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A Proportional Scheduling Protocol for the OFDMA-Based Future Wi-Fi Network

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Abstract—The IEEE 802.11ax (Wi-Fi 6) and IEEE 802.11be (Wi-Fi 7) adopt the OFDMA technology to provide high-speed and uninterrupted communications in the dense network. Until the advent of IEEE 802.11ax standard, Wireless LAN (WLAN) predominantly uses the Random Access (RA) mechanism to access the network. IEEE 802.11ax and IEEE 802.11be (proposed) provide another access mechanism for WLAN (i.e., Wi-Fi), which is known as Scheduled Access (SA). This mechanism utilizes the OFDMA technology to provide high-speed and smooth communications in congested areas. By the way, the performance of the OFDMA-based wireless LAN largely depends on the scheduling protocol. Many researchers propose RA and SA protocols independently, which do not consider the simultaneous implementation of both mechanisms. This paper proposes a Proportional Resource Scheduling (PRS) scheme for the OFDMA-based wireless LAN that simultaneously implements RA and SA mechanisms for data transmission. We design two algorithms for the resource scheduling for the PRS protocol. Algorithm 1 provides the initial scheduling information, which is received by Algorithm 2 as the input. After performing revision, Algorithm 2 provides the final scheduling information to the access point. The PRS distributes the channel resources proportionally to the stations according to their available loads. Thus, it utilizes the resources efficiently and increases the throughput and fairness in accessing the channel. We construct analytical models both for the SA and RA mechanisms and conduct rigorous simulations to measure the efficiency of the PRS protocol. The analyses validate the robustness of the proposed protocol in throughput, goodput, fairness, and retransmissions. The main contribution of the proposed protocol is that it provides a framework for simultaneous implementation of RA and SA mechanisms for the future wireless LAN.

Index Terms—Resource unit, proportional resource scheduling, Wi-Fi protocol, access mechanism, wireless LAN, OFDMA

I. INTRODUCTION

To meet the demand for high-speed communication in the Wi-Fi network, the IEEE releases its latest standard [1], known as the IEEE 802.11ax or Wi-Fi 6. According to the specification of the IEEE 802.11ax, Wi-Fi 6 network would increase the throughput at least four times per station and support ten times stations [2]. The Wi-Fi 6 promises to support highly dense areas such as stadiums, airports, stations, etc., where previous standards are not suitable to meet the growing needs of new user requirements. IEEE 802.11ax leverages the OFDMA (Orthogonal Frequency Division Multiple Access) technology for the next-generation high-speed wireless LAN. IEEE 802.11ax brings several new important features such as increasing the spatial reuse, CCA (Clear Channel Assessment) threshold adaptation, new mechanisms to save energy, etc.

While users rivet their eyes on Wi-Fi 6, the IEEE 802.11 working group turns to the next-generation communication standard, IEEE 802.11be or Wi-Fi 7 [3]. The development of the Wi-Fi 7 standard is going on, and it is expected to be released by 2024. Wi-Fi 7 is supposed to provide an Extremely High Throughput (EHT) [4] to fulfill the requirement of recent applications such as the 4k/8k video, augmented and virtual reality, online gaming, etc. The new amendment also promises a revolution of unlicensed wireless connectivity [5]. The main technical issues to be considered for the 802.11be are advanced PHY and MAC techniques, channel-sounding optimization, multi-link aggregation, 4096-QAM, cooperation between the APs, etc. [6].

The main technological difference between the recent Wi-Fi (Wi-Fi 6 and Wi-Fi 7) and the legacy Wi-Fi (Wi-Fi 1 to Wi-Fi 5) is the adoption of the OFDMA technology. The OFDMA technology that has served the cellular network for many years would significantly contribute to the wireless LAN, especially in enhancing the throughput. The legacy Wi-Fi network predominantly uses the Random Access (RA) mechanism for accessing the channel. However, Wi-Fi 6 has the provision of utilizing the Scheduled Access (SA) mechanism using the OFDMA technology along with the RA mechanism. The SA method has some advantages over the RA methods, such as enhancing the throughput and reducing the retransmission of packets [7]. However, to gain the scheduled access, a station (STA) has to send the BSR (Buffer Status Report) to the Access Point (AP) using the RA mechanism [8]. Moreover, legacy STAs do not support the OFDMA-based SA mechanism. Thus, a hybrid protocol can be designed

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for the wireless LAN to efficiently utilize both the RA and SA mechanisms.

The details of OFDMA technology for WLAN can be found in the standard [1], which is also summarized in Section III. The OFDMA technology forms the Resource Units (RUs) that the stations utilize for data transmission [9]. An RU contains at least 26 sub-carriers (i.e., tones) that are orthogonal to each other's [10]. The resource allocation or scheduling problem determines how the RUs would be distributed to the stations. The downlink scheduling is easier to implement as only the AP sends data to the STAs. Uplink scheduling design is very challenging as many STAs transmit data to the AP simultaneously. For transmitting on the uplink path, all sending stations must be synchronized with the Trigger Frame (TF) that is sent from the AP [11], [12]. Thus, the efficiency of the OFDMA-adopted Wi-Fi network largely depends on the uplink scheduling algorithm.

In this paper, an OFDMA-based uplink scheduling protocol is designed for future wireless LAN to improve the network's performance. The proposed hybrid protocol termed Proportional Resource Scheduling (PRS) distributes resources proportionally to the STAs according to their available loads. PRS involves two scheduling algorithms to perform the scheduling job, namely, "initial scheduling" and "revised scheduling". The revised scheduling receives the output of the initial scheduling as the input then provides the final scheduling information. The proposed PRS protocol would improve the performance of the Wi-Fi protocol by providing high throughput and reducing the retransmission of packets. We measure the throughput of the protocol by constructing analytical models. We also perform rigorous simulations to measure the efficiency of the proposed protocol.

The rest of the paper is organized as follows. Section II describes the related works, problem statement and motivations for this article. Section III, i.e., 'OFDMA System Model', delineates the target system architecture and specifies the constraints of the IEEE 802.11ax network. This article's main contribution is designing two scheduling algorithms illustrated in Section IV, i.e., 'Proportional Resource Scheduling'. We form the analytical models for the SA and RA mechanisms of the PRS protocol analyzed in Section V. Exhaustive simulations are conducted by Network Simulator-3 (NS-3), which are illustrated in Section VI. Finally, Section VII concludes the paper.

II. EXISTING WORKS AND MOTIVATIONS

A. *Existing Works*

The IEEE TGax (TASK GROUP AX) [13] keeps the provisions of using the random access along with the scheduled access for the 802.11ax network. In the 802.11ax, the random access mechanism is exclusively known as the UORA (Uplink OFDMA-based Random Access), which is described in [14], [15]. The UORA method inherits the legacy MAC (Medium Access Control) mechanism for the Wi-Fi 6 network. The authors of [16] and [17] claim that UORA is not efficient in throughput achievement. However, the UORA method can be efficiently used temporarily by the stations for sending the BSR because an STA must send its BSR information to the AP to use the deterministic method (i.e., SA method). In [18], the author reviews the expected future Wireless LAN scenarios and use cases that justify the push for a new PHY/MAC IEEE 802.11 amendment.

The IEEE 802.11ax standard imposes some constraints and restrictions for using OFDMA technology in the Wi-Fi network, which is discussed in [12], [8], [7], etc. The authors of [12] distinguish the OFDMA features for cellular and Wi-Fi networks. They modify some well-known LTE (Long TERM Evolution) schedulers such as the PF and MR and adapt those to the Wi-Fi network. The authors in [8] illustrate the OFDMA peculiarities for the Wi-Fi network and claim that classic cellular protocol would not suit the Wi-Fi network because the fundamentals of OFDMA in cellular networks and Wi-Fi networks are different. The researchers also innovate a novel scheduler named 'MUTAX' that reduces the upload time and increases the goodput. The investigators in [19] propose a fast, scalable, and fully graph-centric method for choosing a channel width and assignment for the access points for any IEEE 802.11 Wireless LAN. The method performs better than other mechanisms consisting of selecting the channel width regardless of the Wireless LAN topology by 15% in fairness and 20% in throughput. The authors in [7] propose an OFDMA-based uplink scheduling protocol, 'ERA', using the scheduled access mechanism. The ERA efficiently increases the throughput and decreases retransmissions in the Wi-Fi network significantly. In [20], the researchers propose a dynamic channel bonding technique that adapts the channel bandwidth on a per-packet transmission which in turn significantly outperforms traditional single-channel on average.

The authors of [21] propose an innovative protocol termed 'OMAX' that addresses the OFDMA synchronization difficulties and overhead problems. The OMAX utilizes the fast backoff for smooth synchronization and reduces the protocol overhead using a new frame structure. However, the protocol ignores the OFDMA deterministic approach (i.e., scheduled access), and hence it is deprived of utilizing the most robust feature of IEEE 802.11ax. In [22], a multi-channel CSMA/CA protocol is proposed using a two-dimensional backoff counter. The performance analysis shows that the protocol performs better than a single-channel system. However, channel utilization of [22] is not satisfactory as the STAs maintain only one backoff timer for all the sub-channels. To solve the problem, [23] uses multiple backoff timers for multiple sub-channels. M. Stojanova *et al.* in [24] find that optimal solution has a co-relation with special network configuration. In general, the larger channels are good for throughput maximization and smaller channels are good for fairness.

