Performance Analysis of Uplink Multi-User OFDMA in IEEE 802.11ax

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***Abstract*—IEEE 802.11ax is the upcoming standard of the IEEE 802.11 wireless local area networks (WLAN) family. Until its most recent standard, i.e. 802.11ac, the primary focus of the 802.11 Working Group has been to increase the overall throughput of the physical (PHY) layer using innovative mechanisms such as multi-user multiple input multiple output (MU-MIMO), higher order modulation and coding schemes etc. However, these PHY layer gains often fail to translate to high throughput at the medium access control (MAC) layer, particularly in dense deployment scenarios. To address this limitation, IEEE 802.11ax introduces new features, most notably the use of Orthogonal Frequency Division Multiple Access (OFDMA), thereby enabling concurrent MU transmissions. In this paper, we first provide an overview of the uplink MU OFDMA in IEEE 802.11ax. Second, we provide an analytical model for characterizing the performance of the 802.11ax MAC layer. We investigate the trade-off between providing high network throughput and supporting new users using a metric—namely, *BSR delivery rate*. Finally, we validate our analyses using extensive NS-3 simulations, and present the resulting findings.**

I. Introduction

The early Wi-Fi standards primarily provided low data rate wireless connectivity for applications such as web browsing, e-mail, etc. 802.11 standards have since evolved to offer high data rates and Quality of Service (QoS) guarantees, thereby supporting a wide range of applications–from bandwidth intensive video streaming to latency restricted voice calls. The upcoming 802.11ax standard is envisioned to take Wi-Fi a large step forward by enhancing wireless connectivity with high and reliable throughput in dense user environments. A typical use-case scenario for 802.11ax is the crowded hot-spot at an airport or a stadium where today's overloaded access points (APs) deliver poor user experience. 802.11ax promises to support a ten-fold increase in the number of supported users over the same unlicensed spectrum, increase average per user throughput by four times, and improve outdoor and multi-path signal robustness.

The High Efficiency (HE) WLAN Task Group (a.k.a. TGax) [1] has been developing the 802.11ax standard since May 2013. Though 802.11ax standard is still in the early stages of its development, the incorporation of a few key features at the PHY and MAC layers have been agreed upon. Among these, the dynamic control of the sensing sensitivity at the PHY layer, referred to as Dynamic Sensitivity Control (DSC) [2], and an Orthogonal Frequency Division Multiple Access (OFDMA) based MAC are the major additions to the current 802.11 standard. In this paper, we focus our attention to the latter. OFDMA divides the available physical resource, i.e. spectrum, into multiple orthogonal sub-channels—referred to as a resource unit (RU) in the 802.11ax terminology. The 20 MHz, 40 MHz, 80 MHz and 160 MHz Wi-Fi channels can be divided into 9, 18, 37 and 74 RUs, respectively. These RUs can be allocated to different users as per their traffic demands, thereby enabling concurrent multi-user (MU) transmissions.

The 802.11ax AP will act as the coordinator during MU OFDMA transmissions for downlink (DL)–from AP to stations (STAs)–as well as uplink (UL)–from STAs to the AP–directions. The AP can "trigger" the MU OFDMA mode by transmitting a Trigger Frame (TF)—a frame structure to be defined in 802.11ax [3]. Upon the reception of a TF, associated STAs enter a scheduled access (SA) mode whereby only those clients can transmit or receive frames that are allocated RUs by the AP. This behavior is in contrast to legacy 802.11 standards that use a contention based mechanism for channel access[1].

For an AP to allocate RUs in a TF, it must be aware of the traffic conditions at the associated STAs. This is straightforward in the DL as all data packets reaching the STAs pass via the AP. However, in the UL, STAs must explicitly communicate their traffic requirements by transmitting regular Buffer Status Report (BSR). Transmission of these BSRs can be elicited by the AP or can be initiated by the STAs. In order to support such elicited BSR transmissions, 802.11ax provisions a random access (RA) mode, namely Uplink OFDMA-based Random Access (UORA) [4], that can be used in conjunction with the SA mode. Essentially, in a TF, the AP assigns a fraction of the total RUs for RA mode and the remaining fraction for SA mode.

