Uplink Resource Allocation in IEEE 802.11ax

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***Abstract*—One of the notable features of the upcoming Wireless Fidelity (Wi-Fi) standard—namely, IEEE 802.11ax—is the use of Multi-User Orthogonal Frequency Division Multiple Access (MU-OFDMA). MU-OFDMA facilitates multiple users to transmit simultaneously in smaller sub-channels (a.k.a. resource units (RUs)), thereby improving the 802.11ax MAC efficiency. The 802.11ax MAC enables MU-OFDMA transmissions in the uplink (UL) by using two types of RUs: i) Random Access (RA) RUs, and ii) Scheduled Access (SA) RUs. In this paper, we investigate the impact of different distributions of RA RU and SA RU on the MAC layer performance. We leverage our analysis in devising a practical UL RU allocation scheme that maximizes the overall 802.11ax network throughput. We implement the 802.11ax MAC in network simulator-3 (NS-3) and perform extensive simulations to validate the efficacy of our proposed scheme.**

I. Introduction

Wireless Fidelity (Wi-Fi) has experienced tremendous growth and has become ubiquitous in today's wireless local area networks (WLANs). To take Wi-Fi a step further, in 2014, the High Efficiency WLAN task group (a.k.a. TGax) was formed with an objective of developing standards for the next generation Wi-Fi, namely IEEE 802.11ax [1]. According to the TGax, 802.11ax will support a ten-fold increase in the number of supported users over the same unlicensed spectrum, increase average user throughput by four times, and improve outdoor and multi-path signal robustness [2].

One of the prominent features of 802.11ax is the use of orthogonal frequency division multiple access (OFDMA) at its MAC layer. OFDMA divides the available spectrum into multiple orthogonal sub-channels—referred to as resource units (RUs). The 20 MHz, 40 MHz, 80 MHz and 160 MHz Wi-Fi channels are divided into 9, 18, 37 and 74 RUs, respectively. These RUs are then allocated to different users, thereby enabling concurrent multi-user (MU) transmissions. The 802.11ax access point (AP) serves as a central controller and triggers the MU OFDMA mode by transmitting a special frame, namely, *Trigger Frame* (TF) [3]. This is in contrast to previous Wi-Fi standards wherein all devices transmit, one at a time, in the entire channel bandwidth.

In the downlink (DL), the AP has global knowledge of the packet queue status for each associated station (STA). Therefore, 802.11ax provisions schedule-based MU-OFDMA transmissions in the DL. However, in the uplink (UL), STAs must explicitly communicate their traffic requirements to the AP by transmitting regular buffer status report (BSR). To facilitate this, 802.11ax supports two modes in which packets can be transmitted in the UL: i) scheduled access (SA), in which the AP schedules a set of STAs to transmit on dedicated contention-free RUs, and ii) random access (RA) in which, multiple STAs contend to transmit their packet using the exponential backoff-based distributed coordination function (DCF), similar to the one used in legacy[1] 802.11 MAC.

SA mode preempts contention from STAs and helps in improving the overall 802.11ax throughput. On the other hand, RA mode facilitates transmissions from STAs whose BSR information is not available at the AP. For example, newly joined STAs may have control frames to transmit or other STAs may have recent packet arrival in their transmit buffer. Unfortunately, they will not be scheduled to transmit in any SA RUs unless the AP is aware of their BSR. The use of RA RUs allows these STAs to transmit their packets and their BSRs (using piggybacking) to the AP. Therefore, in all practical implementations of 802.11ax, the AP must dynamically balance the distribution of SA RUs and RA RUs to achieve the 802.11ax's design goals.

Related Work: The existing literature on 802.11ax provide several insights on its performance. For example, Bellalta et al. [4] compute the 802.11ax saturated throughput when the 802.11ax AP uses both, MU MIMO as well as MU OFDMA transmissions. Lanante et al. [5] compute the saturated throughput in the UL under the assumption that UL OFDMA-based RA (UORA)[2] is the only mechanism for transmitting UL packets. However, most of these works restrict their focus on a sub-problem of the overall network performance. For example, the authors in [4] and [6] do not consider UL OFDMA-based RA (UORA) that enables stations to contend over a subset of the total RUs. The authors in [5] consider an RA-only UL system, thus failing to capture the behavior of a practical 802.11ax network which uses both RA and SA mechanisms simultaneously. Note that the RA mechanism informs BSR information to the AP and facilitates SA transmissions [7]. Hence, we argue that a study that does not jointly consider RA and SA transmissions is incomplete and does not reflect the practical behavior of 802.11ax networks.

