Performance Evaluation of OFDMA and MU-MIMO in 802.11ax Networks

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***Abstract*-IEEE 802.11ax defines a new access method called Orthogonal Frequency Division Multiple Access (OFDMA) which can be used in both downlink (DL) and uplink (UL) directions. OFDMA divides the bandwidth into several Resource Units (RUs) and allows multiple stations to transmit or to receive simultaneously. UL OFDMA supports Scheduled Access (SA) RUs and Random Access (RA) RUs. Only scheduled stations are allowed to send on SA RUs, while the other stations should contend for the RA RUs. Moreover, 802.11ax defines UL MU-MIMO and enhances DL MU-MIMO. In this paper, we introduce and evaluate the efficiency of DL and UL multi-user transmissions using OFDMA and MIMO. Our results show that UL OFDMA is particularly useful when multiple stations regularly need to transmit few MPDUs. In this case, UL OFDMA may outperform full bandwidth access with up to 400%. Moreover, we find that increasing the number of RA RUs does not effectively reduce the collision rate but significantly decreases the throughput. Furthermore, we show that UL MU-MIMO significantly improves the network throughput and that the performance of DL MU-MIMO is clearly enhanced thanks to the decreased duration of the channel sounding procedure.**

I. INTRODUCTION

IEEE 802.11ax [2] is a recent amendment of the IEEE 802.11 standard [1] that defines High Efficiency (HE) WLANs to support a large number of users. The main objective of 802.11ax is to improve the effective throughput of the MAC layer. Therefore, it introduces two major novelties. The first one is a new access method called Orthogonal Frequency Division Multiple Access (OFDMA) that can be used in both downlink (DL) and uplink (UL) directions. The second major novelty of 802.11ax is the support of UL MU-MIMO which allows multiple stations to transmit simultaneously over the same frequency resource to the AP. Moreover, 802.11ax improves the throughput and the scalability of DL MU-MIMO.

OFDMA divides the channel into multiple resource units (RU) that are used simultaneously by different stations. DL OFDMA allows the AP to serve different receivers, while UL OFDMA allows multiple devices to transmit their data to the AP. In UL OFDMA, we distinguish Scheduled Access (SA) RUs and Random Access (RA) RUs. SA RUs are contention-free resources and are reserved for stations that informed the AP about their needs to send data. Stations that did not request resources are allowed to use RA RUs after contention. We note that a RA RU is wasted if it is not used or if it experiences a collision. Therefore, reducing the number of RA RUs increases the network efficiency but increases the waiting delays of stations without SA RUs. On the other hand, increasing the number of RA RUs reduces the transmission delays of the contending stations, but reduces the throughput.

An UL MU-MIMO transmission is initiated by the AP and allows multiple scheduled stations to transmit simultaneously over the same frequency resource. It does not require any channel calibration and increases the network throughput significantly when all the senders use a scheduled access. However, increasing the number of contending stations decreases the medium access rate of the AP and reduces the number of UL MU-MIMO transmissions. Therefore, most stations should use a scheduled access to take a full advantage of the new technique. On the other hand, DL MU-MIMO of 802.11ax still needs a periodic channel sounding procedure. However, the calibration reports may be recovered using UL MU-MIMO. This reduces the sounding duration and improves the throughput and the scalability of DL MU-MIMO.

In this paper, we evaluate the performance of UL OFDMA as a function of the number of RA RUs and the number of contending stations. Besides, we evaluate the throughput of DL OFDMA. We provide simulation results showing that OFDMA is able to improve the network efficiency when few MPDUs are regularly transmitted. Moreover, we evaluate the performance of UL/DL MU-MIMO. We show that UL MU-MIMO is able to improve the throughput significantly when the different senders use a scheduled access. However, increasing the number of contending stations limits the advantage of the new technique. Finally, we show that the throughput and the scalability of DL MU-MIMO are improved thanks to the reduced duration of the sounding procedure.

To summarize, the contribution of this paper is twofold. First, we introduce the major novelties of 802.11ax and we present the transmission procedure of OFDMA and MU-MIMO in HE networks. Second, we develop a simulator [21] and we use it to provide simulation results of the performance of UL/DL OFDMA and UL/DL MU-MIMO.

The remainder of this paper is organized as follows. The next Section introduces related work studying the performance of

802.11ax networks. Then, Section III presents the transmission procedure of UL/DL OFDMA and UL/DL MU-MIMO in HE WLANs. We dedicate Section IV to evaluate the performance of the new transmission techniques, and we discuss the main findings in Section V. Finally we conclude in Section IV.

II. Related Work

Many recent studies have been realized to evaluate the performance of the different features of 802.11ax. A detailed presentation of these features is available in [3]. In [4], the authors introduce the new power saving mechanism of 802.11ax, called Target Wake Time (TWT), and evaluate its performance. The fair sharing of the medium between UL OFDMA and other transmissions is studied in [5]. The authors show that increasing the number of contending stations decreases the number of UL OFDMA transmissions. This is because the UL OFDMA transmissions are initiated by the AP after channel contention, and have the same channel access priority than other transmissions. Thus, the authors propose optimal contention parameters to increase the priority of UL OFDMA transmissions. The study of [6] evaluates the uplink throughput using MU-MIMO and single-stream transmissions. It provides analytical results showing that UL MU-MIMO significantly improves the network efficiency. Unfortunately, the authors consider a limited scenario and do not clearly introduce the main parameters that influence the performance of UL MU-MIMO.

In [7], the authors compare 802.11ax with 802.11ac using simulation. They evaluate the UL and DL throughput of both OFDMA and MU-MIMO for different channel widths. They show that UL OFDMA without MU-MIMO may outperform single-user transmissions by 273%, and the use of both UL OFDMA with MU-MIMO may improve the WLAN performance by 474%. This evaluation is done in a WLAN where the stations are randomly distributed and transmit using different MCS indexes and RU sizes. Therefore, the results are useful to provide a global view of the performance of HE networks but cannot illustrate the effect of the key parameters separately. Moreover, many details are missing, such as the A-MPDU length which has a significant effect on the WLAN efficiency. In addition, the performance of RA RUs is not considered. Another evaluation of 802.11ax is available in [8]. It provides analytical and simulation results of the throughput and delay of UL OFDMA in the presence of legacy stations that contend using EDCA. These results show that the access time is not fairly shared between OFDMA and single-user transmissions due to the large number of legacy stations. Although the study highlights the important issue of the medium sharing and its impact on the use of UL OFDMA, it does not illustrate the real potential of UL OFDMA when it is effectively used.

In [9], the authors perform an experimental evaluation of UL OFDMA in a HE WLAN. In this study, the frame aggregation is disabled and UL MU-MIMO is not used. Moreover, only SA RUs are considered. In [10], the authors propose some schedulers to allocate the SA RUs of UL OFDMA transmissions. They show that the proposed schedulers slightly improve the network throughput. This study is limited to SA RUs and does not take into account RA RUs and MU-MIMO.

In [11], the authors evaluate the efficiency of UL OFDMA when all the RUs are used with random access. They consider various contention parameters and show that the efficiency of RA RUs is very limited due to the wasted resources. Unfortunately, they do not provide a comparison with SA RUs and with single-user (i.e. full bandwidth) transmissions. Moreover, several important details are missing such as the A-MPDU length. A similar study is available in [12] where the authors evaluate the efficiency of UL OFDMA as a function of the RU size and the number of contending stations. They consider that all RUs are used with random access and show that the highest efficiency of UL OFDMA is 40%. In [13], the authors evaluate the performance of UL OFDMA. They consider different numbers of RA RUs and contending stations. The major limitation of this work is that the transmission procedure is not compliant with 802.11ax. Therefore, the obtained results do not illustrate the real performance of UL OFDMA in HE networks.