The adoption of a combination of SA and RA is expected to improve the overall user experience in 802.11ax, especially in dense deployments where network is highly dynamic (users/STAs join and leave the network frequently). In this paper, we provide a quantitative assessment of the user experience offered by 802.11ax. In doing so, we investigate the interplay between RA and SA assignments in UL MU OFDMA and discuss scenarios where it may be appropriate

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This work was partially sponsored by NSF through grants 1265886 and 1563832, and by the industry affiliates of the Broadband Wireless Access & Applications Center and the Wireless@Virginia Tech group.

[1]Point Coordination Function (PCF), a polling based coordinated transmission mechanism exists in the current standard, but is largely unpopular due to its exclusion by most Wi-Fi vendors.

978-1-5386-3180-5/18/$31.00 ©2018 IEEE

for prioritizing one access mode over the other. The main contributions of this paper are summarized below.

- We describe the UL MU OFDMA scheme that is being standardized in the IEEE 802.11ax task group [1], and develop an analytical model that characterizes the performance of the scheme.
- We motivate the need for and propose a new metric, named *BSR delivery rate*, that characterizes how well an 802.11ax network performs in dense and highly dynamic deployments. Using results from our analysis, we show that in densely-deployed highly dynamic networks, there exists a fundamental trade-off between 802.11ax throughput and its capability to support new nodes that need to join or have just joined the 802.11ax network.
- We validate our analysis using extensive simulations performed in Network Simulator-3 (NS-3). In doing so, we extend the NS-3 Wi-Fi module to incorporate MU OFDMA capabilities and the two access modes as per the latest Task Group specifications. To the best of our knowledge, ours is the first effort to implement these capabilities on a widely accepted system level simulator.

II. Related Work

Bianchi's two dimensional Markov model [5] is the seminal work on computing Wi-Fi throughput under saturated traffic conditions. Several extensions of Bianchi's model have been proposed in the literature; some being used to evaluate 802.11ax performance. For example, Bellalta et al. [6] extend the aforementioned model to compute 802.11ax saturated throughput. The authors consider both, MU MIMO as well as MU OFDMA transmissions and show that there exists an optimal number of active users that maximizes the overall throughput. Lanante et al. [7] provide a generalized version of Bianchi's Markov model to compute 802.11ax saturated throughput when UORA is the only mechanism for UL OFDMA transmissions. Sharon et al. [8] provide an analytical model to determine the DL throughput when MU OFDMA is used. Since the traffic to the associated STAs in DL is known to the AP, this model is essentially deterministic.

While the aforementioned works provide deeper insights on the potential gains of using MU OFDMA in 802.11ax, there are limitations in each model. The authors in [6] and [8], for example, do not consider UORA mechanism that enables stations to contend over a subset of the total RUs. Further, although the system model studied in [7] is the most accurate in terms of TGax documents, it is restrictive because only RA based MU UL OFDMA is considered, and provides limited insights on how RUs can be divided between RA and SA in dynamic network settings. In addition to these models, several papers exist in the literature since before the TGax was created in 2015. A detailed summary of these works is provided in [9]. Most of these works do not comply with the MU OFDMA model being considered in the TGax, and thus provide an incomplete understanding of the 802.11ax performance.

In this paper, we consider a system model that is accurate as per the latest TGax submissions, and consider a scenario where UORA is used in conjunction with SA, i.e. when the AP transmits a TF, it provides scheduling information for STAs on a subset of RUs, while the remaining RUs are used for RA. Along with the saturated system throughput, we characterize 802.11ax performance in terms of BSR delivery rate – a metric that is important in dynamic network environments.

