AP-initiated Multi-User Transmissions in IEEE 802.11ax WLANs

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Abstract

Next-generation 802.11ax WLANs will make extensive use of multi-user communications in both downlink (DL) and uplink (UL) directions to achieve high and efficient spectrum utilization in scenarios with many user stations per access point. It will become possible with the support of multi-user (MU) multiple input, multiple output (MIMO) and orthogonal frequency division multiple access (OFDMA) transmissions. In this paper, we first overview the novel characteristics introduced by IEEE 802.11ax to implement AP-initiated OFDMA and MU-MIMO transmissions in both downlink and uplink directions. Namely, we describe the changes made at the physical layer and at the medium access control layer to support OFDMA, the use of *trigger frames* to schedule uplink multi-user transmissions, and the new *multi-user RTS/CTS mechanism* to protect large multi-user transmissions from collisions. Then, in order to study the achievable throughput of an 802.11ax network, we use both mathematical analysis and simulations to numerically quantify the benefits of MU transmissions and the impact of 802.11ax overheads on the WLAN saturation throughput. Results show the advantages of MU transmissions in scenarios with many user stations, also providing some novel insights on the conditions in which 802.11ax WLANs are able to maximize their performance, such as the existence of an optimal number of active user stations in terms of throughput, or the need to provide strict prioritization to AP-initiated MU transmissions to avoid collisions with user stations.

Keywords: IEEE 802.11ax, multi-user downlink and uplink transmissions, high efficiency WLANs, OFDMA

1 Introduction

Wireless local area network (WLAN) technology is continuously evolving to keep the pace with an ever increasing number of users, traffic volume, new scenarios and use-cases. With the goal of offering a sustained multi-Gb/s aggregate throughput in scenarios with high density of access points (APs) and user stations, the IEEE 802.11 community has created the 802.11ax Task Group (TGax) to develop a new set of physical (PHY) layer and medium access control (MAC) layer specifications. The new IEEE 802.11ax amendment, which is also called high efficiency WLAN, is currently available in a draft version [1].

The 802.11ax amendment is based on the IEEE 802.11ac-2013 [2]. It extends 802.11ac multi-user (MU) communication capabilities by including Uplink Multi-user Multiple Input Multiple Output (UL MU-MIMO) and Orthogonal Frequency Division Multiple Access (OFDMA) techniques, among other improvements. MU transmissions allow to simultaneously serve multiple user stations at speeds compatible with their network

Feature	IEEE 802.11ac	IEEE 802.11ax
Supported channel widths [MHz]	20 , 40 , 80 , 80+80 , 160	The same
Sub-channelization [MHz]	N/A	2.22 , 5 , 10
Frequency bands [GHz]	5	2.4 and 5
Modulations	BPSK, QPSK, 16-QAM, 64-QAM, 256-QAM	Adds 1024-QAM
OFDM symbol duration [μs]	3.6 (GI=0.4), 4 (GI=0.8)	13.6 (GI=0.8), 14.4 (GI=1.6), 16 (GI=3.2)
Spatial streams (SS)	Up to 8 SS at the AP, up to 4 SS at user	The same
MU transmissions	DL MU MIMO	UL and DL MU MIMO, UL and DL OFDMA
No. of MU-MIMO users	4	8
Low-density parity check (LDPC)	Optional	Mandatory

Table 1: Comparison of 802.11ac and 802.11ax features.

interfaces (i.e., the rate at which the operating system/driver is able to deliver/read data to/from the 802.11 interface) and channel conditions, achieving high aggregate throughput by reusing the same channel resources among multiple users, and thus minimizing packet and channel access protocol overheads.

In addition to the TGax documents and the current version of the 802.11ax draft, in the literature there are several papers from the research community focusing on TGax developments, future WLAN scenarios and use cases, and the novel PHY/MAC enhancements proposed for 802.11ax WLANs [3, 4, 5, 6, 7]. Additionally, the topic of 802.11 MU communications has been active in the last few years. A detailed survey of the most significant MU-MIMO-related solutions for WLANs is presented in [8]. Similarly, a short survey of the OFDMA-related works is presented in [9]. Other research works related to 802.11ax development focus on the performance of WLANs in dense scenarios, including: the evaluation of the dynamic sensitivity control mechanism [10], the use of BSS coloring [11], static and dynamic channel bonding [12, 13], channel access configuration [14], and more efficient but backward compatible alternatives to the legacy distributed coordination function [15, 16].

In this paper we focus on the analysis of MU transmissions in future 802.11ax WLANs with the goal of understanding the benefits, and possible side effects, in terms of link layer overheads, that MU transmissions bring to WLANs. In our paper we consider both the OFDMA and MU-MIMO capabilities defined in the current 802.11ax draft. Additionally, we describe the possible operation of future 802.11ax WLANs considering the case in which the AP is in charge of scheduling both downlink (DL) and UL MU transmissions. In such a case, the AP can properly apply quality of service (QoS) and load balancing policies to efficiently serve end users based on the knowledge of the network status. The downside of this approach, however, is that the AP needs to get from the user stations: (i) the channel state information (CSI) in both DL and UL directions and (ii) the information about the availability of packets waiting for transmission, which may represent a significant overhead.

To estimate the achievable 802.11ax saturation throughput, we extend Bianchi's 802.11 analytical model

				20 MHz		40 MHz		80 MHz		160 MHz	
MCS	Mod.	DCM	Coding rate	11ac	11ax	11ac	11ax	11ac	11ax	11ac	11ax
0	BPSK	✓	1/4	N/A	3.6	N/A	7.3	N/A	15.3	N/A	30.6
0	BPSK		1/2	6.5	7.3	13.5	14.6	29.3	30.6	58.5	61.3
1	QPSK	✓	1/4	N/A	7.3	N/A	14.6	N/A	30.6	N/A	61.3
1	QPSK		1/2	13	14.6	27.0	29.3	58.5	61.3	117	122.5
2	QPSK		3/4	19.5	21.9	40.5	43.9	87.8	91.9	175.5	183.8
3	16-QAM	✓	1/4	N/A	14.6	N/A	29.3	N/A	61.3	N/A	122.5
3	16-QAM		1/2	26	29.3	54	58.5	117	122.5	234	245
4	16-QAM	✓	3/8	N/A	21.9	N/A	43.9	N/A	91.9	N/A	183.8
4	16-QAM		3/4	39	43.9	81	87.8	175.5	183.8	351	367.5
5	64-QAM		2/3	52	58.5	108	117	234	245	468	490
6	64-QAM		3/4	58.5	65.8	121.5	131.6	263.3	275.6	526.5	551.3
7	64-QAM		5/6	65	73.1	135	146.3	292.5	306.3	585	612.5
8	256-QAM		3/4	78	87.8	162	175.5	351	367.5	702	735
9	256-QAM		5/6	N/A	97.5	180	195	390	408.3	780	816.6
10	1024-QAM		3/4	N/A	109.7	N/A	219.4	N/A	459.4	N/A	918.8
11	1024-QAM		5/6	N/A	121.9	N/A	243.8	N/A	510.4	N/A	1020.8

Table 2: The comparison of 802.11ax and 802.11ac transmission rates given in Mb/s for a single spatial stream. For 802.11ax, the GI is 3.2 μs, and for 802.11ac the GI is 0.8 μs was assumed, which are the largest GI values in both technologies. Note that in 802.11ax, dual carrier modulation (DCM) is used to add further protection against channel errors.

