Scheduling strategies and throughput optimization for the Downlink for IEEE 802.11ax and IEEE 802.11ac based networks

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Abstract

The new IEEE 802.11 standard, IEEE 802.11ax, has the challenging goal of serving more users compared to its predecessor IEEE 802.11ac, enabling consistent and reliable streams of data (average throughput) per station. In this paper we explore some of the IEEE 802.11ax new mechanisms and compare between the upper bounds on the throughputs of the Downlink unidirectional UDP Multi Users (MU) triadic based on Multiple-Input-Multiple-Output (MU-MIMO) and Orthogonal Frequency Division Multiple Access (OFDMA) transmission multiplexing format in IEEE 802.11ax vs. IEEE 802.11ac in the Single User (SU) and MU modes for 1, 4, 8, 16, 32 and 64 stations scenario in reliable and unreliable channels. The comparison is made as a function of the Modulation and Coding Schemes (MCS) in use. In IEEE 802.11ax we consider two flavors of acknowledgment operation settings where the maximum acknowledgment windows are 64 or 256 respectively. In SU scenario IEEE 802.11ax upper bounds on the throughputs outperform IEEE 802.11ac by about 52% and 74% in reliable and unreliable channels respectively. In MU-MIMO scenario IEEE 802.11ax upper bounds on the throughputs outperform IEEE 802.11ac by about 59% and 103% in reliable and unreliable channels respectively. Also, as the number of stations increases, the advantage of IEEE 802.11ax in terms of the access delay also increases.

Keywords: IEEE 802.11ax; IEEE 802.11ac; Throughput; Single User; MU-MIMO; OFDMA;

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1 Introduction

The latest IEEE 802.11 Standard (WiFi) [1], created and maintained by the IEEE LAN/MAN Standards Committee (IEEE 802.11), is currently the most effective solution within the range of Wireless Local Area Networks (WLAN). Since its first release in 1997 the standard provides the basis for Wireless network products using the WiFi brand, and has since been improved upon in many ways. One of the main goals of these improvements is to increase the throughput achieved by users and to improve the standard’s Quality-of-Service (QoS) capabilities. To fulfill the promise of increasing IEEE 802.11 performance and QoS capabilities, a new amendment, IEEE 802.11ax (also known as High Efficiency (HE)) was recently introduced [2]. IEEE 802.11ax is considered to be the sixth generation of a WLAN in the IEEE 802.11 set of types of WLANs and is a successor to IEEE 802.11ac [3, 4]. The scope of the IEEE 802.11ax amendment is to define modifications for both the 802.11 PHY and MAC layers that enable at least four-fold improvement in the average throughput per station in densely deployed networks [5–8]. Currently IEEE 802.11ax project is in a very early stage of development, due to be publicly released in 2019.

In order to achieve its goals, one of the main challenges of IEEE 802.11ax is to enable simultaneous transmissions by several stations and to enable Quality-of-Service. Most of the research papers on IEEE 802.11ax thus far deal with these challenges and examine different access methods to enable efficient multi-user access to random sets of stations. For example, in [9] the authors deal with the introduction of Orthogonal Frequency Division Multiple Access (OFDMA) into IEEE 802.11ax to enable multi user access. They introduce an OFDMA based multiple access protocol, denoted Orthogonal MAC for 802.11ax (OMAX), to solve synchronization problems and reduce overhead associated with using OFDMA. In [10] the authors suggest an access protocol over the UL of an IEEE 802.11ax WLAN based on Multi User Multiple-Input-Multiple-Output (MU-MIMO) and OFDMA PHY. In [11] the authors suggest a centralized medium access protocol for the UL of IEEE 802.11ax in order to efficiently use the transmission resources. In this protocol, stations transmit requests for frequency sub-carriers, denoted Resource Units (RU), to the AP over the UL. The AP allocates RUs to the stations which use them later for data transmissions over the UL. In [12] a new method to use OFDMA over the UL is suggested, where MAC Protocol Data Units (MPDU) from the stations are of different lengths. In [13–16] a new version of the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol, denoted Enhanced
CSMA/CA (CSMA/ECA) is suggested, which is suitable for IEEE 802.11ax. A deterministic backoff is used after a successful transmission, and the backoff stage is not reset after service. The backoff stage is reset only when a station does not have any more MPDUs to transmit. CSMA/ECA enables a more efficient use of the channel and enhanced fairness. In [17] the authors assume a network with legacy and IEEE 802.11ax stations and examine fairness issues between the two sets of the stations.

In this paper we do not suggest any new air access mechanisms as the papers mentioned above do, but assume that the AP is communicating in a regular fashion with a fixed set of stations. The AP and the stations transmit in a Round Robin fashion, without collisions. We explore some of the Downlink (DL) and UL IEEE 802.11ax new mechanisms given that the AP knows with which stations it communicates, and we compare between the upper bounds on the unidirectional UDP throughputs of IEEE 802.11ax and IEEE 802.11ac in Single User (SU) and Multi User (MU) modes for 1, 4, 8, 16, 32 and 64 stations scenarios in reliable and unreliable channels. This is one of the aspects to compare between new amendments of the IEEE 802.11 standard [18]. We note that we do not assume that all the time over the channel is devoted to UDP DL traffic. It is possible that time is partitioned into intervals of UDP DL traffic, UDP UL traffic, TCP traffic etc. In this paper we investigate transmissions in the time interval devoted to UDP DL traffic.

In this paper we are interested in finding the upper bounds on the throughputs that can be achieved by IEEE 802.11ax and IEEE 802.11ac and in comparing between the two. Therefore, we assume the traffic saturation model where all stations always have data to transmit. Second, we neutralize any aspects of the PHY layer as the relation between the Bit Error Rates (BER) and the Modulation/Coding Scheme (MCS) in use, the number of Spatial Streams (SS) in use, the channel correlation when using MU-MIMO, i.e. we assume that there are independent MU-MIMO channels for each station, the use in sounding protocol etc.

The SU scenario implements sequential transmissions in which a single wireless station sends and receives data at every cycle one at a time, once it or the AP has gained access to the medium. The MU scenarios allow for simultaneous transmission and reception to and from multiple stations both in the DL and the UL directions. UL MU refers to simultaneous transmissions, i.e. at the same time, from several stations to the AP over the UL. The existing IEEE 802.11ac standard does not enable UL MU while IEEE 802.11ax enables up to 74 stations to transmit simultaneously over the UL.
The MU transmissions over the DL (DATA) and the UL (Acks) are done by MIMO and OFDMA. The IEEE 802.11ax standard expends MIMO transmissions multiplexing format and specifies new ways of multiplexing additional users using OFDMA. The new IEEE 802.11ax OFDMA is backward compatible and enables scheduling different users in different sub-carriers of the same channel. In the IEEE 802.11ac the total channel bandwidth (20 MHz, 40 MHz, 80 MHz etc.) contains multiple OFDM sub-carriers. However, in IEEE 802.11ax OFDMA, different subsets of sub-carriers in the channel bandwidth can be used by different frame transmissions at the same time. Sub-carriers can be allocated for transmissions in Resource Units (RU) as small as 2 MHz.

Given the above new structure of OFDMA in IEEE 802.11ax, the main contributions of this paper are as follows: First we suggest several scheduling strategies by which the AP can communicate with a set of stations over the DL. Second, we evaluate upper bounds on the throughput and the access delay performance of the different scheduling strategies given the different PHY rates of the RUs in the various scheduling strategies and the different number of RUs in use, which influences the PHY preamble’s length. This paper deals with the DL and a companion paper deals with the UL [19]. The difference between the two papers is in the direction in which data is transmitted: in the current paper the AP transmits data to the stations, while in [19] the stations transmit data to the AP. As an outcome, the current paper suggests scheduling strategies for the transmission of data on the DL, while [19] suggests scheduling strategies for the transmission of data on the UL. The strategies in the two papers are different, using different features of the IEEE 802.11ax amendment, e.g. different control frames.

