AP needs to know the buffer status of those users to avoid allocating resources to users with empty buffers. In downlink, the AP knows how many packets/bytes it needs to send to each user, but in uplink it has to poll the users to obtain buffer status reports (BSRs). When the number of users increases, polling becomes the bottleneck, because the AP does not know in advance which users are going to have data to transmit. In literature, this problem did not gain much attention, and most of the works are focused on optimizing the scheduling procedure in order to satisfy the quality of service (QoS) requirements (see more details in Section III). In this paper, we highlight the polling issue, and propose the A2P algorithm that enables scalable and efficient polling in Wi-Fi networks with a high number of users with sporadic traffic.

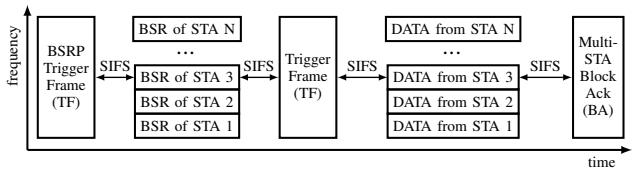

Fig. 1: UL OFDMA frame exchange sequence

The rest of the paper is organized as follows. Section II provides an overview of the main OFDMA features and parameters. In Section III, we analyze the state-of-the-art methods and approaches to configuring and optimizing OFDMA operation in Wi-Fi. In Section IV, we describe the system model. Subsequently, Section V introduces the proposed A2P polling algorithm. In Section VI, we study the performance of the proposed algorithm against common alternatives and baselines. Finally, in Section VII, we conclude the paper.

II. OFDMA Operation in Wi-Fi Networks

IEEE 802.11ax, also referred to as Wi-Fi 6, introduced OFDMA to the Wi-Fi world [1]. When OFDMA is used, the data transmission for each station (STA) does not occupy the whole bandwidth. Instead, the bandwidth is divided into multiple RUs, which are allocated to different STAs. Each RU

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may consist of 26, 52, 106, 242 (20 MHz), 484 (40 MHz), 996 (80 MHz), 2x996 (160 MHz), and since IEEE 802.11be (Wi-Fi 7) [2] 4x996 (320 MHz) tones.

The Wi-Fi standard supports both downlink (DL) and uplink (UL) OFDMA transmissions. Since the focus of this paper is on the polling procedure, that occurs only in UL OFDMA, further we describe the UL case.

OFDMA operates atop random channel access (EDCA), meaning that, to initiate multi-user frame exchange, the AP must access the channel by contending with STAs and other neighboring APs. Once the AP wins the contention, it can initiate UL OFDMA transmission by sending a Trigger Frame (TF). This frame contains, among other parameters, a mapping between the STAs that will transmit and their respective RU allocation. After a time interval referred to as short inter-frame space (SIFS), the UL OFDMA transmission follows. Transmissions in one multi-user OFDMA frame must be synchronized in time. As such, short-length data packets should be padded and/or aggregated to match the size of the largest packet in this OFDMA frame. A SIFS after the transmission finishes, the AP replies with a multi-STA Block Acknowledgement (BA), confirming the reception of the uplink packets from different users.

To schedule RUs to STAs that have UL data, the AP requires information about the buffer status of the queues in those STAs. To obtain this information, the AP polls the STAs with a special TF called buffer status report poll (BSRP) TF. Similarly to the regular TF, the BSRP TF contains the mapping of different users to RUs, in which the AP expects the buffer status report (BSR) in response containing the buffer size in bytes. STAs can provide their BSR explicitly using a QoS-Null frame with no payload in response to a BSR Poll (BSRP) TF matching their Association Identifier (AID), or implicitly through the QoS control field of any transmitted frame. STAs with non-empty buffers are then considered for scheduling in the subsequent TF. The complete frame exchange sequence for the UL OFDMA procedure is depicted in Figure 1.

To promote airtime fairness and reduce contention in a densely deployed network, Wi-Fi introduced the MU EDCA Parameter Set, which contains EDCA parameters (contention window and arbitrary inter-frame space) that should be used by the STA participating in OFDMA transmissions. This way, the network can be configured so that the AP gets more control in orchestrating UL transmissions, while the STAs themselves compete for the channel less aggressively, or do not compete for the channel at all. The MU-EDCA Parameter Set is announced by the AP in beacon frames. Apart from the EDCA parameters, it also contains the validity timer. Once the timer is expired, the STA reverts to the default EDCA parameters. The timer is reset at the STA every time successful OFDMA transmission occurs, i.e., after the successful reception of a BA from the AP. Thus, the STA maintains the updated parameters as long as it gets resources scheduled by the AP.