Khorov *et al.* in [25] adopt the EDCA (Enhanced Distributed Channel Access) method for the 802.11ax network. They use different EDCA parameters (e.g., minimum/maximum contention window size) for the fair and efficient distribution of channel resources. However, a rigorous investigation is required to validate the performance and flexibility of using such protocols as there are not sufficient works available yet. The researchers in [26] propose a hybrid protocol by coalescing the TDMA with CSMA-CA for efficient message broadcasting. It reduces the usage of control packets and hence enhances the performance on the control channel. Xuelin *et al.* [27] design a protocol that combines the strength of the TDMA with the Distributed Coordination Function (DCF). It decreases protocol overheads and increases the throughput remarkably.

Yuan *et al.* [28] and J. Lee [29] devise two protocols for efficient resource utilization. Yuan *et al.* design the protocol 'CCRM' that reliably sends the Channel Reservation Information (CRI). The CRI originated from an STA is relayed further by the cooperation of adjacent STAs in the network. Article [29] innovates a priority-based protocol that uses the Common Control Channel (CCC). The CCC serves the secondary STAs for sending the control packets to determine the priority for accessing primary channels. In the articles [30] and [31], the stations are classified into several groups, and the stations in the same group use a common sub-channel for transmission. The RTS/CTS frames are used for assigning channel resources to the members of the group. In [32], an intermittent carrier sense mechanism is introduced that permits a wireless station to access multiple sub-channels simultaneously.

The throughput of the Wi-Fi STAs can be achieved several times by using the multi-user MIMO (Multiple Input and Multiple Output) and spatial stream. Wilhelmi *et al.* in [33] outline the challenges and limitations of the IEEE 802.11ax Spatial Reuse (SR) operation. Bellalta *et al.* in [34] illustrate the changes at PHY and MAC layer in the 802.11ax and measure the throughput for MU-MIMO transmissions effectively. Chi *et al.* in [35] implement a heuristic technique for network coding to improve the throughput of wireless LANs. The authors in [36] compare uplink and downlink multi-user transmission for Wi-Fi 6 network and show that uplink OFDMA outperforms the downlink transmission when multiple STAs frequently send only a few MPDUs (MAC Protocol Data Units). OFDMA MU transmissions in the Wi-Fi 6 must be synchronized with the TF, and all STAs would get the same amount of time for data transmission. If the packet is too large to send within the allotted time, then the packet can be fragmented, as described in [37]. Similarly, multiple short packets can be sent within a TF cycle. If there are no packets available for a TF cycle, padding is the only option to fill the blank space. Javed and Prakash develop a framework named ‘CHAMELEON’ [38] to coexist the wireless technologies in an unlicensed band.

To enhance the performance, [39] permits the aggregation of packets from different access categories. A Multi-TID BA frame can be used to acknowledge a set of frames of different access categories. A Multi-STA BA frame is also be used to replace ACKs or BAs to several stations [40]. IEEE 802.11ax latest amendment allows the Block Acknowledgement (BA) [41], [42] to acknowledge all STAs using a single frame. The authors in [43] design an adaptive station grouping mechanism to overcome the dense network challenges in Wi-Fi 6 by utilizing a BSR-based Two-stage Mechanism. In [44], the researchers have devised a new protocol for Wi-Fi 6 terms DeepMux, which is a deep-learning-based MU-MIMO-OFDMA transmission mechanism. In paper [45], the authors integrate the MU transmissions with the Target Wake Time (TWT) technique. Simulation results show that their mechanism outperforms the existing techniques in several performance parameters. A.-K. Ajami et al. focus on single unlicensed frequency band transmissions, where the locations of APs, users, and LTE eNBs are modeled as three independent homogeneous Poisson point processes [46]. Their analysis quantifies both single-user and multi-user operation modes of the Wi-Fi 6.

B. Problem Statement and Motivations

Previously, wireless LAN predominantly uses the RA mechanism for channel access. After adopting the OFDMA technology (by Wi-Fi 6 and beyond), the SA mechanism can be utilized for data transmission. Since both mechanisms have some advantages, many researchers design MAC protocols that are based on either RA or SA techniques. However, these protocols have no provisions for simultaneous implementation of RA and SA mechanisms. In this paper, we propose the PRS protocol for the future wireless LAN, which implements RA and SA mechanisms concurrently and significantly improves network performance. In particular, we address the following research questions in this article.

- How to design a protocol that implements RA and SA mechanisms for simultaneous transmissions?
- How to improve the performance of the wireless LAN?
- How to schedule the channel resources to the stations proportionately?

The OFDMA technology leverages the robust OFDM (Orthogonal Frequency Division Multiplexing) modulation. Previous versions of IEEE 802.11, such as the IEEE 802.11ac (Wi-Fi 5) and IEEE 802.11n (Wi-Fi 4), also use the OFDM as the modulation technique. Thus, OFDMA technology derived from the OFDM modulation is highly suitable for the IEEE 802.11ax network to raise the performance further [47]. Another reason for the inclusion of the OFDMA in the ax network is the promising performance of OFDMA in the LTE network. However, usage of the OFDMA technology in the Wi-Fi network is not the same as in the cellular network. The Wi-Fi 6 standard imposes some constraints and specifications that Wi-Fi 6 must follow (discussed in Section III, i.e., 'OFDMA System Model').

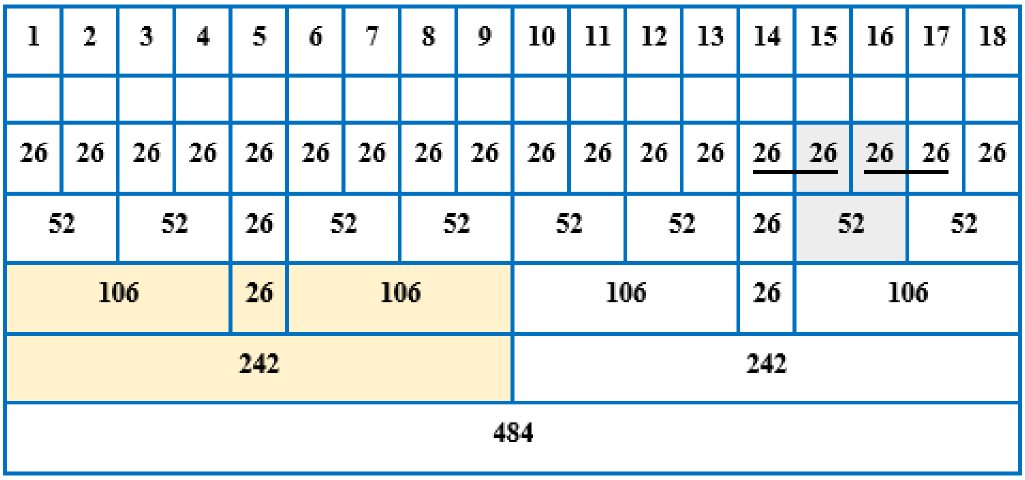

Fig. 1. OFDMA resource unit formation in a 40 MHz channel

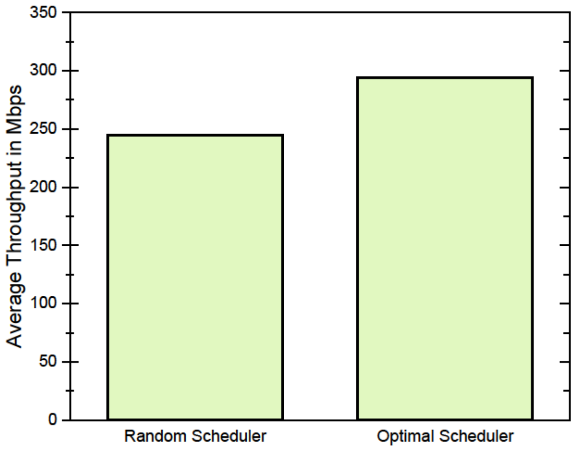

Fig. 2. Comparison between a random scheduler and an optimal scheduler

The performance of the OFDMA-adopted MAC protocol mainly relies on the design of the resource scheduling algorithm. The bandwidth of the whole channel can be distributed to the appropriate STAs by selecting a variety of RU combinations (See Fig. 1). To observe the significance of an efficient resource scheduling algorithm, we conduct a simple simulation for uplink OFDMA transmission. The simulation result is shown in Fig. 2. The network contains 35 STAs where the number of antennas of the AP and STAs is 4 and 1, respectively. The system operates in the 5 GHz band using a bandwidth of 40 MHz, and it uses the best Wi-Fi channel. The transmit power of the devices is 15 dBm, and the radius of the network is 15 meters. The figure shows the throughput of a random scheduler that arbitrarily selects the users without optimizing RUs and an optimal scheduler that selects RUs and users carefully. An optimal scheduler maximizes the throughput of the system as $max \sum_{i=1}^{N} S_i$, where S_i is the throughput of the i^{th} station, and N is the total number of stations in the network. It is observed in Fig. 2, the average throughput of the optimal scheduler (about 294 Mbps) is much higher than a random scheduler (about 245 Mbps).