The remainder of the paper is organized as follows: In Section 2 we describe the new mechanisms of IEEE 802.11ax relevant to this paper. In Section 3 we describe the transmission scenario by which we compare IEEE 802.11ax and IEEE 802.11ac in the SU and MU modes. We assume that the reader is familiar with the basics of the PHY and MAC layers of IEEE 802.11 described in previous papers, e.g. [20]. In Section 4 we analytically compute the IEEE 802.11ax and IEEE 802.11ac throughputs. In Section 5 we make some approximations on the amount of frame aggregation used in our transmission model. In Section 6 we present the throughput of the various protocols and compare them. Section 7 summarizes the paper. Lastly, we denote IEEE 802.11ac and IEEE 802.11ax by 11ac and 11ax respectively.
2 The new features in IEEE 802.11ax

IEEE 802.11ax focuses on implementing mechanisms to efficiently serve more users, enabling consistent and reliable streams of data (average throughput per user) in the presence of multiple users. Therefore, there are several new mechanisms in 11ax compared to 11ac both in the PHY and MAC layers. At the PHY layer, 11ax enables larger OFDM FFT sizes—4X larger—therefore every OFDM symbol is extended from 3.2\(\mu\)s in 11ac to 12.8\(\mu\)s in 11ax. By narrower subcarrier spacing (4X closer) the protocol efficiency is increased, as the same Guard Interval (GI) is used in both 11ax and 11ac.

To increase the average throughput per user in high-density scenarios, 11ax expands the 11ac Modulation Coding Schemes (MCSs) and adds MCS10 (1024 QAM) and MCS 11 (1024 QAM 5/6), applicable for transmission with bandwidth larger than 20 MHz.

In this paper we focus on optimizing the IEEE 802.11 two-level aggregation scheme working point first introduced in IEEE 802.11n [1, 4], in which several MPDUs can be aggregated to be transmitted in a single PHY Service Data Unit (PSDU). Such aggregated PSDU is denoted Aggregate MAC Protocol Data Unit (A-MPDU) frame. In two-level aggregation every MPDU can contain several MAC Service Data Units (MSDUs). MPDUs are separated by an MPDU Delimiter field of 4 bytes and each MPDU contains MAC Header and Frame Control Sequence (FCS) fields. MSDUs within an MPDU are separated by a SubHeader field of 14 bytes. Every MSDU is rounded to an integral multiple of 4 bytes together with the SubHeader field. Every MPDU is also rounded to an integral multiple of 4 bytes.

In 11ax and 11ac the size of an MPDU is limited to 11454 bytes. In 11ac an A-MPDU is limited to 1,048,575 bytes and this limit is extended to 4,194,304 bytes in 11ax. In both 11ac and 11ax the transmission time of the PPDU (PSDU and its preamble) is limited to 5.484\(ms\) (5484\(\mu\)s) due to the L-SIG (one of the legacy preamble’s fields) duration limit [1]. The A-MPDU frame structure in two-level aggregation is shown in Figure 11ax also enables extension of the acknowledgment mechanism by using a 256 maximum acknowledgment window vs. maximum window of 64 in 11ac. In this paper we also assume that all MPDUs transmitted in an A-MPDU frame are from the same Traffic Stream (TS). In this case up to 256 MPDUs are allowed in an A-MPDU frame of 11ax, while in 11ac up to only 64 MPDUs are allowed.

Finally, in 11ac it is possible to transmit simultaneously up to 4 stations only over the DL using MU. In 11ax this number is extended to 74. Also, in 11ax it is possible to transmit by
MU-MIMO or OFDMA both over DL and UL, while in 11ac only UL SU mode is supported.

3 Model

3.1 Transmission patterns

As mentioned, one of the main goals of 11ax is to enable larger throughputs in the network when transmitting to several stations. In 11ax it is possible to transmit/receive simultaneously to/from 74 stations over the DL/UL while in 11ac the number of stations is limited to 4, and only over the DL. In this paper we compare the throughputs received in 11ac and 11ax when transmitting to \( S \) stations, \( S = 1, 4, 8, 16, 32 \) and 64 stations. Transmitting to one station only is done by using the SU mode of transmissions. The AP transmits to one station and receives a Block Ack (BAck) frame in return. In this mode the advantage of 11ax over 11ac is in its more efficient PHY layer and its new MCSs. The unscheduled SU traffic pattern in this case is shown in Figure 2(A) for both 11ac and 11ax.

Transmitting to several stations can be done in two ways. The first is by SU mode. When transmitting to \( S \) stations, the transmission cycle in Figure 2(A) repeats itself \( S \)
Figure 2: Transmissions from the AP to stations in Single User and Multi User modes in IEEE 802.11ac and in IEEE 802.11ax.
Figure 3: The Block Ack (BAck), the Block Ack request (BAR) and the Trigger Frame (TF) frames’ format.

Another alternative is to use MU mode in which the AP transmits simultaneously to several stations in the same transmission opportunity over the channel. In Figure 2(B) we show this possibility for 11ac where the AP transmits to 4 stations simultaneously. This is the maximum number of stations to which the AP can transmit simultaneously in 11ac. In UL the stations transmit 4 sequential BAck frames using the Single User (SU) legacy mode. While the first BAck is transmitted SIFS immediately after receiving the transmission from the AP, the last 3 are solicited by BAck Request (BAR) frames from the AP. Each BAR is transmitted SIFS after the previous BAck. The formats of the BAck and BAR frames are shown in Figures 3(A), 3(B) and 3(C) respectively.

In 11ax, Figure 2(C), the AP transmits over the DL to $S$ stations simultaneously using MU-MIMO or OFDMA or combination, as in 11ac, and the stations transmit their BAck frames simultaneously in the UL using MU-MIMO or OFDMA or a combination. This is possible only in 11ax. The AP allocates the UL Resource Units (RU), i.e. subchannels in the case of OFDMA and Frequency/Spatial Streams in the case of MU-MIMO, for the
transmissions of the stations, by one of two possible UL RU allocation signaling methods: In the first method the AP transmits a unicast Trigger Frame (TF) to every station that contains the UL RU allocation. This frame is a control MAC Protocol Data Unit (MPDU) that is added to the other Data MPDUs which the AP transmits to a station in an A-MPDU frame. The format of the TF frame is shown in Figure 3(D). For a unicast TF the TF information field contains two sub-fields: one is a common part of 8 bytes and the second is a user element of 4 bytes. The other alternative method is to add an HE Control Element to every Data MPDU in the A-MPDU frame that is transmitted to every station. In the following throughput computations we optimize the amount of overhead used due to the above methods by computing the minimum overhead needed as a function of the number of data MPDUs in the A-MPDU frame.

Finally, we assume that the AP and the stations do not contend for the channel and so there are no collisions. The cycles in Figure 2(A), (B) and (C) repeat one after the other. This is possible by e.g. configuring the stations in a way that prevents collisions. For example, the stations are configured to choose their BackOff intervals from very large contention interval, other than the defaults ones [1]. Thus, the AP always wins the channel without collisions.

3.2 DL service transmissions’ scheduling strategies

There are several DL service scheduling strategies to transmit to a group of stations, and we compare between them. We now specify these scheduling strategies for every number $S$ of stations, $S = 1, 4, 8, 16, 32, 64$. By $x \cdot SU_{AX}(1)$ and $x \cdot SU_{AC}(1)$ we denote a transmission to $n$ stations in 11ax and 11ac respectively, using the transmission pattern in Figure 2(A) $x$ times in sequence, every transmission is to a different station. By $x \cdot MU_{AC}(4)$ we denote transmissions to $4x$ stations using the traffic pattern of Figure 2(B) $x$ times in sequence, every transmission is to a different group of 4 stations. By $m \cdot MU_{AX}(n)$ we denote transmissions to $m \cdot n$ stations using the traffic pattern of Figure 2(C) $m$ times in sequence, each transmission to a different group of $n$ stations. In this paper $n = 4, 8, 16, 32$ and 64.

The DL service scheduling strategies are as follows:

- $S = 1$:
  - 11ac : $1 \cdot SU_{AC}(1)$
  - 11ax : $1 \cdot SU_{AX}(1)$
• \( S = 4: \)
  \[ 11ac : 4 \cdot SU_{AC}(1), 1 \cdot MU_{AC}(4). \]
  \[ 11ax : 4 \cdot SU_{AX}(1), 1 \cdot MU_{AX}(4). \]

• \( S = 8: \)
  \[ 11ac : 8 \cdot SU_{AC}(1), 2 \cdot MU_{AC}(4). \]
  \[ 11ax : 8 \cdot SU_{AX}(1), 2 \cdot MU_{AX}(4), 1 \cdot MU_{AX}(8). \]

• \( S = 16: \)
  \[ 11ac : 16 \cdot SU_{AC}(1), 4 \cdot MU_{AC}(4). \]
  \[ 11ax : 16 \cdot SU_{AX}(1), 4 \cdot MU_{AX}(4), 2 \cdot MU_{AX}(8), 1 \cdot MU_{AX}(16). \]

• \( S = 32: \)
  \[ 11ac : 32 \cdot SU_{AC}(1), 8 \cdot MU_{AC}(4). \]
  \[ 11ax : 32 \cdot SU_{AX}(1), 8 \cdot MU_{AX}(4), 4 \cdot MU_{AX}(8), 2 \cdot MU_{AX}(16), 1 \cdot MU_{AX}(32). \]

• \( S = 64: \)
  \[ 11ac : 64 \cdot SU_{AC}(1), 16 \cdot MU_{AC}(4). \]
  \[ 11ax : 64 \cdot SU_{AX}(1), 16 \cdot MU_{AX}(4), 8 \cdot MU_{AX}(8), 4 \cdot MU_{AX}(16), 2 \cdot MU_{AX}(32), 1 \cdot MU_{AX}(64). \]

### 3.3 Channel assignment

We assume the 5GHz band, a 160MHz channel, the AP has 4 antennas and every station has 1 antenna. In SU(1) and in the DL direction the entire channel is devoted to transmissions of the AP in both 11ac and 11ax. In UL SU the BAck frame is transmitted by using the legacy PHY basic rates. Therefore the UL Ack is sent at legacy mode where the station is transmitting in a 20 MHz primary channel and its transmission is duplicated 8 times in order to occupy the entire 160 MHz. The UL PHY rate is set to the largest possible PHY rate in the set that is smaller or equal to the DL Data rate.

