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Efficient resource allocation in the IEEE 802.11ax network leveraging OFDMA technology

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ABSTRACT

The IEEE 802.11ax pave the way to deliver the high-speed communications in the Wi-Fi network even in the dense areas. In this regard, the most challenging task is to enhance the throughput as IEEE 802.11ax standard promises to provide four times improvement in average throughput per station. Unfortunately, none of the existing protocols could satisfy the demand of the standard yet. The performance of the IEEE 802.11ax protocol largely depends on the efficient and wise scheduling of resource units to the stations. The uplink scheduling is more challenging than the downlink since in the uplink path many stations send data to the access point where the stations must be synchronized for the OFDMA transmissions. This paper innovates an uplink scheduling protocol named Efficient Resource Allocation (ERA) that promises to provide a high-throughput to the Wireless LAN along with the reduction of retransmissions of the packets. The simulations and analyses show that the proposed protocol would be a robust one to satisfy the promises of the latest IEEE 802.11ax standard. To the best of our knowledge, the proposed protocol is the unique one of its kind where the resource units are distributed to the stations according to their available loads.

1. Introduction

The IEEE delivered its latest standard IEEE 802.11ax (Standard for Information technology, 2019) also known as Wi-Fi 6 for the communication in Wireless LAN (WLAN) that promises to provide tremendous bandwidth for the next-generation communications. According to IEEE 802.11ax specifications, the Wi-Fi 6 has to gain at least 4X enhancement in data throughput per station (STA) as well as to be robust enough to provide service in the highly-dense areas.

The latest amendment proposes a number of ways for enhancing the performance of the Wireless LAN. The most promising one is the utilization of the OFDMA (Orthogonal Frequency Division Multiple Access) technology. OFDMA technology can decrease overheads for short packet transmissions at a high rate and improve robustness to frequency selective interference. The OFDMA mechanism can also improve power spectral density and hence the rate of users' data. The standard hires some technological developments from the LTE (Long Term Evolution) and other contemporary 4G cellular technologies to support more STAs concurrently in the same channel utilizing the OFDMA technology. Wi-Fi 6 not only employed the OFDM (Orthogonal Frequency Division Multiplexing) modulation scheme but also assigns a group of non-overlapping subcarriers to the STAs efficiently using the latest OFDMA technology. Thus, the large channel is divided into smaller sub-channels with a specified number of orthogonal subcarriers (Introduction to 802.11ax High-Efficiency Wireless, 2019). Following the 4G nomenclature, the Wi-Fi 6 calls the sub-channel as the Resource Unit (RU) that comprises at least 26 subcarriers.

Observing different user's traffic needs, the access point (AP) decides how to allocate the resource units to the stations. The AP may allocate the whole channel to a single STA, or it may partition the large channel into several sub-channels (RUs) to support many STAs simultaneously (Islam and Kashem, 2019). In congested areas such as the stadium, airport, market where lots of terminals i.e.

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users would normally compete inefficiently for channel access, the OFDMA technology can now serve them simultaneously with the smaller but dedicated sub-channels. As a consequence, the average throughput per STA increases remarkably.

However, the performance gain of the OFDMA largely depends on how the AP schedules the channel resources for the stations and the configuration of various wireless transmission parameters (Wang and Psounis, 2018). These sorts of problems are known as resource allocations or scheduling problems. Thus, nowadays, a study of resource scheduling is highly appropriate for the research of the OFDMA-based protocols. In this regard, it is worth mentioning that the main challenge is to design the uplink (UL) scheduling process rather than the downlink (DL). The downlink scheduling is easier to implement since only one station e.g. the AP would send data to the other STAs. However, in the uplink process, many STAs would have to send data to the AP simultaneously. As such, during the UL transmissions, all sending STAs need to be synchronized with the system and PHY preambles generated by the STAs should also be the same (Bankov et al., 2018).

The IEEE 802.11ax MAC (Medium Access Control) facilitates MU-OFDMA transmission in the uplink path utilizing two different types of RUs namely, i) Random Access (RA) RUs, and ii) Scheduled Access (SA) RUs (Bhattarai et al., 2019). The scheduled access method prevents contentions from the stations and helps in enhancing the overall throughput of the network. On the other hand, the random-access method permits data transmission from the stations whose BSR (Buffer Status Report) is not available to the access point. For instance, newly joined stations cannot send packets using scheduled access resource units unless the access point is aware of their BSR information. However, random access resource units allow these stations to send their packets and BSRs to the access point. In this regard, the researcher may also investigate the impact of different distributions of random-access RUs and scheduled access RUs on the performance of the MAC layer.

In this paper, we propose a new protocol named 'ERA' for the resource allocation and scheduling in the IEEE 802.11ax network leveraging the OFDMA technology. The protocol enhances the throughput and goodput as well as reduces retransmissions of the packets in the Wi-Fi network remarkably. The protocol is designed using the Scheduled Access (SA) mechanism utilizing the OFDMA to be used in the UL path. This article gives an innovative idea to distribute and utilize the RUs to the intended STAs based on their available load. The details of load measurement and the classification of STAs based on their loads are explained mathematically in the article. The simulations and model analysis validate that the intended protocol would be very efficient to mitigate the demand of next-generation Wi-Fi network.

The rest of the article is organized as follows. In Section 2, we discuss existing related works and motivation for this work. Section 3 specifies the system model for the proposed protocol. The main contribution of the work is 'Scheduling Design' which is illustrated in Section 4. Section 5 contains the analytical model and simulations for measuring the performance of the protocol. Finally, Section 6 concludes the article.