Observing the efficiency of a robust scheduling protocol, we propose the Proportional Resource Scheduling protocol for the OFDMA-based future network in this article. The protocol increases the throughput and fairness index as well as reduces the retransmissions of packets. We conduct rigorous simulations (in Section VI) to evaluate the proposed PRS protocol's efficiency and compare the PRS scheduler with some other promising schedulers.

We study several cellular protocols such as the MR (Max Rate) discussed in [8], [40], [48], etc., and PF (Proportional Fair) in [49]-[51], etc., and compare those with the PRS protocol. The main objective of the MR protocol is to achieve the highest throughput for the network. Thus, the MR protocol maximizes the cumulative throughput $S = \sum_i S_i(t)$, where S_i is the throughput of the station i at time t. Although MR protocol focuses on the throughput, it ignores the fairness of channel access. Hence, researchers come with the PF protocol to overcome the fairness problems. To increase fairness, PF ensures equal channel time to all stations in the steady-state [50]. By the way, to increase the fairness index, PF has sacrificed some throughput in contrast to the MR protocol. The PF maximizes the utility function, $U_{PF} = \sum_i log\, R_i$, where R_i is the service rate of station i. For maximizing the utility function, it is required to maximize $\sum_i \frac{d_i(t)}{R_i(t)}$, where $d_i(t)$ denotes total transmitted data to station i at time t [52]-[54]. The MR and PF being the cellular protocols, we modify and adapt those to the 802.11ax architecture while conducting the simulations.

The PRS is also compared with the Divide and Conquer algorithm proposed in [9] that optimally assigns RUs to the STAs. Unlike the cellular protocols, divide and conquer permits assigning more than one RUs to a single STA. The throughput gained by this algorithm is a tight upper bound of the optimal user schedule. Hence, the divide and conquer algorithm provides significantly higher throughput than other existing Wi-Fi-6 protocols. Wang and Psounis (2020) [55] develop another efficient algorithm named 'Recursive', which is also appropriate for protocol comparison. They propose a recursive scheduling algorithm that splits the bandwidth into resource units and then schedules those to the STAs in a near-optimal fashion. The algorithm is very efficient in handling variable packet size and limited radio capabilities of the access point. The algorithm solves the scheduling and resource allocation (SRA) problem efficiently and dynamically adjusts the number of resource units. Both the 'Divide and Conquer' and 'Recursive' algorithms focus on the SRA problem and ensure good performance especially, in throughput and fairness.

III. SYSTEM MODEL

The system model for the PRS protocol is designed in light of IEEE 802.11ax and the earlier standards as well. As the PRS is designed for the future WLAN, it is also flexible to deploy in different scenarios where the previous standards may not. The IEEE 802.11ax can operate in 2.4 GHz and 5 GHz frequency bands and supports different channel bandwidths, 20, 40, 80, and 160 MHz [1]. The stations in the PRS are also able to operate in any frequency below the assigned channel bandwidth. Thus, it helps future Wi-Fi networks be more flexible and robust to implement the SA and RA mechanisms concurrently. The whole bandwidth is divided into several sets of orthogonal sub-carriers called resource units or RUs. Thus, a larger channel (e.g., 80 MHz channel) may have more RUs than a smaller channel (e.g., 20 MHz). An RU contains either 26, 52, 106, 242, 484, 996 or 2 × 996 sub-carriers i.e., tones [56]. According to the OFDMA specification for IEEE 802.1ax, a resource unit must contain at least 26 tones, which we term Smallest Resource Unit (SRU). Fig. 1 shows the resource unit formation in a 40 MHz channel. For the demonstration purpose, we numbered the SRUs on top of the figure from left to right. There are 18 SRUs in a 40 MHz channel, where each of the RUs contains 26 tones.

In IEEE 802.11ax, adjacent smaller RUs can combine to form a larger RU, or a larger RU can be split into several smaller RUs. However, the merging and division of RUs are not arbitrarily, as portrayed in Fig. 1. For example, SRU 15 and SRU 16 can be merged to form a larger RU of 52 tones (lighter-gray colored). However, the combinations, such as (SRU 14 and SRU 15) or (SRU 16 and SRU 17) are not valid for merging. Again, a larger RU having 242 tones may split into three smaller RUs as two 106-tone RUs and one 26-tone RU (lighter-gold colored).

All resource units, irrespective of the size, get the same amount of time for data transmission. As such, STAs having larger RU (e.g., 242 tones) can send more data than those having smaller RU (e.g., 52 tones). For example, an STA having an RU of 106 tones can send approximately 4X data of an STA having an RU of 26 tones. In OFDMA, multi-user transmissions can be achieved by splitting the whole channel into several smaller RUs. All of the STAs in the network must be assigned the RUs for transmission then STAs start transmission simultaneously using their RUs. The Trigger Frame (TF) sent by the AP for uplink transmission helps the STAs to be synchronized with the system.

We consider an OFDMA-based infrastructure BSS (Basic Service Set) [57] for the PRS protocol, as shown in Fig. 3. There are N STAs in the network where STAs communicate with each other through the AP. In future WLAN, the stations would support both SA and RA mechanisms which are known as SA STAs and RA STAs, respectively. Therefore, the stations can seek any services (SA or RA), whatever they prefer. Unlike legacy RA stations, the future RA stations are capable of providing feedback to the AP. Initially, the AP computes the entire channel bandwidth in terms of the smallest resource units. The calculated resource units are divided into two portions: one for the SA mechanism and another for the RA mechanism (details in Section 4.1). The SA mechanism is used only by the SA STAs whose BSR information [8], [58] is available to the AP. The RA mechanism is used by all RA STAs and a few low-load SA STAs (if any). The RUs computed for the RA mechanism by the AP will be merged to form a single random access channel. The tasks of all scheduling and decisions are made by the AP, which are discussed in the following section.

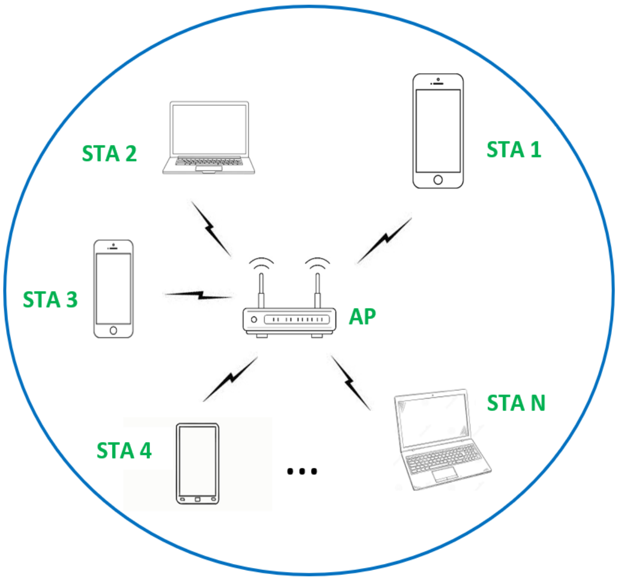

Fig. 3. A Wi-Fi network with N STAs and one AP

IV. PROPORTIONAL RESOURCE SCHEDULING

A. *Division of Resource Units*

The working principle of Proportional Resource Scheduling, i.e., PRS protocol, is delineated in Fig. 4. Fig. 4 represents a window of Wi-Fi channel resources in a 40 MHz channel. The sliding bar of the window divides the whole bandwidth in terms of RUs into two portions. The RUs that reside at the left side of the bar are known as the LRUs (Left Resource Units), and those that reside at the right side are known as RRUs (Right Resource Units). The LRUs are to be assigned to the Scheduled Access (SA) STAs, and RRUs are to be assigned to the Random Access (RA) STAs. According to Wi-Fi 6, a resource unit must contain at least 26 sub-carriers, which PRS terms as Smallest Resource Unit (SRU).