When using MU mode the 160MHz channel is divided into \( \frac{S}{4} \) channels of \( \frac{160 \cdot 4}{S} \) MHz each, \( S = 4, 8, 16, 32, 64 \). The AP transmits to 4 stations in every such channel, using 4 Spatial Streams. For example, for \( S = 64 \) there are 16 channels of 10MHz each; in each of them
the AP transmits to 4 stations. When $S = 4$ only MU-MIMO is used. For $S > 4$ MU-MIMO+OFDMA is used. In the case of $MU_{AC}$, Figure 2(B), it is again possible to transmit the Back frames in the UL direction only in the legacy mode, as in SU(1), and the UL PHY rate is set again to the largest possible PHY basic rate in the set that is smaller or equal to the DL Data rate. Again, the primary 20 MHz channel is duplicated 8 times in all secondary channels to occupy the entire 160 MHz channel.

For the UL Ack transmission in 11ax, Figure 2(C), we assume either MU-MIMO or OFDMA. In the case of UL MU-MIMO the transmissions are symmetrical to those in DL. In the case of UL OFDMA the 160 MHz channel is divided into $S$ channels of $\frac{160}{S}$ MHz each, except in the case of $S = 64$ where each station is allocated a channel of 2 MHz.

### 3.4 PPDU formats

In Figure 4 we show the various PPDU s’ formats in use in the various transmission patterns of Figure 2.

In Figures 4(A) and 4(B) we show the PPDU formats used in the DL SU of 11ac and 11ax respectively, Figure 2(A). In the PPDU format of 11ac are the VHT-LTF fields, the number of which equals the number of SS in use and each is $4\mu s$. In the 11ax PPDU format there are the HE-LTF fields, the number of which equals again to the number of SS in use. In this paper we assume that each such field is composed of 2X LTF and therefore of duration $7.2\mu s$. Notice that in SU mode and when using the same number $X$ of SS, the preamble in 11ax is longer than that in 11ac by $4\mu s + X \cdot (7.2 - 4)\mu s = 4\mu s + X \cdot 3.2\mu s$.

Notice also that the PSDU frame in 11ax contains a Packet Extension (PE) field. This field is mainly used in Multi-User (MU) mode and we assume it is not present in SU, i.e. it is of length $0\mu s$.

In Figures 4(A) and 4(B) we also show the legacy preamble, used in both 11ac and 11ax in the UL SU.

The PPDU format in Figure 4(A) is also used in the DL MU-MIMO in 11ac. In Figure 4(C) we show the PPDU format used in 11ax in DL MU. In this frame format there are again the HE-LTF fields, the number of which equals the number of SS. As in the SU mode we assume each such field is composed of 2X LTF and therefore is of duration $7.2\mu s$. The MCS used in the HE-SIG-B field is the minimum between MCS4 and the one used for the data transmissions. The length of this field is also a function of the number of
stations to which the AP transmits simultaneously. Therefore, in the case of e.g. 4 stations the HE-SIG-B field duration is 8\(\mu s\) for MCS0 and MCS1, and is 4\(\mu s\) for MCS2-4 following section 29.3.9.8 in [2]. For MCS5-MCS11 it is 4\(\mu s\) as for MCS4.

In Figure 4(D) we show the PPDU format used in UL MU in 11ax which is used in the traffic pattern of Figure 2(C). Notice again that in 11ax the PSDU is followed by a Packet Extension (PE) field which is used to enable the receiver of the PSDU additional time to move from a reception mode to a transmission mode. The largest duration of this field is 16\(\mu s\) which we assume in this paper.

### 3.5 Parameters’ values

In Table 1 we show the PHY rates and the preambles used in 11ac and 11ax in SU mode and in the various MCSs. In Table 2 we show the PHY rates and the preambles used in 11ac
Table 1: The PHY rates and the preambles in the DL and UL of IEEE 802.11ac and IEEE 802.11ax in the case of a 160 MHz channel, 1 Spatial Stream and legacy UL channel. Single User mode.

| MCS | SU DL transmission rate in 11ax | SU DL transmission rate in 11ax | UL BAck transmission rate in 11ax | UL BAck transmission rate in 11ax |
|-----|--------------------------------|--------------------------------|---------------------------------|---------------------------------|
|     | PHY Rate (Mbps) | Preamble (µs) | PHY Rate (Mbps) | Preamble (µs) | PHY Rate (Mbps) | Preamble (µs) | PHY rate (Mbps) | Preamble (µs) |
| 1 station IEEE 802 11 ax | 1 station IEEE 802 11 ax | 1 | 1 | 1 | 1 | 1 | 1 |
| 0   | 72.1             | 43.2             | 58.5             | 36.0             | 48.0             | 20.0             | 48.0             | 20.0             |
| 1   | 144.1            | 43.2             | 117.0            | 36.0             | 48.0             | 20.0             | 48.0             | 20.0             |
| 2   | 216.2            | 43.2             | 175.5            | 36.0             | 48.0             | 20.0             | 48.0             | 20.0             |
| 3   | 288.2            | 43.2             | 234.0            | 36.0             | 48.0             | 20.0             | 48.0             | 20.0             |
| 4   | 432.4            | 43.2             | 351.0            | 36.0             | 48.0             | 20.0             | 48.0             | 20.0             |
| 5   | 576.5            | 43.2             | 468.0            | 36.0             | 48.0             | 20.0             | 48.0             | 20.0             |
| 6   | 648.5            | 43.2             | 526.5            | 36.0             | 48.0             | 20.0             | 48.0             | 20.0             |
| 7   | 720.6            | 43.2             | 585.0            | 36.0             | 48.0             | 20.0             | 48.0             | 20.0             |
| 8   | 864.7            | 43.2             | 702.0            | 36.0             | 48.0             | 20.0             | 48.0             | 20.0             |
| 9   | 960.7            | 43.2             | 780.0            | 36.0             | 48.0             | 20.0             | 48.0             | 20.0             |
| 10  | 1080.9           | 43.2             | N/A              | N/A              | 48.0             | 20.0             | N/A              | N/A              |
| 11  | 1201.0           | 43.2             | N/A              | N/A              | 48.0             | 20.0             | N/A              | N/A              |

and 11ax in MU mode, in the various MCSs and in all cases of the number of stations $S$, i.e. $S = 4, 8, 16, 32$ and 64. The values in both tables are taken from [2].

Concerning non-legacy transmissions, we assume a GI of $0.8\mu s$ for transmissions over the DL. For transmissions over the UL we assume a GI of $1.6\mu s$. Therefore, the OFDM symbols are of $13.6\mu s$ and $14.4\mu s$ over the DL and the UL respectively. Regarding legacy transmissions, the OFDM symbols are $4\mu s$.

We assume the Best Effort Access Category in which $AIFS = 43\mu s$, $SIFS = 16\mu s$ and $CW_{min} = 16$ for the transmissions of the AP. The BackOff interval is a random number chosen uniformly from the range $[0, ..., CW_{min} - 1]$. Since we consider a very ‘large’ number of transmissions from the AP and we assume that there are no collisions, we take the BackOff average value of $\left\lceil \frac{CW_{min} - 1}{2} \right\rceil$ and the average BackOff interval is $\left\lceil \frac{CW_{min} - 1}{2} \right\rceil \cdot SlotTime$ which equals $67.5\mu s$ for a $SlotTime = 9\mu s$. We also assume that the MAC Header is of 28 bytes and the FCS is of 4 bytes. We use the above values for the various parameters since these are the default ones suggested by the WiFi Alliance [21].