2. Related works and motivation

2.1. Existing works

The TGax (TASK GROUP AX) has designed an optional mechanism that permits random UL OFDMA transmission along with the deterministic access. The random UL OFDMA transmission is exclusively known as Uplink OFDMA-based Random Access (UORA) illustrated in Ghosh et al. (2015). The random feature is very important when the access point has not received the BSR from the associated STAs but those stations have data for transmission, or when an unassociated station wants to send an association request. An innovative protocol for random UL OFDMA transmissions is proposed in Lanante et al. (2017). The article also provides a comprehensive model using the Markov chain. However, in Avdotin et al. (2019), the authors show that using the standard UORA like (Lanante et al., 2017), a protocol cannot meet the demand of Real-Time Applications (RTA).

In Qu et al. (2015), the authors innovate a novel OFDMA-adopted MAC protocol named 'OMAX'. However, it utilizes the random-access feature only, although TGax designs a flexible and powerful framework both for scheduled and random access. One of the efficient usages of OFDMA is the multiple short packet transmissions from multiple stations simultaneously using scheduled access in accordance with the TF (Trigger Frame). Thus, (Qu et al., 2015) ignores one of the robust features of the OFDMA.

Kwon et al. (2009) propose a MAC protocol that provides more throughput than most of the contemporary protocols. According to the mechanism in Kwon et al. (2009), a terminal maintains a single backoff timer for all of the OFDMA sub-channels allocated in the communication. However, channel utilization performance is not good enough in that mechanism as a single timer cannot reflect the status of the system which has various loads in multiple sub-channels. This limitation is then solved by Wang and Wang (2010), where every station maintains one backoff timer for every sub-channel. Therefore, every backoff timer represents the status of a unique station that might be located in any sub-channel.

The MAC protocol in Yuan et al. (2011) termed 'CCRM' that incorporates cooperative channel reservation mechanism. Existing protocols cannot announce Channel Reservation Information (CRI) reliably because of transmission errors of frame collisions. In the CCRM protocol, CRI originated from the stations having real-time traffic information is further relayed by the cooperation of surrounding stations. As a result, the protocol enhances the reliability of channel reservation by its novel procedure. The authors of Lee (2018) propose a priority-based reservation MAC protocol that utilizes a Common Control Channel (CCC). The CCC is dedicatedly used for secondary users to send control packets for determining the priority to access the primary channels. These two protocols primarily focus on the resource utilization of the channels.

Article (Nguyen et al., 2016) innovates a hybrid TDMA/CSMA MAC protocol for the smooth broadcasting of messages. The protocol also increases the throughput on the control channel by eliminates unnecessary control packets. However, the protocol does not work well in a highly dense environment. The paper (Xuelin et al., 2015) proposes another hybrid multi-channel mechanism termed 'TR-MAC', which coalesce the strength of TDMA technology and DCF access methods. This protocol reduces different overheads and able to provide more throughput than conventional protocols.

The authors of Haile and Lim (2013) and Ferdous and Murshed (2010) arrange STAs into different groups, and the STAs in a common group share the common sub-channel for medium access. In this model, when the AP receives the RTS (Request-to-Send) frame from a sub-channel, then it sends the CTS (Clear-to-Send) frame to the members of the group to assign the channel resources. Xu et al. propose an intermittent carrier sense mechanism (Xu et al., 2013) that allows a single radio STA to access more than one sub-channel concurrently. Still, the system throughput and fairness of the protocol are not good enough to comply with Wi-Fi 6 standard.

MU transmissions in the IEEE 802.11ax must be aligned in the time domain which starts with a TF. If a station has a short frame for transmission then it either uses padding or tries to aggregate the next frame with the current frame. If the remaining space is not sufficient for aggregating the next frame, then padding is the only option to fill up the current frame. To avoid wasting channel resources, Ghosh et al. (2015) allows the IEEE 802.11ax stations to fragment the frames. To improve the efficiency further, Wang et al. (2015) allows the stations aggregate frames from different access categories.

The 802.11ax amendment allows Block ACK (BA) frames to acknowledge all stations by sending a common frame instead of using an individual frame for each station (Merlin et al., 2015; Kim et al., 2015); a mechanism similar to the existing Multi-TID BA frame that is used to acknowledge a set of frames from various access categories. To shorten the transmission, a Multi-STA BA frame can be sent in a legacy manner with only a legacy 802.11a preamble (Khorov et al., 2018).

2.2. Motivations

The IEEE 802.11ax adopts the latest OFDMA technology for the channel access and resource sharing. The OFDMA technology originally derived from the OFDM modulation and an OFDMA system uses a group of non-overlapping sub-carriers to form the RUs that can be assigned to the STAs (Islam and Kashem, 2018). Thus, multiple STAs can transmit data simultaneously without having collision which is not possible in the legacy DCF random access protocol. Inheriting the advantages of the OFDM, OFDMA-adopted protocol can further raise the performance by increasing multiuser diversity. As such superiority of the OFDMA technology, some wireless systems such as the WiMAX and LTE already leverage it to increase the channel throughput (Lee et al., 2009).

We examine some cellular protocols such as the MR (Max Rate) and PF (Proportional Fair). The base station employs the MR scheduler to maximize the cumulative throughput $S = \sum_i S_i\,(t)$ at time t. The MR considers resource units one by one and allocates each resource unit to a user with the highest nominal data rate in the resource unit. However, MR scheduler blocks users with low instant rates in high traffics (Capozzi et al., 2013). To overcome this situation, the researchers develop a new class of protocol termed Proportional Fair (PF) that aims to maximize $\sum_i log\, S_i\,(t)$. Kwan et al. (2009) assert that the PF scheduler ensures the equal channel time to all users in the long run.

The performance of the OFDMA-based Wi-Fi protocols largely depends on the design of an efficient resource allocation algorithm. The resources can be allocated to the users by selecting a variety of resource unit combinations (illustrated in Section 3 'System Model') to the appropriate STAs. To design an efficient new protocol, we especially focus on some promising protocols mentioned in the following paragraph which are designed for the latest IEEE 802.11ax standard.