Another study of UL OFDMA is available in [14]. It evaluates the throughput as a function of the numbers of RA RUs and contending nodes. It shows that increasing the number of RA RUs significantly reduces the throughput. In this study, the frame aggregation is disabled and the comparison with single-user transmissions is missing. Therefore, the results do not clearly illustrate the potential of UL OFDMA. In [15], the authors evaluate the performance of a HE network using OFDMA and MU-MIMO. In this WLAN, the bandwidth is shared between single-user and multi-user transmissions in both DL and UL directions. Since OFDMA and MU-MIMO are used at the same time, the results are useful to provide a global evaluation of 802.11ax but do not clearly show the performance of each technique in each direction.

III. Multi-User Transmissions in 802.11ax

802.11ax defines multi-user (MU) transmissions in UL and DL directions. UL MU transmissions are possible using UL OFDMA, UL MU-MIMO or a mixture of both. They allow multiple STAs to transmit simultaneously to the AP. Similarly, DL MU transmissions allow the AP to serve multiple STAs simultaneously using DL OFDMA, DL MU-MIMO or a mixture of both. To support MU transmissions, 802.11ax defines different formats for the PHY frame (i.e. PPDU: PHY Protocol Data Unit). Therefore, there are 4 HE PPDU formats. The first one is HE SU PPDU and is used for single-user transmissions (either single stream or SU-MIMO). The second format is HE Trigger Based (TB) PPDU and is defined for UL MU transmissions. The third format is HE MU PPDU and is defined for DL MU transmissions. Therefore, it is only used by the AP. The forth format is HE Extended Range (ER) SU PPDU and is beyond the scope of this paper. The first three formats are illustrated in Figure 4(a) where the differences are depicted in bold.

A. Orthogonal Frequency Division Multiple Access

Before 802.11ax, the WLANs only support transmissions on the entire channel width (i.e. full bandwidth transmissions). This allows a single node to transmit at a time. OFDMA is among the major novelties of 802.11ax. It divides the channel into multiple RUs which are allocated to different stations. A RU is composed of a specific number of subcarriers (also called tones). In 802.11ax, the subcarrier width is divided by 4 and its duration is multiplied by 4 compared to the values of 802.11ac. Therefore, the number of subcarriers is almost multiplied by 4. This provides OFDMA with an important number of RUs. The available RU sizes are 26, 52, 106, 242, 484, 996 and 2×996 tones. The maximum number of RUs (depicted in Table 1) depends on the channel width and the RU size. We note that a single OFDMA transmission may contain RUs of different sizes.

Table 1. Maximum number of RUs for different channel widths

RU size	Channel width			
	20 MHz (242 subcarriers)	40 MHz (484 subcarriers)	80 MHz (996 subcarriers)	160 MHz (1 992 subcarriers)
26 tones	9	18	37	74
52 tones	4	8	16	32
106 tones	2	4	8	16
242 tones	1	2	4	8
484 tones	-	1	2	4
996 tones	-	-	1	2
2×996 tones	-	-	-	1

The transmission data rates corresponding to the different MCS indexes for the different RU sizes and channel widths are illustrated in Table 2. These rates correspond to the shortest Guard Interval (GI) of 0.8µs and to a single spatial stream. To obtain the data rates for a given number of spatial stream (Nss), we need to multiply the data rates of Table 2 by Nss, where Nss varies from 1 to 8. Thus, the highest rate of 802.11ax is **1201 × 8 = 9608 Mbps** (i.e. **9.6 Gbps**).

Table 2. Data rates in Mbps for 1 spatial stream and GI=0.8µs

MCS	RU-26	RU-52	RU-106	20 MHz RU-242	40 MHz RU-484	80 MHz RU-996	160 MHz RU-2x996
0	0.9	1.8	3.8	8.6	17.2	36.0	72.1
1	1.8	3.5	7.5	17.2	34.4	72.1	144.1
2	2.6	5.3	11.3	25.8	51.6	108.1	216.2
3	3.5	7.1	15.0	34.4	68.8	144.1	288.2
4	5.3	10.6	22.5	51.6	103.2	216.2	432.4
5	7.1	14.1	30.0	68.8	137.6	288.2	576.5
6	7.9	15.9	33.8	77.4	154.9	324.3	648.5
7	8.8	17.6	37.5	86.0	172.1	360.3	720.6
8	10.6	21.2	45.0	103.2	206.5	432.4	864.7
9	11.8	23.5	50.0	114.7	229.4	480.4	960.7
10	-	-	-	129.0	258.1	540.4	1080.9
11	-	-	-	143.4	286.8	600.4	1201.0

B. UL OFDMA

OFDMA may be used in DL and UL directions. An UL OFDMA transmission starts with a Trigger Frame (TF) transmitted by the AP, followed by a HE TB PPDU transmitted by the STAs. The TF notifies the stations having scheduled resources about SA RUs they should use to transmit, and informs the other stations about RA RUs that they may use after contention. The AP acknowledges the received data either using multiple BACK frames transmitted at different RUs, or using a single Multi-STA BACK frame transmitted at the entire channel width. The Multi-STA BACK allows the AP to acknowledge all the A-MPDUs of the different stations. Figure 1 depicts an UL OFDMA transmission. We illustrate the frame format of TF and Multi-STA BACK in Figures 4(c) and 4(e), respectively.

In UL OFDMA, the TF contains the Association Identifier (AID) of the stations allowed to transmit on the different SA RUs. The AID corresponding to RA RUs is 0. A STA that has a SA RU should not contend for RA RUs. Besides, if a STA contends for RA RUs but does not succeed to gain one, it is allowed either to contend for channel access using EDCA after the end of the current UL OFDMA transmission or to contend for RA RUs within the subsequent UL OFDMA transmissions.

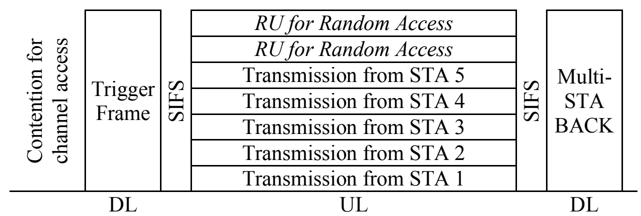

Figure 1. UL OFDMA transmission with Multi-STA BACK

A STA should maintain an OFDMA Contention Window (OCW) and an OFDMA BackOff (OBO) counter to contend for RA RUs. The value of OBO is randomly selected in the range [0, OCW], where the initial value of OCW is OCWmin. Upon the reception of a TF, if OBO is higher than the number of RA RUs, the STA decreases it with the number of RA RUs and defers its transmission. Otherwise, it sets the value of OBO to 0 and transmits over a randomly selected RA RU among those available. When the transmission fails, the STA increases its OCW to 2×OCW+1 if OCW is less than OCWmax (otherwise, OCW remains equal to OCWmax), and randomly selects a new value for its OBO counter in the range [0, OCW]. If the transmission succeeds, the STA initiates its OCW to OCWmin. According to this contention procedure, it is clear that increasing the number of RA RUs allows the OBO counter to decrease rapidly and the stations to transmit more frequently. Therefore, increasing the number of RA RUs does not reduce the collision rate efficiently.

The default values of OCWmin and OCWmax are 7 and 31, respectively. The use of reduced values of OCWmin and OCWmax is practical to reduce the contention time and to enhance the throughput when the number of contending nodes is relatively limited. But 802.11ax is mainly proposed as a solution for high density networks. In such networks, the number of contending stations is expected to be significant during some periods, and the use of reduced values of OCWmin/OCWmax during these periods is able to increase the collision rate and to reduce the throughput. However, 802.11ax allows the AP to adjust the values of OCWmin/OCWmax using management frames (i.e. Beacon, Probe Response and Association Response frames). Therefore, when the AP notices that the number of the contending STAs increases and the collision rate on RA RUs becomes high, it can increase OCWmin/OCWmax and transmit the new values to the different STAs. When the network load decreases, the AP can adjust the values again. Therefore, we believe that proposing an algorithm for an optimal selection of OCWmin/OCWmax is an interesting future work to enhance the performance of 802.11ax networks.