Finally, we consider several channel conditions which are expressed by different values of the Bit Error Rate (BER) which is the probability that a bit arrives corrupted at the destination. We assume a model where these probabilities are bitwise independent [22].
Table 2: The PHY rates and the preambles in the DL and UL of IEEE 802.11ac and IEEE 802.11ax in the case of a 160 MHz channel, 4 Spatial Streams and legacy UL channel in IEEE 802.11ac. Multi User mode.

|        | 1 DL MU data | 2 UL MU-MIMO B Ack | 3 UL OFDMA B Ack | 4 DL MU-MIMO data | 5 UL B Ack |
|--------|--------------|--------------------|------------------|-------------------|------------|
|        | transmission rate in 11ax | PHY Rate (MBps) | Preamble (μs) | GI= 0.8μs | PHY Rate (MBps) | Preamble (μs) | GI= 1.6μs | PHY Rate (MBps) | Preamble (μs) | GI= 0.8μs | PHY Rate (MBps) | Preamble (μs) |
| 0      | 72.1         | 72.8               | 68.1             | 64.8             | 16.3        | 64.8             | 58.5          | 48.0             | 48.0             | 20.0          | 58.5          | 48.0           | 48.0          | 20.0           |
| 1      | 144.1        | 72.8               | 136.1            | 64.8             | 32.5        | 64.8             | 117.0         | 48.0             | 48.0             | 20.0          | 117.0         | 48.0           | 48.0          | 20.0           |
| 2      | 216.2        | 68.8               | 204.2            | 64.8             | 48.8        | 64.8             | 175.5         | 48.0             | 48.0             | 20.0          | 175.5         | 48.0           | 48.0          | 20.0           |
| 3      | 288.2        | 68.8               | 272.2            | 64.8             | 65.0        | 64.8             | 234.0         | 48.0             | 48.0             | 20.0          | 234.0         | 48.0           | 48.0          | 20.0           |
| 4      | 324.2        | 68.8               | 408.3            | 64.8             | 97.5        | 64.8             | 351.0         | 48.0             | 48.0             | 20.0          | 351.0         | 48.0           | 48.0          | 20.0           |
| 5      | 576.5        | 68.8               | 544.4            | 64.8             | 130.0       | 64.8             | 468.0         | 48.0             | 48.0             | 20.0          | 468.0         | 48.0           | 48.0          | 20.0           |
| 6      | 648.5        | 68.8               | 612.5            | 64.8             | 146.3       | 64.8             | 526.5         | 48.0             | 48.0             | 20.0          | 526.5         | 48.0           | 48.0          | 20.0           |
| 7      | 720.6        | 68.8               | 680.6            | 64.8             | 162.5       | 64.8             | 585.0         | 48.0             | 48.0             | 20.0          | 585.0         | 48.0           | 48.0          | 20.0           |
| 8      | 864.7        | 68.8               | 816.7            | 64.8             | 195.0       | 64.8             | 702.0         | 48.0             | 48.0             | 20.0          | 702.0         | 48.0           | 48.0          | 20.0           |
| 9      | 960.7        | 68.8               | 907.4            | 64.8             | 216.7       | 64.8             | 780.0         | 48.0             | 48.0             | 20.0          | 780.0         | 48.0           | 48.0          | 20.0           |
| 10     | 1080.9       | 68.8               | 1020.8           | 64.8             | 243.8       | 64.8             | N/A           | N/A              | N/A              | 20.0          | N/A           | N/A            | N/A          | 20.0           |
| 11     | 1201.0       | 68.8               | 1134.2           | 64.8             | 270.8       | 64.8             | N/A           | N/A              | N/A              | 20.0          | N/A           | N/A            | N/A          | 20.0           |

|        | 4 stations IEEE 802.11 ax | 4 stations IEEE 802.11 ax |
|--------|--------------------------|---------------------------|
| 0      | 68.8                     | 64.8                      |
| 1      | 72.8                     | 72.8                      |
| 2      | 101.2                    | 72.8                      |
| 3      | 136.1                    | 72.8                      |
| 4      | 204.2                    | 68.8                      |
| 5      | 272.2                    | 68.8                      |
| 6      | 306.3                    | 68.8                      |
| 7      | 340.3                    | 68.8                      |
| 8      | 408.3                    | 68.8                      |
| 9      | 453.7                    | 68.8                      |
| 10     | 510.4                    | 68.8                      |
| 11     | 567.1                    | 68.8                      |

|        | 16 stations IEEE 802.11 ax | 4 stations IEEE 802.11 ax |
|--------|---------------------------|---------------------------|
| 0      | 84.8                     | 64.8                      |
| 1      | 85.5                     | 64.8                      |
| 2      | 117.0                    | 64.8                      |
| 3      | 148.8                    | 64.8                      |
| 4      | 180.5                    | 64.8                      |
| 5      | 206.5                    | 64.8                      |
| 6      | 224.8                    | 64.8                      |
| 7      | 258.1                    | 64.8                      |
| 8      | 286.8                    | 64.8                      |
| 9      | 287.8                    | 64.8                      |
| 10     | 322.8                    | 64.8                      |
| 11     | 351.0                    | 64.8                      |
Table 2: (cont.)

| MCS | PHY Rate (Mbps) | Preamble (µs) | PHY Rate (Mbps) | Preamble (µs) | PHY Rate (Mbps) | Preamble (µs) | PHY Rate (Mbps) | Preamble (µs) |
|-----|----------------|--------------|----------------|--------------|----------------|--------------|----------------|--------------|
| 0   | 8.6            | 104.8        | 8.1            | 64.8         | 1.7            | 64.8         | 58.5           | 48.0         |
| 1   | 17.2           | 104.8        | 16.3           | 64.8         | 3.3            | 64.8         | 117.0          | 48.0         |
| 2   | 25.8           | 84.8         | 24.4           | 64.8         | 5.0            | 64.8         | 175.5          | 48.0         |
| 3   | 34.4           | 84.8         | 32.5           | 64.8         | 6.7            | 64.8         | 234.0          | 48.0         |
| 4   | 51.6           | 80.8         | 48.8           | 64.8         | 10.0           | 64.8         | 351.0          | 48.0         |
| 5   | 68.8           | 80.8         | 65.0           | 64.8         | 13.3           | 64.8         | 466.0          | 48.0         |
| 6   | 77.4           | 80.8         | 73.1           | 64.8         | 15.0           | 64.8         | 526.5          | 48.0         |
| 7   | 86.0           | 80.8         | 81.3           | 64.8         | 16.7           | 64.8         | 585.0          | 48.0         |
| 8   | 103.2          | 80.8         | 97.5           | 64.8         | 20.0           | 64.8         | 702.0          | 48.0         |
| 9   | 114.7          | 80.8         | 108.3          | 64.8         | 22.2           | 64.8         | 780.0          | 48.0         |
| 10  | 129.0          | 80.8         | 121.9          | 64.8         | N/A            | N/A          | N/A            | N/A          |
| 11  | 143.4          | 80.8         | 135.4          | 64.8         | N/A            | N/A          | N/A            | N/A          |
4 Throughput analysis

Let \( X \) be the number of MPDU frames in an A-MPDU frame, numbered \( 1, \ldots, X \), and \( Y_i \) is the number of MSDUs in MPDU number \( i \). Let \( \text{MacHeader}, \text{MpduDelimiter} \) and \( \text{FCS} \) be the length, in bytes, of the MAC Header, MPDU Delimiter and FCS fields respectively, and let \( O_M = \text{MacHeader} + \text{MpduDelimiter} + \text{FCS} \). Let \( L_{\text{DATA}} \) be the length, in bytes, of the MSDU frames. Also, let \( \text{Len} = 4 \cdot \lceil \frac{L_{\text{DATA}} + 14}{4} \rceil \) and \( C_i = 8 \cdot 4 \cdot \lceil \frac{O_M + Y_i \cdot \text{Len}}{4} \rceil \). \( C_i \) is the length, in bits, of MPDU number \( i \).

In the entire analysis ahead we assume that the Ack frames’ transmissions are all successful because Ack frames are short and in most cases are transmitted in legacy mode.