The authors in Wang and Psounis (2018) investigate how to optimally distribute the sub-carriers to the STAs and STA groups to maximize the user sum rate. They propose a greedy algorithm that splits the bandwidth into resource units and schedules STAs on them. The researchers of Bankov et al. (2018) discuss the OFDMA constraints and requirements for IEEE 802.11ax in contrast to cellular communications. Then propose a set of schedulers for the IEEE 802.11ax by modifying some well-known cellular schedulers. In Bankov et al. (2017), the authors elaborate the peculiarities of the OFDMA implementation for the IEEE 802.11ax and explains why the classic schedulers could not show good performance for the IEEE 802.11ax. Then the researchers propose a brand-new scheduler named MUTAX (Minimizing Upload Time in 11AX) and show that the performance of MUTAX is far better than the existing protocols. The overall performance of the protocols of Wang and Psounis (2018); Bankov et al. (2018), and Bankov et al. (2017) is outstanding than the contemporary protocols. The researchers of the mentioned articles conduct rigorous simulations and analyses to prove that their protocols are very efficient for the latest Wi-Fi network. However, the articles do not cover the retransmission impacts and we believe the performance of the protocols especially the throughput still be enhanced further.

Perceiving the significance of the robust resource allocation and scheduling protocol for the Wi-Fi 6, we propose a protocol named 'ERA' i.e. Efficient Resource Allocation. The protocol enhances the throughput of the STAs as well as reduces the number of retransmissions. We conduct extensive simulations (See Section 5.2) using the robust NS-3 simulator to observe the efficiency of the proposed ERA scheduler over several well-known existing schedulers. The details of the protocol are explained in Section 4.

3. System model

We consider an OFDMA-based Wireless LAN that operates in the infrastructure BSS (Basic Service Set) (O'Hara and Petrick, 2005). There are N STAs in the BSS that connect to the single AP as shown in Fig. 1 where four STAs are communicating through the AP. The system can operate in any frequency bandwidth (20/40/80/160 MHz) that is proposed for the 802.11ax (Standard for Information technology, 2009; Islam and Kashem, 2019) by the IEEE standard. The whole bandwidth of a particular channel is divided into several RUs by the AP, then the AP assigns the RUs to the STAs (See Algorithm 1) whose BSR information (Bankov et al., 2017; Nurchis and Bellalta, 2019) is available. Thus, leveraging different RUs, different STAs can communicate with the AP concurrently without suffering from channel contentions (i.e. an inherent constraint of random-access protocols) and co-channel interference. The protocol for the system is designed agreeing to the OFDMA specifications outlined in Section 3.1 and conforming to the constraints mentioned in Section 3.2.

3.1. OFDMA specifications

Like the cellular networks, the whole channel in IEEE 802.11ax can be divided into several sets of OFDMA orthogonal subcarriers which are known as the resource units. Each resource unit in OFDMA consists of 26, 52, 106, 242, 484, 996 or 2 × 996 subcarriers (Naik et al., 2018); (Khorov et al., 2016) . The size of the resource unit depends upon the channel width. The 802.11ax supports 20 MHz, 40 MHz, 80 MHz, 160 MHz, and (80 + 80) MHz (i.e. merges two 80 MHz channels). The 20 MHz, 40 MHz, 80 MHz, and 160 MHz channels can be split into at most 9, 18, 37, and 74 RUs, respectively where each RU contains 26 tones. Fig. 2 shows how a 40 MHz channel in 802.11ax is partitioned in terms of resource units. Removing the 1st level (i.e. 484-tone RU) from the 40 MHz channel and vertically dividing the channel into two halves then each half would represent the RUs formation of a 20 MHz channel. In a similar fashion, merging two 40 MHz channels vertically and adding a 996-tone RU at the 1st level (bottom side of the figure) would create the RUs formation of an 80 MHz OFDMA channel. The same procedure would valid to the 160 MHz channel.

IEEE 802.11ax permits the 160 MHz channel, which is very wide and encompasses multiple narrower channels. With the 160 MHz channels, we will get the fastest Wi-Fi, delivering multi-gigabit low latency connections. These high-speed connections are essential for supporting 5G services in wireless LAN. The 160 MHz channel bandwidth can be used only in the 5 GHz band on the devices that support the wireless standard Wi-Fi 6 (802.11ax) or Wi-Fi 5 (802.11ac). This wider channel can contain up to 74 RUs where each RU contains 26 tones and can provide a speed of up to 1722 Mbps. There are only a few wider channels are available to be used in Wi-Fi in different regions. For example, for 802.11ac operation, there is only one 160-MHz channel is available in North America and only two 160-MHz channels in Europe.