To schedule RUs for STAs having buffered frames, the AP should be aware about their bandwidth requirements. This is possible using the Buffer Status Report (BSR) field of the HE MPDU header. The STA indicates the remaining frames in its transmission queue in the BSR field of the last transmitted MPDU. This field allows the AP to schedule enough resources for the different stations.

Since multiple transmitters are involved in an UL OFDMA transmission, they should synchronize their transmission time and power to avoid interference issues at the AP. Therefore, the AP includes the targetRSSI (i.e. the expected signal strength of the frames received by the AP) in the TF, and each station adjusts its transmission power to allow the AP to receive its data with a signal strength equal to targetRSSI. We note that in UL OFDMA, the AP is responsible of selecting the MCS that should be used by the different transmitters.

C. DL OFDMA

DL OFDMA allows the AP to serve multiple stations simultaneously using different RUs. We note that DL OFDMA transmissions do not need control frames to notify the RU sizes and to identify the receivers of each RU, since this information is available in the HE-SIG-B field of the HE MU PPDU preamble. Moreover, the AP should contend for the channel using EDCA to perform a DL OFDMA transmission. After the successful reception of the data, the different receivers send their acknowledgements simultaneously using the same RUs used to receive the data. This means that the feedback recovery is realized using UL OFDMA and requires synchronization information. This information is called trigger and is delivered to the receivers as part of the A-MPDU. An example of a DL OFDMA transmission is illustrated in Figure 2. In this example, the AP contends for the channel using EDCA then starts a DL OFDMA transmission and sends a HE MU PPDU containing multiple A-MPDUs. Each A-MPDU is transmitted at a different RU and contains data and trigger information. Upon the reception of the PPDU, the receivers read the PPDU preamble to determine which RU they should decode. If the reception succeeds, they send a BACK at the appropriate RU.

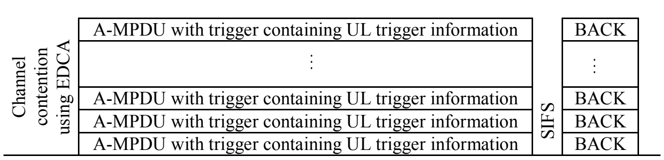

Figure 2. DL OFDMA transmission with UL OFDMA acknowledgement

D. UL MU-MIMO

In addition to OFDMA, the second major novelty of 802.11ax is the support of UL MU-MIMO. It allows multiple STAs to transmit simultaneously using the same frequency resource. This technique does not require beamforming and does not need the channel sounding procedure. However, the AP should initiate the UL MU-MIMO transmissions using TF, and then the STAs transmit their data using the HE TB PPDU format. We note that an UL MU-MIMO transmission may occur on the full bandwidth or on a RU of an UL OFDMA transmission. However, only RU sizes equal or larger than 106 tones may be used with UL MU-MIMO. In addition, UL MU-MIMO is possible with scheduled access only; if two stations transmit simultaneously on the same RA RU, their data will be lost.

E. DL MU-MIMO

DL MU-MIMO allows the AP to transmit up to 8 spatial streams on the same frequency resource and to serve a maximum of 4 STAs per RU, simultaneously. It relies on beamforming and requires a periodic channel sounding procedure. In a DL MU-MIMO transmission, the AP is the sender and is called the beamformer while the receivers are called the beamformees. The channel sounding allows the AP to gather beamforming reports about the location of every station and to transmit the streams toward the precise direction of the different receivers. The channel sounding procedure starts with a Null Data Packet (NDP) Announcement (NDPA) followed by a NDP and a Beamforming Report Poll (BRP) frame transmitted by the AP. The different beamformees identified in the BRP reply simultaneously and send HE Compressed Beamforming/CQI frames using UL MU-MIMO. The AP may transmit other BRP Trigger frames to gather more feedbacks if necessary. An example of the HE sounding procedure is depicted in Figure 3. NDP is an empty frame that only contains the PPDU header. The frame formats of HE NDPA, BRP Trigger and HE Compressed Beamforming/CQI are depicted in Figures 4(b), 4(c) and 4(d), respectively.

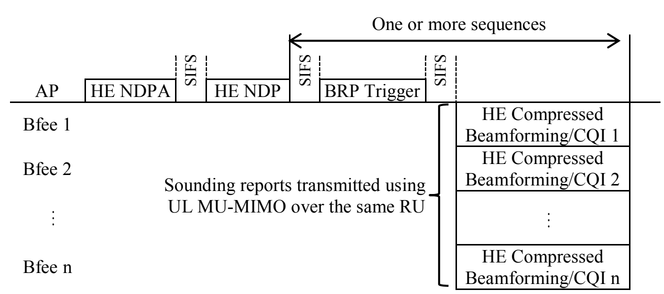

Figure 3. Channel sounding protocol for DL MU-MIMO in 802.11ax

We note that the channel sounding for DL MU-MIMO should be done periodically to provide the AP with accurate channel measurements. A typical calibration interval varies between 40ms (the default value of Realtek RTL8812BRH 802.11ac chipset [16]) and 10ms [17]. It may be even less than 10ms [18]. In addition, the use of UL MU-MIMO to gather the sounding reports improves the efficiency of DL MU-MIMO in HE networks.

8µs	8µs	4µs	4µs	8µs	**4µs / 8µs**[1]	**4µs**[2]	Variable duration	**0µs**[3]
L-STF	L-LTF	L-SIG	RL-SIG	HE-SIG-A	**HE-STF**	**HE-LTF**	Data	**PF**

[1] 4µs for HE SU PPDU and 8µs for HE TB PPDU
[2] 4µs if 1 spatial stream (1ss); 8µs if 2ss; 16µs if 3ss/4ss; 24µs if 5ss/6ss; 32µs if 7ss/8ss
[3] optional field with possible durations of 0µs, 4µs, 8µs, 12µs, and 16 µs

a) HE PPDU format (802.11ax)

SERVICE (16 bits)	MAC frame (MPDU or A-MPDU)	Tail (6 bits)	Padding

Frame Control	Duration	RA	TA	Sounding Dialog Token	STA Info 1	…	STA Info n	FCS
2 **octets**	2	6	6	1	2		2	4

b) MAC frame: HE NDP Announcement (NDPA) frame format

Frame control	Duration	RA	TA	Common Info	User Info 1	…	User Info n	Padding	FCS
2 **octets**	2	6	6	8	6		6	variable	4

c) MAC frame: Trigger frame (types Basic Trigger and Beamforming Report Poll (BRP) Trigger) format

AID12	RU Allocation	Coding Type	MCS	DCM	SS Allocation / RA-RU Information	Target RSSI	Reserved	Trigger Dependent User Info
12 **bits**	8	1	4	1	6	7	1	8

Trigger Type	Length	More TF	CS required	BW	GI and LTF Type	MU-MIMO LTF mode	Number of HE-LTF Symbols	STBC	LDPC Extra Symbol Segment	AP Tx power	Packet Extension	Spatial Reuse	Doppler	HE-SIG-A Reserved	Reserved
4 **bits**	12	1	1	2	2	1	3	1	1	6	3	16	1	9	1

Frame control	Duration	Address 1	Address 2	Address 3	Sequence Control	HT Control	Frame Body	FCS
2 **octets**	2	6	6	6	2	4	variable	4

d) MAC frame: Action frame (type HE Compressed Beamforming/CQI with MU feedback) format