4.1 Single User mode

The throughput in both 11ax and 11ac for the traffic pattern in Figure 2(A) is given by Eq. 1 \[20\] where BER is the Bit Error Rate:

\[
Thr = \frac{\sum_{i=1}^{X} 8 \cdot Y_i \cdot L_{\text{DATA}} \cdot (1 - BER)^{C_i}}{\text{AIFS} + \text{BO(average)} + P_{\text{DL}} + T(\text{DATA}) + \text{SIFS} + P_{\text{UL}} + T(\text{BAck})}
\]  

(1)

where:

\[
T(\text{DATA}) = T_{\text{Sym}_{DL}} \cdot \left\lceil \frac{\sum_{i=1}^{X} C_i + 22}{T_{\text{Sym}_{DL}} \cdot R_{DL}} \right\rceil
\]

(2)

\[
T(\text{BAck}) = T_{\text{Sym}_{UL}} \cdot \left\lceil \frac{(30 \cdot 8) + 22}{T_{\text{Sym}_{UL}} \cdot R_{UL}} \right\rceil
\]

The term \( \text{BO(average)} \) refers to the average value of the BackOff interval, as given in Section 3.5. As was explained in Section 3.5 we use an average value for this interval since there are no collisions.

\( T(\text{DATA}) \) and \( T(\text{BAck}) \) are the transmission times of the data A-MPDU frames and BAck frames respectively. \( T(\text{BAck}) \) is based on the BAck frame’s lengths given in Figure 3. When assuming 30 bytes we consider the acknowledgment of 64 MPDUs in the BAck.

\( T_{\text{Sym}_{DL}} \) and \( T_{\text{Sym}_{UL}} \) are the lengths of the OFDM symbols on the DL and the UL respectively, and every transmission must be of an integral number of OFDM symbols. The
additional 22 bits in the numerators of \(T(DATA)\) and \(T(BAck)\) are due to the SERVICE and TAIL fields added to every transmission by the PHY layer conv. protocol \([1]\). \(R_{DL}\) and \(R_{UL}\) are the DL and UL PHY rates respectively and \(P_{DL}\) and \(P_{UL}\) are the preambles used in the DL and in the UL respectively (see Figure \(4\)).

The term in Eq. \(1\) is not continuous, so it is difficult to find the optimal \(X\) and \(Y_i\(s\), i.e. the values for \(X\) and \(Y_i\(s\) that maximize the throughput. However, in \([20]\) it is shown that if one neglects the rounding in the denominator of Eq. \(1\) then the optimal solution has the property that all the MPDUs contain almost the same number of MSDUs: the difference between the largest and smallest number of MSDUs in MPDUs is at most 1. The difference is indeed 1 if the limit on transmission time of the PPDU does not enable transmission of the same number of MSDUs in all MPDUs.

If neglecting the rounding of the denominator of Eq. \(1\), the received throughput for every \(X\) and \(Y\) (\(Y\) is the equal number of MSDUs in MPDUs) is as large as that received in Eq. \(1\). The difference depends on denominator size.

We therefore use the result in \([20]\) and look for the maximum throughput as follows: We check for every \(X\), \(1 \leq X \leq 64\) (also \(1 \leq X \leq 256\) for 11ax) and for every \(Y\), \(1 \leq Y \leq Y_{\text{max}}\), what is the received throughput such that \(Y_{\text{max}}\) is the maximum possible number of MSDUs in an MPDU. All is computed taking into account the upper limit of \(5.484\,ms\) on the transmission time of the PPDU (PSDU+preamble). If it is not possible to transmit the same number of MSDUs in all the MPDUs, part of the MPDUs have one more MSDU than the others, up to the above upper limit on the transmission time. We found that the smallest denominator of any of the maximum throughputs is around \(1000\,\mu s\). Neglecting the rounding in the denominator reduces its size by at most \(2 \cdot \frac{13}{6}\,\mu s\) in 11ax and \(2 \cdot 4\,\mu s\) in 11ac. Thus, the mistake in the received maximum throughputs is at most 2.8%.

4.2 Multi User mode

The throughputs of 11ac and 11ax are given in Eq. \(3\) and their derivation can be found in \([20]\).

The throughput of 11ac for the traffic pattern in Figure \(2\)(B) is given in Eq. \(3\):

\[
Thr_{AC} = \frac{4 \cdot \sum_{i=1}^{X} 8 \cdot Y_i \cdot L_{DATA} \cdot (1 - BER)^{C_i}}{AIFS + BO(\text{average}) + P_{DL} + T(DATA) + 7 \cdot (SIFS + P_{UL}) + 4 \cdot T(BAck) + 3 \cdot T(BAR)}
\]
where:

\[
T(DATA) = TSym_{DL} \cdot \left[ \sum_{i=1}^{X} C_i + \frac{22}{TSym_{DL} \cdot R_{DL}} \right]
\]

\[
T(BAck) = TSym_{UL} \cdot \left[ \frac{(30 \cdot 8) + 22}{TSym_{UL} \cdot R_{UL}} \right]
\]

\[
T(BAR) = TSym_{UL} \cdot \left[ \frac{(24 \cdot 8) + 22}{TSym_{UL} \cdot R_{UL}} \right]
\]

are the transmission times of the data A-MPDU frames, the BAck frames and the BAR frames respectively. The transmission times of the BAck and BAR frames are based on their lengths given in Figure 3. \(R_{DL}\) is the DL PHY rate and \(R_{UL}\) is the UL PHY rate. We have the multiplier of 4 in the numerator of Eq. 3 since the AP transmits simultaneously to 4 stations. Also, \(P_{DL}\) and \(P_{UL}\) are the lengths of the preambles in the DL and in the UL respectively and \(TSym_{DL}\) and \(TSym_{UL}\) are the lengths of the OFDM symbols used in the DL and UL respectively.

The throughput of 11ax for the traffic pattern in Figure 2(C) is given in Eq. 5:

\[
Th_{rAX} = \frac{S \cdot \sum_{i=1}^{X} 8 \cdot Y_i \cdot L_{DATA} \cdot (1 - BER)^{C_i}}{\text{AIFS} + \text{BO(average)} + P_{DL} + T'(DATA) + PE + SIFS + P_{UL} + T'(BAck) + PE}
\]

where:

\[
T'(DATA) = TSym_{DL} \cdot \left[ \sum_{i=1}^{X} C_i + \frac{(O_M + 72) \cdot 8 + 22}{TSym_{DL} \cdot R_{DL}} \right]
\]

\[
T'(BAck) = TSym_{UL} \cdot \left[ \frac{(30 \cdot 8) + 22}{TSym_{UL} \cdot R_{UL}} \right]
\]

\(P_{DL}\) and \(P_{UL}\) are again the preambles in the DL and UL respectively.

In the term for \(T'(DATA)\) we assume the case of a Trigger Frame which holds for \(X\) data MPDUs in the A-MPDU frame such that 19 \(\leq X \leq 64\). For 1 \(\leq X \leq 18\) it is more efficient to use the HE Control Element of 4 bytes added to every data MPDU, and the term \(((O_M + 72) \cdot 8)\) is therefore replaced by \((X \cdot 4 \cdot 8)\). Notice that the 72 bytes come from 33 bytes of the TF frame, 28 bytes of the MAC Header, 4 bytes of the FCS field, 4 bytes of the MPDU Delimiter and rounding to an integral number of 4 bytes. For the BAck frame,
$T'(BAck)$ is based on a BAck frame acknowledging 64 MPDUs. In 11ax it is also possible to acknowledge 256 MPDUs and in this case the 30 bytes in $T'(BAck)$ are replaced by 54 bytes. See Figure 3(B). Notice the multiplier $S$ in the numerator of Eq. 5. $S$ is either 4, 8, 16, 32 or 64, the number of stations to which the AP transmits simultaneously.

Again, the terms in Eqs. 3 and 5 are not continuous and therefore we again use the result in [20], as in the SU mode, and look for the maximum throughput as specified in Section 4.1.

The analytical results of 11ax have been verified by an 11ax simulation model running on the $ns3$ simulator [24] and the simulation and analytical results are the same. This outcome is not surprising however, because there is not any stochastic process involved in the scheduled transmissions in 11ax assumed in this paper. Therefore, we do not mention the simulation results any further in this paper.

5 An approximation of the optimal A-MPDU structure

In this section we show an approximation to the value of $X_{OPT}$, the number of optimal MPDUs in an A-MPDU, i.e. the number of MPDUs that maximizes the throughput, as a function of the BER. We concentrate on 11ax although the computation is valid for 11ac as well.