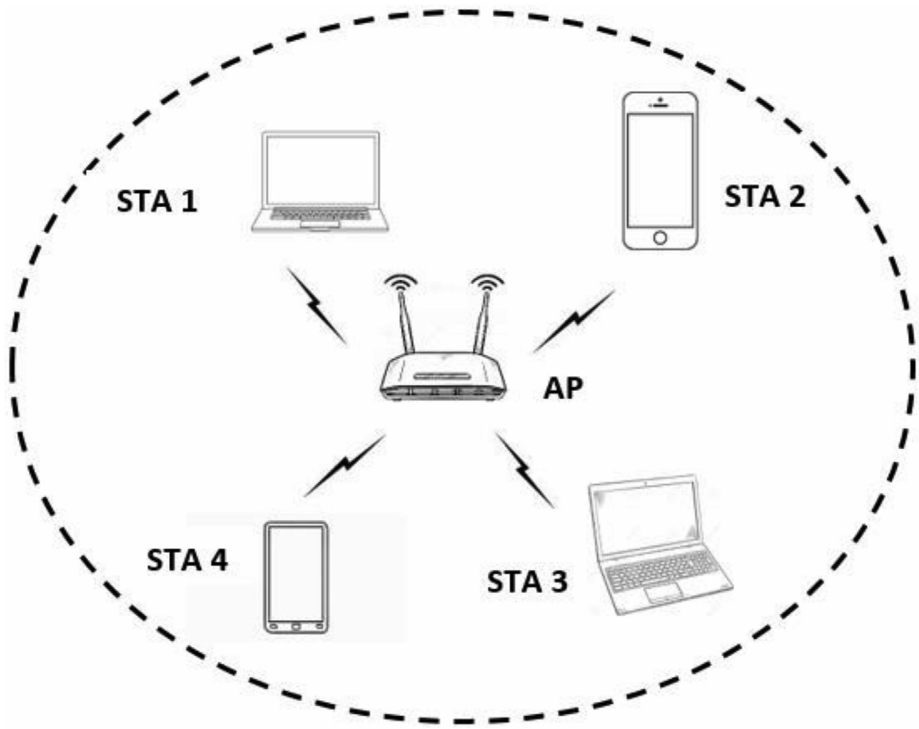

Fig. 1. A Wireless LAN having four stations and one access point.

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Fig. 2. RUs formation in a 40 MHz channel.

3.2. OFDMA constraints

According to IEEE 802.11ax, a RU contains at least 26 sub-carriers. On the other hand, wider RUs (i.e. larger than 26 sub-carriers) can be split into narrower RUs. For instance, in a 40 MHz channel, the RU arrangement may be as one 242-tone RU, one 106-tone RU, one 52-tone RU, and three 26-tone RUs. It is noted that the RU positions are not arbitrary, for example, we cannot form a 52-tone RU from the second and third 26-tone RUs or the fifth and sixth 26-tone RUs (underlined in Fig. 2) in the 40 MHz channel.

The AP assigns the resource units to different stations as per their traffic requirements, thereby enabling multi-user (MU) transmissions simultaneously. However, unlike the LTE, there are several restrictions regarding the assignment of RUs to the STAs. In the IEEE 802.11ax, a resource unit cannot be allocated to more than one station and a station also cannot acquire more than one resource unit. Another requirement is an RU must contain at least 106 sub-carriers for the MU-MIMO transmissions and the novel 1024 QAM (Quadrature Amplitude Modulation) can be used only in the 242-tone RUs or the larger RUs (Standard for Information technology, 2009).

The amount of data that can be carried on a resource unit depends on the size of the resource unit. For example, using 1024-QAM, a 242-tone RU can provide up to 135.4 Mbps while a 484-tone RU can provide twice i.e. 270.8 Mbps (Bankov et al., 2018). The interesting point is that during the OFDMA transmissions, all RUs irrespective of their size would get an exact amount of time to transfer their data and all OFDMA transmissions are concurrent. Hence, we design Algorithm 1 such that a high-load STA gets a larger RU than a low-load STA.

4. Scheduling design

4.1. Indexing of RUs

The bandwidth of an OFDMA channel can be assigned to different RUs into at most L levels. In Fig. 3 there are 4 levels (i.e. $l = 4$) in the 20 MHz channel whereas in Fig. 2 there are 5 levels (i.e. $l = 5$) in the 40 MHz channel. The number of levels increases in accordance with the channel bandwidth. We denote each level by assigning a level number (l) from the bottom (by assigning $l = 0$) to up gradually increasing the value l. Thus, in Fig. 3, $l = 0$ represents the largest

$l = 3$	(3, 0)	(3, 1)	(3, 2)	(3, 3)	(3, 4)	(3, 5)	(3, 6)	(3, 7)
$l = 2$	(2, 0)		(2, 1)		(2, 2)		(2, 3)	
$l = 1$	(1, 0)				(1, 1)			
$l = 0$	(0, 0)							

Fig. 3. Levelling and indexing the RUs in a 20 MHz channel.

RU level (at the bottom) and $l = 3$ represents the smallest RUs level (on the top) in a 20 MHz channel.

For simplicity, we consider each of the resource units (having more than 26 tones) can be partitioned into two equal smaller resource units. We denote each resource unit as RU (l, i) where i denotes the index of a resource unit at level l. The whole bandwidth can be split into 2^{l} uniform (equal-size) resource units at level l ($l \in \{0, 1, \ldots, L\text{-}1\}$), labeled as 0, 1, 2, …, 2^{l}-1. Each resource unit RU (l, i) with $l < L - 1$ can be divided into two resource units RU ($l + 1$, $2i$) and RU ($l + 1$, $2i + 1$). Following the procedure, we label the resource units of a 20 MHz OFDMA channel shown in Fig. 3.

4.2. Load measurement

Every STA in the BSS (Basic Service Set) that has data send their load information to the AP through BSR (Buffer Status Report). Receiving the BSR, the AP classifies the STAs according to their load as a) Low-Load (LL) b) Medium-Load (ML) and c) High-load (HL). The AP sets a reasonable/practical value for the LL parameters observing the load of the STAs which have comparatively lower traffic demand. Considering traffic volumes in the channel the AP can adjust this value so that most of the STAs in the BSS fall in the LL group. Then, parameters for ML and HL calculates as the following equations:

$$\mathrm{ML} = 2 * \mathrm{LL}. \quad (1)$$

$$\mathrm{HL} = 2 * \mathrm{ML} = 4 * \mathrm{LL}. \quad (2)$$

Now, All STAs would belong to a particular load group according to the load range mentioned in the following equations:

$$0 < \mathrm{LL\ STAs} \leq (\mathrm{LL} + \mathrm{ML})/2. \quad (3)$$

$$(\mathrm{LL} + \mathrm{ML})/2 < \mathrm{ML\ STAs} \leq (\mathrm{HL} + \mathrm{ML})/2. \quad (4)$$

$$(\mathrm{HL} + \mathrm{ML})/2 < \mathrm{HL\ STAs}. \quad (5)$$

Suppose, in a BSS there are 5 STAs namely A, B, C, D, and E having load 4, 1.5, 2.7, 30, and 3 Mbps respectively. If the AP sets LL = 2, then according to the above equations, the STAs would be classified as:

LL STAs: B, C, E; ML STAs: A; HL STAs: D

Since wider resource units can provide more data than the smaller RUs, we allocate comparatively wider RUs to the HL STAs. Thus, in Algorithm 1 in the following section, we ensure larger RUs to the HL STAs, intermediate RUs to the ML STAs, and small RUs to the LL STAs.

4.3. Resource allocation

For simplicity and better efficiency, we allocate resource units at most tree levels irrespective of channel bandwidth. Thus, all available bandwidth in Wi-Fi 6 (20/40/80/160 MHz) can utilize only three levels. Following our previous discussions, the lowest bandwidth (20 MHz) has four levels ($L = 4$) while the largest bandwidth (160 MHz) has 7 levels ($L = 7$). We do not employ the bottom level ($l = 0$) that provide only one resource unit RU ($l = 0$, $i = 0$) that consists of whole channel bandwidth. Because allocating RU (0, 0) we can serve only one STA at a time and hence we would be deprived of the utilization of the OFDMA feature. Since we want to serve more STAs concurrently we attempt to allocate resource units from the next three levels i.e. l = 1, 2, and 3.

We develop Algorithm 1 for the allocation of the RUs to the participating STAs in the network. The wider resource element RU (1, 0) assigns to an HL STA, a medium element RU (2, 2) to an ML STA, and two shorter element RU (3, 6) and RU (3, 7) to two LL STAs. If HL STA is not available at the moment then its RU (1, 0) split into two as RU (2, 0) and (2, 1). The RU (2, 0) assigns to an ML STA, and RU (2, 1) is further split into two shorter RUs as RU (3, 2) and RU (3, 3) which will be assigned to two LL STAs. Similarly, if any ML STA is not available during the allocation then its resource element split into two which will be assigned to the LL STAs. It is obvious, scheduling process executes only when at least one LL STA is available in the network.

Since the main purpose of this protocol is to distribute the RUs based on the load measurement, we ignore the channel condition on a particular RU. Because the throughput difference for channel condition is very insignificant comparing the size of the RUs. Thus in the above case, if we assign RU (1, 1) to an HL STA, RU (2, 1) to an ML STA, and RU (3, 0) and RU (3,1) to two LL STAs do not bring any significant difference in throughput. By the way, good RU selection based on the channel condition is of particular interest in wireless communication (especially in cellular communication) where all RUs are of equal length.

The algorithm repeatedly executes for each flow of data. From the above discussion and constraints, it is understandable that in each flow at most one HL STA and one ML STA can transmit data. If more than one HL or ML STAs are available in the current flow, then the AP chooses the oldest STA according to the BSR submissions i.e. First Come First Served (FCFS). Subsequent STAs will get a chance to send data in a later flow. The same policy can apply to the similar HL or ML STAs (although it is very unusual that two STAs have exactly the same load), where STAs would get priority according to the BSR submissions i.e. FCFS.

Algorithm 1: RU Assignment

```
//Assignment of larger RU to LL STAs
IF HL STA is available THEN
    Assign RU (1, 0) to an HL STA
ELSE
    Split RU (1, 0) into RU (2, 0) and RU (2, 1)
    Split RU (2, 1) into RU (3, 2) and RU (3, 3) and assign
  to two LL STAs
    IF ML STA is available THEN
        Assign RU (2, 0) to an ML STA
    ELSE
        Split RU (2, 0) into RU (3, 0) and RU (3, 1) and
  assign to two LL STAs
    END IF
END IF
  //Assignment of intermediate RU to ML STAs
IF ML STA is available THEN
    Assign RU (2, 2) to an ML STA
ELSE
    Split RU (2, 2) into RU (3, 4) and RU (3, 5) and assign
  to two LL STAs
END IF
  //Assignment of smaller RUs to LL STAs
Assign RU (3, 6) and RU (3, 7) to two LL STAs
```

Following the IEEE 802.11ax standard, in our system, the AP schedules channel time and regulates the parameters for uplink and downlink transmissions. For scheduling purpose, the access point sends a novel Trigger Frame (TF) (Avdotin et al., 2019) to the stations in the network. The AP grants channel access, allocates resources for sending stations, regulates transmission parameters, and synchronize participating stations. The transmission parameters include MCSs (Modulation and Coding Schemes), MIMO, transmission power, transmission duration, etc.

5. Analytical model and simulations

5.1. Analytical model

As discussed earlier, the proposed protocol 'ERA' is designed for allocating RUs utilizing the Scheduled Access (SA) method. Thus, in this section, we design an analytical model assuming that only the 802.11ax STAs are the candidates to receive the SA RUs (Scheduled Access RUs). Thus, in the system, there is no capture effect or collisions in the channel by the hidden nodes (Forouzan and York, 2013; Perahia and Stacey, 2013), since every STAs intended to transmit data priorly sent their BSR to the AP.