III. MAC Scheme for 802.11ax

In this section, we describe the MU OFDMA MAC protocol under development for 802.11ax. We note that in the DL, the AP has a global view of its associated STAs. Traffic to every STA passes through the AP, and hence, the AP can consider factors such as QoS requirements, fairness etc. while scheduling resources for the DL. The important point to note is that as long as the AP's transmission queue is full (enough to require all RUs at all times), the DL throughput is deterministic. The resulting system throughput has been studied in [8]. In this paper, we restrict our attention to UL traffic where the AP does not necessarily know the occupancy status of the transmission queues at the STAs. As a result, the STAs must explicitly transmit BSRs to notify the AP that packets exist in their transmission queues.

We now describe the assumptions made in our system model. First, we consider a network comprising of only 802.11ax devices. We make this assumption to keep the analysis simple and focus only on the gains achieved by 802.11ax. We keep the analysis of such a heterogenous network as a part of our future work. Second, we assume that BSRs are not piggybacked over payload frames. While this provision is being discussed in the TGax [10], we make the above choice because the resulting system gives a lower bound of the achievable throughput. Third, we claim that when the AP transmits the TF, STAs other than those that are assigned RUs will defer their transmissions for an interval specified by the TF's Network Allocation Vector. Fourth, throughout our model, we assume that there is no capture effect, i.e. if two or more 802.11ax nodes have overlapping transmissions, the intended receivers will be unable to decode any of the signals.

The MU OFDMA mode starts when the AP transmits a TF. In principle, TF is a frame that announces the subset of STAs that are allowed to transmit, the RUs that the transmitting STAs must use, and the duration for which the transmissions must last. These parameters are communicated using the Common Info. and Per User Info. fields within the TF [3]. An STA can be allocated one or more RUs by the TF. This mechanism is called SA as the allocated STAs know exactly when to begin their transmissions and which RUs to use.

In addition to SA, 802.11ax will enable a RA mode–UORA–that will facilitate transmissions from STAs that have a packet to transmit while MU OFDMA transmissions from other STAs are in progress. UORA begins when the AP transmits a TF with at least one RU reserved for RA. Such a TF is referred to as a TF-Random access (TF-R). UORA has been provisioned for two primary reasons, (i) unassociated STAs can transmit control packets (e.g. Association Request) over RA RUs, and (ii) STAs with payload data in their queues can transmit their BSRs on the RA RUs.

The exact procedure for UORA is still under discussion in the TGax. In what follows, we describe the most general version under discussion. It must be noted that UORA can be used in conjunction with SA, i.e., the AP can divide the total available RUs between RA and SA RUs. Thus, a key parameter in the UORA mechanism is N_{RA}, which denotes the number of RUs assigned for RA by the AP.

The UL MU OFDMA mechanism is illustrated in Fig. 1. Contending STAs maintain four contention parameters, OFDMA Contention Window (OCW), OFDMA $\mathrm{CW}_{\mathrm{min}}$ ($\mathrm{OCW}_{\mathrm{min}}$), OFDMA $\mathrm{CW}_{\mathrm{max}}$ ($\mathrm{OCW}_{\mathrm{max}}$) and OFDMA backoff counter (OBO). OBO is picked uniformly in [0, OCW - 1]. The TF-R allocates a subset of the total RUs for RA (denoted by association ID (AID) = 0). When contending STAs recieve TF-R, they decrement their respective OBO by N_{RA} (N_{RA} = 3 in Fig. 1). If the OBO of a particular STA reaches 0, then it picks one of the RUs allocated for RA at random and transmits its BSR after SIFS. The RUs specified by AID subfield $>$ 0 are allocated for SA. On these RUs, the allocated STAs transmit their payload frames at the same time as the payload transmissions on RA RUs.