[17] to capture the 802.11ax WLAN dynamics when the proposed AP-initiated MU transmissions scheme is employed. By solving the analytical model we obtain the DL and UL throughput, thus allowing us to explore different WLAN configurations to investigate how to improve 802.11ax WLAN performance. In detail, we show that *i*) there is an optimal number of user stations for maximizing the aggregate throughput in terms of the trade-off between the performance gains achieved by scheduling large MU transmissions and the corresponding overheads, and *ii*) to maximize the uplink throughput we need to reduce the rate at which user stations attempt transmissions to avoid collisions with AP-initiated uplink MU transmissions.

The paper structure is as follows. Section 2 introduces how 802.11ax handles MU transmissions. Section 3 presents the system model considered in this paper, including the main assumptions done. Section 4 presents the analytical model. Section 5 presents the results and the 802.11ax performance evaluation. Finally, a summary of the most relevant contributions of the paper is gathered in Section 6.

2 IEEE 802.11ax: MU transmissions in WLANs

In this section we introduce the operation of OFDMA and MU-MIMO transmissions as described in the IEEE 802.11ax draft, together with other important PHY and MAC changes being introduced in comparison to the IEEE 802.11ac-2013 amendment (cf. Table 1). We have considered the documents provided by the TGax, including the recently proposed draft D1.3 [1], as the main references to build this section.

2.1 Physical Layer

Similarly to 802.11ac, the 802.11ax PHY layer is based on OFDM. However, in contrast to 802.11ac in which each 20 MHz is divided into 64 subcarriers, 802.11ax is based on a 256-tone OFDM scheme. The increase in the number of subcarriers is proportional to the increase in the OFDM symbol duration (from the maximum of 4 μs used in IEEE 802.11ac to the maximum of 16 μs used in 802.11ax) and guard interval (GI) duration (legacy 0.8 μs and new 1.6 μs and 3.2 μs are supported). In terms of available transmission rates, both amendments are almost equivalent (see Table 2). However, the use of longer OFDM symbols allows for larger coverage areas as the system becomes more robust to propagation delays, and longer GIs decrease inter-symbol interference.

Additionally, 802.11ax keeps the same channelization as 802.11ac, i.e., 20 MHz, 40 MHz, 80 MHz, non-contiguous 80+80 MHz, and contiguous 160 MHz channels are supported. However, it extends the current OFDM scheme to multiplex several users simultaneously in the frequency domain. To this end it introduces UL and DL OFDMA transmissions and supports additional 2.22 MHz, 5 MHz and 10 MHz subchannel widths. OFDMA sub-channels are composed of groups of subcarriers called resource units (RUs). The maximum number of users in a 20 MHz channel is 9, and in a 160 MHz channel up to 74 users can be multiplexed using 2.22 MHz subchannels.

Furthermore, 802.11ax, similarly to 802.11ac, assumes a maximum number of eight antennas at the AP and four at the user stations. However, it extends the maximum number of MU-MIMO transmissions allowed from 4 to 8, in both downlink and uplink directions, with up to four SU-MIMO spatial streams per user station. It is important to remark that with 802.11ax OFDMA, both DL and UL MU-MIMO transmissions can be performed in RUs greater than or equal to 106 subcarriers. In this way, 802.11ax provides simultaneously user multiplexing in the spatial and frequency domains.

The 802.11ax PHY layer includes the following additional improvements in comparison to 802.11ac: higher-order modulations (including 1024-QAM which helps to achieve 1 Gb/s throughput per spatial stream) and mandatory low density parity check (LDPC) codes (with up to 1.5-2 dB gain compared with traditionally used convolutional codes [18]). Given the maximum transmission power of a node operating in the ISM band is fixed, the combined use of denser constellations and improved channel coding allows for higher transmission rates and coverage ranges.

2.2 MAC Layer

The enhanced distributed channel access (EDCA) mechanism is used in 802.11ax for channel contention at both AP and user stations. EDCA provides traffic differentiation by considering multiple access categories (ACs). In EDCA, each AC operates as an independent EDCA function (EDCAF) instance, where EDCAF basically consists of a random backoff counter to avoid collisions, a carrier sense mechanism to detect the channel state, and pause the backoff counter in case of busy medium. In case when multiple EDCAF instances in the same node select the same backoff counter value, EDCA defines an internal collision resolution mechanism, which guarantees the transmission from the highest priority AC involved in it.

To support MU transmissions, 802.11ax introduces several new control frames and procedures to the MAC layer operation: *i*) trigger-based UL MU transmissions, *ii*) MU-RTS/CTS procedure, and *iii*) multi-station block ACK (MU-ACK) procedure. The details of the new procedures are the following:

- **Trigger-based UL MU transmission**: To signal the selected user stations to perform an UL MU transmission, the AP transmits a new frame called *trigger*. A trigger frame contains the following information: *i*) list of user stations involved in the transmission, and *ii*) user-specific information (e.g., RU and spatial stream allocation, modulation and coding scheme). User stations, after receiving this frame, start to transmit in the assigned resources.

- **MU-RTS/CTS procedure**: In order to protect large MU UL and DL transmissions, the AP initiates a MU transmission sending a MU-RTS frame[1], which includes information about user stations involved in the upcoming MU transmission and informs about the width of the primary channels of the expected CTS frames. User stations reply with simultaneous CTS frames on their primary channels (i.e., one or more 20 MHz channels). In case not all CTS frames are received, the AP may decide to distribute the channel resources only between the user stations that have replied.

- **MU-ACK procedure**: In order to reduce the large overhead required to individually acknowledge all UL MU transmissions, the block ACK frames directed to each user can be aggregated in a single multi-station block ACK (MU-ACK) frame.

2.3 Data Transmissions

802.11ax supports both single user (SU) and MU transmissions. MU transmissions can be allocated by the AP in both UL and DL directions. The positive side of this approach is that since the AP has a complete

[1] Note that the MU-RTS frame is a variant of the trigger frame.

view of the state of each user station, it can select the best stations at every transmission, which is especially relevant for uplink MU transmissions. The negative side is that the AP needs to gather channel and buffer state information from user stations, which may cause significant overhead. Therefore, a trade-off exists between the amount and the rate at which such information is required, and the overhead it causes.

2.3.1 SU Transmissions

SU transmissions are performed over the entire channel width and they engage all available spatial streams in SU-MIMO mode. The standard RTS/CTS procedure can additionally be used to reserve the desired channel width, and frame aggregation can be enforced to improve transmission efficiency (cf. Figure 1(a)).

2.3.2 AP-initiated MU Transmissions

The AP may schedule (i) DL MU (Figure 1(b)), and (ii) UL MU transmissions (Figure 1(c)). For DL MU transmissions, since the AP is the initiator of the transmission, user selection and resource distribution between different stations does not require any further signaling mechanism. However, for UL MU transmissions, user stations are scheduled by the AP to start their transmissions simultaneously using trigger frames.