Let us consider an IEEE 802.11ax infrastructure network consists of only one AP and N STAs. We assume the network is in the saturation stage i.e. every STA in the network always has some packets to deliver. The OFDMA transmission starts when the AP sends the TF to the STAs. The TF contains the scheduling information determined by algorithm 1. The TF also contains transmission information and helps the STAs to synchronize with the system. The duration of a TF cycle is shown in Fig. 4 that calculated as,

$$T = T_H + (T_{TF} + SIFS + \delta) + (T_P + SIFS + \delta) + (T_{ACK} + SIFS + \delta) \quad (6)$$

where T denotes the total time duration of a TF cycle, T_H is the duration of the header field transmission, T_{TF} is the duration of sending the TF to the STAs, $SIFS$ is the duration of Short Inter-frame Space, δ is the propagation delay, T_P is the duration of sending the user data, and T_{ACK} is the duration of sending the ACK frames to the STAs by the AP.

The path-loss model is considered as in Meinila et al. (2009) and the value is calculated as follows,

$$PL = Alog_{10}(d[m]) + B + Clog_{10}(f_c[GHz]/5.0) + X \quad (7)$$

where d is the distance between the STA and the AP; A, B, C, and X are the parameters related to the scenarios explained in Meinila et al. (2009).

Finally, the saturation throughput calculates as follows,

$$S = \frac{M\ E[P]}{T} \quad (8)$$

where S is the saturation throughput in bits per second, M is the number of RUs, T is the duration of the TF cycle represented in Eq. (6), and $E[P]$ is the average payload size in bits which can be calculated as follows,

$$E[P] = \frac{1}{Pmax - Pmin} \int_{Pmin}^{Pmax} f(x)dx \quad (9)$$

where $f(x)$ is the function for the packet's payload size, $Pmax$ is the maximum payload size, and $Pmin$ is the minimum payload size.

5.2. Simulations

In this sub-section, the performance of the proposed ERA (Efficient Resource Allocation) protocol is measured and compared with several promising existing protocols. The well-known NS-3 (The ns-3 network simulatot) simulator is used to evaluate the efficiency by setting different performance parameters. We consider, uplink OFDMA transmissions in an IEEE 802.11ax BSS that operates in a 40 MHz channel at 5 GHz band. The path-loss (PL) model is shown in Eq. (7), where the channel is modeled following the WINNER II model (Meinila et al., 2009). All stations transmit data at the power of 15 dBm. The simulation is set up considering the analytical model described in Section 5.1.

At first, we compare the average throughput of the STAs of the ERA protocol with that of Greedy (Wang and Psounis, 2018), SRTF (Bankov et al., 2018), and MUTAX (Bankov et al., 2017) protocols. The protocols of (Wang and Psounis, 2018; Bankov et al., 2018), and (Bankov et al., 2017) are very promising than the existing protocols which are described in Section 2.1 titled 'Existing Works'. In this simulation, parameters are adjusted as: number of STAs (N) = 25, radius of BSS (r) = 15 m, number of antennas of the AP (A_{AP}) = 4, and number of antennas of the STAs (A_{STA}) = 1. Throughput the paper, we set the number of antennas of the STAs to 1 for all of the simulations because the Wi-Fi STAs are usually of small-size that are also driven by low power. Table 1 summarizes the general parameters for the simulation shown in Fig. 5. Unless specified, all subsequent simulations hold the same parameters as shown in Table 1. Fig. 5 shows the average throughput of four protocols where the ERA protocol provides the highest throughput i.e. 238 Mbps. The throughput of the Greedy algorithm is much lower i.e. 196 Mbps than others because it assigns a smaller portion of the resource units to the users. The throughput of SRTF (Shortest Remaining Time First) scheduler is also not good enough which

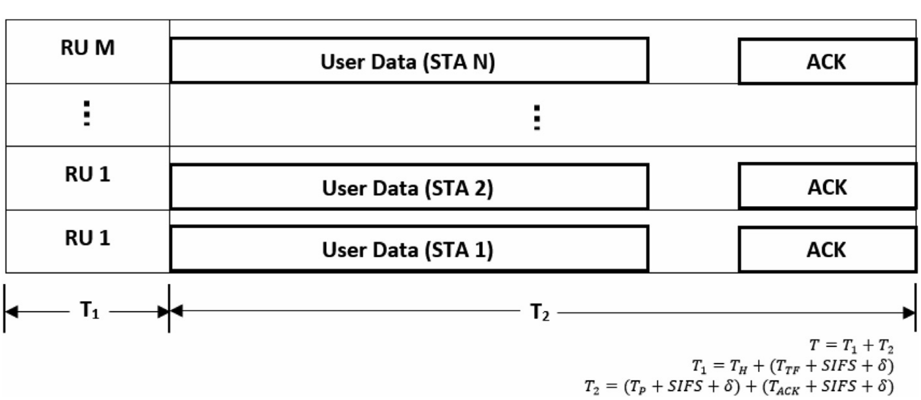

Fig. 4. Uplink OFDMA transmissions using the SA method.

Table 1
General simulation parameters.

Parameters	Value
Number of STAs (N)	25
Radius of BSS (r)	15 m
Number of antennas of the AP (A_{AP})	4
Number of antennas of the STAs (A_{STA})	1
Transmit power	15 dBm
Band	5 GHz
Channel bandwidth	40 MHz

Fig. 5. Comparison of the throughput between different protocols.

is based on exhaustive service while the throughput of MUTAX is promising which uses a channel-splitting scheduler. The MUTAX employs an adaptive strategy to split the channel into the resource units. For each of the configuration of the resource units, MUTAX solves the optimization problem and hence find the best scheduling. The throughput of the ERA protocol is higher than all other protocols because of its dynamic adapting scheduling approach based on the load of the stations which elaborated throughout Section 4 i.e. "Scheduling Design".