A BSR sent on a particular RU can be decoded correctly at the AP only if no other transmissions occur on that RU (For example, STAs 5 and 8 collide in Fig. 1). In response to the BSR the AP transmits BSR ACK on the corresponding RU after SIFS[2]. BSR ACK notifies the STA that its BSR was successfully received at the AP, and that it can proceed with its payload transmission. For an STA, if the transmission of its BSR is successful (characterized by the reception of BSR ACK), its OCW is reset to $\mathrm{OCW}_{\mathrm{min}}$. Otherwise, OCW is doubled until it reaches $\mathrm{OCW}_{\mathrm{max}}$.

IV. Performance Analysis

In this section, we analyze the performance of the UL MU OFDMA scheme described in the previous section. Specifically, we focus on the following two performance metrics.

A. Throughput

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. 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 pure schedule-based transmissions, the DL throughput is invariant to network size. Thus, we focus our attention on the UL performance of the 802.11ax MAC.

Suppose that the 802.11ax channel consists of N_{RU} RUs, where N_{RA} RUs are allocated for RA and the remaining $N_{\mathrm{SA}} = N_{\mathrm{RU}} - N_{\mathrm{RA}}$ RUs are allocated for SA. Since there is one STA assigned to each N_{SA} RU in a TF cycle, the remaining $n_{\mathrm{ra}} = n - N_{\mathrm{SA}}$ 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 $\mathrm{OCW}_{\mathrm{min}}$. Let m be the maximum back-off state and $W_{\max} = 2^m W$ be $\mathrm{OCW}_{\mathrm{max}}$. 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 [5], [11],

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

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} RUs, and collision among transmissions from multiple STAs occur only when they transmit at the same time in the same RU. Assuming that a packet is transmitted on a randomly chosen RU among N_{RA} available RUs, the probability that a transmitted packet results in a collision can be computed as,

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

Equations (1) and (3) can be solved using numerical methods for given values of W, m, N_{RA} and n_{ra}. Using the values of τ and p, we can compute the probability that at least one STA transmits in a considered RU during the TF as follows,

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

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

$$P_s = \frac{n_{ra}\frac{\tau}{N_{\mathrm{RA}}}\left(1 - \frac{\tau}{N_{\mathrm{RA}}}\right)^{n_{\mathrm{ra}}-1}}{1 - \left(1 - \frac{\tau}{N_{\mathrm{RA}}}\right)^{n_{\mathrm{ra}}}}. \tag{5}$$

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,

$$P_{\mathrm{idle}} = (1 - P_{tr})^{N_{\mathrm{RA}}}. \tag{6}$$

Next, we define the following time periods (see Equation (2)) based on the TF cycle of Figure 1 as follows:

- T_1**:** This is the time duration of a TF cycle when there is at least one RA-RU that is able to successfully deliver a packet. In this case, the AP reserves the channel for a duration that corresponds to the packet (and its ACK) transmission time after a BSR-ACK is sent by the AP.
- T_2**:** T_2 represents the time duration of a TF cycle when all RUs are assigned for SA, i.e., there are no RA RUs in the TF cycle. Clearly, in the absence of the RA procedure, T_2 is the time taken for transmitting a packet (and corresponding ACK) after the transmission of a TF.

[2] The exact behavior of the AP in response to BSR reception remains undecided. Two possibilities exist, (i) the AP sends BSR ACK immediately, or (ii) the AP schedules the corresponding STA in the next TF cycle