Three different types of MU transmissions are considered in 802.11ax: MU OFDMA, MU-MIMO, and joint MU-MIMO and OFDMA transmissions:

- **MU-MIMO**: Using multiple antennas at the AP, several beams can be created in the downlink to transmit data to different user stations. In the uplink, the different signals received in the antennas can be also used to separate the data send by multiple user stations. In both cases, CSI is required at the AP, including the channel signatures of each station in both uplink and downlink directions.

- **MU OFDMA**: By splitting the channel width in different subchannels, called RUs, they are allocated to different user stations for transmitting data simultaneously.

- **Joint MU-MIMO and OFDMA**: In RUs larger than or equal to 106 subcarriers, MU-MIMO transmissions can be also performed, thus increasing the possible number of stations multiplexed at the same time.

In all cases, the remaining available spatial streams, i.e., streams not used for MU-MIMO transmissions in a given RU, can also be used to increase the number of spatial streams allocated to individual user stations in SU-MIMO mode.

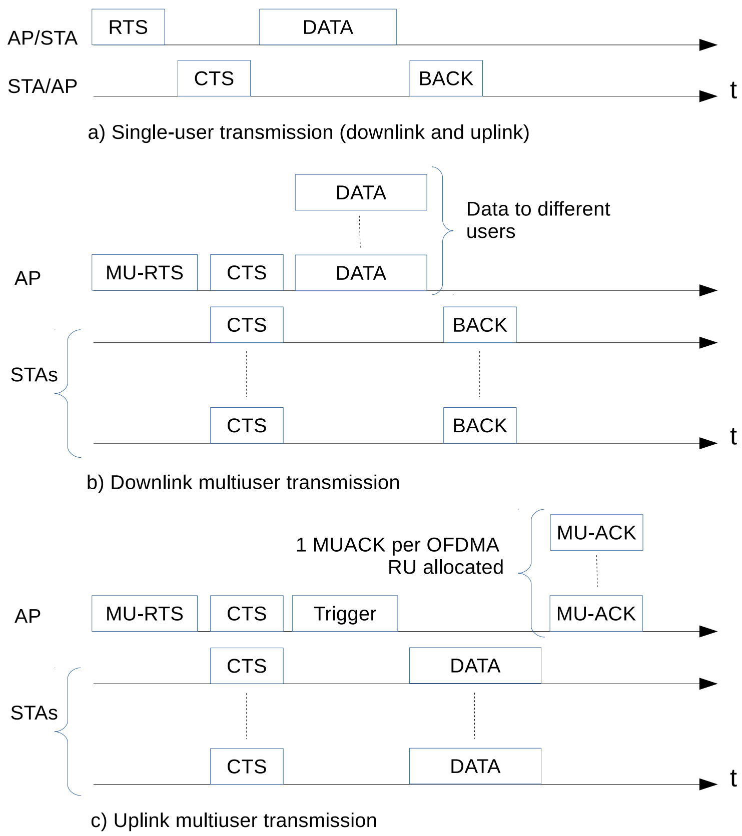


Figure 1: SU and MU transmissions using OFDMA and MU-MIMO. BACK stands for Block ACK, RTS for Request To Send, and CTS for Clear to Send.

2.4 Channel and Buffer State Information

2.4.1 Channel State Information (CSI) Acquisition

The AP must know the CSI of each user station included in a MU transmission in order to create multiple beams in the downlink, and to separate the multiple received streams in the uplink. The 802.11ax amendment extends the procedure included in IEEE 802.11ac by using the new uplink MU capabilities, i.e., CSI reports can be transmitted simultaneously from a group of stations after receiving a trigger frame.

The explicit channel sounding mechanism presented in the 802.11ax draft is depicted in Figure 2. In order to achieve channel sounding, the AP sends a null data packet announcement (NDPA) frame followed by an NDP frame. Additionally, in order to solicit the feedback from user stations it transmits a trigger frame. As a response to the trigger frame, stations send their CSI reports. Note that multiple trigger rounds may be necessary until all CSI reports are collected if there are more stations than the number of the supported

MU transmissions.

Since the instantaneous channel state information (CSI) may change very fast, such a procedure must be carried periodically, which may result in a large overhead. Moreover, since there will be some delay from the time between the CSI was acquired until a station is scheduled, the CSI information collected may be inaccurate, thus also causing inefficiencies in both the user station selection and the MU beamforming.

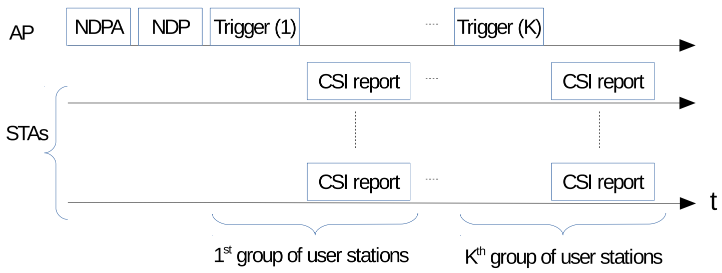


Figure 2: CSI exchange for 802.11ax which takes advantage of the UL MU transmissions. In this figure all user stations sounded are grouped in K groups, where the user stations in each group transmit the CSI report simultaneously to the AP.

2.4.2 Buffer State Information (BSI) Acquisition

In order to assist the AP to schedule UL MU transmissions, 802.11ax introduces two complementary mechanisms for the stations to send buffer state reports (BSRs), i.e., information about the buffer status of each station, to the AP:

- **Solicited BSR**: each station explicitly delivers its BSRs in any frame sent to the AP as a response to a BSR Poll (BSRP) send by the AP.
- **Unsolicited BSR**: user stations implicitly report its BSRs in the QoS Control field of any frame sent to the AP.

The use of the solicited BSR scheme comes at a cost of higher temporal overheads. However, it provides timely and accurate information to the AP about the current state of the stations's buffers, which should result in more efficient UL MU scheduling decisions. A possible solution to improve the efficiency of the solicited BSR mechanism is to integrate it into the periodic CSI sounding.

Table 3: Notation used in the 802.11ax analysis.

Parameter	Description
L_D	Packet size in bits
N_a	Number of aggregated packets in an A-MPDU
N	Number of 802.11ax stations
CW_{min} (BE)	Minimum contention window value for the AC BE
CW_{max} (BE)	Maximum contention window value for the AC BE
AIFS (BE)	AIFS length for AC BE
AIFS_{csi}	AIFS length for high priority CSI AC
SIFS	Short IFS
σ	OFDM symbol duration
T_e	Empty backoff slot
M_{ap}	Number of antennas at the AP
M_{sta}	Number of antennas at the user stations
B	Channel width
N_{ru}	Number of RUs in a MU transmission
B_{ru}	Min. channel width (min. OFDMA sub-channel width)
Y_m	Modulation used in bits/symbol
Y_c	Coding rate used
$Y_{\text{sc}}(B_{\text{ru}})$	Num. of data sub-carriers in B_{ru}
$r(V_s, B_{\text{ru}})$	Transmission rate
V_u	Num. of users included in a MU transmission
V_b	Num. of OFDMA sub-channels used in a MU tx
V_m	Num. of MU-MIMO spat. streams in each RU
V_s	Num. of SU-MIMO spat. streams per station
B_{ru}	Bandwidth of RU (OFDMA sub-channel)
α	Fraction of SU DL transmissions
β	Fraction of MU DL transmissions

3 System Model

We consider an 802.11ax network that consists of a single AP and N stations (Figure 3). All stations are within the data communication range of the AP and of all the other stations, they are able to transmit and receive data using the same modulation and coding scheme, and they have exactly the same MU-MIMO and OFDMA capabilities. Table 3 summarizes the notation used in this paper.