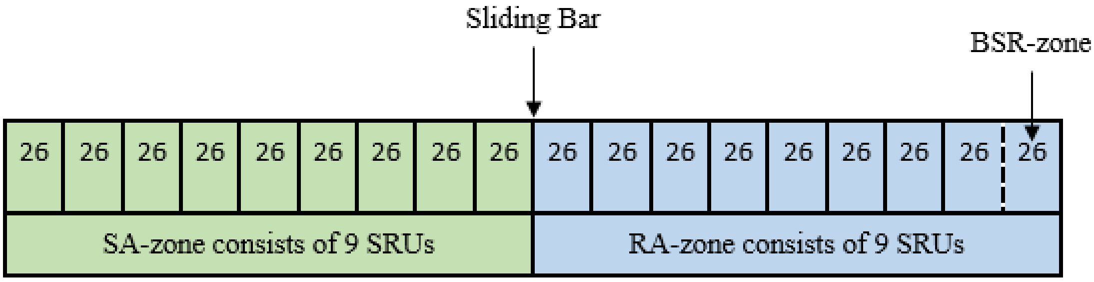

Fig. 4. Dividing the RUs where SA-zone = RA-zone

The AP determines the proportion of LRUs and RRUs based on the total load of the candidate STAs (SA and RA stations). According to the PRS protocol, in general, SA STAs utilize the scheduled access mechanism for payload transmission, and RA STAs use the inherent random access mechanism. Thus LRU-zone (green colored) is dedicated to the SA STAs only. Similarly, the RRU-zone (blue colored) is to be shared primarily by the RA STAs. A few SA STAs (removed from LRU-zone) may also share the RRU-zone, which will be discussed during revised scheduling. The right-most SRU that contains 26 tones is termed as BSR-zone, a sub-zone of RRU-zone. In the PRS protocol, the BSR-zone is of fixed size (1 SRU) and must be preserved. It can be used to send the BSR (Buffer Status Report) or other control information even if no other RUs available for random access and can be used by both SA and RA STAs.

The PRS is a hybrid MAC protocol since it utilizes both the scheduled access and random access mechanism. It is noted that an STA must send its BSR to the access point for acquiring scheduled access. The BSR contains the load information of an STA, and AP needs this information for resource scheduling for that STA. Thus, for gaining the scheduled access, an SA STA has to send its BSR to the AP through the random access mechanism. That is why the proposed PRS protocol reserves the BSR-zone.

B. *Division of Resource Units*

The Proportional Resource Scheduling protocol allocates RUs proportionally to LRU-zone (SA-zone) and RRU-zone (RA-zone) based on the total load of SA and RA STAs. For example, if the total loads of SA STAs and RA STAs are equal, then the LRU-zone (for SA STAs) and RRU-zone (for RA STAs) are also equal or nearly equal. This example applies to the previous Fig. 4, where both green-zone and blue-zone comprise 50% of each of the total resources. For simplicity of the design, RRU-zone also contains the BSR-zone, which size (i.e., only 1 SRU) is tiny comparing the whole channel. During initial scheduling, due to the presence of BSR-zone, RA STAs get a slightly reduced space than what should be by the exact proportional distribution. However, during the revised scheduling, this would be compensated.

Again, the proportional distribution also depends on the minimum RU size. Since the minimum RU size is 26 tones, the PRS divides the LRU-zone and RRU-zone on the boundary of the RUs (i.e., not in the middle of a RU). To under the phenomena, we consider a scheduling problem which is demonstrated below.

Scheduling Problem Example: Suppose there are five SA STAs (e.g., A, B, C, D, E) and three RA STAs (e.g., X, Y, Z) in an infrastructure basic service set. The load of the STAs A, B, C, D, E are 3.1, 2.2, 2.9, 1.3, 0.7 MB, respectively, and the load of the STAs X, Y, Z are 3.4, 1.2, 2.1 MB, respectively.

TABLE I: NOTATION GLOSSARY FOR THE ALGORITHMS

Notation	Description
p_i	Load of the SA STA i
P	Total number of SA STAs
$L1$	Total load of SA STAs
q_i	Load of the RA STA i
Q	Total number of RA STAs
$L2$	Total load of RA STAs
$L3$	Total load of all STAs in the network
M	Total number of SRUs in the channel
S	Number of SRUs for SA-zone for initial scheduling
T	Number of SRUs for RA-zone for initial scheduling
r_i	Number of SRUs for STA i
U	Number of SRUs for SA-zone for revised scheduling
V	Number of SRUs for RA-zone for revised scheduling

The PRS protocol first applies the initial scheduling algorithm, i.e., Algorithm 1, to solve the scheduling problems, then uses the revised scheduling algorithm, i.e., Algorithm 2. The revised scheduling algorithm works on the output of the initial scheduling algorithm and gives the final scheduling results. Table I shows the meaning of all notations used in the algorithms.

Algorithm 1: Initial Scheduling

```
01: // Load calculation
02: Find the total load of SA STAs, $L1 = \sum_{i=1}^{P} p_i$
03: Find the total load of RA STAs, $L2 = \sum_{i=1}^{Q} q_i$
04: Total load of all STAs, $L3 = L1 + L2$
05: // Finding the number of SRUs for the zones
06: Number of SRUs for SA-zone, $S = \lfloor (L1/L3)M \rfloor$
07: Number of SRUs for RA-zone, $T = \lceil (L2/L3)M \rceil$
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Apply Initial Scheduling Algorithm

According to Algorithm 1, the total load of SA STAs $(L1)$ i.e., Step 02:

$$L1 = \sum_{i=1}^{P} p_i. \tag{1}$$

Thus, load of the SA STAs = (3.1 + 2.2 + 2.9 + 1.3 + 0.7) MB = 10.2 MB. Similarly, total load of RA STAs, $(L2)$ i.e., Step 03:

$$L2 = \sum_{i=1}^{Q} q_i. \tag{2}$$

Hence, load of the RA STAs = (3.4 + 1.2 + 2.1) MB = 6.7 MB. Total load of all STAs (in Step 04), $L3 = L1 + L2$ = (10.2 + 6.7) = 16.9 MB.

Number of SRUs for SA-zone, (S) i.e., Step 06:

$$S = \lfloor (L1/L3)M \rfloor. \tag{3}$$

In a 40 MHz channel, there are 18 SRUs (i.e., $M = 18$), as shown in Fig. 4.

Thus, the total number of SRUs for SA-zone = $\lfloor 10.2/16.9 \times 18 \rfloor = \lfloor 10.86 \rfloor = 10$.

Number of SRUs for RA-zone, (T), i.e., Step 07:

$$T = \lceil (L2/L3)M \rceil. \tag{4}$$

Therefore, the total number of SRUs for RA-zone = $\lceil 6.7/16.9 \times 18 \rceil = \lceil 7.14 \rceil = 8$.

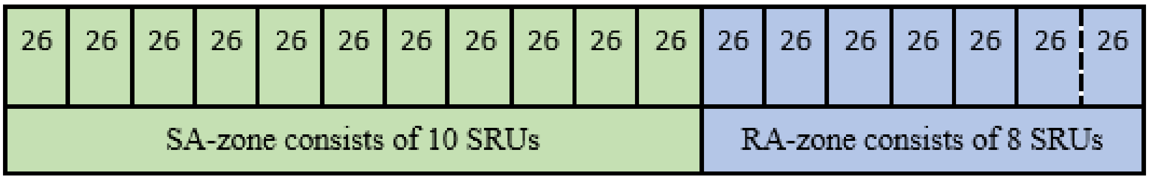


Fig. 5. Distribution of SRUs after initial scheduling

In the above calculation, the algorithm takes the floor value for the SA method and the ceiling value for the RA method to compensate RA-zone, which contains the BSR-zone. Now, the resource window looks like Fig. 5, where SA-zone contains 10 SRUs and RA-zone contains 8 SRUs. However, this proportion is subject to change after applying the revised scheduling algorithm.

Algorithm 2: Revised Scheduling