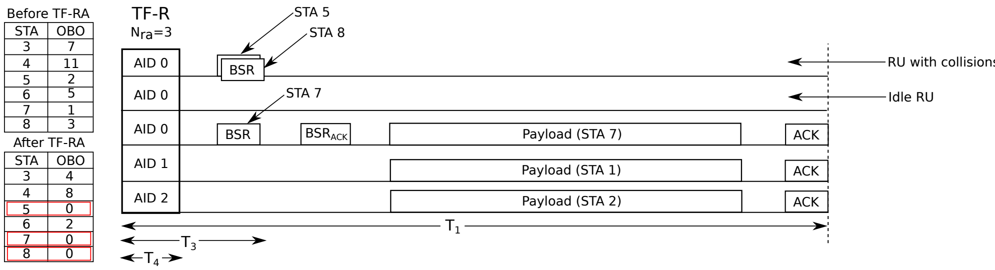


Fig. 1: Illustration of UL MU OFDMA in 802.11ax

$$
\begin{aligned}
T_1 &= T_H + (T_{\text{TF}} + \text{SIFS} + \delta) + (T_{\text{BSR}} + \text{SIFS} + \delta) + (T_{\text{BSR}_{\text{ACK}}} + \text{SIFS} + \delta) + (T_P + \text{SIFS} + \delta) + (T_{\text{ACK}} + \text{SIFS} + \delta) \\
T_2 &= T_H + (T_{\text{TF}} + \text{SIFS} + \delta) + (T_P + \text{SIFS} + \delta) + (T_{\text{ACK}} + \text{SIFS} + \delta) \\
T_3 &= T_H + (T_{\text{TF}} + \text{SIFS} + \delta) + (T_{\text{BSR}} + \text{SIFS} + \delta) \\
T_4 &= T_H + (T_{\text{TF}} + \text{SIFS} + \delta)
\end{aligned} \tag{2}
$$

- T_3**:** T_3 denotes the time duration of a TF cycle when all RUs are assigned for RA—i.e., there is no SA RUs in the TF cycle—and none of the packet transmissions are successful due collisions. In this case, the time duration of a TF cycle is the time spent in the contention process. Since no packets are successfully received by the AP, the latter does not transmit a BSR-ACK.
- T_4**:** T_4 corresponds to the duration of a TF cycle when all RUs are assigned for RA (no SA RUs in the TF cycle) and none of the STAs are able to transmit their BSRs as they do not finish their back-off procedure. In this case, there will be no BSR transmissions from any STA.

T_H and T_δ in Equation (2) refer to the time taken to transmit frame header bits and the propagation delay respectively.

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

1. $N_{\text{SA}} = N_{\text{RU}}$ (all RUs are assigned for SA)
   In this case, transmissions on all RUs are based on SA. Therefore, the duration of the TF cycle is T_2 and the throughput is,
   $$S = \frac{N_{\text{SA}} E[P]}{T_2}, \tag{7}$$
   where, $E[P]$ denotes the expected packet size in bits.
2. $1 \leq N_{\text{SA}} < N_{\text{RU}}$ (a fraction of RUs are assigned for SA and the rest are assigned for RA)
   When some RUs are assigned for SA and others for RA, the throughput of a TF cycle is given as,
   $$S = \frac{(N_{\text{SA}} + N_{\text{RA}} P_{tr} P_s) E[P]}{T_1}. \tag{8}$$
   Note that when a TF contains a combination of RA-RUs and SA-RUs, the AP must reserve the channel for T_1 duration. This is because when STAs scheduled in the SA-RUs finish their transmissions, there is no way for them to know the status of BSR transmissions on RA-RUs. Therefore, the duration of TF cycle has to be set conservatively (assuming that at least one of the RA-RUs will successfully deliver a packet).
3. $N_{\text{RA}} = N_{\text{RU}}$ (all RUs are assigned as RA-RUs)
   In this case, the throughput of the TF cycle is,
   $$S = \frac{N_{\text{RA}} P_{tr} P_s E[P]}{P_1 T_1 + P_{\text{idle}} T_4 + (1 - P_1 - P_{\text{idle}}) T_3}. \tag{9}$$
   The first term in the denominator is the time taken when there is at least one BSR delivered to the AP (T_1), while the second and third terms correspond to cases when no BSRs reach the AP due to none of the STAs finishing their respective backoffs (second term, T_4) or because all transmitted BSRs collide (third term, T_3). Here P_1 is the probability that at least one BSR is delivered to the AP.