Our Contributions: In this paper, we investigate the impact of distribution of RA RU and SA RU on the MAC layer performance of 802.11ax. We leverage our findings in devising an optimal RU allocation scheme that maximizes the overall 802.11ax network throughput. The proposed scheme is practical in that it allows an 802.11ax AP to learn network dynamics on the fly and converge to the optimal allocation. We implement the 802.11ax MAC and perform extensive NS-3 simulations—that consider different use-case scenarios,

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[1]Throughout the paper, we use the terms "legacy Wi-Fi" and "legacy 802.11" interchangeably to refer to all previous versions of Wi-Fi.

[2]We describe the UORA scheme in Sec. II

including asymmetric traffic requirements in UL and DL—to validate the performance of our scheme.

II. MAC Scheme for 802.11ax

802.11ax supports MU OFDMA in both DL and UL. In DL, the AP has knowledge of the packet queue for each STA which can be used to schedule MU transmissions. However, in UL, the packet queue status needs to be collected from STAs via BSRs. A BSR is sent by an STA to notify the status of its transmit buffer to the AP. BSRs can be AP-invoked (AP explicitly requests BSRs from its STAs) or unelicted (STAs transmit their BSRs without the AP's request).

802.11ax provisions two types of RUs for facilitating UL transmissions. Using a TF, the AP allocates a sub-set of RUs, namely SA RUs, for allowing contention-free transmissions from STAs whose BSR is known to the AP. For allowing other STAs to transmit their BSRs, the AP assigns remaining RUs as RA RUs. RA RUs can be used by: i) STAs that seek to join the network (to send control frames such as Association Requests), or ii) STAs that have recent packet arrival in their transmit buffer (to send their BSR information). A TF that supports at least one RA RU is referred to as a Trigger Frame-Random Access (TF-R). In a TF-R, RA RUs are identified by a value 0 in the Association ID (AID) field, while each SA RU is identified by a non-zero AID value.

The contention process for transmitting packets on RA RUs is referred to as UORA. Each contending STA picks a random integer—the OFDMA Backoff Counter (OBO)—uniformly in the range [0, OCW-1], where OCW stands for OFDMA Contention Window. Upon the reception of TF-R, STAs willing to transmit their BSR contend on RA RUs. Each STA decrements its OBO by the number of advertised RA RUs (N_{RA}) in that TF-R. When OBO decrements to zero, the packet is transmitted on a randomly chosen RA RU. If not, the contention process resumes in the next TF-R. Much alike the contention used in legacy 802.11, OCW is reset to OCW_{min} after a successful transmission and is doubled for every collision until OCW = OCW_{max}. We assume that contending STAs transmit their payload frames with the TXOP field in the QoS Control sub-frame set to indicate their respective BSR. Once an STA successfully transmits a packet (along with piggybacked BSR), it does not contend on RA RUs until the AP assigns enough SA RUs for it to be able transmit all the packets reported in its latest BSR.

Fig. 1 provides an illustration of UORA operation in conjunction with SA. The figure corresponds to one cycle of UL MU OFDMA transmissions. Throughout the paper, we refer to this cycle as *TF cycle*. The AP can assign RUs for SA in the TF-R because it is aware of BSRs of STAs 1 and 2. After this TF cycle, the AP will have knowledge of STA 7's BSR which may be assigned SA RUs in next TF cycles.

Throughout this paper, we assume that the only mechanism for transmitting BSR is to piggyback the BSR on payload frames. Although a null QoS frame (i.e. a QoS frame with no payload) can be used to convey BSR, doing so is not efficient unless all RUs are RA RUs. Also, we assume that only RA RUs are used for BSR transmissions. This is because the sub-field (TXOP duration) in the QoS Control sub-frame (which is used for piggybacking BSR) can have different interpretations based on the mode in which the 802.11ax AP operates.

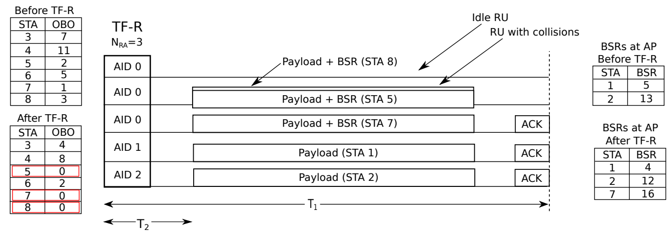


Fig. 1: UORA Scheme. STAs 1 and 2 are assigned SA RUs, while other STAs contend for transmissions on the three RA RUs. STAs 5, 7 and 8 decrement their OBOs to zero and transmit on randomly selected RUs leading to a collision on the second RA RU and successful transmission on the third RA RU; the first RA RU remains idle.