We fix the minimum RU size to 242 data sub-carriers, which corresponds to a 20 MHz channel. In each RU, up to M_{ap} MU-MIMO streams can be allocated. Therefore, with a $B = 160$ MHz channel and $M_{\text{ap}} = 8$ antennas, up to 64 single stations can be multiplexed allocating a single spatial stream per station.

A full-buffer traffic model is assumed for the AP and the stations, i.e., they have always a packet ready for transmission. At each transmission, N_a packets of L_D-bits long are aggregated and sent following the Aggregated MAC Protocol Data Unit (A-MPDU) packet aggregation scheme. EDCA is used to access the

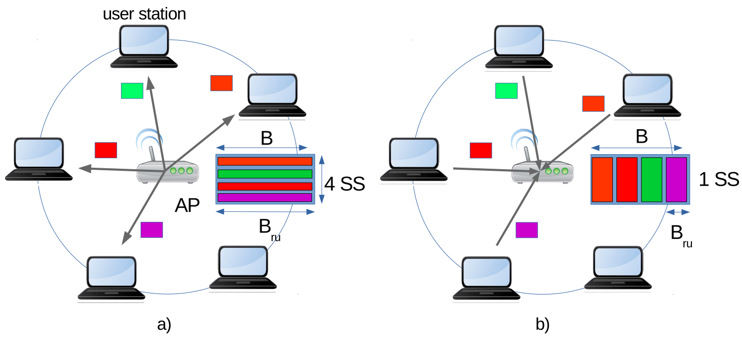


Figure 3: The considered scenario and two examples of MU transmissions: a) downlink MU transmission using MU-MIMO only (4 multiuser spatial streams (SS)), over the entire channel width B and b) uplink MU transmission using OFDMA only (4 RUs), with 4 single-user SSs per station.

wireless channel, though only the best effort (BE) access category (AC) is considered to be active. Following the EDCA operation, when the AP backoff counter reaches zero, it starts a SU or a MU transmission with probability α and $1-\alpha$, respectively. MU transmissions are DL with probability β and UL with probability $1-\beta$. Similarly, when a user station finishes its backoff countdown, it always initiates a SU UL transmission. Unsolicited BSR is used by the stations to deliver the buffer status information to the AP.

For each MU transmission, the AP selects $V_u \leq N$ stations randomly. When $N \geq M_{\text{ap}}$, the value of V_u is set as the largest value multiple of M_{ap} that results in an even distribution of the transmission resources between all selected stations (i.e., we consider that all RUs allocated have the same width (B_{ru}), the same number of stations is spatially multiplexed in each RU, and the same number of SU spatial streams are assigned to each station). Otherwise, the AP selects all available stations, i.e., $V_u = N$.

Given the V_u stations, the number of RUs allocated is given by $N_{\text{ru}} = \left\lceil \frac{V_u}{M_{\text{ap}}} \right\rceil$, with $V_m = \frac{V_u}{N_{\text{ru}}}$ the number of stations allocated to each RU, and $B_{\text{ru}} = \frac{B}{N_{\text{ru}}}$ is the width of each of them. The value of V_s, i.e., the number of spatial streams allocated to a single user, is set after assigning the MU spatial streams, and is given by $V_s = \min\left(M_{\text{sta}}, \left\lfloor \frac{M_{\text{ap}}}{V_m} \right\rfloor\right)$. For example, if $B = 160$ MHz, $M_{\text{ap}} = 6$, and $N = 40$ stations, we will select $V_u = 24$ stations, which use $N_{\text{ru}} = 4$ RUs of $B_{\text{ru}} = 40$ MHz each, and $V_m = 6$ stations are multiplexed in each RU using MU-MIMO, with a single spatial stream ($V_s = 1$) allocated to each station in the SU-MIMO mode. SU transmissions, in both DL and UL, use all available bandwidth, B, and all available spatial streams in SU mode, i.e., $V_s = \min(M_{\text{sta}}, M_{\text{ap}})$.

Regarding the channel access protocol, we also consider the following aspects: i) Control frames such as the Request To Send (RTS), MU-RTS, and Trigger frames transmitted by the AP are duplicated in every 20 MHz channel of B. ii) Clear To Send (CTS) and Block ACK (BACK) frames are duplicated in every 20

$$
\begin{aligned}
T_{su}(V_s, B) &= T_{\mathrm{RTS}} + T_{\mathrm{SIFS}} + T_{\mathrm{CTS}} + T_{\mathrm{SIFS}} + T^{\mathrm{D}}_{\mathrm{su}}(V_s, B) + T_{\mathrm{SIFS}} + T_{\mathrm{ACK}} + \mathrm{AIFS} \qquad (1)\\
T_{\mathrm{mu,d}}(V_u, V_s, B_{\mathrm{ru}}) &= T_{\text{MU-RTS}}(V_u) + T_{\mathrm{SIFS}} + T_{\mathrm{CTS}} + T_{\mathrm{SIFS}} + T^{\mathrm{D}}_{\mathrm{mu}}(V_u, V_s, B_{\mathrm{ru}}) + T_{\mathrm{SIFS}} + T_{\mathrm{BA}} + \mathrm{AIFS}\\
T_{\mathrm{mu,u}}(V_u, V_m, V_s, B_{\mathrm{ru}}) &= T_{\text{MU-RTS}}(V_u) + T_{\mathrm{SIFS}} + T_{\mathrm{CTS}} + T_{\mathrm{SIFS}} + T_{\mathrm{trigger}}(V_u) + T_{\mathrm{SIFS}} +\\
&\quad + T^{\mathrm{D}}_{\mathrm{mu,u}}(V_s, B_{\mathrm{ru}}) + T_{\mathrm{SIFS}} + T_{\text{MU-ACK}}(V_m) + \mathrm{AIFS}
\end{aligned}
$$

MHz sub-channel of B_{ru}, and in the case multiple users are allocated to the same RU through MU-MIMO, the CTS and BACK frames are transmitted in parallel; and *iii*) MU-ACK frames transmitted by the AP are duplicated in every 20 MHz sub-channel of B_{ru}, containing the information to acknowledge the transmissions from all stations assigned to that RU.

The data rate used at each transmission is given by $r(V_s, B_{\mathrm{ru}}) = \frac{V_s Y_m Y_c Y_{\mathrm{sc}}(B_{\mathrm{ru}})}{\sigma}$, where Y_m is the number of bits per symbol of the constellation used, Y_c is the coding rate, $Y_{\mathrm{sc}}(B_{\mathrm{ru}})$ is the number of data subcarriers in a given B_{ru}, and σ is the OFDM symbol duration. Similarly, control frames are transmitted at the basic rate $r(1, 20\ \mathrm{MHz}) = \frac{1 \cdot Y_m Y_c Y_{sc}(20\ \mathrm{MHz})}{\sigma}$, with all control frames duplicated in every 20 MHz sub-channel when wider channels are used, as well as transmitted using a single spatial stream. Note that for SU transmissions, B_{ru} corresponds to the full channel width, i.e., $B_{\mathrm{ru}} = B$.