B. BSR Delivery Rate

Consider a use-case scenario where an AP is deployed in a dense and dynamic environment[3]. An example of such scenario is a wireless hotspot in a crowded street (e.g., Times Square in New York city), where STAs join and leave the network frequently. In such settings, it is challenging for the AP to schedule RUs for all STAs, especially the ones who need to join or have just joined the network (because the AP has limited information about such STAs). In the worst case, an incoming STA might have to wait for a prohibitively long time before it can access the channel for transmitting its packets. Therefore, we argue that in dense and dynamic networks, network throughput is not the only suitable metric for capturing the network performance.

In order to assess how well a network supports transmissions from new users, the efficiency of the RA scheme must be quantified. To facilitate this, we coin a new metric, namely *BSR delivery rate*, denoted by β that measures the efficiency of the RA scheme in delivering BSR packets. In particular, β is the average number of BSRs successfully delivered by the contending STAs to the AP in a TF cycle. That is,

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

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

We note that β is closely related to the efficiency of the RA mechanism. However, we use β instead because computation of β takes the RA efficiency as well as N_{RA} into consideration. Ideally, the best network performance is achieved when both the throughput and the BSR delivery rate are high. However, we must note that these two are conflicting requirements. If the goal is to maximize the throughput, one should allocate all RUs as SA RUs, but that will result in zero BSR delivery rate. 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 network throughput. Clearly, there exists a trade-off between network throughput and BSR delivery rate.

V. Performance Evaluation and Discussions

In this section, we first investigate the MAC layer performance of 802.11ax by using the analysis presented in Sec. IV and compare it with legacy 802.11. We also validate our analytical model by comparing it with results obtained from extensive NS-3 simulations. Using our analysis, we demonstrate the trade-off between throughput and BSR delivery rate. Finally, we use the results from NS-3 simulations and show that there exists a strong correlation between BSR delivery rate and latency[4] in dense 802.11ax deployments. The parameters used for this study are outlined in Table I.

At the time of writing this paper, the latest release of NS-3 does not support an MU OFDMA MAC. Custom 802.11ax simulators have been developed by authors in [12] and [6]. However, these simulators do not take into consideration UORA or the joint operation of SA and RA in UL MU OFDMA. In order to capture the effect of these mechanisms, we significantly extended the Wi-Fi module of NS-3 to support OFDMA capabilities as described in the latest TGax documents. The Wi-Fi module was modified such that for each node, parallel transmit and receive chains were created—one for each RU. This enables transmissions to occur concurrently over orthogonal RUs, thereby simulating OFDMA. To the best of our knowledge, this is the first system level implementation of 802.11ax MU OFDMA developed over a reliable and widely accepted simulator. Therefore, in order to facilitate fellow researchers in conducting similar studies, we have released the beta version of our simulator [13].

TABLE I: Simulation parameters.

Parameter	Value	Parameter	Value
H	$16(\mathrm{PHY})+28(\mathrm{MAC})$ bytes	P	1023 bytes
TF-R	$50+10N_{\mathrm{SA}}$ bytes	ACK	14 bytes
BSR	32 bytes	$\mathrm{BSR}_{\mathrm{ACK}}$	30 bytes
R	1 Mbps	SIFS	16 μs
δ	3 μs	N_{RU}	9
$\mathrm{CW}_{\min}$	32	$\mathrm{CW}_{\max}$	1024

In Fig. 2(a), the MAC layer throughput of an 802.11ax network is plotted for different values of n and N_{RA}. The thick and thin lines represent results from our analysis and NS-3 simulations respectively. For comparison, we also plot the legacy 802.11 throughput. Note that all plots represent *normalized throughput* values that were computed by considering PHY rate $=1$ Mbps during analysis[5]. An interesting observation from the plots is that the throughput of 802.11ax does not decrease as sharply as legacy 802.11 with the increase in number of STAs. In case of legacy 802.11, since there is only one channel, an increase in the number of STAs leads to increased collisions. In 802.11ax, however, contending STAs (STAs that contend in RA-RUs) transmit in one of the N_{RA} RUs chosen at random, thereby reducing the collision probability significantly (by approx. a factor of N_{RA}) when compared against legacy 802.11. The 802.11ax throughput does decrease slightly with increase in the number of STAs.