```
01: // Finding the number of SRUs for each of the SA STAs
02: Number of SRUs for STA i, $r_i = \lfloor (p_i/L1)S \rfloor$
03: // Finding the number of SRUs for the zones
04: Number of SRUs for SA-zone, $U = \sum_{i=1}^{P} r_i$
05: Number of SRUs for RA-zone, $V = M - U$
```

Apply Revised Scheduling Algorithm

Again, each of the SA STAs gets SRUs proportionally to their available loads. Hence, 10 SRUs getting from initial scheduling to be distributed as follows by the revised scheduling algorithm,

Number of SRUs for STA i, (r_i), i.e., Step 02:

$$r_i = \lfloor (p_i/L1)S \rfloor. \tag{5}$$

Therefore,

STA A gets $\lfloor 3.1/10.2 \times 10 \rfloor = \lfloor 3.03 \rfloor = 3$ SRUs;
STA B gets $\lfloor 2.2/10.2 \times 10 \rfloor = \lfloor 2.16 \rfloor = 2$ SRUs;
STA C gets $\lfloor 2.9/10.2 \times 10 \rfloor = \lfloor 2.84 \rfloor = 2$ SRUs;
STA D gets $\lfloor 1.3/10.2 \times 10 \rfloor = \lfloor 1.27 \rfloor = 1$ SRU;
STA E gets $\lfloor 0.7/10.2 \times 10 \rfloor = \lfloor 0.69 \rfloor = 0$ SRU;

Since Algorithm 2 takes the floor value of the integer, the total number of SRUs for all SA STAs is now 8. There is no SRU for STA E, and hence STA E is to be moved from SA-zone to RA-zone for random access. Since the initial distribution has a total of 10 SRUs and revised distribution requires 8 out of 10 SRUs, the residual (10-8) = 2 SRUs to be moved from the green zone (SA-zone) to the blue zone (RA-zone). It compensates RA-zone to mitigate the following:

i) Compensate for the BSR-zone
ii) Compensate for the extra STAs that come from SA-zone

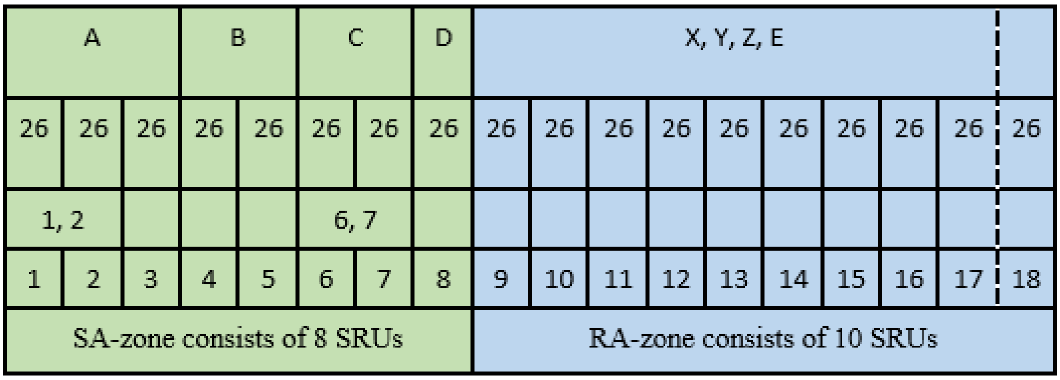


Fig. 6. Final distribution of SRUs after revised scheduling

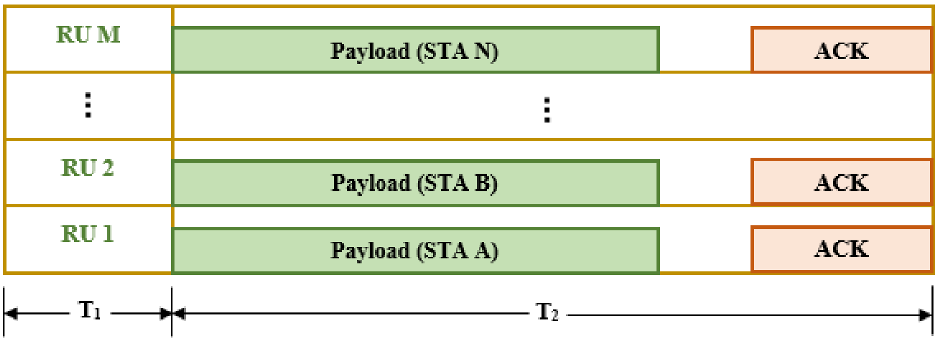
According to the revised and final distribution, the scheduling window looks like Fig. 6, where SA-zone contains 8 SRUs and RA-zone contains 18-8 = 10 SRUs. On the top row of Fig. 6, the boundary of SRUs in the RA-zone is also removed since all resources in the RA-zone (blue-zone) work as a single random access channel. The RA-zone is to be shared by the RA STAs X, Y, Z, and SA STA E. Recall that 1 SRU must be preserved for the BSR-zone, even if RA-zone gets 0 SRU after revised scheduling.

The AP approximates the number of RUs for the SA-zone and RA-zone applying the algorithms and finally distributes the resources according to Fig. 6. The LRUs that resided in the SA-zone would be distributed to the SA stations in terms of RUs leveraging the OFDMA technology. On the other hand, the RRUs that resided in the RA-zone would be distributed to the SA and RA stations in terms of bandwidth. It is noted that RA stations would not receive the RUs from the AP; rather, those receive equivalent bandwidth in terms of frequency. As mentioned in the previous paragraph, the whole bandwidth of the RA-zone would work as a single random access channel, and the stations in that zone would compete for the channel access according to the RA mechanism. After the final scheduling (See Fig. 6), the capacity of the RA-zone may not be a multiple of 20 MHz, which is not necessary for future WLAN as described in the 'System Model'.

C. Access Mechanisms

The proposed PRS protocol is a hybrid one that utilizes both the SA mechanism and RA mechanism to access the wireless channel. In PRS, the candidates for the SA mechanism are those which get resource units in the SA-zone (green zone), and for the RA mechanism are those which get bandwidth in the RA-zone (blue zone), after the final scheduling. It is also observed that after revised scheduling, a few SA STAs whose load is comparatively lower may migrate to the RA-zone and hence use the RA mechanism to access the channel.

In the PRS protocol, the access point schedules the channel resources and regulates downlink and uplink transmission parameters. The access point grants access to the channel, distributes resources to the eligible STAs, regulates transmission parameters, and synchronizes STAs for uplink OFDMA transmission. The transmission parameters include transmission power, transmission duration, modulation and coding schemes, MIMO, etc.



$$T = T_1 + T_2$$
$$T_1 = T_H + (T_{TF} + SIFS + \delta)$$
$$T_2 = (T_P + SIFS + \delta) + (T_{ACK} + SIFS + \delta)$$

Fig. 7. OFDMA transmissions using the scheduled access mechanism

SA mechanism

The IEEE 802.11ax innovates the Trigger Frame (TF) [17] concept to serve the OFDMA transmissions. The AP sends the TF to all stations in the Wi-Fi network, containing transmission information, scheduling information, and other wireless channel parameters. All participating STAs in the SA-zone synchronize using the TF and start transmissions simultaneously, as shown in Fig. 7. Each of the RUs that acts as a sub-channel will get the same amount of time for uplink transmission. However, their data transfer rates depend on the size of the resource unit. Stations which having larger RU can send more data than those having smaller RU.

For the scheduling problem, Algorithm 2 finds the number SRUs for each of the SA stations. The PRS protocol assigns the SRUs to the stations on the FCFS (First Come First Served) basis from left to right, as shown in Fig. 6. The left-most SRU numbered 1, and the right-most SRU numbered 18 (i.e., 2nd row from the bottom of Fig. 6). STA A gets SRU 1, 2, 3; STA B gets SRU 4, 5; STA C gets SRU 6, 7; and STA D gets the SRU 8. According to IEEE 802.11ax, some adjacent smaller RUs can combine to form a large RU. Details of the merging procedure are portrayed in Fig. 2 of Section 3. Abide by the rules, STA A can merge SRUs 1 and 2 to form a larger resource unit RU (1, 2). Similarly, STA C can combine SRUs 6 and 7 to form the RU (6, 7). No more merging is possible for the scheduling problem example, following the configuration of Fig. 6. The merg-ing reduces the number of individual RUs (i.e., sub-channels), and broader channels (e.g., 80 or 160 MHz) may have more merging configurations due to more SRUs.

RA mechanism

Random access mechanism is the legacy technique for accessing the channel that the Wi-Fi stations predominantly used before adopting the OFDMA technology in the latest Wi-Fi 6 and Wi-Fi 7 standards. The PRS keeps provision of using both the RA and SA mechanisms as Wi-Fi 6 standard. In the problem scheduling example, STAs X, Y, Z, and E use the RA mechanism shown in Fig. 6. According to the proposed protocol, all computed RUs in the RA-zone are merged to form a single random access channel after revised scheduling. As mentioned earlier, all SA STAs must use the RA mechanism momentarily to send their BSR to the AP. Thus RA-zone always reserves an SRU to support the

STAs for sending the BSR. The RA mechanism is governed by the renowned Binary Exponential Backoff (BEB) algorithm. The two-frame (DATA/ACK) or four-frame (RTS/CTS, DATA/ACK) exchange methods can be used for the data transmission for the RA mechanism. To ensure a higher degree of reliability and deal with the hidden node problem [59], [60], the four-frame exchange method is preferable.