5.1 The case BER>0

We re-write Eq. 5 by ignoring the rounding of $T'(DATA)$ and $T'(BAck)$, ignoring the 22 bits in the numerators of $T'(DATA)$ and $T'(BAck)$, settings $O_p = AIFS + BO + SIFS + P_{UL} + T'(BAck) + PE$, assuming that every MPDU has the same number $Y$ of MPDUs, $O_M = MacHeader + MpduDelimiter + FCS$ and ignoring the overhead due to the TF frame:

$$Thr = \frac{S \cdot X \cdot Y \cdot 8 \cdot L_{DATA} \cdot (1 - BER)^8 \cdot (Y \cdot Len + O_M)}{O_p + P_{DL} + \frac{X \cdot 8 \cdot (Y \cdot Len + O_M)}{R_{DL}}}$$ (7)

Notice that given a number $Y$ of MPDUs in an A-MPDU, the throughput increases as $X$ increases. Therefore, it is worthwhile to transmit as large A-MPDUs as possible, up to
the limit on the transmission time of the A-MPDU frame. Let $T$ be this limit, $5484 \mu s$ in our case. Then, the following approximation on the relation between $X$ and $Y$ can be written:

$$T = \frac{X \cdot 8 \cdot (Y \cdot \text{len} + O_M)}{R_{DL}} + P_{DL}$$  \hspace{1cm} (8)$$

or:

$$X = \frac{R_{DL} \cdot (T - P_{DL})}{8 \cdot (Y \cdot \text{Len} + O_M)}$$  \hspace{1cm} (9)$$

In Eqs. 8 and 9 we approximate that the sum of the A-MPDU transmission time plus the DL preamble is $T$.

We now substitute the term for $X$ in Eq. 7 by the term in Eq. 9 and receive:

$$Th_r = \frac{S \cdot \frac{R_{DL}(T - P_{DL})}{8(Y \cdot \text{Len} + O_M)} \cdot Y \cdot 8 \cdot L_{DATA} \cdot (1 - BER)^{8(Y \cdot \text{Len} + O_M)}}{T + O_p - P_{DL}}$$  \hspace{1cm} (10)$$

Notice that the denominator of Eq. 10 is a constant and so to find the maximum throughput as a function of $Y$ one needs to find the maximum of the following function:

$$\frac{Y}{8 \cdot (Y \cdot \text{Len} + O_M)} \cdot (1 - BER)^{8(Y \cdot \text{Len} + O_M)}$$  \hspace{1cm} (11)$$

The optimal $Y$, $Y_{OPT}$, is given in Eq. 12:

$$Y_{OPT} = \frac{O_M \cdot (\sqrt{1 - \frac{4}{8 O_M \cdot \ln(1 - BER)}} - 1)}{2 \cdot \text{Len}}$$  \hspace{1cm} (12)$$

Notice that by Eq. 9 we can now write the optimal X, $X_{OPT}$, as:

$$X_{OPT} = \frac{R_{DL} \cdot (T - P_{DL})}{8 \cdot O_M \left(\sqrt{\frac{1}{8 O_M \cdot \ln(1 - BER)}} - 1\right) + 1}$$  \hspace{1cm} (13)$$

Notice that we look for an integer $Y_{OPT}$ and that $Y_{OPT}$ must be at least 1. Therefore, Eq. 13 is only an approximation for $X_{OPT}$.

Consider now Figure 8(F) as an example (we refer to Figure 8 more deeply later). We have for this case $P_{DL} = 88.8 \mu s$, $R_{DL} = 50 Mbps$ and $O_M = 36$ bytes. We also have three cases of $\text{Len}$, $\text{Len} = 1516, 528$ and 80 bytes for MSDUs of lengths 1500, 512 and 64 bytes respectively. For all three cases we receive that $Y_{OPT} = \frac{653}{\text{Len}}$. For $\text{Len} = 1516, 528$ and 80 bytes we receive $Y_{OPT} = 0.43, 1.23$ and 8.16 respectively. For $Y_{OPT} = 0.43$ we need to round
up to 1 and receive $X_{OPT} = 21.72$. It turns out that $X_{OPT} = 21$ yields a larger throughput than 22 MPDUs. For $Y_{OPT} = 1.23$ we can take either $\lfloor Y_{OPT} \rfloor = 1$ or $\lceil Y_{OPT} \rceil = 2$. For the two cases we receive $\lfloor X_{OPT} \rfloor = 59$ and 30 respectively where the first case yields a larger throughput. We handle the case for $Len = 80$ similarly, where the $X_{OPT}$ is now 50. All these values for $X_{OPT}$ appear in Figure 8(F).

In Figure 5 we plot three curves for the values of $X_{OPT}$ as a function of the BER for MSDUs of 1500, 512 and 64 bytes respectively. Notice that for an MSDU of 1500 bytes 21 MPDUs of 1 MSDU is the optimal number of MPDUs over a wide range of BER values. This is because as the BER increases it is worthwhile transmitting short MPDUs, but one MSDU must be included in an MPDU. For MSDUs of 512 bytes there is more flexibility in the number of MSDUs per MPDU and so the optimal number of MPDUs is more flexible. For MSDUs of 60 bytes the number of MSDUs per MPDU varies according to the BER in the most flexible way and so does the number of MPDUs. The number of optimal MPDUs is smaller than in MSDUs of 512 bytes because the smaller size of the MSDUs enables using the MPDUs more efficiently, the MPDUs are little longer than in the case of 512 bytes MSDUs and due to the limit on the A-MPDU transmission time, a smaller number of MPDUs is needed.

5.2 The case BER=0

For BER=0 Eq. 7 becomes:

$$Thr = \frac{S \cdot X \cdot Y \cdot 8 \cdot L_{DATA}}{O_p + P_{DL} + \frac{X \cdot 8 \cdot (Y \cdot Len + O_M)}{R_{DL}}}$$

and one needs to optimize the function:

$$Y \cdot 8 \cdot (Y \cdot Len + O_M)$$

which reveals that in every MPDU it is worthwhile to contain the maximum number of MPDUs, $Y_{MAX}$, which is $\lceil \frac{11454 - O_M}{Len} \rceil$.

Therefore:

$$X_{OPT} = \frac{R_{DL} \cdot (T - P_{DL})}{8 \cdot (\lceil \frac{11454 - O_M}{Len} \rceil \cdot Len + O_M)}$$
Figure 5: $X_{OPT}$ as a function of the BER and MSDU length, 64 stations, in IEEE 802.11ax.

For example, for Figure 8(D) we have $R_{DL} = 50Mbps$, $P_{DL} = 88.8\mu s$, $O_M = 36$ bytes and $X_{OPT} = \frac{33720}{\left\lfloor \frac{11418}{Len} \right\rfloor} \cdot Len + 36$.

For MSDUs of 1550, 512 and 64 bytes one receives $Len = 1516, 528$ and 80 bytes respectively, which gives $X_{OPT} = 3.166, 3.031, 2.958$ respectively. Since we look for an integer $X_{OPT}$ one needs to choose between 3 or 4 MPDUs for the first two cases and between 2 or 3 MPDUs for the third case. It turns out that 3, 3, 3 are the optimal number of MPDUs respectively, as appears in Figure 8(D).

6 Throughput’s models and results

6.1 Transmissions’ models and scenarios

We compare between all applicable configurations and DL service scheduling flavors of the AP transmissions to up to 64 stations. The service scheduling flavors are as follows:

Concerning 11ac:

- DL SU, UL SU Back transmission in legacy mode, up to 64 MPDUs in an A-MPDU
frame, denoted previously as $SU_{AC}(1)$.

- DL 4 users MU-MIMO, UL 4 times SU BAck transmission in legacy mode, up to 64 MPDUs in an A-MPDU frame, denoted previously as $MU_{AC}(4)$.

Concerning 11ax:

- DL SU, UL SU BAck transmission in legacy mode, up to 64 or 256 MPDUs in an A-MPDU frame, denoted previously as 11ax/64 and 11ax/256 $SU_{AX}(1)$ respectively.

- DL 4 users MU-MIMO, UL MU-MIMO or OFDMA BAck transmission, up to 64 or 256 MPDUs in an A-MPDU frame, denoted previously as 11ax/64 and 11ax/256 $MU_{AX}(4)$ respectively.

- DL $S=8, 16, 32, 64$ users DL MU-MIMO + OFDMA, UL MU-MIMO + OFDMA or OFDMA BAck transmission, up to 64 or 256 MPDUs in an A-MPDU frame, denoted previously as 11ax/64 and 11ax/256 $MU_{AX}(S)$ respectively.

For every number $S$ of stations we analyze the optimal DL service scheduling working point, i.e. the one that optimizes throughput, as a function of the transmission flavor, MCS in use and the A-MPDU frame structure.

First, we checked for every number of stations all possible transmission DL service scheduling flavors that are applicable for this number of stations. For example, for 64 stations one can use 64 cycles of Figure 2(A) sequentially both in 11ac and 11ax, i.e. $64 \cdot SU_{AC}(1)$ or $64 \cdot SU_{AX}(1)$. One can also use 16 cycles of Figures 2(B) and 2(C) in 11ac and 11ax respectively, namely $16 \cdot MU_{AC}(4)$ and $16 \cdot MU_{AX}(4)$ respectively. Finally, one can also use 8, 4, 2 and 1 cycles of Figure 2(C) in 11ax, denoted previously $MU_{AX}(8), MU_{AX}(16), MU_{AX}(32)$ and $MU_{AX}(64)$ respectively.