At small values of n, the 802.11ax throughput (except for the case when $N_{\mathrm{RA}}=0$) is low as the probability that no STAs complete their back-off is high. This results in RA RUs being idle during the TF cycle, contributing to low throughput. However, as n increases, the aforementioned probability decreases and the throughput increases. At small n values, the throughput can be improved by reducing $\mathrm{CW}_{\min}$, but doing so results in reduced throughput when n is large (due to increased contention). The $\mathrm{CW}_{\min}$ value can be optimized based on n for maximizing throughput.

Another observation in Fig. 2(a) is that the throughput of 802.11ax is maximum for all values of n when $N_{\mathrm{RA}}=0$, i.e., when all RUs are assigned for SA. Since there is no contention, SA offers higher throughput than RA; hence the result. In contrast, the throughput is minimum when $N_{\mathrm{RA}}=N_{\mathrm{RU}}$. Thus, as expected, the 802.11ax throughput depends significantly on the distribution of RUs between SA and RA.

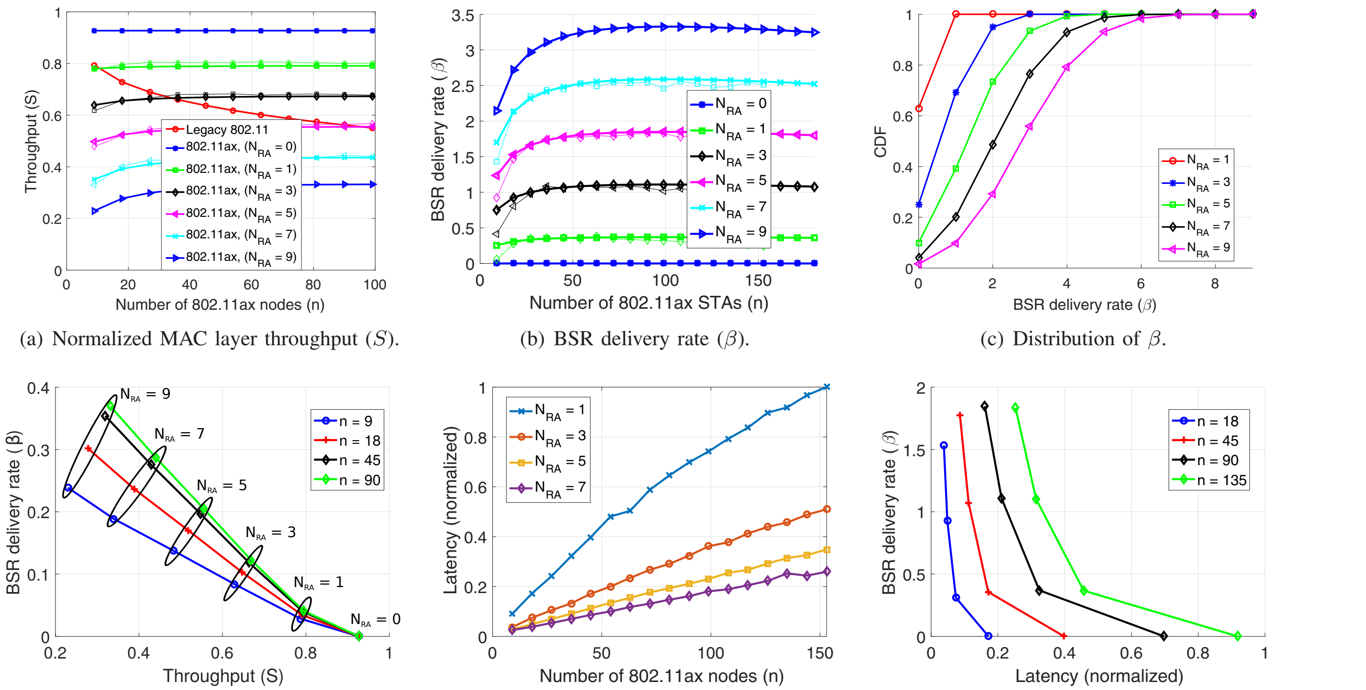
In Fig. 2(b), the BSR delivery rate, β, is plotted against n. The value of β first increases with n and then slowly decreases with further increase in n for any value of N_{RA}. At first, increasing n decreases P_{idle} leading to improved β (β is directly proportional to $(1-P_{\mathrm{idle}})$), but increasing n further leads to increased collisions among BSRs. In our model, BSR is transmitted only on the RA RUs. Therefore, there also exists a strong correlation between N_{RA} and β. The value of β is zero when N_{RA} is zero and is maximum when $N_{\mathrm{RA}}=N_{\mathrm{RU}}$.