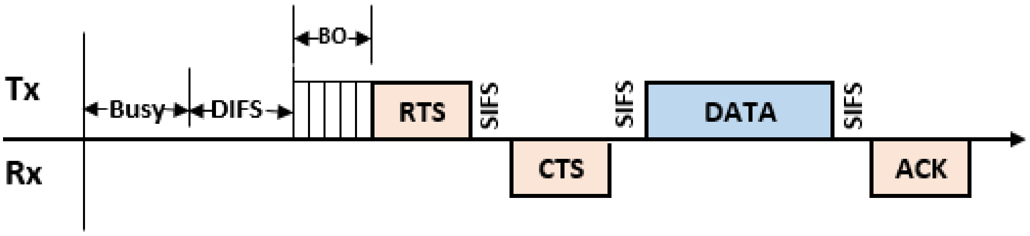


Fig. 8. Four-way handshaking in the random access channel

The four-frame exchange method (also known as four-way handshaking) is delineated in Fig. 8. When the medium (i.e., channel) is not busy, it passes the DIFS (distributed inter-frame space) interval. Then, sending STA enters into the backoff interval. When the backoff counter reaches zero, sending STA sends the RTS (request-to-send) frame to the receiver. After another interval known as SIFS (short inter-frame space), the receiver replies with the CTS (clear-to-send) frame. After reception of the CTS, sending STA waits for another SIFS period and then sends its DATA frame. Receiving the data, the receiving STA passes another SIFS period and then sends ACK (acknowledgment) frame to the sender as a token of receipt.

In the RA mechanism, every STA has to generate a random backoff counter using the BEB algorithm. In the random access method, only one STA can send data at a time. If more than one STA sends data simultaneously, then a collision must occur between the data frames, and therefore sending STA has to resend the data. The BEB algorithm reduces the probability of frame collision of the random access protocol by generating the random backoff counter. The algorithm calculates the backoff value in a range [0, W−1], where W denotes the contention window size. Initially, the contention window size is set to a minimum value (W_{min}). After each of the failed transmissions, the contention window size is doubled, and it may reach up to the maximum value, $W_{max} = 2^{\alpha}W_{min},$ where α denotes the number of backoff stages [10], [57].

V. ANALYTICAL MODELS AND ANALYSES

The PRS adopts both the SA and RA mechanisms for accessing the channels as the IEEE 802.11ax. Therefore, separate analytical models are formed to evaluate the performance of the proposed protocol. Section 5.1 contains the analysis of the SA method, and Section 5.2 contains the analysis of the RA method. We consider an infrastructure network that contains both SA and RA devices. There are only one access point and N stations in the network that communicate through the access point. The network is in the saturation stage, where every STAs always has some packets for transmission.

Before protocol analysis, we model the path loss for the PRS protocol in the indoor environment. The free space path loss (PL_{FS}) is defined (in dB) by the following equation, where d denotes the distance between the transmitter and receiver in meter, and f denotes the carrier frequency in hertz.

$$PL_{FS}(d) = 20\ log_{10}(d) + 20\ log_{10}\ (f) - 147.55. \quad (6)$$

IEEE 801.11n [61], [62] follows the following equation (7) for the path loss for indoors, which is also applicable for the IEEE 802.11ax [1], [63]. [62] defines the indoor propagation model where path loss has a slope of 2 up to a breakpoint distance (d_{BP}) and a slope of 3.5 after the breakpoint distance. Thus, we get the path loss for indoors (PL) as follows,

$$PL(d) = PL_{FS}(d), if\ d \leq\ d_{BP}$$

$$PL(d) = PL_{FS}(d) + 35\ log_{10}(d/d_{BP}), if\ d > d_{BP}. \quad (7)$$

IEEE 802.11ax [63] specifies that extra floor penetration loss (PEL_{floor}) and wall penetration loss (PEL_{wall}) should be added to the path loss in the equation in (7). Thus, the overall indoor path loss ($PL_{overall}$) is represented by equation (8) as follows,

$$PL_{overall} = PL(d) + PEL_{floor} + PEL_{wall}. \quad (8)$$

A. Analysis of SA Mechanism

As discussed in Section 4, the scheduled access method applies only to the SA-zone (green-zone) stations that contain only the SA devices. The SA mechanism leverages the OFDMA technology and hence supports multi-channel communication. Each RUs acts as a sub-channel, and STAs send data using their acquired RUs according to the PRS protocol. Fig. 7 shows the uplink OFDMA transmissions using the SA method where for example, STA A gets RU 1, STA B gets RU 2, and so on. All RUs get the same amount of time to send the payload. All STAs start transmission at the same time after receiving the TF from the AP. The TF contains all necessary information, such as the scheduling and transmission information, to facilitate the OFDMA transmission [7]. The duration of the TF cycle (T) is calculated as below (See Fig. 7),

$$T = T_1 + T_2 = T_H + (T_{TF} + SIFS + \delta) + (T_P + SIFS + \delta) + (T_{ACK} + SIFS + \delta) \quad (9)$$

where T_H, T_{TF}, T_P, and T_{ACK} represent the duration of the header field, trigger frame, payload, and acknowledgment frame transmission time, respectively. δ is the propagation delay, and $SIFS$ is Short Inter-frame Space duration.

Finally, the saturation throughput can be measured using the following equation,

$$S = \frac{M\,E[P]}{T}. \tag{10}$$

where M denotes the number of RUs for SA mechanism, and $E[P]$ is the average payload size in bits that the following integral formula can estimate,

$$E[P] = \frac{1}{Pmax-Pmin}\int_{Pmin}^{Pmax} f(x)\,dx. \tag{11}$$

where $f(x)$ represents the function of the packet payload size, $Pmax$ and $Pmin$ denote the maximum and minimum payload size, respectively.

B. *Analysis of RA Mechanism*

The random access mechanism follows the DCF (Distributed Coordination Function) method standardized for the legacy Wi-Fi network. DCF adopts the CSMA/CA (Carrier Sense Multiple Access / Collision Avoidance) mechanism along with the BEB algorithm for efficient random access. The BEB algorithm restricts the maximum contention window size as $W_{max} = 2^{\alpha}W_{min}$ (details in Section 4.3). This assumption is to be kept for the Markov chain analysis for the RA mechanism. The candidate STAs for the RA mechanism resides in the RA-zone (blue-zone) after applying the revised scheduling algorithm (i.e., Algorithm 2).

Many pieces of literature, such as [64]-[67], etc., are available that measure the performance of the random access MAC protocol. Based on the literature, we adopt the Markov chain model for the RA mechanism of the PRS protocol. The transition diagram for the contention window size is shown in Fig. 9, where p denotes the conditional collision probability of a packet in the RA-zone. The transition diagram is drawn using the Markov chain model for the 802.11 RA operation.

Let $s(t)$ and $b(t)$ be the stochastic processes that represent the backoff stage and backoff time counter, respectively, for a given STA. In the Markov chain, the non-null one-step transition probabilities are represented by the equation (12). In equation (12), we use the short notation as:

$$P\{i_1, k_1 \mid i_0, k_0\} = P\{s(t+1) = i_1, b(t+1) = k_1 \mid s(t) = i_0, b(t) = k_0\}.$$

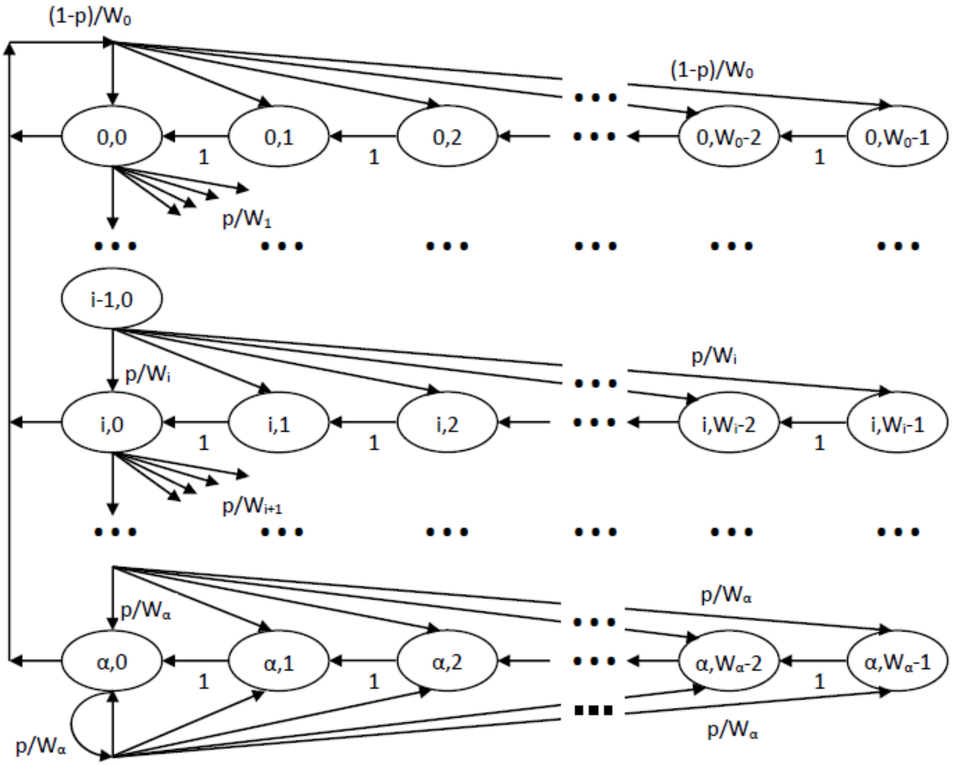


Fig. 9. State transition diagram by the markov chain model

$$\begin{cases} P\{i,k \mid i,k+1\} = 1 \; where \; k \in [0, W_i - 2], i \in [0, \alpha] \\ P\{0,k \mid i,0\} = (1-p)/W_0 \; where \; k \in [0, W_0 - 1], i \in [0, \alpha] \\ P\{i,k \mid i-1,0\} = p/W_i \; where \; k \in [0, W_i - 1], i \in [1, \alpha] \\ P\{\alpha,k \mid \alpha,0\} = p/W_\alpha \; where \; k \in [0, W_\alpha - 1]. \end{cases} \tag{12}$$