Fig. 6 shows the average throughput of the protocols in different congestion scenarios. Here, simulation is conducted for three congestion scenarios terms as low, medium, and high congestion respectively where 5, 20, and 60 STAs respectively participated in the communications. Like the first simulation, here ERA shows the best performance whereas Greedy shows the worst performance due to the causes explained in the previous simulation. It is observed that average throughput increases slightly as congestion increases in the network. It happens because a greater number of STAs are accessing the network residing the same boundary (r = 15 m). It means more STAs approaching the AP thereby reducing the communication distance and hence receiving stronger signals. It is also noticed that the MUTAX algorithm comparative performs very good in high congestion than its medium and low congestions scenarios. For example, from low to high congestion MUTAX increases throughput by (238–225.5) Mbps = 12.5 Mbps (i.e. 5.54%) whereas SRTF increases by (212–202) Mbps = 10 Mbps (i.e. 4.95%). However, the throughput difference of the ERA in various congestions is comparatively uniform while always providing the highest throughput than the competitors. This indicates the ERA is suitable for the home environments as well as for the congested areas (e.g. markets, airports, stadiums, etc.) while the MUTAX is less suitable for the homes than the outside.

The impact of the number of antennas of the AP (A_{AP}) on the throughput is shown in Fig. 7. In this simulation, we vary the number of antennas of the AP to observe the change in throughput of different protocols. It is noted that in all simulations number of antennas of the STAs (A_{STA}) sets to a low value i.e. (A_{STA}) = 1 since the STAs (especially smartphones) generally have a fewer number of antennas than the AP due to its power constraint, hardware size, etc. The chart of Fig. 7 shows that an increase in the values of A_{AP} increases the throughput and vice versa. However, this change in the throughput is not linear since the total transmit power is constant. For example, increasing the number of antennas of the AP from 2 to 4 increases the throughput by 25 Mbps of the ERA protocol while it is only 16.5 Mbps increasing the number of antennas from 4 to 6 for the same protocol. The same explanation applies to the rest of the protocols.

The throughput is proportional to the transmit power. Due to the power constraint of the Wi-Fi network (mentioned in the IEEE 802.11ax standard), we always keep the transmit power the same. Thus, increasing the number of antennas by 2X does not increase the throughput two times. Thus, the reason for the enhancement of the throughput in this simulation is only increasing the number of antennas although this enhancement could be extended further by increasing the transmit power.

We conduct another simulation to observe the impact of the number of STAs on the upload time. The flow sizes are drawn from

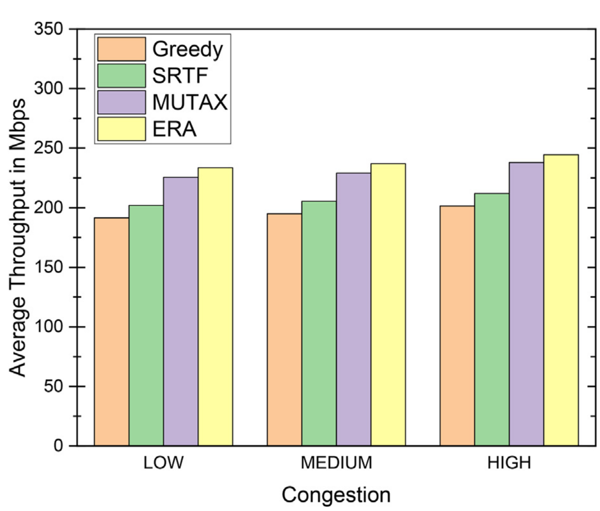

Fig. 6. Impact of the number of STAs on the throughput.

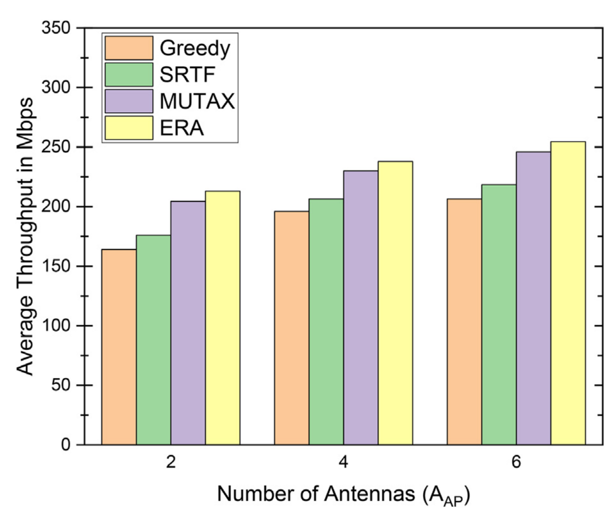

Fig. 7. Impact of the number of antennas of the AP on the throughput.

the truncated lognormal distribution where minimum, average, and maximum size of packets are of 1 KB, 500 KB, and 5 MB, respectively. After delivering a flow, the next flow is generated after a random delay drawn from a truncated exponential distribution where minimum, average and maximum values of time are 0.1 s, 0.3 s, and 0.6 s, respectively. Fig. 8 depicts that upload time is increasing exponentially with the number of STAs. For a small number of stations, the difference in upload time between the protocols is negligible however, for a large number of stations this difference is significant. In this regard, the MUTAX and SRTF protocols perform well (between 0.60 and 0.66 s only for 60 STAs) as these protocols are specially designed to minimize the upload time.

Another simulation is conducted to measure the goodput of the protocols by varying the number of stations keeping the simulation parameters the same as the previous one. The goodput is the measurement of the useful data that reflects the real user experience. Goodput is not the same as throughput because goodput does not include undesirable data such as the retransmitted data, or protocol overhead data. Fig. 9 illustrates the result for the number of stations 1 to 60. As expected, ERA performs the best among the protocols for its innovative algorithm designed for the 802.11ax stations. For a single station, all the protocols provide almost the same goodput i.e. approximately 188.5 Mbps. However, the difference in goodput is very significant when the number of stations increases gradually. For example, when the number of stations is 20, ERA provides a goodput of 235.34 Mbps while Greedy provides only 191.1 Mbps. Again, when the number of stations is 60, ERA provides a goodput of 239.61 Mbps while SRTF provides a much lower goodput of 201.4 Mbps.