Clearly, explicit solicitation of BSRs from STAs through BSRP TF does not scale well in scenarios with many STAs associated with the same AP. More specifically, in scenarios such as large teleconferencing applications, where only a handful of users are actively talking (i.e., transmitting data), while many others are following the conversation (i.e., only receiving data), the polling of idle STAs without data to transmit wastes resources and degrades the overall network performance. In this paper, we show that inefficient polling leads to violation of QoS requirements, and propose a solution that outperforms the alternative schemes in terms of the achieved latency and ratio of packets delivered on time.

III. Related Work

Numerous works in literature propose solutions and improvements for OFDMA performance optimization in Wi-Fi networks. Many papers [3]–[8] consider resource allocation algorithms, while BSR collection is not considered as a potential bottleneck for UL OFDMA performance. In [3], the resource allocation problem was formulated as an optimization problem and addressed using a sub-optimal divide-and-conquer recursive algorithm. In [4], the authors propose an adaptation of three well-known scheduling algorithms — MaxRate, Proportional Fair and Shortest Remaining Processing Time — to Wi-Fi. In [5], the authors propose a scheduling algorithm for deadline-constrained traffic. To estimate the delay the packet will spend in the queue before the transmission, the authors apply queuing theory using the buffer statuses reported by the STAs. In [6], a heuristic algorithm is designed to prioritize users based on the reported buffer sizes for each access category (AC). In more recent papers [7], [8], a deep reinforcement learning approach is applied. For most of the solutions proposed in these papers, the knowledge of buffer statuses plays a crucial role, but the overhead related to the BSR collection procedure is left out of scope.

A common approach considered in literature for BSR is to utilize Uplink OFDMA-based Random Access (UORA) defined in the IEEE 802.11 standard. Since it is based on random access, collisions are possible. After a collision, the STA will have to retransmit lost packets, that is why UORA is often considered as a solution only for BSRs, because they are generally significantly shorter than data packets. There are multiple papers in literature evaluating performance of UORA and proposing enhancements. In [9], [10], the metric BSR delivery rate is introduced. The performance evaluation shows that BSR delivery is of crucial importance for the performance of the scheduling algorithm. Besides, the authors propose a resource allocation algorithm that varies the number of random access RUs depending on the number of STAs with non-zero BSRs. However, the proposed algorithm will not allocate any RUs to UORA if the number of STAs with non-zero BSRs is higher or equal than the number of available RUs, thus significantly favoring the STAs with already known BSR. In [11]–[13], the authors propose different schemes for collision resolution in UORA to reduce latency related to retransmissions of the lost packets. In this paper, we leave

UORA out of scope for several reasons. First, we argue that UORA sacrifices the part of available bandwidth leading to its underutilization when there are not many STAs with new data. Second, UORA is not a mandatory feature in the IEEE 802.11ax standard. Third, there is no verified and publicly available implementation of UORA in the available network simulators. However, it will be considered in our future works.

Recently, a few papers proposed solutions that do not rely on UORA. In [14], the authors consider the problem of providing fully deterministic channel access in Wi-Fi. For that, they propose to completely disable random access procedures, and let the AP orchestrate all UL transmissions. Although such an approach is very powerful when the traffic pattern is known, e.g., when it is periodic, we show in this paper that it will lead to significant performance degradation in scenarios with many devices with unpredictable on-off traffic. In [15], the BSR collection is proposed based on multiple rounds of BSRP TF and BSR exchanges to collect BSRs from all STAs before scheduling resources for data transmission. This approach can improve the fairness by giving more information to the scheduling algorithm before it makes its decision, but does not solve the problem of BSR collection overhead. In [16], client-side access manipulation is proposed. According to this manipulation, the STA switches between two channel access schemes, EDCA and OFDMA, depending on its latest buffer status. In the OFDMA state, it fully disables EDCA, while in the EDCA state it competes for the channel with other STAs and the AP. However, according to the standard it is the AP who controls these two states via the MU EDCA Parameter Set. Moreover, excluding the AP from the decision process may lead to inconsistent behavior and resource waste, as the AP does not know the STA's state.