Next, we demonstrate the trade-off between throughput and β in Fig. 2(d). The markers in each curve represent results for different N_{RA} values. In all cases, β is maximum, as suggested by Fig. 2(b), when $N_{\mathrm{RA}}=N_{\mathrm{RU}}$, which is the case when throughput is minimum (see Fig. 2(a)). On the other hand, β is zero when $N_{\mathrm{RA}}=0$ (i.e., $N_{\mathrm{SA}}=N_{\mathrm{RU}}$), and this results in maximum throughput. These plots demonstrate the inherent trade-off between β and throughput.

Finally, we use results from NS-3 simulations to plot the average per-packet latency as a function of n and β in Fig. 2(e) and Fig. 2(f), respectively. We normalize all latencies by the largest observed latency. This is done because the focus of this discussion is the trend of variation of latency as a function of different system parameters as opposed to the absolute value of the latency observed. While it is obvious that latency increases with n due to increased collisions, Fig. 2(e) provides

[4]We use the term "latency" to represent the average delay experienced by a packet in the transmit queue

[5]This is achieved in simulations by considering a fixed PHY rate for data and control frames and dividing the observed throughput by the corresponding factor. For example, factor = 6 if the fixed PHY rate = 6 Mbps



(a) Normalized MAC layer throughput (S). (b) BSR delivery rate (β). (c) Distribution of β.

(d) Trade-off between S and β. (e) Latency vs n. (f) BSR delivery rate vs latency.

Fig. 2: Performance of UORA-based 802.11ax MAC. In the first two subplots, the thick and thin lines represent results from analysis and simulations, respectively.

an additional insight that latency also depends on the choice of N_{RA}. For instance, when N_{RA} is small, contending nodes will not be able to transmit their BSR immediately. In such cases, there might be instances when these STAs will be starved because the AP cannot accommodate their transmissions (due to unavailability of BSRs). This strong correlation between β and latency is demonstrated in Fig. 2(f).

It can be inferred that N_{RA} must be chosen carefully so as to offer better Wi-Fi experience to users by adapting to different network sizes. When the network size is small and/or static, a small number of N_{RA} is sufficient for collecting BSRs from users, and doing so improves the network throughput. However, as the network size gets large and becomes dynamic, as in many envisioned 802.11ax deployment scenarios, N_{RA} must not be chosen to be too small. Otherwise, although small N_{RA} leads to high throughput, it results in low BSR delivery rate and also high latency, which can starve some of the nodes in the network. We plan to investigate mechanisms for optimally balancing this trade-off in our future work.

VI. Conclusions

In this paper, we described the UL MU OFDMA scheme that is being studied in the IEEE 802.11ax task group for standardization. We analytically characterized the performance of such scheme and validated our analysis using extensive NS-3 simulations. Through our newly coined metric – BSR delivery rate – we show that in dense and dynamic deployments, there exists a fundamental trade-off between 802.11ax throughput and its capability to support new nodes that are willing to join or have just joined the 802.11ax network.

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