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Scheduling Strategies and Throughput Optimization for the Downlink for IEEE 802.11ax and IEEE 802.11ac Based Networks

Oran Sharon[1], **Yaron Alpert**[2]

[1]Department of Computer Science, Netanya Academic College, Netanya, Israel
[2]Intel, Ra'anana, Israel
Email: oran@math.haifa.ac.il, Yaron.Alpert@intel.com

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Abstract

The new IEEE 802.11ax standard is aimed to serve many users while enabling every station to transmit a consistent stream of data without interruption. In this paper we evaluate the upper bound on the throughput of a Downlink IEEE 802.11ax channel using the Single User (SU) mode and using the Multi User Multiple-Input-Multiple-Output (MU-MIMO) and Orthogonal Frequency Division Multiple Access (OFDMA) mode. We compare between IEEE 802.11ax and IEEE 802.11ac for the case of 1, 4, 8, 16, 32 and 64 stations in different Modulation/Coding schemes (MCS) and different transmission windows' sizes, 64 and 256 frames in IEEE 802.11ax. IEEE 802.11ax outperforms IEEE 802.11ac in the SU and MU modes by 52% and 74% in a reliable channel respectively, while in an unreliable channel the improvements are by 59% and 103% respectively. Also, in terms of the access delay, the advantage of IEEE 802.11ax increases as the number of stations increases.

Keywords

IEEE 802.11ax, IEEE 802.11ac, Throughput, Single User, MU-MIMO, OFDMA

1. Introduction

1.1. Background

IEEE 802.11 Standard (WiFi) [1], first released in 1997, provides the basis for wireless network products using the WiFi brand. This standard is continuously being updated over the years, increasing its throughput and Quality-of-Service (QoS) capabilities. The last version of the standard, IEEE 802.11ax (also known as High Efficiency (HE)) was recently introduced [2] [3] [4]. This version defines modifications for both the IEEE 802.11 PHY and MAC layers that enable larger average throughput per station in densely deployed networks [5] [6] [7] [8]. Currently IEEE 802.11ax project is in an early stage of development, due to be publicly released in 2019.

1.2. Research Question

In this paper we assume that the AP is communicating with a fixed set of stations in a Round Robin fashion, without collisions. We explore some of the Downlink (DL) and Uplink (UL) IEEE 802.11ax new mechanisms and we compare between the upper bounds on the unidirectional DL 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 [9]. 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.

In the SU transmission mode a single station transmits to the AP over the UL and the AP transmits to a single station over the DL in a given time. In the MU transmission mode the AP transmits to several stations simultaneously over the DL and several stations transmit simultaneously to the AP over the UL. In IEEE 802.11ac the MU mode is not possible over the UL. In IEEE 802.11ax up to 74 stations can transmit simultaneously over the UL [2].

The MU transmissions over the DL (DATA) and the UL (Acks) are done by MIMO and OFDMA. The IEEE 802.11ax standard enables new ways of multiplexing users using OFDMA and expends MIMO transmissions multiplexing format. In the IEEE 802.11ac the total channel bandwidth (20 MHz, 40 MHz, 80 MHz etc.) contains multiple OFDM sub-carriers while 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.

The main contributions of this paper relate to the new OFDMA structure in 11ax. We suggest new scheduling strategies over the DL where the AP transmits UDP traffic to the stations and the stations reply with acknowledgments at the

MAC layer. For each scheduling strategy we also evaluate upper bounds on the throughput and access delay which are influenced by the different PHY rates that are used in the different scheduling strategies. This paper deals with the DL and a companion paper deals with the UL [10]. 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 [10] 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 [10] 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.

1.3. Previous Works

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. In [11] 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 [12] the authors deal with the introduction of Orthogonal Frequency Division Multiple Access (OFDMA) into IEEE 802.11ax to enable multi user access. They introduce a new access protocol, denoted Orthogonal MAC for 802.11ax (OMAX), to reduce overhead and synchronization problems associated with OFDMA.

In [13] the authors suggest a centralized medium access protocol for the UL of IEEE 802.11ax in order to efficiently use the transmission resources. The AP allocates RUs to the stations following requests from the stations, which later use them for data transmissions over the UL. Paper [14] deals with the case of different length MAC Protocol Data Units (MPDU) and proposes a protocol to transmit such MPDUs over the UL using OFDMA. Papers [15] [16] [17] [18] suggest a new backoff mechanism where a station resets its backoff stage when it has no more MPDUs to transmit; this is different from the common backoff mechanism where the backoff stage is reset after a successful transmission. This new backoff mechanism improves efficiency and fairness and it is incorporated into a new version of the CSMA/CA MAC protocol, denoted Enhanced CSMA/CA (CSMA/ECA). Paper [19] deals with fairness issues arising in networks with legacy and IEEE 802.11ax stations.

The remainder of the paper is organized as follows: In Section 2 we mention some new features of IEEE 802.11ax that we later use in transmission scheduling strategies that are described in Section 3 for both the SU and MU modes. In our descriptions of the transmission scenarios we assume that the reader is familiar with the basics of the IEEE 802.11 systems, as can be found in e.g. [20]. In

Section 4 we analyze the performance of IEEE 802.11ax and IEEE 802.11ac and 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 and in the appendix we show the PHY rates used in the various transmission strategies in IEEE 802.11ac and IEEE 802.11ax. Lastly, we denote IEEE 802.11ac and IEEE 802.11ax by 11ac and 11ax respectively.

2. The New Features in IEEE 802.11ax

The new IEEE 802.11ax standard is aimed to serve many users while enabling every station to transmit a consistent stream of data without interruption. Therefore, 11ax incorporates some new mechanisms in the PHY and MAC layers.