In this paper, we propose a fully standard compliant A2P algorithm that significantly improves the latency compared to the state of the art. This is verified in a challenging teleconference scenario with a high number of STAs.

IV. System Model

We consider a teleconferencing system, where multiple participants with wireless microphones and headphones are connected to the server through a single AP. We assume that the communication channel between the server and the AP is extremely fast (e.g., fiber connection), hence we consider both as a single entity. Furthermore, we assume that the microphone and headphones are integrated into a single tabletop unit, which we call a Station (STA). In this paper, we restrict the scope of our model to only the bidirectional audio streams, from microphones to the server and from the server to the headphones. Although not all microphones are active at the same time, the total number of STAs can be very high in large-scale teleconferencing settings (e.g., in large debating halls such as a parliament); easily exceeding 100.

When a user presses it's microphone button to start speaking, the STA generates an UL constant bit rate (CBR) audio data stream, which stops when the button is released, resulting in a stochastic on-off data streaming pattern. The streaming

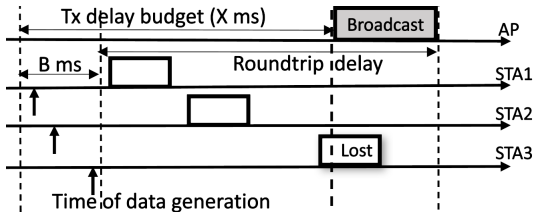

Fig. 2: Model of system's traffic pattern

timeline is divided into $X\text{ms}$ windows, and within first B ms of the window, the STA can generate the audio packet. Each packet contains M samples of audio information with N bit resolution, and a W bits application layer header, resulting in a packet size of $M \times N + W$ bits, and a bitrate of $1000 \times (M \times N + W) / X\text{bps}$.

To avoid overload, the STAs should deliver their packets within the transmission delay budget ($X\text{ms}$), defined as the maximum allowable time for a packet to be received by the AP after its generation. UL packets that arrive later than $X\text{ms}$ are considered lost, and hence ignored by the server. For instance, in Figure 2, STA1 and STA2 successfully transmit within the delay budget. In contrast, STA3's packet is received by the AP after the delay budget, and is, therefore, lost.

After the server receives data packets from all the active STAs or the end of delay budget is reached, it generates a single DL data packet containing mixed audio information received from the STAs. This DL packet contains P samples with resolution of Q bits, and an application layer header of W bits. The packet size is therefore $P \times Q + W$ bits. As it follows the same packet generation interval $X\text{ms}$ as the STA, the DL bitrate is $1000 \times (P \times Q + W) / X$ bps. The packet is broadcast to all STAs. This way the participants can follow the ongoing conversation. The broadcast packet in Figure 2 contains mixed samples received only from STA1 and STA2. Note that the packet size of the DL packet is independent of the number of successfully received UL packets.

Since the AP should have access to the channel to orchestrate UL transmissions, it cannot request it only when it has enqueued DL packets. Hence, it periodically requests the channel with periodicity T ms called Access Request Interval (ARI). To avoid unnecessary attempts to request the channel, we count down this interval from the last time the AP obtained access to the channel.

V. A2P Polling Algorithm

Our proposal towards a more efficient polling for UL OFDMA involves the combination of the two main channel access mechanisms in Wi-Fi, EDCA and OFDMA. The AP maintains a list of active STAs (i.e., STAs that are expected to transmit data), called the *polling list*. These STAs use only UL OFDMA channel access, thus reducing the amount of channel time wasted on EDCA contention. All other STAs use the EDCA mechanism. To get on the polling list, a STA that wins access to the channel transmits its initial packet, thus announcing the start of of data stream. After a successful uplink EDCA data exchange, the AP disables EDCA on the

STA for a period of Y Time Units (TUs) using the MU EDCA Parameter Set. Meanwhile, STAs that have not reported any data after being polled during Y TUs are removed from the polling list. If the size of the polling list exceeds the number of available RUs for the chosen bandwidth, a simple round-robin method is used to choose which STAs to poll. Additionally, the AP can request access to the channel only after waiting one ARI from the previous granted access, provided there is no enqueued downlink frame.