Every transmission flavor is checked over all applicable MCSs. For 11ac these are MCS0-MCS9. For 11ax these are MCS0-MCS11 except in the case of 64 stations, where only MCS0-MCS9 are applicable. We also check for every transmission flavor and MCS the optimal working point by optimizing the number of MPDUs and number of MSDUs in every MPDU that yields the maximum throughput, i.e. we look for the optimal A-MPDU frame structure. We checked all the above for MSDUs of 64, 512 and 1500 bytes and BER=$0, 10^{-6}, 10^{-5}$.

In the next section we show three sets of results. In Figure 6 we show the maximum throughputs received for every number of stations in every transmission flavor for MSDUs
of 1500 bytes. The results for MSDUs of 64 and 512 bytes are similar. In Figure 7 we demonstrate for $MU_{AX}(4)$ and $MU_{AX}(64)$ the maximum throughputs received in the various DL service scheduling flavors of 11ax, as a function of the MCSs. The maximum among them is shown in Figure 6. Figure 7 shows the influence of the maximum number of MPDUs in an A-MPDU frame, 64 or 256 on the received throughput, as well as the influence of using UL MU-MIMO or UL OFDMA on the received throughput. Finally, in Figure 8 we show the influence of the number of MPDUs in an A-MPDU frame on the received throughput in cases of 4 and 64 stations, for BER=0, $10^{-6}$ and $10^{-5}$.

### 6.2 Throughput results

Recall that in Figure 6 we show the maximum throughputs received as a function of the number of stations to which the AP transmits. We show results for MSDUs of 1500 bytes only; similar results are received for MSDUs of 64 and 512 bytes.

In Figure 6(A) we show the results for BER=0. When referring to e.g. 11ax MU(4) in the legend we refer to $MU_{AX}(4)$, i.e. the case in which the AP transmits to 4 stations in 11ax simultaneously using DL MU-MIMO, Figure 2(C). When showing the results for $MU_{AX}(4)$ for the case of e.g. 64 stations, the traffic cycle in Figure 2(C) repeats itself 16 times; every transmission is to a different group of 4 stations, i.e. $16 \cdot MU_{AX}(4)$.

We see from Figure 6(A) that the largest throughput is received in $MU_{AX}(4)$. Notice that the throughout of $MU_{AX}(8)$ is only slightly smaller than that of $MU_{AX}(4)$. From Table 2 one can see that the PHY rates in $MU_{AX}(8)$ are half of those of $MU_{AX}(4)$. This is balanced by twice the number of stations to which the AP transmits. However, in $MU_{AX}(4)$ 522 MSDUs are transmitted in an A-MPDU frame compared to 520 MSDUs in $MU_{AX}(8)$. Also, the DL preamble in $MU_{AX}(8)$ is slightly larger than in $MU_{AX}(4)$ due to the HE-SIG-B field. These two factors reduce the throughput of $MU_{AX}(8)$ compared to $MU_{AX}(4)$.

In $MU_{AX}(16)$ the PHY rates are less than half of those in $MU_{AX}(8)$ and together with the larger preamble this explains why $MU_{AX}(16)$ has a smaller throughput than $MU_{AX}(8)$ and $MU_{AX}(4)$. The explanation for the throughputs of $MU_{AX}(32)$ and $MU_{AX}(64)$ is similar to those given above for $MU_{AX}(8)$ and $MU_{AX}(16)$. Notice that the PHY rates in $MU_{AX}(64)$ are less than half of those of $MU_{AX}(32)$ and also that MCS10 and MCS11 are not applicable for $MU_{AX}(64)$, which is a main factor in the sharp decrease in the throughput of $MU_{AX}(64)$ compared to $MU_{AX}(32)$. 

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Notice also that for all stations 11ax outperforms 11ac due to larger PHY rates and simultaneous transmissions of B Ack frames in the UL compared to sequential transmissions in legacy mode in 11ac. For 4, 8, 16, 32 and 64 stations and using MU-MIMO, 11ax outperforms 11ac by 59%, 4470 vs. 2808 Mbps, the throughputs in $MU_{AX}(4)$ and $MU_{AC}(4)$ respectively. In SU when transmitting to 1 station only, 11ax outperforms 11ac by 52%, 1133 vs. 742 Mbps.

Although the throughput metric is important, so is the access delay metric, defined in this paper as the time elapsed between two consecutive transmissions from the AP to the same station. Notice for example that in the case of $MU_{AX}(4)$ that achieves the largest throughput, the access delay in the case of 64 stations is 16 times the cycle of Figure 2(C) while in $MU_{AX}(64)$ the access delay is only one such cycle. Notice also that we refer here to the access delay and not to the packet delay. Since there are retransmissions in the IEEE 802.11 MAC, the packet delay is defined as the delay since a packet is first transmitted and until it is successfully received.

In Figure 6(B) we show the access delays for the various DL service scheduling transmissions’ flavors. Some applications benefit primarily from lower latency, especially real-time streaming applications such as voice, video conferencing or even video chat. The trade-off between latency and throughput becomes more complex as applications are scaled out to run in a distributed fashion. The access delay results are as expected; the access delay is lower when the AP transmits simultaneously to additional stations. It seems that the cycles are about the same in length in all DL service scheduling transmissions’ flavors and the relation between access delays is about the same between the number of stations to which the AP transmits simultaneously.

In Figures 6(C) and 6(D) we show the results for BER=$10^{-6}$. There are some trends in this BER that become more prominent in BER=$10^{-5}$ so we concentrate now only on BER=$10^{-5}$.

In Figure 6(E) we show the maximum throughput as a function of the number of stations for the case BER=$10^{-5}$. An interesting difference compared to BER=0 is that the best transmission flavor is $MU_{AX}(8)$ compared to $MU_{AX}(4)$ in BER=0. $MU_{AX}(8)$ outperforms $MU_{AX}(4)$ due to the short MPDUs and its smaller PHY rates. The optimal A-MPDU frame structure in both DL service scheduling flavors is 255 MPDUs of one MSDU each. In $MU_{AX}(4)$ a cycle lasts 2.944 ms and in $MU_{AX}(8)$ it is 5.583 ms. In $MU_{AX}(8)$ twice the number of MSDUs are transmitted than in $MU_{AX}(4)$, but this is done in less than twice
the cycle length of $MU_{AX}(4)$ due to equal overhead in both DL service scheduling flavors. This leads to a larger throughput in $MU_{AX}(8)$. In BER=0 the cycle length of $MU_{AX}(4)$ is 5.596ms compared to 5.583ms in $MU_{AX}(8)$, i.e. about the same. However, the number of MSDUs in $MU_{AX}(4)$ is slightly larger than twice the number of MSDUs in $MU_{AX}(8)$ (522 vs. 520) and the preamble is slightly shorter. Therefore in BER=0 $MU_{AX}(4)$ has a slightly larger throughput.

When comparing between the throughputs of $MU_{AX}(8)$ and $MU_{AC}(4)$, 11ax outperforms 11ac by 103%, 3872 vs 1902 Mbps respectively. For SU(1) 11ax outperforms 11ac by 74%, 940 vs. 540 Mbps respectively.

In Figure 6(F) we show the corresponding access delays of the DL service scheduling transmissions’ flavors for BER=$10^{-5}$. Notice that the access delay of $SU_{AX}(1)$ is much larger than that of $SU_{AC}(1)$, in contrast to BER=0 where they are about the same. The difference is because the maximum throughput of $SU_{AC}(1)$ is received when transmitting 64 MPDUs of 1 MSDU each while in $SU_{AX}(1)$ the A-MPDU contains 256 MPDUs of 1 MSDU each. In BER=0 the MPDUs contain 7 MSDUs each, and in both 11ac and 11ax the cycles are around 5.5ms. Therefore, access delays are similar.

Also worth mentioning is the relation between the access delays of $MU_{AX}(4)$ and $MU_{AX}(8)$. For BER=$10^{-5}$ they are about the same because the maximum throughput in both DL service scheduling flavors is received when an A-MPDU frame contains 255 MPDUs of 1 MSDU each. Since the PHY rates in $MU_{AX}(8)$ are about half of those in $MU_{AX}(4)$, the cycle length in $MU_{AX}(8)$ is about double in length than in $MU_{AX}(4)$. However, this is compensated by double the number of stations to which the AP transmits in $MU_{AX}(8)$ compared to $MU_{AX}(4)$; overall the access delays are similar in both DL service scheduling flavors.