III. Performance Analysis of 802.11ax

In this section, we analyze the performance of the 802.11ax MAC and derive expressions for the following two key performance metrics: i) Throughput, and ii) BSR delivery rate.

Let us consider an 802.11ax network consisting of a single AP and n STAs. Assume a saturated network, where the transmission queue of every STA is always non-empty. Nevertheless, STAs still need to inform the AP about their BSR information because the AP only schedules those STAs in the UL SA RUs whose BSR is known to it. Since MU transmissions is one the characteristic features of 802.11ax MAC, we assume that the AP as well as all STAs support MU transmissions in both UL and DL. However, since the DL MU OFDMA is based on purely schedule-based transmissions, the DL throughput is invariant to network parameters and we will discuss it briefly towards the end of the section. First, we focus our attention on the UL throughput of the 802.11ax MAC.

Suppose that the 802.11ax channel is divided into N_{RU} RUs, where N_{RA} RUs are allocated for RA and the remaining $N_{\text{SA}} = N_{\text{RU}} - N_{\text{RA}}$ RUs are allocated for SA. Since there is one STA assigned to each N_{SA} RU in a TF cycle, the remaining $n_{\text{ra}} = n - N_{\text{SA}}$ STAs contend for transmission on N_{RA} RUs. Similar to many previous works on 802.11, let us assume that all nodes can hear transmissions from other nodes; i.e., there are no hidden nodes. Also, we assume that channel conditions are ideal, i.e. there are no PHY layer impairments. Thus, in our model, packet errors occur only when multiple STAs transmit at the same time in the same RU.

Let us use the notation $W_i = 2^i W$ to denote the size of the OCW, where W_i denotes the OCW for back-off state i and W denotes the OCW_{min}. Let m be the maximum back-off state and $W_{\max} = 2^m W$ be OCW_{max}. An STA transmits a frame when its OBO decrements to 0. As opposed to the back-off procedure in legacy 802.11, in 802.11ax, the OBO is decremented by N_{RA} after receiving the TF. The back-off process can then be modeled by a two-dimensional Markov chain, and the probability that an STA transmits its BSR in any of the N_{RA} RUs can be computed as follows [8], [9],

$$\tau = \frac{2(1-2p)}{(1-2p)\left(\frac{W}{N_{\text{RA}}}+1\right) + p\frac{W}{N_{\text{RA}}}(1-(2p)^m)}. \qquad (1)$$

where, p denotes probability that a transmitted packet collides.

Similar to legacy 802.11, there is only one contention process running in the 802.11ax MAC. However, there are N_{RA} RA RUs, and collisions occur only when STAs transmit at the same time on the same RA RU. Assuming that a packet is transmitted on a randomly chosen RA RU among N_{RA} available RA RUs, the probability that a transmitted packet results in a collision can be computed as,

$$p = 1 - \left(1 - \frac{\tau}{N_{\mathrm{RA}}}\right)^{n_{\mathrm{ra}}-1}. \tag{2}$$

Equations (1) and (2) can be solved using numerical methods for given values of W, m, N_{RA} and n_{ra}. We can compute the probability that at least one STA transmits in a considered RA RU during the TF as follows,

$$P_{tr} = 1 - \left(1 - \frac{\tau}{N_{\mathrm{RA}}}\right)^{n_{\mathrm{ra}}}. \tag{3}$$

Now, the probability P_s that a transmission in an RA RU is successful is given by the probability of exactly one transmission given that there has been a transmission on the considered RA RU.

$$P_s = \frac{n_{\mathrm{ra}} \frac{\tau}{N_{\mathrm{RA}}} \left(1 - \frac{\tau}{N_{\mathrm{RA}}}\right)^{n_{\mathrm{ra}}-1}}{1 - \left(1 - \frac{\tau}{N_{\mathrm{RA}}}\right)^{n_{\mathrm{ra}}}}. \tag{4}$$

Similarly, the probability P_{idle} that all RA RUs are idle because none of the STAs were able to complete their back-off procedure is given as,

$$P_{\mathrm{idle}} = (1 - P_{tr})^{N_{\mathrm{RA}}}. \tag{5}$$

Next, we define the following two time periods T_1 and T_2 (see Equation (6)) based on the TF cycle of Figure 1.

$$\begin{aligned} T_1 &= T_H + (T_{\mathrm{TF}} + \mathrm{SIFS} + T_\delta) + (T_P + \mathrm{SIFS} + T_\delta) \\ &\quad + (T_{\mathrm{ACK}} + \mathrm{SIFS} + T_\delta) \\ T_2 &= T_H + (T_{\mathrm{TF}} + \mathrm{AIFS} + T_\delta) \end{aligned} \tag{6}$$

where, T_H and T_δ refer to the time taken to transmit frame header bits and the propagation delay respectively.