Figure 3 illustrates the A2P STA-side procedures as a flow chart. A STA that gains access to the channel through contention transmits data and, upon receiving an ACK, disables EDCA for a duration of MU-EDCA timer value, i.e., Y TUs. The MU-EDCA timer is reset to its original value if, before it counts down to zero, the STA takes part in UL-OFDMA (i.e., successfully transmits frames and receives the BlockAck). Otherwise, EDCA is re-enabled when the timer reaches zero, and the STA can contend for the channel again.

The flow chart for the AP side is shown in Figure 4. After acknowledging the reception of the frames that were transmitted by STAs, the AP adds the new STAs to the polling list and sets a timer (i.e., Y TUs) for each STA. When the AP wins channel contention, it decides on either performing DL or UL frame exchange. For simplicity and fairness between UL and DL, we assume that these alternate each other, i.e., a DL frame exchange after every UL frame exchange and vice versa. Since the considered teleconferencing system requires only a single broadcast DL transmission, this logic does not affect the performance. During UL transmission, the AP selects a group of STAs to participate in the poll-based frame exchange using round-robin scheduling. The maximum number of selected STAs depends on the number of available RUs for the chosen bandwidth. To maximize the number of supported simultaneous transmissions, we consider only the smallest 26-tones RUs. For instance, a $40\,\mathrm{MHz}$ channel can serve up to 18 STAs. Note that this assumption is reasonable for audio traffic, because it has a relatively low bitrate. For heavier traffic it may lead to performance degradation. Following the UL OFDMA frame exchange, the AP resets the timer of those STAs that successfully transmitted data.

VI. Performance Evaluation

We validate the performance of the proposed A2P algorithm using the network simulator, NS-3. It is a system-level discrete event network simulator written in C++ that allows simulating the functions of the various elements of the network stack [17], [18].

We compare A2P to the following baseline schemes: 1) *EDCA*: Disabling OFDMA to only use EDCA. 2) *OFDMA*: Utilising only OFDMA, where all STAs in the network are polled. EDCA is disabled using MU EDCA Parameters Set. The MU EDCA timer is set to the maximum allowable duration of $2088.96\,\mathrm{ms}$, thus EDCA can still be used sporadically, e.g., for the initial packet of a new data flow. 3) *OFDMA + EDCA*: Utilising both OFDMA and EDCA concurrently. In this case, the MU EDCA Parameters Set is not used.

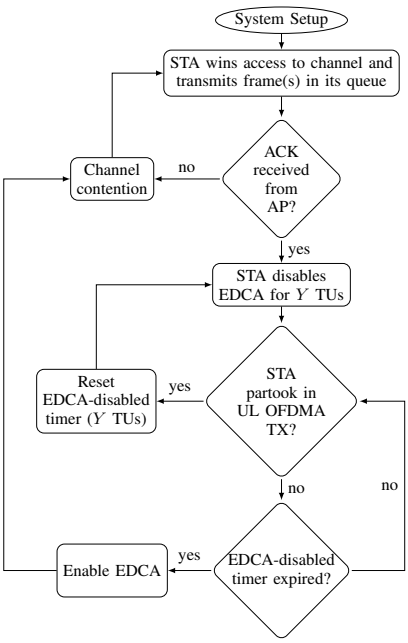

Fig. 3: Flow chart of the algorithmic procedure at STA side

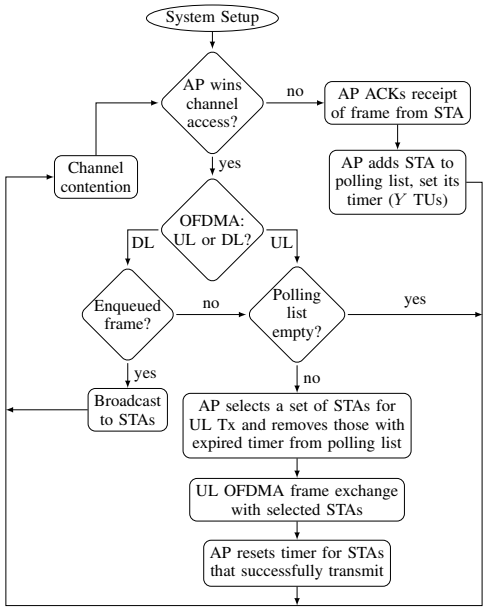

Fig. 4: Flow chart of the algorithmic procedure at AP side

The evaluation is based on the following performance indicators: 1) *End-to-End (E2E) Delay*: The total round-trip time from the UL packet generation at a STA to the DL packet reception by this STA. 2) *Packet Loss Ratio*: Ratio of lost and outdated (i.e., arriving outside the TX delay budget) packets to the total number of transmitted packets. 3) *Wake Up Delay*: Delay of the first packet announcing an activated microphone.