The AP periodically requests the channel state information (CSI) from the stations at a rate λ_{csi} requests/second. The CSI procedure has a duration of T_{csi} seconds. To achieve a higher priority than other transmissions for the channel sounding, we consider that the AP uses a high priority AC for control and management frames that is configured with the minimum feasible AIFS value and $\mathrm{CW}_{\mathrm{min}} = 1$. These values guarantee that when the AP decides to start the channel sounding process it will get access to the channel as soon as the channel is detected idle, and without colliding with any UL transmission[2]. Therefore, the available time for data transmissions is limited to $T_{\mathrm{data}} = \frac{1}{\lambda_{\mathrm{csi}}} - T_{\mathrm{csi}}$.

Finally, in order to provide a clear picture of the link-layer 802.11ax saturation throughput for a single WLAN, we consider an ideal channel without errors. Moreover, there is no capture effect, and in all cases, when two or more stations transmit at the same time, all packets are lost, to which we refer as a collision.

[2]In dense scenarios, this approach may cause inter-WLAN collisions when two APs decide to initiate the CSI operation exactly at the same time. Therefore, appropriate overlapping basic service set (OBSS) management mechanisms are needed, though, this is out of the scope of this paper.

4 Saturation Throughput Model

In this section we introduce the analytical model used to calculate the expected saturation throughput under assumptions listed in Section 3. Our analysis is based on the well-known Bianchi's IEEE 802.11 DCF model [17], which has been proven accurate for the analysis of WLAN performance. However, in comparison to Bianchi's model, the following parts have been extended to capture the IEEE 802.11ax characteristics: types and lengths of transmissions (cf. Section 4.1), duration of channel sounding procedure (cf. Section 4.2), probability of successful transmissions and collisions in the presence of different types of single and multi-user transmissions (cf. Section 4.3), and performance metrics (cf. Section 4.4).

4.1 SU and MU Transmission Duration

4.1.1 Successful transmissions

The duration of SU (T_{su}) and MU (downlink $T_{\text{mu,d}}$ and uplink $T_{\text{mu,u}}$) transmissions are given by (1), where the duration of individual data frames is the following:

$$\begin{aligned}
T^D_{\text{su}}(V_s, B) &= T_{\text{PHY-SU}} + \left\lceil \frac{L_{\text{SF}} + N_a(L_{\text{MD}} + L_{\text{MH}} + L_{\text{D}}) + L_{\text{TB}}}{r(V_s, B)} \right\rceil \sigma \\
T^D_{\text{mu,d}}(V_u, V_s, B_{\text{ru}}) &= T_{\text{PHY-MU-DL}}(V_u) + \left\lceil \frac{L_{\text{SF}} + N_a(L_{\text{MD}} + L_{\text{MH}} + L_{\text{D}}) + L_{\text{TB}}}{r(V_s, B_{\text{ru}})} \right\rceil \sigma \\
T^D_{\text{mu,u}}(V_s, B_{\text{ru}}) &= T_{\text{PHY-MU-UL}} + \left\lceil \frac{L_{\text{SF}} + N_a(L_{\text{MD}} + L_{\text{MH}} + L_{\text{D}}) + L_{\text{TB}}}{r(V_s, B_{\text{ru}})} \right\rceil \sigma
\end{aligned}$$

and the duration of control frames is the following:

$$\begin{aligned}
T_{\text{RTS}} &= T_{\text{PHY-basic}} + \left\lceil \frac{L_{\text{SF}} + L_{\text{RTS}} + L_{\text{TB}}}{r(1, 20\text{ MHz})} \right\rceil \sigma \\
T_{\text{MU-RTS}}(V_u) &= T_{\text{PHY-basic}} + \left\lceil \frac{L_{\text{SF}} + L_{\text{MU-RTS}}(V_u) + L_{\text{TB}}}{r(1, 20\text{ MHz})} \right\rceil \sigma \\
T_{\text{CTS}} &= T_{\text{PHY-basic}} + \left\lceil \frac{L_{\text{SF}} + L_{\text{CTS}} + L_{\text{TB}}}{r(1, 20\text{ MHz})} \right\rceil \sigma \\
T_{\text{trigger}}(V_u) &= T_{\text{PHY-basic}} + \left\lceil \frac{L_{\text{SF}} + L_{\text{trigger}}(V_u) + L_{\text{TB}}}{r(1, 20\text{ MHz})} \right\rceil \sigma \\
T_{\text{BA}} &= T_{\text{PHY-basic}} + \left\lceil \frac{L_{\text{SF}} + L_{\text{BA}} + L_{\text{TB}}}{r(1, 20\text{ MHz})} \right\rceil \sigma \\
T_{\text{MU-ACK}}(V_m) &= T_{\text{PHY-basic}} + \left\lceil \frac{L_{\text{SF}} + L_{\text{MU-ACK}}(V_m) + L_{\text{TB}}}{r(1, 20\text{ MHz})} \right\rceil \sigma
\end{aligned}$$

where σ is the duration of an OFDM symbol (cf. Table 1) and N_a is the number of aggregated packets in an A-MPDU. Additionally, $L_{\text{SF}} = 16$ bits, $L_{\text{MD}} = 32$ bits, $L_{\text{MH}} = 360$ bits, and $L_{\text{TB}} = 18$ bits are the lengths of the service field, the MPDU delimiter, the MAC header, and the tail bits, respectively. The duration of the

PHY headers depend on the type of frame that is transmitted. We consider the following values (with the assumption of GI = 3.2 μs): $T_{\text{PHY-SU}} = 164\ \ \mu$s, $T_{\text{PHY-MU-DL}}(V_u) = 164 + 4 \cdot V_u\ \ \mu$s, $T_{\text{PHY-MU-UL}} = 168\ \ \mu$s, and $T_{\text{PHY-basic}} = 20\ \ \mu$s for HE SU frames, DL HE MU frames, UL HE MU frames, and non-HT frames, respectively. The duration of the control frames are: $L_{\text{RTS}} = 160$ bits, $L_{\text{MU-RTS}}(V_u) = 216 + 40V_u$ bits, $L_{\text{CTS}} = 128$ bits, $L_{\text{trigger}}(V_u) = 224 + 48V_u$ bits, $L_{\text{BA}} = 240$ bits, and $L_{\text{MU-ACK}}(V_m) = 176 + 96V_m$ bits.

4.1.2 Collisions

The duration of a collision is given by the larger transmission involved in it. We must consider the following two cases:

1. A SU transmission from the AP, or from one of the stations, collides with one or more SU transmissions from stations. In this case, the collision event has a duration of $T_{\text{c,su}} = T_{\text{RTS}} + T_{\text{SIFS}} + T_{\text{ack-time-out}}$, where the ack-time-out is the time which a node waits to restart its normal activity.

2. A DL or UL MU transmission collides with one or more SU transmissions from the stations. In this case, the duration of the collision is given by $T_{\text{c,mu}} = T_{\text{MU-RTS}}(V_u) + T_{\text{SIFS}} + T_{\text{ack-time-out}}$, as the trigger duration is larger than the RTS sent by the station. Note, in addition, that in this case the collision duration depends on the number of stations included in the MU transmission.