Category (= HE)	HE Action (= HE Compressed Beamforming/CQI)	HE MIMO Control	HE Compressed Beamforming Report	HE MU Exclusive Beamforming Report
1 **octet**	1	3	variable (see **Table X**)	variable (see **Table X**)

Frame Control	Duration	RA	TA	BA Control	BA Information	FCS
2 **octets**	2	6	6	2	variable	4

e) MAC frame: BACK frame (type Multi-STA BACK) format

Per AID TID Info	Per AID TID Info	…	Per AID TID Info
variable	variable		variable

AID TID Info	Block Ack Starting Sequence Control	Block Ack Bitmap
2 **octets**	2 or 0	0, 4, 8, 16 or 32

Figure 4. HE PPDU and MAC frame formats

The acknowledgement procedure of DL MU-MIMO may be achieved like in 802.11ac with the exchange of multiple Block Ack Request (BAR) and Block Ack (BACK) frames with the different receivers. This method requires significant time and is not efficient. Another feedback recovery method relies on UL MU-MIMO and allows the different beamformees to acknowledge immediately and simultaneously. It requires the AP to include trigger information in the transmitted A-MPDUs. This method is efficient and scalable since it requires a single acknowledgement round for all the receivers. We consider the use of this method in the rest of the paper. An example of DL MU-MIMO transmission with UL MU-MIMO feedback is shown in Figure 5.

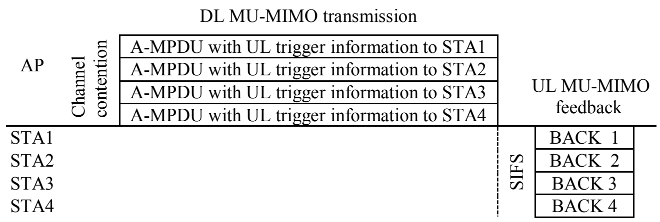

Figure 5. DL MU-MIMO transmission over one RU with UL MU-MIMO feedback

IV. EVALUATION RESULTS

Since 802.11ax is very recent, none of the well-known simulators fully supports it. For example, the newest version of NS3 simulator (version 3.30.1 released on September 2019) [20] supports some features of 802.11ax such as SU-MIMO, HE-MCS indexes and spatial reuse, but does not support OFDMA and MU-MIMO. Therefore, we implement our own simulator in C++ to evaluate the performance of the major novelties of 802.11ax. Our tool does not simulate the transmission failures related to path loss, but supports frame losses related to collisions. We note that the frame loss rate in good channel conditions (i.e. appropriately selected MCS and in the absence of collisions) is almost 0% using NS3 and other well-known simulators. This rate increases when the selected MCS is not suitable or when the collision rate rises. Since our simulator considers that the only loss factor is the collisions, it provides realistic results under the assumption that the selected MCS is suitable. This is an acceptable assumption that allows us to focus on the efficiency of OFDMA and MU-MIMO techniques of 802.11ax.

Our simulator supports UL and DL OFDMA in addition to UL and DL MU-MIMO. It allows the measurement of throughput, delays and collision rates. It supports different channel widths, RU sizes and spatial streams. Besides, the simulator allows the selection of a variable number of contending stations. In the case of UL OFDMA and UL MU-MIMO, it is possible to configure the number of RA RUs and SA RUs. In the case of DL MU-MIMO, it is possible to evaluate the performance as a function of the channel sounding rate and the number of beamformees. Actually, 802.11ax does not introduce any scheduling algorithm for UL multi-user transmissions. Since defining and evaluating the performance of a scheduling algorithm is beyond the scope of this paper, we consider that the scheduled stations remain scheduled and contending devices remain unscheduled during the entire simulation time. In addition, the number of scheduled stations is equal to the maximum number of scheduled transmissions (i.e. number of SA RUs × number of AP antennas). This allows SA RUs to be continuously used. More information on the use of the simulator is available at [21]. We use the simulator with the configuration parameters of Table 3.

Table 3. Simulation parameters

Parameter	Value
Simulator	802.11ax lightsim [21]
Simulation time	1000 seconds
Channel width	80 MHz
Number of antennas at the AP	Variable (depends on the scenario)
Number of antennas at the STAs	1
MCS	6
Guard Interval (GI)	0.8µs
CWmin	15 (default value)
CWmax	1023 (default value)
Ethernet frame length	1500 Bytes (maximum length)
PPDU duration	5.484 ms (maximum duration)
SIFS	16µs
SlotTime	9µs
AIFS (Best Effort)	43µs (default value)
TXOP	0

A. Evaluation of UL OFDMA without MIMO

In this sub-section, we compare 3 transmission methods. **The first one** is the full bandwidth transmission. It allows a single station to transmit at a time at the entire channel width after winning the EDCA contention. **The second method** is default UL OFDMA which requires a channel contention using EDCA. This is the standard operating mode of UL OFDMA. We note that 802.11ax allows the AP to perform successive UL OFDMA transmissions separated with SIFS within an obtained transmission opportunity (TXOP). The default values of TXOP (2.080ms, 2.528ms or 4.096ms, depending on the Access Category) are smaller than the maximum PPDU duration (5.484ms). However, the value TXOP=0 allows the transmission of a single PPDU that may reach the maximum PPDU duration. In our case, we consider TXOP=0. Therefore, every UL OFDMA transmission requires a channel contention. We note that 802.11ax allows unscheduled stations to contend for the channel and for the RA RUs. However, stations with SA RUs should not contend (neither for the channel nor for RA RUs) till they use their scheduled resources. **The third method** is pure UL OFDMA which allows the AP to perform cascading UL OFDMA transmissions separated with SIFS. In this method, there is no contention for the channel but only for the RA RUs. This method is not explicitly defined by 802.11ax but is compliant with the standard since it relies on the centralized control of the medium and allows all HE STAs to transmit either using SA RUs or RA RUs. Moreover, it allows us to evaluate the performance of UL OFDMA when RA RUs are used without the correlation of the full bandwidth transmissions. In the remainder, the 3 transmission methods are referred to as 1) **full bandwidth**, 2) **default UL OFDMA**, and 3) **pure UL OFDMA**, respectively. In addition to the general parameters of Table 3, we use the UL OFDMA parameters of Table 4.

Table 4. UL OFDMA parameters

Parameter	Value
RU size	52-tone
Number of RUs	16 RUs
Number of Spatial Streams per RU	1 stream (no MU-MIMO)
OCWmin	7 (default value)
OCWmax	31 (default value)

Throughout all the simulations, we suppose that the different stations always have data to send and we consider that the A-MPDU size (i.e. the number of MPDUs within an A-MPDU) is limited by the maximum PPDU duration and the maximum A-MPDU size. Then we set the maximum A-MPDU size to 10 MPDUs in all the measurements except otherwise stated. This means that UL OFDMA transmissions consume the maximum PPDU duration since a single 52-tone RU allows the transmission of a maximum of 7 aggregated MPDUs at MCS6. However, a full bandwidth transmission can carry up to 142 MPDUs. So an A-MPDU transmitted on the full bandwidth is limited by the maximum A-MPDU size and contains 10 MPDUs. Moreover, the AP has no data to send but should initiate the UL OFDMA transmissions by sending the TF.

At the beginning, we evaluate the collision rate of UL OFDMA. This rate is expressed as the number of RA RUs experiencing more than one transmission divided by the number of occupied RA RUs (i.e. experiencing at least one transmission). We measure the collision rate of pure UL OFDMA but the results are identical to the collision rate of default UL OFDMA. The obtained results are illustrated in Figure 6. We observe that the collision rate increases significantly with the increasing number of contending stations. For example, in the presence of 30 contending nodes and using 16 RA RUs, the collision rate reaches 56%. This is a very high rate particularly for the large number of RA RUs that are used. Moreover, we notice that the use of 1, 2 or 4 RA RUs provides similar results, and the use of a large number of RA RUs (8 and 16) slightly reduces the collision rates. For example, in the presence of 30 contending stations, the use of 1, 2, 4, 8 and 16 RA RUs incur a collision rate of 73%, 72%, 70%, 65% and 56%, respectively. This limited decrease is explained by the fact that increasing the number of RA RUs allows the OBO counter to expire rapidly and the contending stations to transmit more frequently. Therefore, using more RA RUs does not efficiently reduce the collision rate.