A. Simulation Setup

In the simulation, we model a single basic service set (BSS) comprising multiple STAs and a single AP that support the 802.11ax standard. The traffic parameters are based on those of a state-of-the-art teleconferencing application. Each

TABLE I: List of simulation parameters

Parameter	Value
Carrier frequency	5 GHz
Bandwidth	40 MHz
Guard Interval	0.8 µs
Propagation Loss Model	IEEE Indoor Model B [19]
MCS Index	8
Resource Unit Type	26-tone only
Transmit Opportunity	2080 µs
AP Access Request Interval (ARI), T	16 µs
MU EDCA Timer	40 ms
EDCA Access Category	VO
Downlink Payload Size	500 B
Uplink Payload Size	740 B
Inter-Packet Interval, X	5 ms
UL Packet Generation Window Part, B	1 ms
Off- to on- & On- to off-time interval, τ	Bounded Exp. Distribution, (mean 10 s, max 25 s)
Number of STAs	100
Duration of Simulation	30 s

STA generates constant bit rate UDP traffic of approximately 1.2 Mbps (each packet contains $M = 240$ samples with $N = 24$ bit resolution, and $W = 20$ byte application-layer header is used). The AP broadcasts UDP traffic to all STAs at a rate of around 0.1 Mbps (each packet contains $P = 240$ samples with $Q = 16$ bit resolution, and the same header size $W = 20$ byte is used). All traffic is set to the Voice (VO) AC.

We ensure that the transmission power is sufficiently high that the probability of packet loss due to channel errors is negligibly small. Hence, in the considered setup the packets can be lost only due to collisions or delays. Furthermore, the impact on performance of STAs implicitly reporting their buffer status is negligible, and thus disabled.

Not all STAs transmit UL data in any given experiment; those transmitting are called *active*, while those that do not send any data are called *idle*. The total number of STAs associated with the AP is equal to 100. Prior to the start of simulation, two sets of STAs are randomly selected; *initial* 8 active STAs, and a varying number of *joining* STAs (that will become active during the experiment). The AP establishes Block ACK agreements with each STA at the start of simulation (cf., system setup in Figures 3 and 4), thus determining the ACK sequence that will be employed throughout the simulation. The initial 8 STAs randomly transmit their first packets within $B = 1$ ms after the system setup. After this step, the joining STAs randomly decide when to start transmitting (referred to as *on-time*) and when to stop (i.e., *off-time*). The time between the consecutive UL data streams on the same STA (between off-time and next on-time) and the stream duration (time between on-time and off-time), τ, follow an exponential distribution with a mean of 10 s and an upper bound of 25 s. This on-off

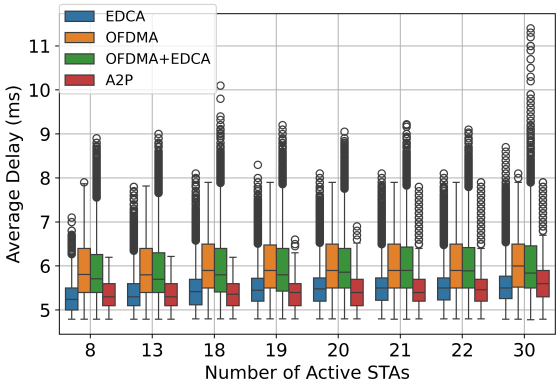

Fig. 5: Performance evaluation: average delay

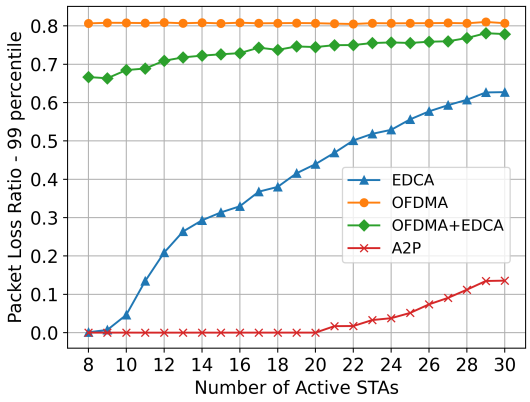

Fig. 6: Performance evaluation: 99% packet loss ratio

transmission pattern of the joining STAs continues for the duration of the simulation. This simulation scenario depicts a teleconferencing system where participants wish to join or leave the ongoing discussion. Table I lists the parameter values used in the experiments.