- T_1**:** T_1 represents the time spanned by a TF cycle when there is at least one RU on which a packet is transmitted. This includes two cases: i) a TF cycle that allocates at least one RU as SA RU (this case always results in transmissions in the allocated SA RUs), and ii) a TF cycle that allocates all RUs as RA RUs and there is at least one STA that transmits on an RA RU. In either case, the duration of a TF cycle is T_1.
- T_2**:** T_2 denotes the time duration of a TF cycle for which all RUs are assigned as RA RUs (i.e., $N_{RA} = N_{RU}$) but none of the STAs transmits a packet due to non-zero OCW values. In this case, the AP can transmit a new TF with same/different RU assignments after sensing the channel idle for an AIFS duration.

Based on the allocation of RA RUs and SA RUs in a TF cycle, the following throughput expressions can be derived.

1. $1 \le N_{\mathrm{SA}} \le N_{\mathrm{RU}}$ (at least one RU assigned for SA): When a TF has least one SA RU, irrespective of whether transmissions occur in RA RUs, the AP must reserve the channel for T_1 duration to allow transmissions in the SA RUs. In this case, the throughput is computed as,

$$S_{ul} = \frac{(N_{\mathrm{SA}} + N_{\mathrm{RA}} P_{tr} P_s) E[P]}{T_1}. \tag{7}$$

where, $E[P]$ denotes the expected packet size in bits.

2. $N_{\mathrm{RA}} = N_{\mathrm{RU}}$ (all RUs are assigned as RA RUs): This includes two sub-cases: i) none of the STAs are able to finish their respective back-off procedure, resulting in no packets being transmitted on any of the RA RUs (this event occurs with probability P_{idle}), and ii) at least one STA completes its back-off procedure and transmits on an RA RU. Combining these mutually-exclusive events, the throughput of a TF cycle can be computed.

$$S_{ul} = \frac{N_{\mathrm{RA}} P_{tr} P_s E[P]}{(1 - P_{\mathrm{idle}}) T_1 + P_{\mathrm{idle}} T_2}. \tag{8}$$

Finally, let us use the notation S_{dl} to denote the downlink throughput of 802.11ax. As DL transmissions are schedule-based, S_{dl} is independent of n and is computed as $S_{dl} = \frac{N_{\mathrm{RU}} E[P]}{T_1}$. Note that each TF cycle used for DL transmissions delivers N_{RU} packets whereas each TF cycle designated for UL transmissions delivers $(P_{tr} P_s N_{RA} + N_{SA})$ packets on average. Therefore, if the the DL to UL traffic/packet ratio in an 802.11ax network is $\eta : 1$, then the aggregate 802.11ax throughput can be computed using Equation (9).

$$S_{11ax} = \frac{\eta (P_{tr} P_s N_{RA} + N_{SA}) S_{dl} + N_{RU} S_{ul}}{\eta (P_{tr} P_s N_{RA} + N_{SA}) + N_{RU}} \tag{9}$$

Consider a highly dense and dynamic use-case scenario for 802.11ax, such as a wireless hot-spot in a crowded street (e.g., Times Square in New York city)[3]. In such settings, due to severe contention on RA RUs, many STAs might fail to report their BSR information to the AP. Thus, the AP cannot schedule them in the SA RUs of subsequent TF cycles. This effect is more pronounced for STAs that need to join (by sending control packets on an RA RU) or have just joined the network but haven't reported their BSR to the AP. In order to assess how well an 802.11ax network supports such STAs in dense and dynamic use-cases, quantifying the UL throughput itself is not sufficient. Rather, the efficiency of the MAC layer in terms of the average number of BSRs collected per TF cycle must be analyzed. We coin a new metric, namely *BSR delivery rate*, denoted by β for facilitating this measurement. In particular, β can be calculated using Equation (10).

$$\beta = N_{\mathrm{RA}} P_{tr} P_s. \tag{10}$$

Ideally, an 802.11ax network delivers best performance to STAs by simultaneously offering high throughput and β. However, we must note that these two are conflicting requirements in the UL. If the goal is to maximize the UL throughput, the AP must allocate all RUs as SA RUs, but that will lead to $\beta = 0$. When $\beta = 0$, the AP cannot schedule enough STAs in the subsequent TF cycles, thus lowering the throughput.