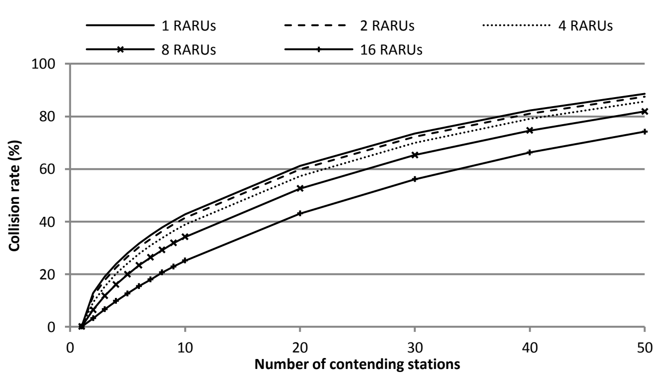

Figure 6. Collision rate in pure UL OFDMA as a function of the number of contending stations

Figures 7 and 8 illustrate the WLAN throughput and the average transmission delays (in ms), respectively, as a function of the number of contending stations. We use pure UL OFDMA to illustrate the performance of UL OFDMA without the effect of the full bandwidth transmissions. In this case, unscheduled stations are only allowed to contend for the RA RUs. We consider different numbers of RA RUs. As indicated in Table 4, we consider 16 RUs within an OFDMA transmission. The purpose of Figures 7 and 8 is to illustrate the effect of the number of RA RUs and the collisions on the throughput and the transmission delays of UL OFDMA. Therefore, we vary the number of contending nodes which contend for RA RUs. Recall that stations with scheduled resources do not contend for RA RUs.

Figure 7 shows that increasing the number of SA RUs improves the throughput of UL OFDMA significantly. This is because SA RUs are always used for transmission. However, the use of RA RUs is subject to contention, and unselected RA RUs remain idle during the entire duration of the UL OFDMA transmission. Moreover, a RA RU that is selected by more than one station will experience a collision. In both cases (i.e. a RA RU remaining idle or experiencing collision), the RA RU is wasted. Only those selected by a single station are effectively used. Therefore, increasing the number of RA RUs increases the number of wasted resource units and affects the performance of OFDMA. For example, the curve “0 RA RUs” achieves the highest throughput since it corresponds to 16 stations transmitting on 16 SA RUs, and no RA RUs are used. Then, the throughput decreases in the case of “4 RA RUs” because 4 RUs among 16 are dedicated for random access. We observe that the curve “16 RA RUs” has the lowest throughput since all the RUs are RA RUs.

In addition, Figure 7 shows that increasing the number of contending stations initially improves the throughput then degrades the performance. In the case of “16 RA RUs”, increasing the number of stations till 20 senders improves the throughput since it allows more RA RUs to be used. But for more than 20 stations, the collision rate becomes very high and degrades the network performance. The same behavior is observed with the other curves, with an increase of the overall throughput. This increase is explained by the use of an increasing number of SA RUs which improve the efficiency.

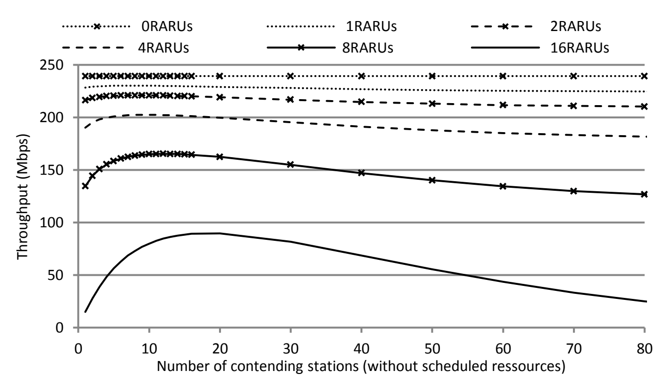

Figure 7. Throughput of pure UL OFDMA as a function of the number of contending stations

In the rest of this paper, the average transmission delay is the average time between taking a new A-MPDU from the transmission queue to the successful delivery of the A-MPDU. Thus, we eliminate the queue delays which depend on the network load and do not reflect the performance of 802.11ax. Figure 8 illustrates the average transmission delays (in ms) as a function of the number of RA RUs and the number of contending stations. We observe that these delays increase rapidly with the increasing number of contending stations. The lowest delays are clearly obtained in the case of 16 RA RUs and start at 5.6ms for one contending station, then increase to 10.4ms and 50ms for 10 and 40 stations, respectively. In the case of a single RA RU, the average delays start at 20.3ms for a single station, then increase to 147ms and 1377ms for 10 and 40 stations, respectively. These delays are very high because the OBO counter decreases in units of OFDMA transmissions instead of SlotTimes. Based on Figures 7 and 8, we notice that increasing the number of RA RUs decreases the throughput but reduces the delays. We note that increasing the number of RA RUs is not necessarily a good solution to reduce the delays because it may increase the buffering delays as a result of reducing the network throughput. We believe that the best method to decrease the delays while improving the throughput is to schedule all active stations in order to reduce the number of contending nodes. Therefore, defining a scheduling algorithm and evaluating its performance is a promising topic that should be studied in a future work.

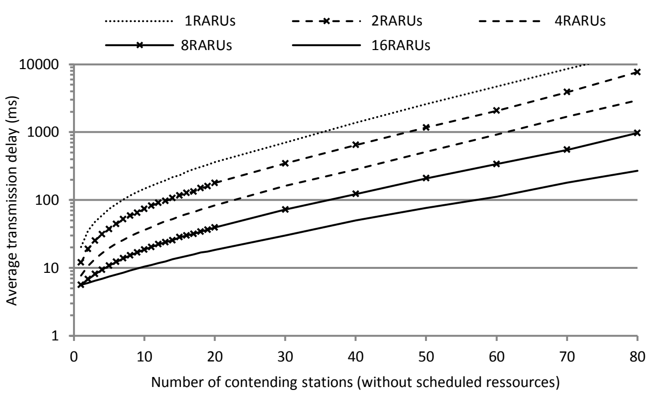

Figure 8. Average transmission delays (in ms) of pure UL OFDMA as a function of the number of contending stations

In Figure 9, we set the number of stations (with and without scheduled resources) to 16 (the same as the number of RUs) and we compare the throughput of full bandwidth, default UL OFDMA, and pure UL OFDMA as a function of the number of RA RUs. In full bandwidth, there is no use of OFDMA, and the 16 stations transmit on the entire channel width after channel contention. Thus, the throughput does not depend on the number of RA RUs. In the case of pure UL OFDMA, we observe that the highest throughput is achieved when there is no RA RU. This is because all the RUs are used for scheduled access. Then the throughput decreases progressively with the increasing number of RA RUs. This shows that the excessive use of RA RUs degrades the network throughput significantly. Finally, we notice that the performance of default UL OFDMA is between full bandwidth and pure UL OFDMA. This is expected, since default UL OFDMA is a mixture of full bandwidth transmissions and UL OFDMA.