The value of the $T_{\text{ack-time-out}}$ is set to $T_{\text{ack-time-out}} = T_{\text{CTS}} + T_{\text{DIFS}} + T_e$ to guarantee all nodes re-start their backoff counter at the same time.

4.2 Duration of the Channel Sounding Procedure

The duration of the CSI process, T_{csi}, in 802.11ax follows the description given in Figure 2, and it is given by:

$$T_{\text{csi}}(b, V_u) = \text{AIFS}_{\text{csi}} + T_{\text{NDPA}} + T_{\text{SIFS}} + T_{\text{NDP}} + \left\lfloor \frac{N}{M_{\text{ap}}} \right\rfloor \cdot \left(T_{\text{SIFS}} + T_{\text{trigger}}(M_{ap}) + T_{\text{SIFS}} + T_{\text{CSIREP}}(B)\right). \tag{2}$$

where AIFS_{csi} is the AIFS duration of the high priority AC used for the channel sounding.

The duration of the Null Data Packet Announcement (NDPA), Null Data Packet (NDP) and CSI reports is the following:

$$T_{\text{NDPA}} = T_{\text{PHY-basic}} + \frac{168 + 32N}{r(1, 20\text{ MHz})},$$
$$T_{\text{NDP}} = T_{\text{PHY-SU}},\ \text{and}$$
$$T_{\text{CSIREP}}(B) = T_{\text{PHY-basic}} + \frac{40 + \frac{N_{\text{ang}} Y_{\text{sc}}(B)(b_\psi + b_\phi)}{N_{\text{sg}}} + 2 \cdot M_{\text{ap}} Y_{\text{sc}}(B)}{r(1, 20\text{ MHz})},$$

where the size of the CSI reports depends on the number of angles used to estimate the channel matrice for each subcarrier (N_{ang}), the number of bits used to quantise those angles (b_ψ and b_ϕ), the total number of subcarriers ($Y_{sc}(B)$), and the number of subcarriers grouped (N_{sg}).

4.3 Probability of Successful Transmissions and Collisions

The temporal evolution of a WLAN can be considered slotted under saturation conditions if all nodes are able to decrease their backoff counter at exactly the same time, with the duration of a slot defined as the time between two consecutive backoff decrements by a node, which can be variable depending on the number of transmissions initiated at each slot. Therefore, the duration of each slot depends on the probability that nodes transmit in it or remain idle, and if it contains a successful transmission or a collision. When the number of transmissions in a slot is zero, we refer to it as an empty slot of duration T_e seconds.

Under these conditions, since we have only two types of nodes (AP and user stations), and all user stations operate exactly in the same way, we know from [19] that either the AP or a single user station transmits in a randomly chosen slot with probability

$$\begin{aligned} \tau_{\text{ap}} &= \frac{1}{E[\Phi(\text{CW}_{\text{min,ap}}, m_{\text{ap}}, p_{\text{c,ap}})] + 1},\ \text{and} \\ \tau_{\text{sta}} &= \frac{1}{E[\Phi(\text{CW}_{\text{min,sta}}, m_{\text{sta}}, p_{\text{c,sta}})] + 1}, \end{aligned} \tag{3}$$

respectively, with $E[\Phi(\text{CW}_{\text{min}}, m, p_c)]$ the expected backoff duration,

$$E[\Phi(\text{CW}_{\text{min}}, m, p_c)] = \frac{1 - p_c - p_c(2p_c)^m}{1 - 2p_c} \frac{\text{CW}_{\text{min}}}{2} - \frac{1}{2},$$

where CW_{min} is the minimum contention window, m is the number of backoff stages, and p_c is the collision probability.

The probability that a transmission from the AP results in a collision is given by the probability that at least one station has also initiated a transmission at the same backoff slot that the AP,

$$p_{c,\text{ap}} = 1 - (1 - \tau_{\text{sta}})^N.$$

Similarly, the probability that a transmission from a station results in a collision is given by the probability that either another station or the AP have initiated a transmission at the same backoff slot,

$$p_{c,\text{sta}} = 1 - (1 - \tau_{\text{ap}})(1 - \tau_{\text{sta}})^{N-1}.$$

A backoff slot contains a successful transmission only when the AP or a single station transmits in it. Since we have four types of transmissions (i.e., DL and UL SU transmissions, and DL and UL MU transmissions) we calculate the successful transmission probabilities for each type as:

1. Probability that the AP initiates a DL SU transmission and none of the user stations transmit: $a_1 = \alpha\tau_{\text{ap}}(1 - \tau_{\text{sta}})^N$.
2. Probability that one user station transmits (i.e., it initiates an UL SU transmission) and neither the AP nor the other user stations transmit: $a_2 = N\tau_{\text{sta}}(1 - \tau_{\text{ap}})(1 - \tau_{\text{sta}})^{N-1}$.
3. Probability that the AP starts a DL MU transmission, and none of the user stations transmit: $a_3 = (1 - \alpha)\beta\tau_{\text{ap}}(1 - \tau_{\text{sta}})^N$.
4. Probability that the AP starts a UL MU transmission, and none of the user stations transmit: $a_4 = (1 - \alpha)(1 - \beta)\tau_{\text{ap}}(1 - \tau_{\text{sta}})^N$.

In all previous four cases there are always two conditions to meet to have a successful transmission: 1) the probability that the AP or one user station performs a transmission in a given slot, and 2) the probability that the remaining nodes do not transmit in it. For example, a_3 requires the AP transmits (τ_{ap}), the transmission is of MU type $(1 - \alpha)$, it is performed in the DL direction (β), and all the user stations are silent in that slot ($(1 - \tau_{\text{sta}})^N$).

The probability that one slot remains 'empty' is $b_1 = (1 - \tau_{\text{ap}})(1 - \tau_{\text{sta}})^N$, representing the case in which neither the AP nor the stations transmit in that slot.

When more than one node starts a transmission in the same slot, we have a collision. Similarly to the case with successful transmissions, there are four situations to consider:

1. a collision between the AP when it starts a SU transmission and one or more transmissions initiated by the stations, $c_1 = \alpha\tau_{ap}\left(1-(1-\tau_{sta})^N\right)$,
2. a collision between the DL MU transmission initiated by the AP and one or more transmissions initiated by the stations, $c_2 = (1-\alpha)\beta\tau_{ap}\left(1-(1-\tau_{sta})^N\right)$,
3. a collision between the UL MU transmission initiated by the AP and one or more transmissions initiated by the stations, $c_3 = (1-\alpha)(1-\beta)\tau_{ap}\left(1-(1-\tau_{sta})^N\right)$, and
4. a collision between two or more transmissions initiated by the stations, $c_4 = 1 - a_1 - a_2 - a_3 - a_4 - b_1 - c_1 - c_2 - c_3$, which is equivalent to compute all possible combinations in which two or more user stations transmit in the same slot and sum their occurrence probabilities.

Note that in the three first cases the probability that a backoff slot contains a collision is computed as the probability that the AP performs a transmission multiplied by the probability that at least one station also transmits.