[3] We use the term "dynamic" to refer to a network use-case scenario where STAs join/leave the network frequently.

On the other hand, if the objective is to maximize β, i.e., maximally support new STAs for reducing their latency, then all RUs should be allocated as RA RUs. However, this would reduce the UL throughput because the efficiency of RA RUs in successfully transmitting a packet is significantly low due to contention. Clearly, an optimal balance between throughput and β can be achieved by carefully allocating RA RUs and SA RUs. We study this issue in detail in the next section.

IV. Optimal RU Allocation Scheme

As discussed in the previous section, striking an optimal balance between N_{SA} and N_{RA} is critical in achieving a stable UL throughput in 802.11ax networks. On one hand, in order to increase the aggregate throughput, the AP can assign a large fraction of RUs as SA RUs; contention-free transmissions on the SA RUs provide the maximum possible throughput. On the other hand, the AP cannot assign STAs for schedule-based transmissions unless it knows their BSRs. Since the only mechanism for BSR delivery is through contention on the RA RUs, the AP must select N_{SA} and N_{RA} such that it never runs out of BSR values. An arbitrarily chosen division of RUs may imply that the network either lacks enough resources to meet STAs' demand for transmission (when it assigns a larger N_{RA} than is required). It may also imply that the network wastes some resources because of unavailability of STAs' BSR information (when it assigns small N_{RA}).

If the objective is to maximize the throughput, the AP must select N_{SA} and N_{RA} such that BSRs are collected from STAs at exactly the same rate at which these STAs can be scheduled on SA RUs, at least on an average sense. We refer to such a system state as the *steady state* of the system. We now outline the requirement for a system to be in steady state. Suppose that the AP uses N_{RA} RA RUs and, on an average, successfully collects BSR information from $\beta = P_{tr}P_sN_{RA}$ STAs in each TF cycle. The AP allocates the remaining N_{SA} SA RUs for serving the UL traffic demand of STAs whose BSR information is known to the AP.

We assume that STAs report BSRs to the AP in terms of the number of available packets in their transmit buffer. Further, we assume that the mean length of the BSR field is λ. This implies that if one SA RU allocation to an STA results in transmission of one packet, then that STA must be scheduled in λ TF cycles before its UL buffer is empty. If an STA s reports a BSR of λ_s, we assume that the STA will not contend for transmissions on RA RUs until it is scheduled for transmitting λ_s packets in the subsequent UL TF cycles by the AP. We claim that this assumption is pragmatic because the AP has a knowledge of at least λ_s packets available in the buffer of STA s. Therefore, any further transmission attempt from the same STA on RA RUs will only increase the overall contention.

Given this, for an 802.11ax network to be stable, the demand from STAs—i.e., $\beta \times \lambda$ packet transmission requests—must be equal to the supply—i.e., N_{SA} packet transmission opportunities. If this condition is not satisfied, either the AP collects BSR information from a larger number of STAs on average than can be assigned using the available SA RUs, or there might a fewer number of STAs for which the AP knows the BSR information than the available SA RUs. Equation (11) concisely characterizes the mathematical representation of a stable 802.11ax network.

$$N_{SA} = \lambda\beta \implies N_{SA} = \lambda P_{tr} P_s N_{RA} \tag{11}$$

Algorithm 1 Algorithm for optimal RU allocation in 802.11ax.

Initialize: $\Psi \leftarrow \{\}$
while true **do**
  Compute $N_{\text{SA}} = \min(|\Psi|, N_{\text{RU}})$
  Sort BSRs in descending order
  Select N_{SA} STAs with largest BSRs in Ψ
  BSR[s] = BSR[s] - #scheduled_packets $\forall s \in \phi$
  if BSR$[s] = 0, \quad \forall s \in \Psi$ **then**
    $\Psi = \Psi \setminus \{s\}$
  end if
  Allocate $N_{\text{RA}} = N_{\text{RU}} - N_{\text{SA}}$ RUs for random access
  Transmit Trigger Frame
  if $N_{\text{RA}} > 0$ and BSR received on RA RU k **then**
    $\Psi \cup \{k\} \quad \forall k \in \psi$
    Update BSR[k] $\forall k \in \psi$
  end if
end while

Given that a system is in steady state, on an average, the AP knows BSR values of exactly as many STAs that are assigned SA RUs for transmissions. Equation (11) further implies that, on an average, the AP only knows the BSR information of N_{SA} STAs. Thus, if there are a total of n nodes, in the steady state, $n - N_{SA}$ nodes contend for transmission on N_{RA} RA RUs and N_{SA} nodes transmit on contention-free SA RUs.