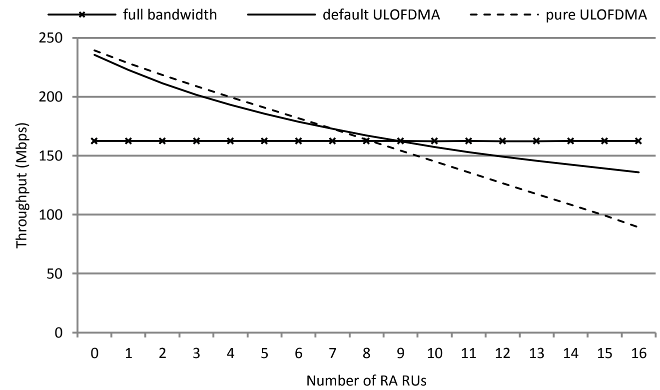

Figure 9. Throughput comparison for different numbers of RA RUs

Figure 10 illustrates the aggregated network throughput using the different transmission methods as a function of the number of contending stations. For the cases of default and pure UL OFDMA, we consider two scenarios; 1) all the RUs are used for scheduled access (i.e. 0 RA RU), and 2) all the RUs are used for random access (i.e. 16 RA RU). We notice that the throughput of full bandwidth decreases progressively when the number of stations increases. This decrease is caused by the increasing collision rate. In the case of UL OFDMA with 0 RA RU, there are 16 scheduled stations in addition to the contending nodes. We note that the scheduled stations transmit on the SA RUs and do not contend for the channel. We observe that UL OFDMA with 0 RA RU achieves the highest throughput when there are no contending stations. This throughput is maintained in the case of pure UL OFDMA since the medium is controlled by the AP and the contending nodes cannot transmit. But in the case of default UL OFDMA, increasing the number of contending stations increases the collisions and decreases the throughput. On the other hand, the throughput of **pure UL OFDMA with 16 RA RUs** increases to a maximum, then decreases with the increasing number of contending stations. Finally, we observe that the throughput of **default UL OFDMA with 16 RA RUs** is between those of full bandwidth and pure UL OFDMA with 16 RA RUs.

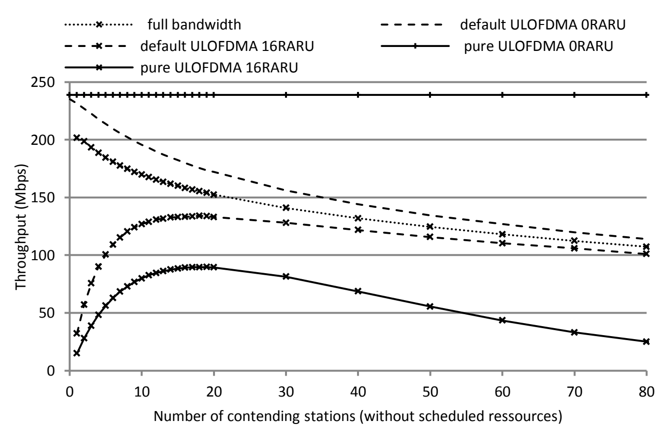

Figure 10. Throughput comparison for different numbers of stations

Figure 11 shows the average delays for different transmission methods. We observe that full bandwidth has the lowest delays while **pure UL OFDMA with 16 RA RUs** has the largest delays under high contention. This is because the backoff time of the EDCA contention decreases in units of SlotTimes. However, the OBO counter decreases in units of OFDMA transmissions which are significantly larger than the SlotTime duration. In the case of **default UL OFDMA**, we notice that the use of 16 RA RUs slightly reduces the delays compared to no RA RUs. This is expected since the stations are allowed to contend for both the channel and the RA RUs and can start their transmissions more rapidly.

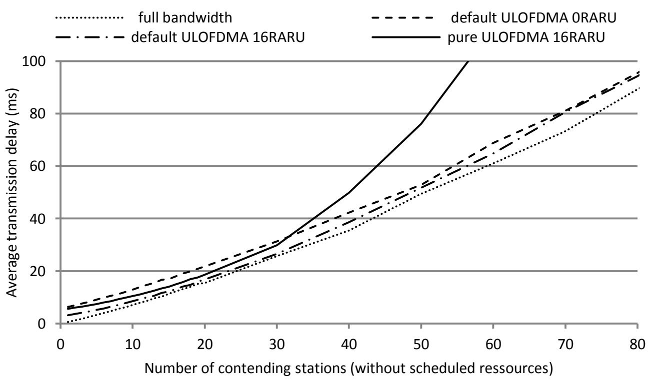

Figure 11. Comparison of the average transmission delays (in ms) as a function of the number of contending stations

Furthermore, we evaluate the network throughput as a function of the A-MPDU size. Therefore, we replace the fixed maximum A-MPDU size of 10 MPDUs with a variable size ranging from 1 to 140 MPDUs. Moreover, we consider the presence of 16 stations and the AP in the WLAN. These stations use scheduled access when using UL OFDMA with 0 RA RU. But they contend to transmit when using full bandwidth or UL OFDMA with 16 RA RUs. The objective of this evaluation is to show the effect of the A-MPDU size on the network efficiency. Figure 12 depicts the obtained results.

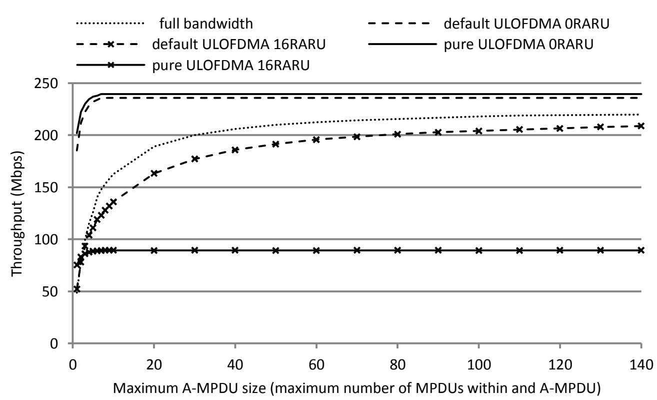

Figure 12. Throughput comparison for different queue sizes

Figure 12 shows that default and pure UL OFDMA with 0 RA RU reach the maximum throughput starting from an A-MPDU size of 7 MPDUs. This is because an RU allows the aggregation of up to 7 MPDUs. However, a transmission at the entire channel width allows the aggregation of up to 142 MPDUs. Thus, the throughput of full bandwidth increases with the increasing number of aggregated frames and reaches the maximum value when the maximum size is 142 MPDUs.

B. Evaluation of DL OFDMA without MIMO

To evaluate the performance of DL OFDMA, we still consider an RU size of 56 tones, and we compare the throughput of DL OFDMA with that of full bandwidth as a function of the maximum A-MPDU size. Therefore, we vary this size from 1 to 140 MPDUs. Since DL OFDMA is used by the AP to transmit the data to the receivers, we consider that only the AP is contending for the channel and that there are no collisions. Figure 13 depicts the obtained results. As previously explained, a 56-tone RU allows a maximum of 7 aggregated MPDUs while a full bandwidth transmission enables up to 142 MPDUs within an A-MPDU. Therefore, DL OFDMA and full bandwidth reach the highest throughput starting from a maximum A-MPDU size of 7 and 142 MPDUs, respectively. However, we notice that for large A-MPDU sizes, full bandwidth outperforms DL OFDMA. This is because the data rate of a single 56-tone RU is 15.9 Mbps and the aggregated data rate of the 16 RUs is $16 \times 15.9 = 254.4$ Mbps. This is lower than the data rate of the full bandwidth which is 324.3 Mbps.