Finally, a fixed-point approach is used to solve the non-linear system of equations given by τ_{ap}, τ_{sta}, $p_{c,\text{ap}}$ and $p_{c,\text{sta}}$.

4.4 UL and DL Throughput

The throughput in the DL and UL is given by

$$S_d = \frac{T_{\text{data}}}{T_{\text{csi}} + T_{\text{data}}}\left(\frac{a_1 N_a L_D + a_3 V_u N_a L_D}{b_1 T_e + \sum_{i=1}^{4} a_i (T_{a_i} + T_e) + \sum_{i=1}^{4} c_i (T_{c_i} + T_e)}\right)$$

and

$$S_u = \frac{T_{\text{data}}}{T_{\text{csi}} + T_{\text{data}}}\left(\frac{a_2 N_a L_D + a_4 V_u N_a L_D}{b_1 T_e + \sum_{i=1}^{4} a_i (T_{a_i} + T_e) + \sum_{i=1}^{4} c_i (T_{c_i} + T_e)}\right)$$

respectively, where $T_{a_1} = T_{\text{su}}(V_s, B)$ is the duration of a DL SU transmission, $T_{a_2} = T_{\text{su}}(V_s, B)$ is the time of an UL SU transmission, $T_{a_3} = T_{\text{mu,d}}(V_u, V_s, B_{\text{ru}})$ is the time of a DL MU transmission, $T_{a_4} = T_{\text{mu,u}}(V_u, V_m, V_s, B_{\text{ru}})$ is the duration of an UL MU transmission, $T_{c_1} = T_{c_4} = T_{\text{c,su}}$ are the collision duration for SU transmissions, and $T_{c_2} = T_{c_3} = T_{\text{c,mu}}$ are the collision duration for MU transmissions. The term $\frac{T_{\text{data}}}{T_{\text{csi}}+T_{\text{data}}}$ takes into account the fraction of time used for the channel sounding.

Table 4: Parameters used in the analysis.

Parameter	**Value**
L_D	12000 bits
N_a	64 packets
$\mathrm{CW}_{\mathrm{min,ap}}$ (BE)	32
$\mathrm{CW}_{\mathrm{min,sta}}$ (BE)	32
Number of backoff stages, $m = \log_2 \frac{CW_{\max}}{CW_{\min}}$ (BE)	5
AIFS (BE)	34 μs
$\mathrm{AIFS}_{\mathrm{csi}}$	25 μs
SIFS	16 μs
T_e	9 μs
σ	16 μs
M_{ap}	8
M_{sta}	4
B	160 MHz
GI	3.2 μs
MCS index (data & control frames)	6 ($Y_m = 6$, $Y_c = 3/4$)
λ_{csi}	5 attempts/second
CSI sounding: N_{ang}, b_ψ, b_ϕ, N_{sg}	56 angles, 2 bits, 4 bits, 2 subcarriers

Once the saturation throughput is computed, the expected service time per transmission is simply given by $E[D_u] = \frac{L_D}{S_u}$ and $E[D_d] = \frac{L_D}{S_d}$, respectively for uplink and downlink. Note that the service time includes the transmission delay, backoff duration and other temporal overheads.

5 Results

In this section we investigate the saturation throughput of an 802.11ax WLAN by applying the analysis developed in Section 4. We focus our attention on understanding the throughput gains provided by the new MU transmission capabilities included in the IEEE 802.11ax draft. We also investigate if there exists an optimal number of active stations that maximize the WLAN throughput, given the efficiency vs overheads tradeoff when large MU transmissions are scheduled. Finally, we show the benefits of reducing the stations' transmission attempts when the AP is allowed to schedule uplink MU transmissions with respect to their own throughput.

To validate the correctness and accuracy of the analytical model, we include the throughput values obtained by simulation. The simulator has been developed in Matlab[3], and it accurately reproduces the features described in Section 2. Each simulation point has been obtained by averaging 20 executions of 10

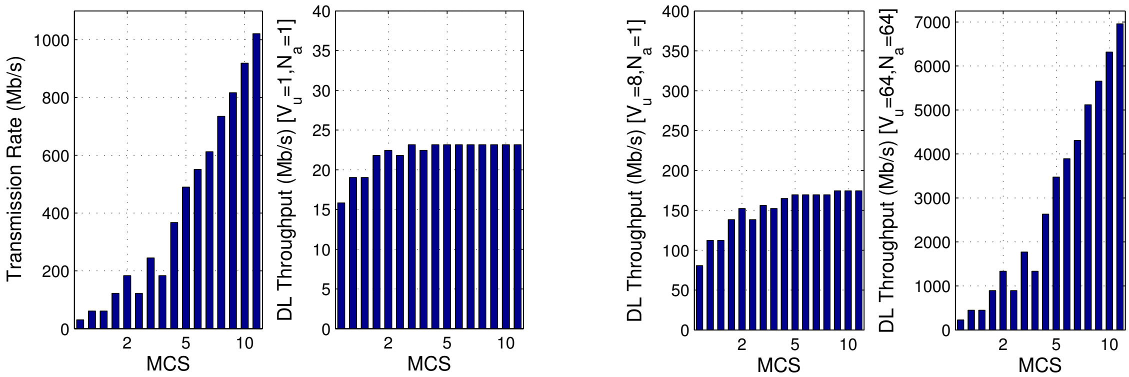
[3]Since the required modules to support MU transmissions in IEEE 802.11ax are not yet available in NS3, we chose to develop a simulator from scratch to validate the correctness of the presented analysis.

seconds. The error bars show the standard deviation of the throughput values obtained at each execution.

Table 4 shows the values of the parameters considered to obtain the results presented in this section, unless otherwise stated. In our analysis, we have assumed that the CSI is requested every 200 ms, although TGax results show that even values higher than 500 ms may be acceptable between two consecutive CSI requests in low mobility scenarios [20].

5.1 MU Transmissions to Overcome WLAN Inefficiency

Figure 4 shows the rate and throughput for each 802.11ax MCS in different configurations. In this subsection, we consider that only the AP is transmitting, and therefore there are no collisions. The channel sounding mechanism is also disabled. The results illustrate the inefficiency of 802.11ax (and of 802.11 WLANs in general) when performing SU transmissions and how such inefficiency can be mitigated by using packet aggregation and MU-transmissions. Comparing the left-side (transmission rate) with the right-side (throughput) of Figure 4(a) it is observed that transmission rates of several Gb/s result in an effective throughput of less than 25 Mb/s. These low throughput values are the result of the high overheads included in each transmission: duration of the backoff, the RTS/CTS exchange, inter-frame spaces, the PHY and MAC headers, and the duration of the acknowledgment procedure, among others. The use of MU transmissions and packet aggregation (cf. Figure 4(b)) allows to mitigate such high inefficiency, achieving aggregate throughput values of up to 6 Gb/s.