From Equation (11), it is clear that the optimal values of N_{SA} and N_{RA} depend on λ. Further, since P_{tr} and P_s depend on the network size (n), the optimal N_{SA} and N_{RA} also depend on n. In practical 802.11ax networks, λ for each STA might be different and change with respect to time. Generally speaking, the AP may not be able to track this information for all associated STAs. Consequently, although an optimal N_{RA} can be computed theoretically by jointly solving Equations (1), (2) and (11), a real-world AP does not have this luxury. Therefore, an AP must be able to learn the changing network dynamics on the fly and arrive at the steady state regardless of n and the distribution of λ across STAs. Towards this objective, we now describe an algorithm, Algorithm 1, that can be implemented at an 802.11ax AP for achieving the optimal distribution of SA RUs and RA RUs.

In Algorithm 1, Ψ denotes the set of STAs whose non-zero BSRs are known at the AP. In a given TF cycle, let ϕ and ψ denote the set of STAs that are assigned SA RUs and the set of STAs that successfully deliver a BSR to the AP, respectively.

In each TF cycle, the AP updates BSR values of all scheduled STAs by decrementing their respective BSR values by the number of scheduled packets. Following the successful reception of BSR(s) from contending STA(s) on one or more RA RUs, BSR values of the corresponding STA(s) are updated.

The core idea used in Algorithm 1 is that as long as the AP is aware of the BSR information of N_{RU} STAs, the AP assigns all RUs for schedule-based transmissions, one for each STA. If not, the AP assigns an SA RU, one for each of those STAs whose BSR information is available at the AP, while the remaining RUs are assigned for RA. BSRs, once delivered, are valid at the AP until λ packets are scheduled in the UL. Thus, after λ packets have been scheduled in the UL for a particular STA, the AP no longer knows its buffer status. In Algorithm 1, $N_{\mathrm{RA}} > 0$ only when there are fewer than N_{RU} BSRs are known to the AP. These conditions ensure that the AP collects just the right number of BSRs that it can schedule on the SA RUs. In Section V, we evaluate the performance of Algorithm 1 by implementing it in NS-3 and performing simulations therein.

V. Results and Discussions

In this section, we investigate the MAC layer performance of 802.11ax by applying the analysis presented in previous sections. We then validate our analysis by implementing the MU OFDMA based 802.11ax MAC in NS-3 and comparing analytical results with those obtained from extensive NS-3 simulations for various use-case scenarios. Henceforth, unless explicitly stated otherwise, we use the following set of parameters (see Table I) for all of our simulations.

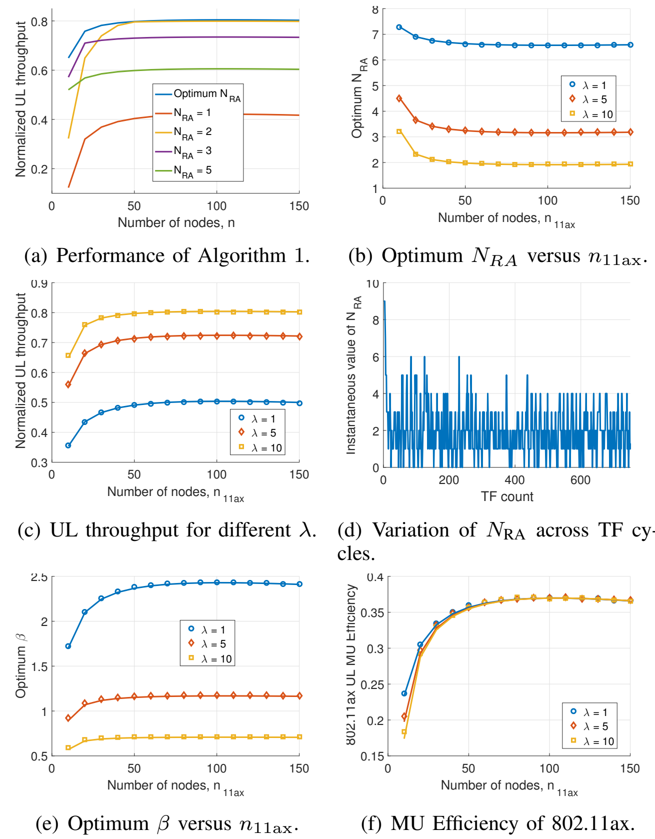
Throughout this section, results pertaining to throughput represent the normalized throughput (ratio of payload size in bits to the time taken to transmit the payload) observed at the MAC layer assuming a PHY rate of 1 Mbps. Each simulation run lasts for 90 seconds, and the results presented are averaged over 10 simulation runs with different seed values. In each plot, unless explicitly stated otherwise, markers represent results from NS-3 simulations whereas the lines without markers correspond to analytical results.