Let P_b denotes the probability that the channel is busy, and P_S denotes the probability that a successful transmission occurs in a slot time. The P_b and P_S can be expressed by the equations (13) and (14) respectively as follows,

$$P_b = 1 - (1-\tau)^N. \tag{13}$$

$$P_S = n\tau(1-\tau)^{N-1}. \quad (14)$$

where τ denotes the probability that an STA transmits in randomly chosen slot time, and N is the number STAs for the RA mechanism. Then the normalized throughput can be measured as follow,

$$S = \frac{P_S E(P)}{(1-P_b)\sigma + P_S T_S + (P_b - P_S)T_C}. \quad (15)$$

where,

T_S denotes the average successful transmission time of the channel,

T_C denotes the average collision time of the channel,

σ denotes the duration of an empty slot time and

$E(P)$ denotes the average packet payload size, expressed by the same integral formula represented by equation (11) in the SA mechanism.

VI. SIMULATION RESULTS

We conduct a lot of simulations to measure the efficiency of the PRS protocol using the Network Simulator (NS-3) [68]. We measure the performance for the uplink transmissions as PRS proposes the scheduling for the uplink purpose. The downlink scheduling in OFDMA is easier to implement [11], [69] and does not be considered for the simulations. In the first two simulations (Fig. 10 and Fig. 11), we evaluate the PRS protocol for different proportions of SA and RA STAs. In the rest of the simulations (Fig. 12 to Fig. 16), we compare the PRS with other contemporary promising protocols. All simulations are conducted for the indoor network, and the network is in the saturation stage. The simulations follow the analytical models developed in Section V. In general, all experiments are regulated by the simulation parameters shown in Table II unless otherwise specified.

TABLE II: TYPICAL SIMULATION PARAMETERS

Parameters	**Values**
Number of stations (N)	60, 35, 10 for high, medium, and low congestion, respectively
Radius of BSS (r)	15 meters
Transmit power	15 dBm
Frequency band	5 GHz
Channel bandwidth	40 MHz
Number of antennas of the stations (A_{STA})	1
Number of antennas of the access point (A_{AP})	4

At first, we measure the throughput and number of retransmissions of PRS protocol for different distributions of STAs according to their access mechanisms. We classify the distributions as SA, RA, and Hybrid. In the SA distribution: all STAs belong to the SA-zone (green zone) and utilize the SA mechanism. Similarly, in the RA distribution: all STAs belong to the RA-zone (blue-zone) and use the RA mechanism. In the Hybrid distribution: half of the STAs belong to the SA-zone (green-zone), and another half of the STAs belong to the RA-zone (blue-zone). According to the revised scheduling algorithm (i.e., Algorithm 2 in Section 4.2), many varieties of distributions of the STAs can produce; however, for the sake of simplicity, we consider here only three distributions (i.e., SA, RA, Hybrid). Simulations in Fig. 10 and Fig. 11 helps to observe the superiority of the SA mechanism over the RA mechanism in terms of throughput and retransmissions.

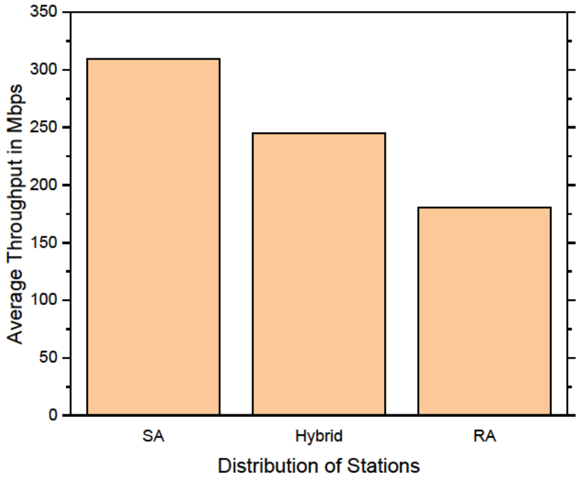


Fig. 10. Throughput of the PRS protocol for different distribution of stations

Fig. 10 shows the average throughput for the different distribution of stations. The simulation considers a dense environment (i.e., 60 STAs). Thus, in the SA distribution, all 60 STAs utilize the SA mechanism; in the RA distribution, all 60 STAs utilize the RA mechanism; and in the Hybrid distribution, half of the stations (30 STAs) uses the SA, and another half of the stations (30 STAs) uses the RA mechanism. It is observed that SA distribution provides the highest throughput, i.e., 309.2 Mbps, while RA distribution provides only around 180.6 Mbps. In the SA distribution, all 60 STAs utilize the scheduled access mechanism using the latest OFDMA technology. There is no possibility of collisions in the SA mechanism since the absence of the hidden nodes and no need for the backoff window like the RA mechanism. Thus, the SA distribution significantly outperforms the RA distribution in terms of throughput. The Hybrid distribution provides approximately 245 Mbps around the average of SA and RA distributions as half of the STAs use the SA method and another half use the RA method for the channel access.

Fig. 11 shows the number of retransmissions for the different distribution of stations. As expected, SA distribution performs the best, and RA distribution shows the worst performance. The retransmission of packets reduces the goodput of the network, and it happens due to several reasons, such as the collision of packets and transmission impairment. The causes of transmission impairment are noise, distortion, attenuation, etc., which are the general propagation problems of wireless channels. We can ignore these problems here as the impact is comparatively little than the collision problem. Again, the collision problem occurs to only random access mechanism due to two reasons. One is the presence of the hidden nodes, and another is the same backoff value produced by two RA STAs. It is observed in Fig. 11 when the number of STAs is meager (e.g., 1 STA), the number of retransmissions is nearly zero for all of the distributions. As the number of STAs increases, the impact of RA distribution becomes severe while SA distribution shows excellent performance. Even in the dense scenario (i.e., 60 STAs), the number of retransmissions of SA distribution is below 1. As in the previous simulation, the impact of Hybrid distribution on the retransmission is in between SA and RA distributions. The robustness of the OFDMA scheduled access over the legacy random access mechanism can be perceived by the above two simulations shown in Fig. 10 and Fig. 11.

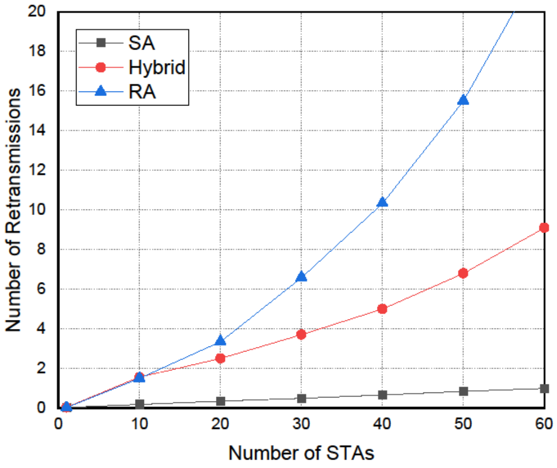


Fig. 11. Number of retransmissions of the PRS protocol for different distribution of stations

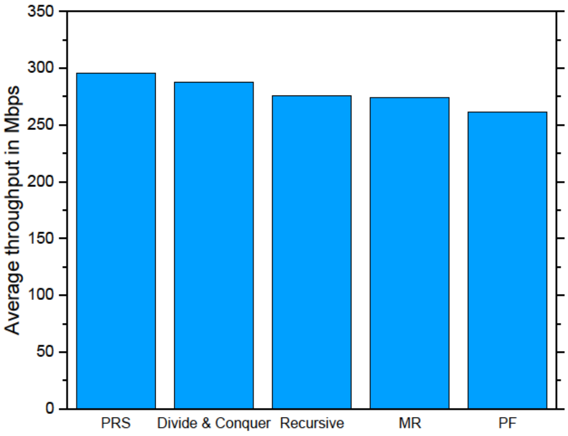


Fig. 12. Throughput comparison between different protocols

In the rest of the simulations (Fig. 12 to Fig. 16), the proposed PRS protocol is compared with other promising protocols: Divide and Conquer, Recursive, MR, and PF. As discussed earlier, MR and PF are the cellular protocols that we adapt to the 802.11ax network. The details of the competing protocols are discussed in Section 2.2, i.e., 'Problem Statement and Motivations'. A medium congestion scenario (e.g., 35 STAs) is considered for the rest of the simulations in this article unless otherwise specified. All protocols execute only OFDMA transmissions during simulations, and all STAs are OFDMA-capable (i.e., SA STAs). Thus, during the comparison in the rest of the simulations, PRS leverages only the OFDMA SA mechanism.

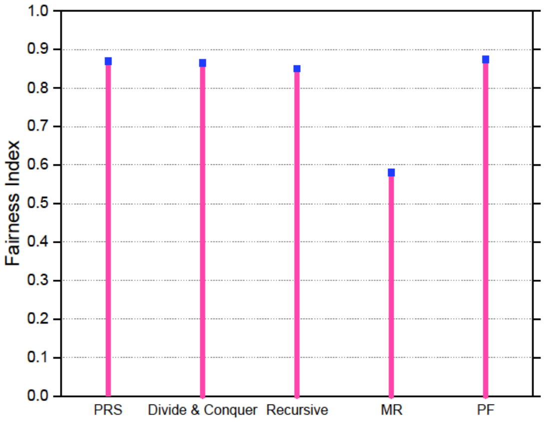


Fig. 13. Fairness comparison between different protocols