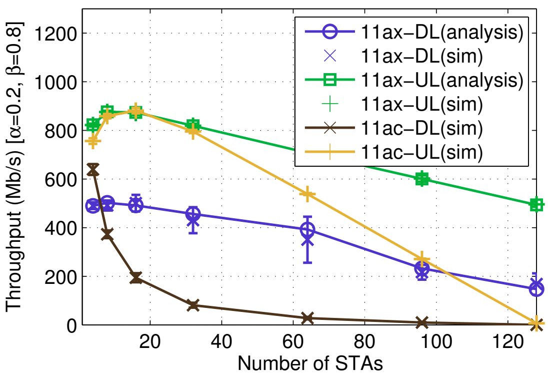


(a) Transmission rates and SU DL throughput

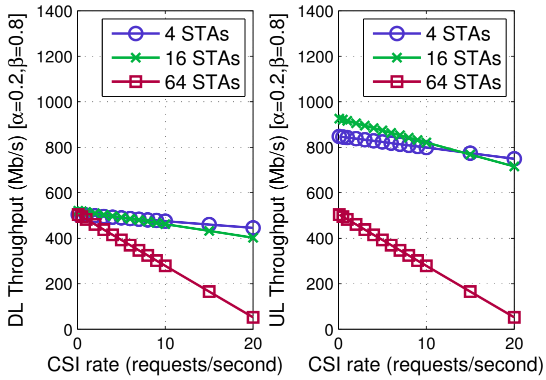
(b) MU DL throughput

Figure 4: Transmission rates versus SU and MU throughput of DL transmissions when only the AP is transmitting (i.e., the AP is the only node with packets to transmit in the WLAN.) for each MCS (cf. Table 2).

5.2 Negative Effect of Collisions and CSI Requests



(a) DL and UL 802.11ax and 802.11ac throughput as a function of the number of stations.



(b) Impact of CSI overheads on througput for a variable number of stations.

Figure 5: DL and UL throughput.

In 802.11ax WLANs the presence of many active user stations allows to schedule large and efficient MU transmissions which, as we have seen before, may result in significant high throughput values. However, the presence of a large number of active stations contending for the channel may also result in collisions, thus negatively affecting the overall WLAN performance. In addition, a high number of active user stations also results in high temporal overheads due to the channel sounding.

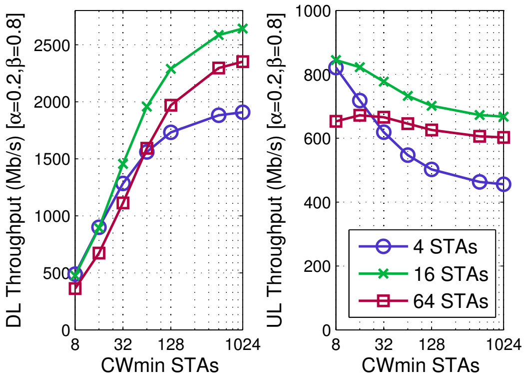
Here, we show that there is an optimal number of active stations that maximizes the WLAN throughput in terms of the aforementioned tradeoff. Figure 5(a) shows DL and UL throughput for $\alpha = 0.2$ and $\beta = 0.8$. We can observe that the maximum throughput is reached when the number of user stations is equal to 8. For a higher number of stations, such as 32, the use of more efficient MU transmissions does not compensate the cost of the collisions and CSI overheads. It is worth to mention that using the same $\mathrm{CW}_{\min}$ parameter for both the AP and user stations results in a higher UL throughput even when the 80 % of MU transmissions are DL (i.e., $\beta = 0.8$)[4]. The impact of the CSI overheads in the achievable throughput is shown in Figure 5(b). They are directly related to the number of stations to be sounded and the rate at which the sounding process is performed (i.e., λ_{csi}).

Figure 5(a) also shows the throughput achieved by an 802.11ac WLAN in exactly the same scenario. It can be observed that for a few number of stations, the 802.11ac offers the same or a better performance for both DL and UL than 802.11ax. The reason is that the overheads introduced by 802.11ax to support MU transmissions (i.e., trigger frames and MU-RTS) do not compensate their use when only few user stations

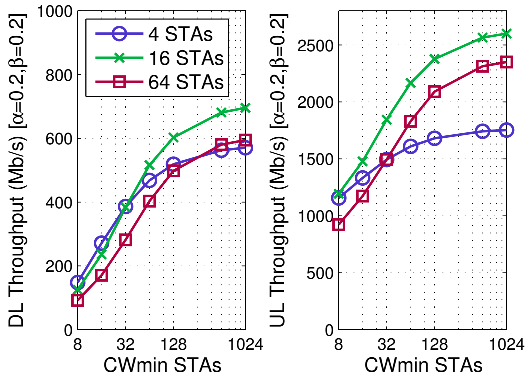
[4]Adjusting the fraction of MU transmissions that are DL or UL (i.e., β), the AP can improve the balance between DL and UL throughput, prioritizing one of them when required, which allows 802.11ax WLANs to adapt to changing scenarios.

can be scheduled to transmit simultaneously.

5.3 UL Throughput Improvement



(a) $\alpha = 0.2$, and $\beta = 0.8$



(b) $\alpha = 0.2$, and $\beta = 0.2$

Figure 6: Effect of increasing the station's CW_{min} on the DL and UL throughput. The AP CW_{min} is set to 8.

Collisions between transmissions initiated by the AP and those from user stations severely harm the WLAN performance. It is interesting to consider the case where an UL MU packet sent by the AP collides with a packet transmitted by one of the user stations that was included in the MU transmission. In order to avoid such a situation, a mechanism is required to reduce the chances that user station transmissions collide with AP transmissions. To do so, we propose to reduce the CW_{min} of the AP (for instance, from 32 to 8, as it has been done to obtain the results presented in this section) and to increase the CW_{min} for the user stations supporting UL MU transmissions[5]. The benefits of such an approach are observed in Figures 6(a) and 6(b), where reducing the rate at which user stations attempt transmissions results in a higher uplink throughput. Only when there are few stations and the AP is prioritizing downlink MU transmissions (i.e., the β parameter is close to 1), such a policy is not beneficial for user stations (cf. the 4 user stations curve in Figure 6(a)). Finally, it is worth to mention that in those cases in which the UL throughput is higher when the user station's CW_{min} is increased, the expected packet transmission delay will be lower, since the user stations are scheduled by the AP more often than when they are aggressively contending to access the channel.

[5] User stations not supporting UL MU transmissions should keep the recommended CW_{min} size to fairly access the channel.

6 Conclusions

This paper overviews the new PHY/MAC characteristics of 802.11ax WLANs, with emphasis on their MU transmission capabilities. Based on them, we introduce a possible operation of 802.11ax WLANs that exploits efficiently both MU-MIMO and OFDMA techniques. The presented results provide novel insights on how 802.11ax WLANs can be configured to maximize their operation, such as the existence of an optimal number of active user stations in terms of throughput or the need to provide strict prioritization to the AP to avoid collisions with user stations.

The 802.11ax amendment is still in its development phase. Although most of its fundamental characteristics are already included and consolidated in the current version of the 11ax draft amendment, there are still many aspects that need to be refined and detailed in the next few years. We expect that this work will contribute to a better understanding of the performance of future 802.11ax networks.

Future work on the performance analysis of MU transmissions in 802.11ax WLANs should focus on the analysis of the effects of miscellaneous traffic and channel conditions, including multiple traffic classes and different available transmission rates per station. In such a scenario, the design of efficient schedulers to select the stations that will be included in a MU transmission are key for maximizing the WLAN performance and reach 802.11ax expectations. Additionally, non-saturation case should be considered, which should be supported by the packet delay analysis.

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