TABLE I: Simulation parameters.

Parameter	Value	Parameter	Value
Prop. loss model	Okumura Hata	SIFS	16 μs
AP coverage	40 meters	T_δ	3 μs
$N_{\mathrm{RA}}/N_{\mathrm{SA}}$	From Alg. 1	N_{RU}	9
$\mathrm{CW}_{\min}/\mathrm{OCW}_{\min}$	32	m	5
TF-R	140 bytes	P	1023 bytes
ACK	14 bytes	H	44 bytes

A. Performance of the 802.11ax MAC

Figure 2 shows the performance of UL MU OFDMA for a network that consists of only 802.11ax STAs. As described in the previous sections, λ represents the mean number of packets available in the transmit buffer of 802.11ax STAs. Figure 2(a) shows the MAC layer UL throughput of the network when $\lambda = 10$ and fixed N_{RA} values are used by the AP. The performance of these fixed allocation of RA RUs are compared with that of Algorithm 1. We first note that no fixed N_{RA} allocation offers throughput performance comparable to that of Algorithm 1. This is owing to the fact that the optimal N_{RA} value depends on λ as well as the network size, i.e., $n_{11\mathrm{ax}}$. Thus, for each value of λ and $n_{11\mathrm{ax}}$, the optimal N_{RA} is different. Furthermore, as discussed in Sec. IV, for the optimal allocation of RA RUs and SA RUs, the number of BSRs available at the AP must be N_{SA} on an average. To achieve this, Algorithm 1 dynamically changes the value of N_{RA} so



(a) Performance of Algorithm 1. (b) Optimum N_{RA} versus $n_{11\mathrm{ax}}$.

(c) UL throughput for different λ. (d) Variation of N_{RA} across TF cycles.

(e) Optimum β versus $n_{11\mathrm{ax}}$. (f) MU Efficiency of 802.11ax.

Fig. 2: UL performance of the 802.11ax MAC.

as to maintain the steady state condition (Equation (11)). The variation of N_{RA} across TF cycles when an AP uses Algorithm 1 is shown in Figure 2(d). As seen in the figure, the instantaneous value of N_{RA} varies considerably, but its mean value converges to the optimal value obtained from Equation (11). This validates that Algorithm 1 indeed facilitates the optimal allocation of UL RUs in 802.11ax.

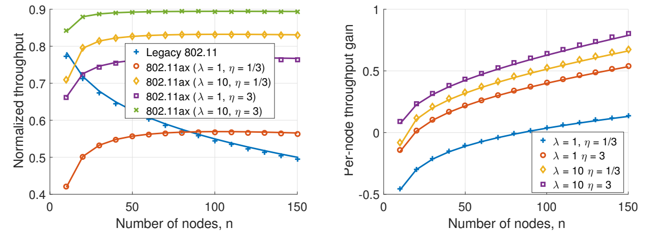
Figure 2(b) shows the optimal value (on an average) of N_{RA} for different values of λ, and corresponding optimal throughputs are shown in Figure 2(c). For small values of λ, for example $\lambda = 1$ (which means, on an average, when an STA transmits a BSR, it informs the AP that it has one packet available in its buffer), the optimal N_{RA} value is much higher than that for larger values of λ (for example $\lambda = 10$). This is intuitive because a small value of λ implies that the AP can schedule only a few packets on SA RUs in the UL based on the corresponding BSR. As a result, the AP needs to provision RA RUs frequently in order to collect enough BSRs and strike a balance between the demand on RA RUs and supply on the SA RUs. Further, a large value of N_{RA} implies that a larger fraction of RUs are used as RA RUs. This is corroborated by Figure 2(e), which shows the value of β, i.e. number of packets transmitted on RA RUs, for different values of λ. Now, since the efficiency of the random access mechanism in UL MU OFDMA can at best be around 38%, as seen in Figure 2(f), the throughput achieved is significantly lower than cases where N_{RA} is small.