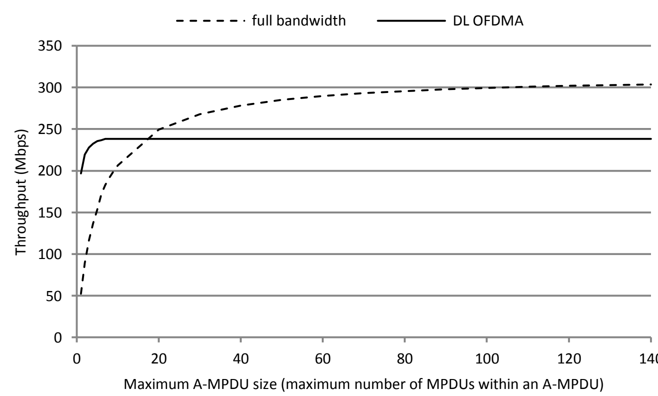

Figure 13. Throughput evaluation of DL OFDMA

C. Evaluation of UL MU-MIMO

As previously mentioned, MU-MIMO transmissions are possible on RUs of size equal to 106 tones or larger. Therefore, we consider these RUs to perform the evaluations, and we still use a channel width of 80 MHz. Figure 14 depicts the throughput of UL MU-MIMO as a function of the maximum A-MPDU size. We consider 2, 4, 6 and 8 spatial streams and we provide a comparison with legacy single stream (SISO) transmissions. In this evaluation, all the transmissions occur on the full bandwidth (i.e. on a 996-tone RU). In the case of UL MU-MIMO, all the transmitting stations use a scheduled access. So only the AP contends for the channel to transmit the Trigger frames and to initiate the uplink transmissions. For SISO, there is a single station that continuously contends for the channel to transmit. Therefore, there are no collisions in both cases. Figure 14 shows that UL MU-MIMO significantly improves the network efficiency and provides a throughput that is proportional to the number of streams.

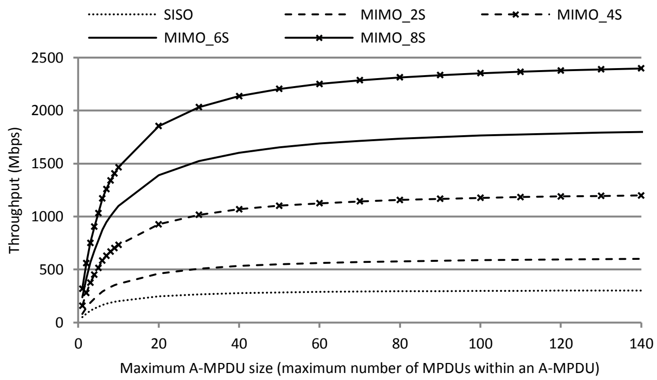

Figure 14. Throughput of UL MU-MIMO using full bandwidth transmissions as a function of the maximum A-MPDU size

Figure 15 shows the effect of the RU size on the performance of UL MU-MIMO with 4 spatial streams and provides the throughput as a function of the maximum A-MPDU size. It also provides a comparison with SISO. These results are obtained in the absence of collisions (i.e. all the stations use a scheduled access) and show the highest achievable throughput. We observe that the use of narrow RUs is more efficient when the A-MPDU size is small. This is because narrow RUs allow more stations to transmit and increase the number of MPDUs per OFDMA transmission. For large numbers of buffered frames, we notice that 106-tone RUs are less efficient than the other RU sizes. This is because the 8×106-tone RUs together use $8\times106 = 848$ tones among the 996 subcarriers available in the 80 MHz channel. Therefore, several subcarriers are wasted. Moreover, it is clear that UL MU-MIMO significantly outperforms SISO transmissions.

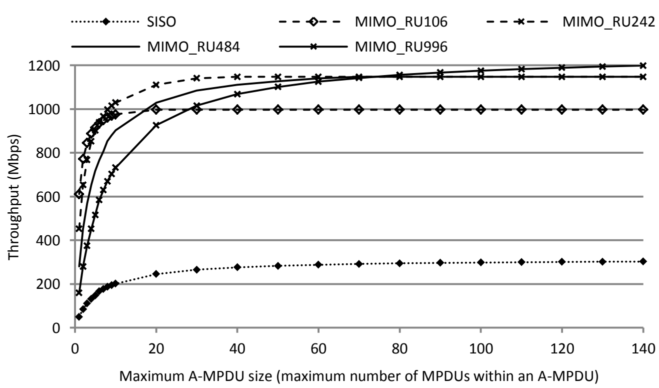

Figure 15. Throughput of UL MU-MIMO with 4 spatial streams as a function of the maximum A-MPDU size

We show the effect of the collisions on the performance of UL MU-MIMO (case of 4 spatial streams and a maximum A-MPDU size of 10 MPDUs) in Figure 16. We observe that the highest throughput is obtained when all the stations use the scheduled access and the AP is the only contending node. In the presence of contending stations, the channel becomes shared proportionally between the stations which perform single stream transmissions and the AP which initiates the UL MU transmissions. Hence, the network throughput decreases from the highest throughput of MIMO to the throughput of SISO transmissions. We deduce that reducing the number of the contending stations is required to take a full advantage of UL MU-MIMO. Thus, stations with frequent transmissions should be scheduled and those with occasional transmissions should request SA RUs to transmit large frames.

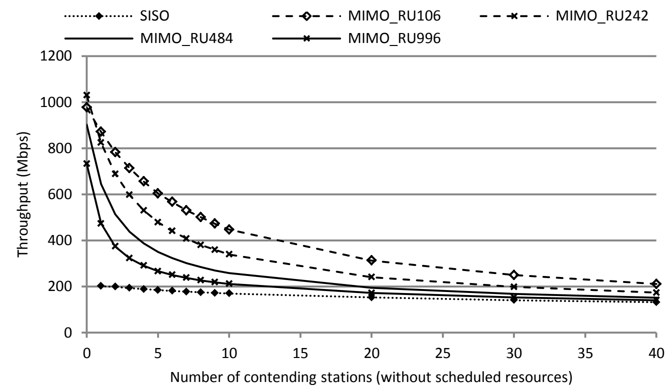

Figure 16. Throughput of UL MU-MIMO with 4 spatial streams as a function of the number of contending stations

D. Evaluation of DL MU-MIMO

To evaluate the performance of 802.11ax DL MU-MIMO, we set the maximum A-MPDU size to 10. We consider that the AP transmits 4 spatial streams per RU and that each station is able to receive a single stream. Moreover, we consider that the AP is the only node that contends for the channel to transmit, so there are no collisions. Figures 17 and 18 illustrate the throughput and the delays, respectively, of UL MU-MIMO as a function of the channel calibration period. We consider that the number of receivers is equal to the number of RUs multiplied by the number of spatial streams, thus, a single sounding sequence is required.

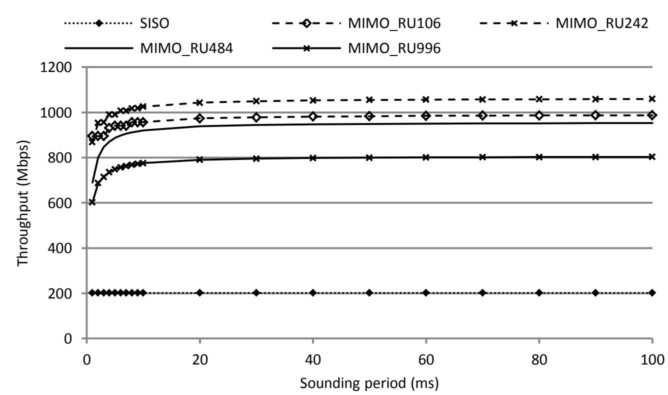

Figure 17. Throughput of DL MU-MIMO with 4 spatial streams as a function of the sounding period

Figure 17 shows that the throughput of SISO is constant since it does not require a channel calibration. We notice that a sounding period of 1ms incurs a throughput decrease of 20% in average. However, periods larger than 5ms ensure a high throughput. We note that in [19], we find that a sounding period of 10ms reduces the performance of DL MU-MIMO of 802.11ac significantly. But in the present study, we show that 802.11ax defines an efficient sounding procedure thanks to the use of UL MU-MIMO to deliver the sounding reports.