The comparison of throughput between the PRS and other protocols is shown in Fig. 12, where PRS provides the highest throughput, i.e., 295.7 Mbps. The PRS algorithm distributes the RUs proportionally to the SA stations and ensures efficient exploitation of RUs by the stations. The Divide and Conquer algorithm, which is closest to the PRS, also provides a very high throughput, i.e., 287.5 Mbps. The throughput gained by this algorithm is a tight upper bound for the optimal user schedule. Another ax scheduler, i.e., Recursive that schedules RUs to the STAs in a near-optimal fashion and adjusts the number of resource units dynamically, also provides a good throughput of 275.4 Mbps. The MR, which is very good in providing high throughput in the cellular network, is not the best for the Wi-Fi network, giving a throughput of around 273.8 Mbps. The PF, another cellular protocol designed for fair access to the medium, provides the lowest throughput among all competing protocols.

The fairness in accessing the Wi-Fi channel of the competing protocols is shown in Fig. 13. We use Jain's fairness index for measuring the fairness of the protocols. The Proportional Fair, i.e., PF protocol, offers the best performance in this regard. The PF, designed for the LTE network for increasing fairness, also performs very well (i.e., index 0.874) in the Wi-Fi network. The PRS also ensures very good fairness (i.e., index 0.87) since it distributes RUs according to the available loads of the stations. The performance of Divide & Conquer and Recursive algorithms are also satisfactory since the algorithms solve the SRA problem optimally and hence ensure an index of 0.865 and 0.85, respectively. The MR performs the worst (i.e., index 0.58) as it ignores the fairness effect and focuses on the throughput in the cellular network.

Let's examine the overall performance of the protocols in Fig. 12 and Fig. 13. The overall performance of ax-based protocols (PRS, Divide and Conquer, Recursive) is better than the cellular protocols (PF, MR), although we adapt the cellular protocols in Wi-Fi 6 environment during the simulation. These phenomena suggest that it is not good to hire the LTE protocols for Wi-Fi 6 network. The LTE network predominantly uses the OFDMA technology that IEEE 802.11ax has recently adopted. However, the OFDMA specifications are somewhat different for Wi-Fi 6 than those for cellular networks. That's why the overall performance of PF and MR is not satisfactory in the Wi-Fi network, which is validated by the last two simulations.

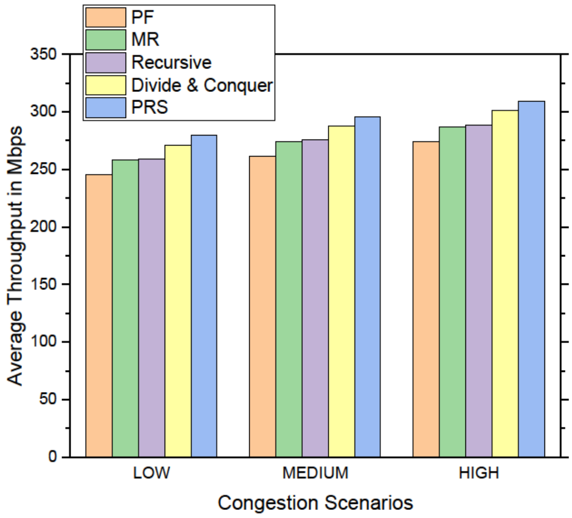


Fig. 14. Impact of the number of stations on the throughput

Throughput for different distributions of stations of the competing protocols is compared in Fig. 14. Three congestion scenarios, namely, Low (i.e., 10 STAs), Medium (i.e., 35 STAs), and High (i.e., 60 STAs), are considered here. The throughput of all protocols increases as the number of STAs increases and vice versa. When the number of STAs increases, more STAs reside in the same radius (r = 15 meters) and approach the access point. Thus, STAs get a stronger signal and increase the throughput thereby. For example, the PRS protocol provides a throughput of 279.5 Mbps, 295.7 Mbps, and 309.2 Mbps for Low, Medium, and High congestions. All protocols show similar performance (i.e., throughput enhancement) as the density of the STAs increases.

Fig. 15 shows how the throughput varies according to the number of antennas of the access point (A_{AP}). We observe the average throughput of the protocols for the number of antennas 2, 4, and 6. The number of antennas of the STA (A_{STA}) always keeps to the minimum value of 1 for all simulations conducted for this article since STAs (especially the cell phones) are low-power devices and are small in size. It is evident from the chart; the throughput increases gradually with the number of antennas of the AP. However, this enhancement is not linear because the total transmit power is constant. For example, if we look at the behavior of MR protocol, we see the throughput increases by 29.6 Mbps for incrementing the number of antennas from 2 to 4. On the other hand, this enhancement is only 22.1 Mbps for incrementing antennas from 4 to 6.

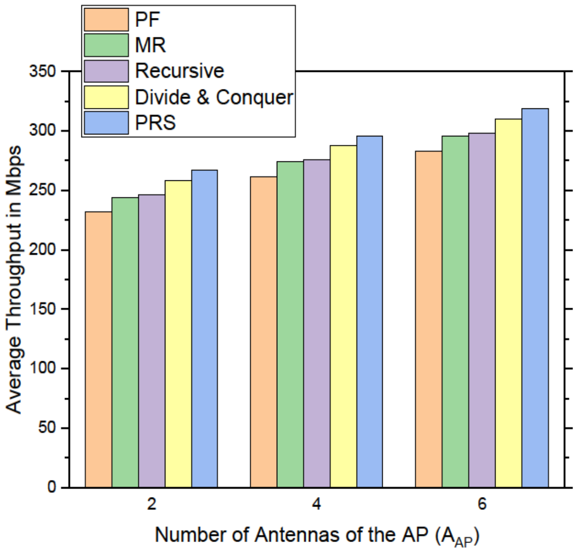


Fig. 15. Impact of the number of antennas on the throughput

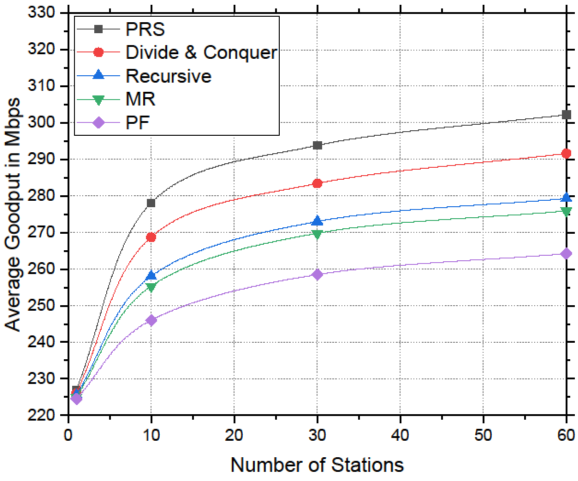


Fig. 16. Goodput vs. number of stations

Fig. 16 exhibits the goodput scenario of the participating protocols for a different number of STAs. The difference between the throughput and goodput is that goodput does not count the undesirable data (e.g., retransmissions, overhead). Unlike the random access, in OFDMA transmissions, the number of retransmissions is meager (illustrated in Fig. 11); hence the goodput is almost the same as the throughput. We vary the number of STAs from 1 to 60 to observe the change in goodput provided by different protocols. As the number of STAs increases, the goodput also increases and vice versa. When the number of STAs is only one, the goodput of each of the protocols is almost the same, i.e., around 225 Mbps. As the number of STAs increases, the difference in goodput becomes significant. For example, when the number of STAs is 30, the difference between the goodput of PRS and PF protocols is (293.8 - 258.5) = 35.3 Mbps.

VII. CONCLUSION

In this paper, an OFDMA-based innovative scheduling protocol is designed for the future wireless LAN. To the best of our knowledge, this is the first scheduling protocol for Wi-Fi that investigates the SA and RA mechanisms together for scheduling and estimates the amount of resources for both mechanisms proportionally according to available loads. Besides, the PRS also calculates the number of RUs for each of the STAs of the SA mechanism. The process of scheduling is thoroughly investigated using a practical scheduling problem which is illustrated in Section 4. We design two exclusive scheduling algorithms (i.e., Algorithm 1 and Algorithm 2) for the PRS protocol to perform the scheduling. The main novelty of the PRS protocol lies in the design of the algorithms. Lastly and most importantly, the PRS enhances the performance of the wireless LAN by increasing the throughput, goodput, and fairness index as well as reducing the retransmission of packets.

DECLARATION OF COMPETING INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

AUTHOR CONTRIBUTIONS

The main credit goes to the first author, Gazi Zahirul Islam who has been pursuing a Ph.D. at the Centre for Higher Studies and Research (CHSR), Bangladesh University of Professionals. This article is produced as one of the requirements of the degree. The first author contributes in every step from the conceptualization to the implementation of the protocol. He innovates the idea, draws the frameworks, and conducts data analysis and simulations for the protocol. The second author, Prof. Dr. Mohammod Abul Kashem supervises the work thoroughly and provides support and guidance throughout the process.

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