B. Discussion of Results

In this section, we compare the performance of the four schemes in terms of the main metrics for the considered application, namely delay and packet loss ratio. Figure 5 represents the round-trip delay (from microphone to headphones) for different numbers of active STAs. Here by active STAs we mean the number of joining STAs plus the initial 8 STAs. We show the results as a box plot, where the median, lower and upper quartiles and extreme values of delay can be clearly seen. A2P and EDCA both show relatively low median and interquartile range compared to OFDMA and OFDMA+EDCA. However, for EDCA the height of outliers increases significantly when moving from 8 to 19 active STAs. With an UL delay budget of 5 ms and no budget constraints on DL broadcasts, outliers are primarily attributed to DL transmissions. While EDCA DL transmissions compete for the channel with UL transmissions and are vulnerable to losses due to collisions, A2P manages to orchestrate UL and DL transmissions without competition. The higher delay experienced by OFDMA and OFDMA+EDCA is due to additional latency of polling the large number of idle STAs.

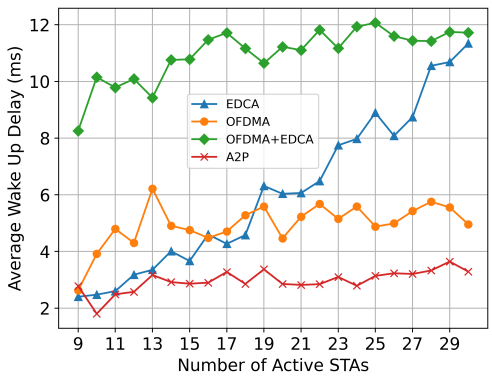

Fig. 7: Performance evaluation: average wake up delay

Besides the delay, we also compare the schemes in terms of the system capacity, i.e., the number of STAs that we can support without experiencing packet loss. Figure 6 shows that, in one BSS, up to 20 and 27 devices are supported by A2P with $0\,\%$ and $10\,\%$ packet loss, respectively. With similar QoS requirements, EDCA supports a maximum of 10 active STAs. Furthermore, the poor performance of OFDMA and OFDMA+EDCA schemes utilising legacy polling algorithm is caused by inability to poll the STAs with UL data on time.

With EDCA, the average latency of initial packets announcing a STA's activation (wake up delay) drastically increases with the growing number of active STAs due to contention. Nonetheless, as shown in Figure 7, A2P addresses this by disabling EDCA on transmitting STAs, thereby reducing the number of contending STAs. In particular, the average wake up delay is less than $4\,\mathrm{ms}$ for up to 30 active STAs. When an inactive device with disabled EDCA is reactivated after the MU EDCA timer expires, the initial packet is transmitted through EDCA, thereby reducing the wake up delay compared to an UL OFDMA round-robin polling scheme. Note that OFDMA provides relatively low delay even in case of high number of active STAs, because the activated STA still uses EDCA for the initial packet due to expiration of the MU EDCA timer. In the OFDMA + EDCA case, OFDMA and EDCA operate independently, thus the performance is degraded due to cumulative effect of the drawbacks of each scheme. More specifically, the channel time is wasted on both EDCA contention between the active STAs and on the transmission of unnecessary trigger frames to poll idle STAs.

VII. Conclusion

In this work, we proposed the A2P polling algorithm that empowers Wi-Fi to meet the stringent QoS requirements of real-time wireless systems. Our approach leverages the combination of two channel access schemes, EDCA and OFDMA, where OFDMA is used to orchestrate transmissions of active stations, while EDCA provides a faster way of indicating the active state of a station. More specifically, the AP maintains the list of active stations that are regularly polled to update the information about their buffer statuses. Using a representative use case of a dense teleconferencing system comprising a large number of stations, we prove with simulation that A2P outperforms the legacy schemes, such as EDCA only, OFDMA only and OFDMA+EDCA. In particular, with 40 MHz bandwidth A2P supports up to 20 stations without packet loss, and achieves the lowest delay.

We plan to use mathematical modelling to develop algorithms for the optimal selection of parameters (e.g., ARI) that provides efficient polling and data transmission.

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