Thus, in summary, a larger throughput can be achieved in UL MU OFDMA when λ is large. Large λ implies that the AP does not need to frequently collect BSRs from an STA, thereby allowing the former to allocate a large fraction of RUs as contention-free SA RUs. Additionally, Algorithm 1 facilitates the AP in optimally allocating RUs in the UL. The AP uses Algorithm 1 to dynamically adjust the value of N_{RA} on the fly and achieves optimal throughput for all values of $n_{11\mathrm{ax}}$ and λ. In all plots, the overlap between the markers (results from NS-3 simulations) and solid lines (results from analysis) validate the correctness of our analysis.

Next, we look at the aggregate (i.e., combined UL and DL) throughput performance of 802.11ax for different values of λ and η (i.e. DL to UL traffic ratio) and compare with legacy 802.11. Figure 3 summarizes our results. An important observation is that for legacy 802.11 networks, the aggregate throughput falls sharply as the network size increases, thus highlighting its lack of scalability to the network size. In contrast, an 802.11ax network scales well with the network size, which suggests that it can be deployed in use-case scenarios where an AP needs to support a large number of STAs (e.g., concerts, stadiums, etc.). However, it is also noteworthy that for certain values of λ and η, the performance of 802.11ax may not be as good as that of the legacy network. For instance, when UL dominates the DL traffic (i.e., small η) and λ (packet arrival rate at the MAC layer) is small, the AP must allocate a large number of RA RUs for collecting BSRs which hurts the network throughput. *Thus, although in general, 802.11ax offers an improved performance over its legacy counterpart, our results indicate that a naive usage of 802.11ax without consideration of the network size and use-case scenario (η and λ) may lead to poor throughput performance in some cases.*

It must be noted that for legacy 802.11 systems, there is no explicit differentiation between UL and DL traffic. In most implementations of Wi-Fi, the legacy AP and STAs use the same set of contention parameters, resulting in same priority for UL and DL traffic. On the other hand, in 802.11ax systems, the DL traffic comprises of schedule-based transmissions, resulting in a deterministic and high DL throughput in comparison to UL traffic that comprises of both schedule-based and contention-based transmissions. Consequently, it follows that larger the value of η, higher is the aggregate network throughput. In most practical scenarios, the traffic in the DL dominates traffic in the UL [10], which implies that in most scenarios, for an 802.11 network of a given network size (particularly, larger values of $n_{11\mathrm{ax}}$), the aggregate network throughput in 802.11ax will be higher than that in a legacy network of same network size. Figure 3(b) shows the relative gain in per-STA throughput at the MAC layer for an 802.11ax network compared to a legacy 802.11 network. Thus, the per-node-throughput-gain, as specified in the functional requirements of 802.11ax, can be achieved in many scenarios. Admittedly, the gain reported in Figure 3(b) is further amplified if we consider the PHY-layer enhancements adopted by 802.11ax. A key observation is that *the gain in per-node-throughput is more pronounced for larger network sizes and for large η values.*

Although Algorithm 1 achieves an optimal throughput for a given 802.11ax network, it has a limitation in that it favors those STAs whose BSR is already known at the AP. This could be unfair towards STAs that are waiting to transmit their packets/BSRs on the RA RUs, particularly when λ is large. In practical scenarios, λ is large for applications that are bandwidth intensive (such as file transfer and downloads). However, such applications usually dominate the DL traffic. Moreover, these applications are less sensitive to delay; consequently making the algorithm practical in most realistic scenarios. A class of application that can be bandwidth intensive as well as delay sensitive is media streaming. Algorithm 1 may likely offer poor performance in such scenarios, and alternate approaches to maximize throughput in such scenarios remains a part of our future work.



(a) Aggregate throughput.

(b) Gain in per-node throughput offered by 802.11ax.

Fig. 3: Aggregate MAC-layer throughput.

VI. Conclusions

In this paper, we described the MU OFDMA-based MAC scheme that has been considered for IEEE 802.11ax. We investigated the impact of distribution of RUs on the MAC layer performance and devised a practical algorithm for optimally distributing RA RUs and SA RUs. Results from extensive NS-3 simulations, that consider a wide range of deployment scenarios, show that a balance between RA RUs and SA RUs is key to achieving the 802.11ax design objectives.

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