The purpose of our final simulation is to show the number of retransmissions by varying the number of STAs of various generalized methods (Lanante et al., 2017) employed by different protocols. We categorize the protocols into four types i.e. Scheduled Access, Random Access, Full Search Method, and Low Complexity Method according to their design for the simulation purpose. Our ERA protocol belongs to the class of pure scheduled access protocols. It is observed in Fig. 10 that the random access protocol performs worst among the mechanisms and pure scheduled access protocols such as the ERA performs the best.

The main reason for retransmissions is due to the presence of hidden nodes in the network and the hidden nodes cause serious performance degradation of the random access protocols. In the beginning, when the number of STAs is only 1, the number of retransmissions of all mechanisms is almost 0. When the number of STAs in the BSS increases, the possibility of the presence of hidden STAs in the surrounding areas also increases. However, hidden STAs cannot create problems for the pure scheduled access protocols because there is no provision for contending channel access randomly here. As such, even in a high congestion scenario (e.g. 60 STAs in the network), the number of retry of the ERA protocol is below 1, where the number of retry of random access protocol is around 23 for the same scenario. The only reason for retransmissions (although negligible) for the ERA protocol is the transmission impairments e.g. attenuation, distortion, noise, etc. The full search method also shows good performance although it shows an unpredictable behavior for different numbers of STAs.

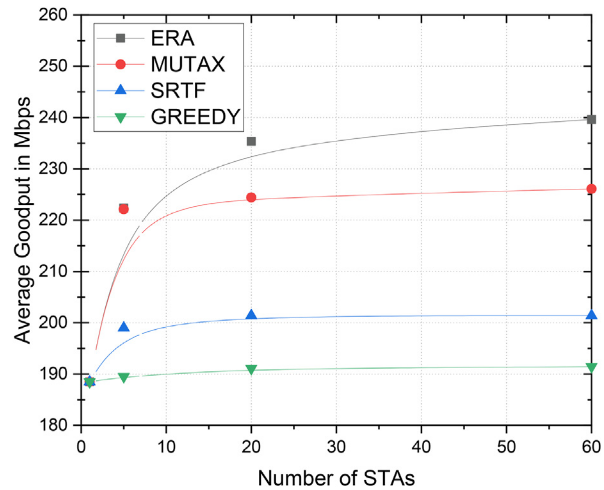

Fig. 9. Goodput vs number of STAs.

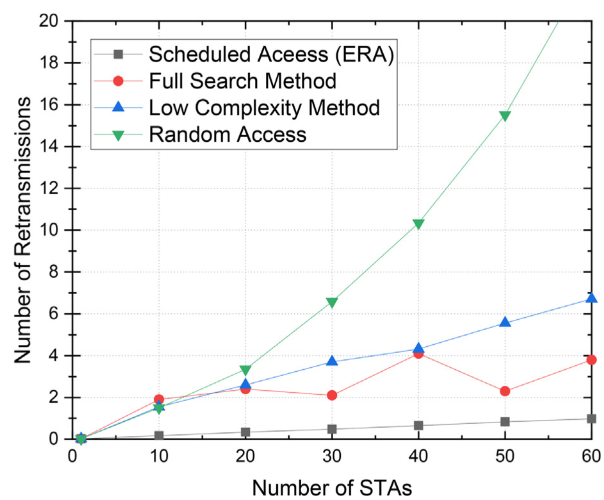

Fig. 10. Number of retransmissions vs number of STAs.

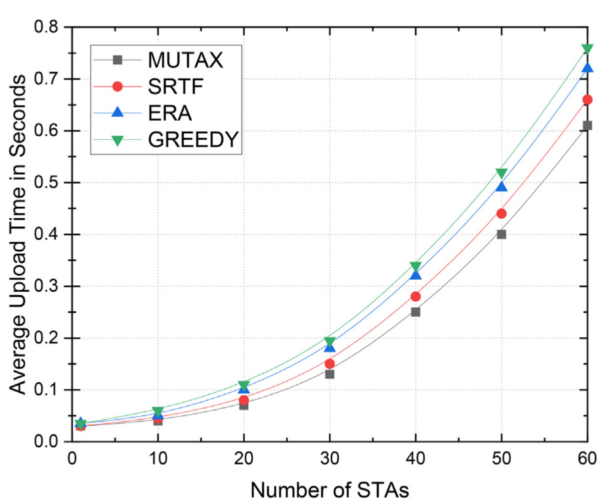

Fig. 8. Upload time vs number of STAs.

6. Conclusion

The IEEE 802.11ax promises to support the high-speed communications in the dense scenarios where Wireless LAN would support more devices as well as increase the throughput per user. In this regard, the OFDMA mechanism plays a vital role in enhancing performance. In this paper, a protocol is proposed for resource allocation and scheduling leveraging the OFDMA technology. In this regard, an innovative algorithm is designed that employs the scheduled access method for resource allocation and scheduling. The protocol distinguishes the stations according to their load and then assigns the resource units wisely and efficiently. The protocol enhances the performance of the Wireless LAN significantly in terms of throughput, goodput, and retransmissions. We conduct extensive simulations and analyses for the validation of the protocol. The simulations show that the proposed ERA protocol provides the highest throughput and goodput among all competitive protocols. Moreover, the number of retransmissions of packets of the ERA protocol is nearly zero even in the high-congestion scenario. The simulations and analyses show that the proposed protocol would be very efficient to satisfy the promises of the latest IEEE 802.11ax standard.

Declaration of Competing Interest

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jksuci.2020.10.019.

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