In BER=0 the cycle length in both $MU_{AX}(4)$ and $MU_{AX}(8)$ are about the same, around 5.5ms, transmitting as many MSDUs as possible. The access delay in $MU_{AX}(4)$ is now twice than that of $MU_{AX}(8)$ because of the 4 vs. 8 stations to which the AP transmits in $MU_{AX}(4)$ and $MU_{AX}(8)$ respectively.

Overall it can be concluded from Figure 6 that there is not any one best flavor. For example, $MU_{AX}(8)$ achieves the maximum throughput but $MU_{AX}(16)$ and $MU_{AX}(32)$ also achieve high throughput but with smaller access delays compared to $MU_{AX}(8)$.

In Figure 7 we show the throughput optimization performance of $MU_{AX}(4)$ and $MU_{AX}(64)$ for every MCS, for the case of UL MU-MIMO and UL OFDMA, for the cases
using 64 and 256 MPDUs in an A-MPDU frame and for BER=0, 10^{-6} and 10^{-5}. We again concentrate only on BER=0, 10^{-5} because the results for BER=10^{-6} are similar in trend. In Figures 7(A) and 7(C) we show the results for $MU_{AX}(4)$ for BER=0 and BER=10^{-5} respectively. In Figures 7(D) and 7(F) the same results are shown for $MU_{AX}(64)$. Notice that for $MU_{AX}(64)$ there are no results for MCS10 and MCS11 which are not applicable in this case due to low PHY rates.

The maximum throughput is always received in $MU_{AX}(4)$ in MCS11 (MCS9 in $MU_{AX}(64)$) due to the highest PHY rates in this MCS. Considering $MU_{AX}(4)$ notice that for BER=0 11ax/256 outperforms 11ax/64 only in MCS10 and MCS11 while in BER=10^{-5} 11ax/256 outperforms 11ax/64 starting from MCS2 (starting from MCS5 in BER=10^{-6}). In BER=0 it is efficient to transmit large MPDUs. Therefore, the limit on the A-MPDU frame size is imposed by the limit of 5.484 ms on the transmission time of the PPDU. Only in larger PHY rates there is room for more than 64 MPDUs and in these cases 11ax/256 has an advantage over 11ax/64. In BER=10^{-5} it is efficient to transmit short MPDUs. In this case the significant limit is the number of MPDUs. 11ax/256 outperforms 11ax/64 from MCS2 because it enables transmitting more short MPDUs than 11ax/64. A detailed analysis of this phenomenon can be found in [23].

Another interesting phenomenon is the relation between UL MU-MIMO and UL OFDMA. When using UL OFDMA the UL PHY rates are much smaller than those in UL MU-MIMO (see Table 2). However, rounding $T'(BAck)$ to an integral number of OFDM symbols of 14.4 $\mu$s (12.8 $\mu$s + 1.6 $\mu$s Guard Interval) and the small size of the BAck frames results in similar $T'(BAck)$ times in $MU_{AX}(4)$. In $MU_{AX}(64)$ the UL PHY rates in UL OFDMA are even smaller and an additional OFDM symbol is needed. Therefore, there is a slight advantage to UL MU-MIMO. This phenomenon is seen in Figure 7(F) where transmission to 64 stations is assumed. Using DL MU-MIMO with up to 64 or 256 MPDUs in the A-MPDU frame outperforms the same DL service scheduling transmission flavors respectively when using UL OFDMA. On the other hand this phenomenon is not seen in Figure 7(C) when transmitting to 4 stations.

In Figure 8 we show the impact of the number of MPDUs in A-MPDU frames on the received throughput. In Figures 8(A), 8(B) and 8(C) results are shown for $MU_{AX}(4)$ in MCS11, for BER=0, 10^{-6} and 10^{-5} respectively. Similar results are shown for $MU_{AX}(64)$ for MCS9 in Figures 8(D), 8(E) and 8(F) respectively. We show results for MSDUs of 64, 512 and 1500 bytes. We again concentrate on BER=0 and BER=10^{-5} only.
Considering $MU_{AX}(4)$ and BER=0, Figure 8(A), there is an optimal number of MPDUs of around 72 for all sizes of the MSDUs. In BER=0 it is efficient to transmit the largest possible MPDUs. Around 72 MPDUs, all the MPDUs contain the largest possible number of MSDUs and transmission time is used efficiently. Above 72 MPDUs the limit of 5.484 ms on the PPDU transmission time and the MPDUs’ overhead cause a smaller number of MSDUs to be transmitted and the throughput decreases.

In the case of BER=10$^{-5}$, Figure 8(C), the optimal number of MPDUs is 256 since MPDUs are short (to increase the MPDUs’ transmission success probability) and there is enough transmission time for 256 MPDUs in the A-MPDU frame; every additional MPDU increases the throughput.

In $MU_{AX}(64)$, Figures 8(D), 8(E) and 8(F), the PHY rates are smaller and the limit on the PPDU transmission time does not enable transmission of many MPDUs with MSDUs of 512 and 1500 bytes. Up to 21 and 58 MPDUs of these sizes can be transmitted respectively for BER=10$^{-5}$, containing one MSDU. For BER=0 an optimal number of 3 MPDUs yields the maximum throughput for all MSDUs’ sizes. A larger number of MPDUs decreases the number of MSDUs transmitted due to MPDUs’ overhead and the throughput decreases. In the case of BER=10$^{-5}$ the MPDUs are shorter, and increasing the number of MPDUs increases the throughput since more MSDUs are transmitted. An exception is the case of 64 bytes MSDUs. In this case it is possible to transmit 256 MPDUs and several MSDUs can be transmitted in every MPDU. Increasing the number of MPDUs in this case over 50 MPDUs decreases the number of MSDUs transmitted with a decrease in the throughput. In the Appendix we derive an approximation for the optimal number of MPDUs in an A-MPDU as a function of the BER.

7 Summary

In this paper we compare between DL service scheduling flavors to optimize throughputs of 11ac and 11ax over the DL when considering UDP like traffic and several DL service scheduling stations are transmitting in the system. We also consider several transmission flavors in 11ac and 11ax using MU-MIMO and OFDMA. We look for upper bounds on the throughput received at the MAC layer after neutralizing any aspects of the PHY layer as the relation between the BER and the MCSs in use, the number of Spatial Streams (SS) in use, channel correlation when using MU-MIMO, the sounding protocol etc.
Figure 6: Maximum throughputs and corresponding access delays in Single User and Multi User in IEEE 802.11ac and IEEE 802.11ax.
11ax outperforms 11ac by the order of several tenths of percentage because it enables simultaneous transmissions on both the DL and the UL while 11ac has this capability over the DL only, and for 4 stations only. Also, 11ax has larger PHY rates which also improve its efficiency compared to 11ac.

In 11ax there is not one best DL service scheduling transmission flavor. $MU_{AX}(8)$ achieves good results in terms of throughput, but $MU_{AX}(16)$ and $MU_{AX}(32)$ also achieve good throughput results, but with significantly smaller access delay. 11ax achieves its best throughputs in MCS11 in the case of up to 32 stations, and in MCS9 in the case of 64 stations.

There is an optimal A-MPDU frame structure. In $MU_{AX}(4)$ it is sufficient to transmit around 70 MPDUs and 256 MPDUs in an A-MPDU frame for BER=0 and BER=10^{-5} respectively. For $MU_{AX}(64)$ these numbers of MPDUs are smaller, around 3 for BER=0 and 21, 58 and 50 for MSDUs of 1500, 512 and 64 bytes respectively, due to smaller PHY rates.

Finally, using up to 256 MPDUs in an A-MPDU frame outperforms the case of using up to 64 MPDUs in the cases where the PHY rates are large and/or the channel is unreliable,
Figure 8: The throughputs vs. the number of MPDUs in A-MPDU frames in IEEE 802.11ax Multi User for 4 stations in MCS11 and 64 stations in MCS9.
i.e. $\text{BER}=10^{-5}$. 
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(A) The Block Ack Request (BAR) Frame format (compressed)

| Frame control | Duration ID | RA | TA | BAR control | BAR information | FCS |
|---------------|-------------|----|----|-------------|-----------------|-----|
| 2             | 2           | 6  | 6  | 2           | 2               | 4   |

(B) The Unicast Trigger Frame format (destined to one station)

| Frame control | Duration ID | RA | TA | TF information | FCS |
|---------------|-------------|----|----|-----------------|-----|
| 2             | 2           | 6  | 6  | 13              | 4   |