Figure 18 illustrates the average delays of DL MU-MIMO as a function of the sounding period. Since the AP is the only sender, we notice that the delays are relatively low (up to 4.3ms). Besides, the DL MU-MIMO delays decrease slightly with the increasing sounding period. This shows that the sounding procedure incurs a limited overhead even at high calibration rates. However, we observe that large RUs experience lower delays than narrow ones. This is because we set the maximum A-MPDU size to 10. Thus, a transmission on large RUs contains less RUs and less A-MPDUs, and requires less time. If we increase the maximum A-MPDU size to the maximum transmission capacity, we will obtain similar delays at the different RU sizes.

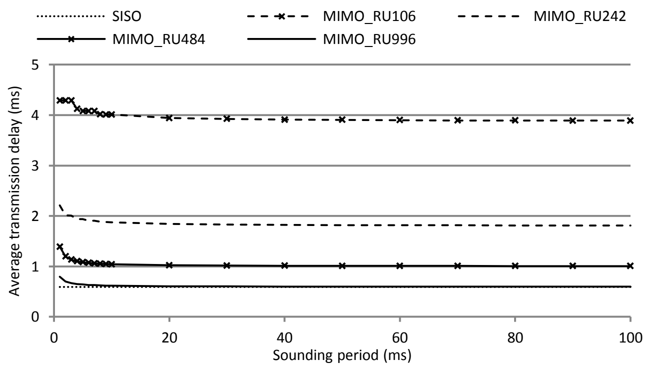

Figure 18. Average transmission delays (in ms) of DL MU-MIMO with 4 spatial streams as a function of the sounding period

Furthermore, we evaluate the scalability of DL MU-MIMO. Thus, we consider a sounding period of 10ms and we vary the number of beamformees. The results are depicted in Figure 19. We note that the number of receivers depend on the RU size and the number of spatial streams. Thus, DL MU-MIMO is used starting from 4 beamformees in the case of 1 × 996-tone RU (i.e. full channel width) and from 32 beamformees in the case of 8 × 106-tone RUs. We notice that the throughput of DL MU-MIMO decreases with the increasing number of receivers. This is because the sounding procedure requires an increasing number of sequences to gather the different reports. Therefore, the sounding overhead increases and reduces the network throughput. However, DL MU-MIMO has a high scalability and outperforms SISO significantly even in the presence of 200 receivers.

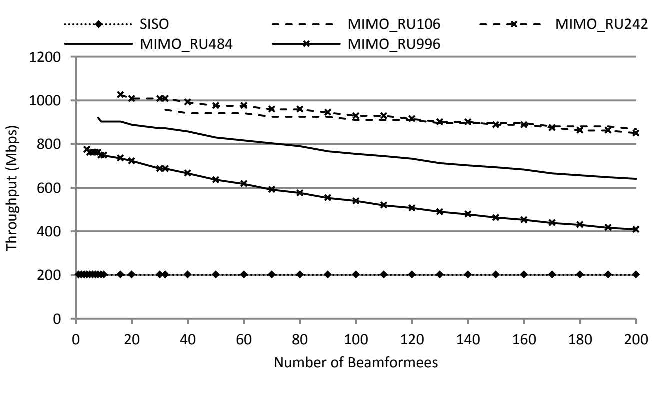

Figure 19. Throughput of DL MU-MIMO with 4 spatial streams and 10ms sounding period as a function of the number of beamformees

We evaluate the throughput of DL MU-MIMO as a function of the maximum A-MPDU size and we depict the results in Figure 20. It is clear that the network efficiency increases with the increasing length of the A-MPDU. We observe that the use of narrow RUs is more efficient when there are few buffered MPDUs per receiver. This is because the AP serves multiple stations simultaneously and aggregates their A-MPDUs within a single DL MU-MIMO transmission. This allows narrow RUs to transmit more MPDUs and to be more efficient than wide RUs.

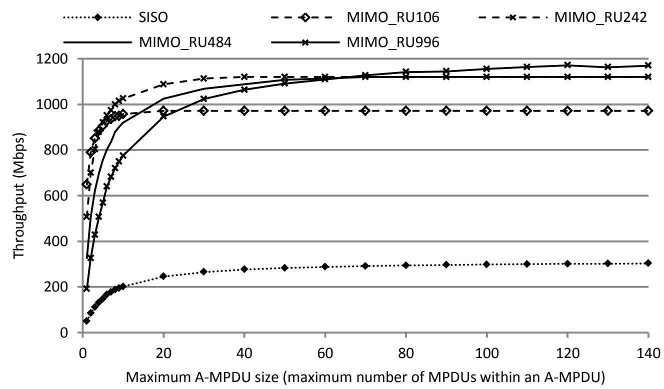

Figure 20. Throughput of DL MU-MIMO with 4 spatial streams and 10ms sounding period for different queue sizes

V. Discussion

Our measurements confirm many thoughts about the performance of UL OFDMA. **First**, we show that increasing the number of RA RUs does not effectively decrease the collision rate. Therefore, the efficient solution to reduce the collisions is to increase the values of OCWmin and OCWmax. This is possible using management frames that allow the AP to adjust the contention parameters of the different contending stations. **Second**, during contention, the effect of an unused RA RU is similar to the effect of a collision and implies the waste of the RU. This is unlike EDCA where the Backoff timer decreases with units of SlotTime, and the wasted time during EDCA contention is only few SlotTimes. **Third**, increasing the number of SA RUs improves the throughput of UL OFDMA while increasing the number of RA RUs significantly affects the performance. However, if the AP uses UL OFDMA in a centralized mode (i.e. pure UL OFDMA) for a long duration, the only way for the contending stations to transmit is using RA RUs. In this case, it is necessary to provide some RA RUs to allow these stations to send their data and to request scheduled resources. But if UL OFDMA is used after channel contention, the obtained results show that RA RUs are not efficient and should not be allocated. **Forth**, UL OFDMA with EDCA does not allow the effective use of UL OFDMA when the number of contending nodes is large. This is because the AP should contend for the channel to gain a TXOP during which it can use UL OFDMA. So it should fairly share the medium with all the contending nodes. **Fifth**, the main advantage of UL OFDMA is to allow multiple stations with few buffered frames to transmit over different narrow RUs in order to reduce the effect of the transmission overhead and to maximize the network efficiency. In this case, UL OFDMA with SA RUs is able to outperform full bandwidth transmissions. But if the senders have a large number of buffered frames, the use of frame aggregation without OFDMA is enough to improve the network efficiency.

Moreover, our results show that UL MU-MIMO can improve the uplink throughput significantly. However, we show that increasing the number of contending stations reduces significantly the advantage of this technique. As a solution, it is necessary that most stations use the scheduled access to transmit their data. Besides, stations without scheduled resources should not send large frames after EDCA contention. Instead, they should send requests for RUs.

VI. Conclusion

In this paper we introduce the major novelties of 802.11ax and we evaluate the performance of OFDMA and MU-MIMO. We show that UL OFDMA improves the efficiency when multiple stations regularly transmit few amounts of data. Besides, increasing the number of RA RUs does not effectively reduce the collision rate but decreases the throughput significantly. We show that the use of UL OFDMA with an important number of RA RUs is less efficient than legacy full bandwidth transmissions. Furthermore, we show that UL MU-MIMO efficiently improves the uplink throughput, but is dependent on the number of the contending stations. We also find that DL MU-MIMO has a high scalability and performance. We conclude that the use of scheduled resources is necessary to maximize the throughput and to take a full advantage of UL OFDMA and UL MU-MIMO. Therefore, we believe that proposing and evaluating scheduling algorithms is a promising future work to improve the performance of 802.11ax WLANs.

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