First, in 11ax there are two new Modulation/Coding schemes, 1024 QAM 3/4 and 1024 QAM 5/6, denoted MCS10 and MCS11 respectively. These MCSs can be used only in channels with bandwidths larger than 20 MHz. Also, 11ax uses larger OFDM FFT sizes, 4 times larger, and thus every OFDM symbol is 12.8 μs in 11ax, compared to 3.2 μs in 11ac.

In this paper we also use the two-level aggregation scheme, first introduced in IEEE 802.11n [1] [4]. In this aggregation several MPDUs are transmitted within the same PHY Protocol Data Unit (PPDU), denoted Aggregated MPDU (A-MPDU). Several Mac Service Data Units (MSDU) are transmitted within one MPDU. In 11ax the maximum size of an A-MPDU is 4,194,034 bytes, compared to 1,048,575 bytes in 11ac. In both standards the largest MPDU size is 11454 bytes. The transmission time of a PPDU, together with its PHY preamble, is limited to 5484 μs in both standards. The structure of an A-MPDU frame is shown in **Figure 1**.

Another important new feature in 11ax is the ability to use a transmission window of 256 frames, compared to 64 frames only in 11ac.

Finally, in 11ax MU-MIMO or OFDMA are supported on both the UL and DL, while in 11ax only UL SU is possible. In 11ax it is possible to transmit to 74 stations simultaneously over the DL, while in 11ac this number is limited to 4.

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

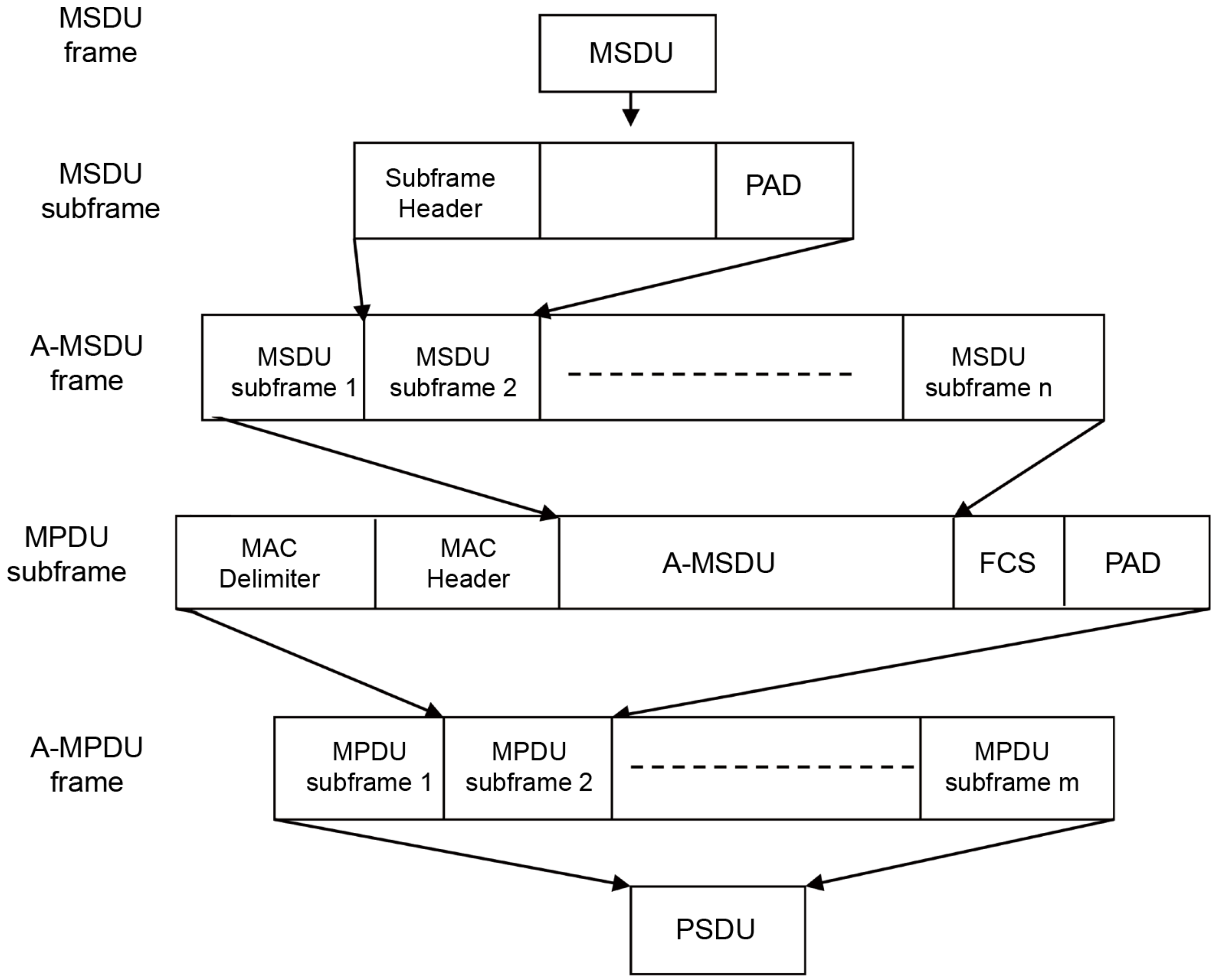

Figure 1. The two-level aggregation mechanism.

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 times. 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 **Figure 3(a)**, **Figure 3(b)** and **Figure 3(c)** respectively.

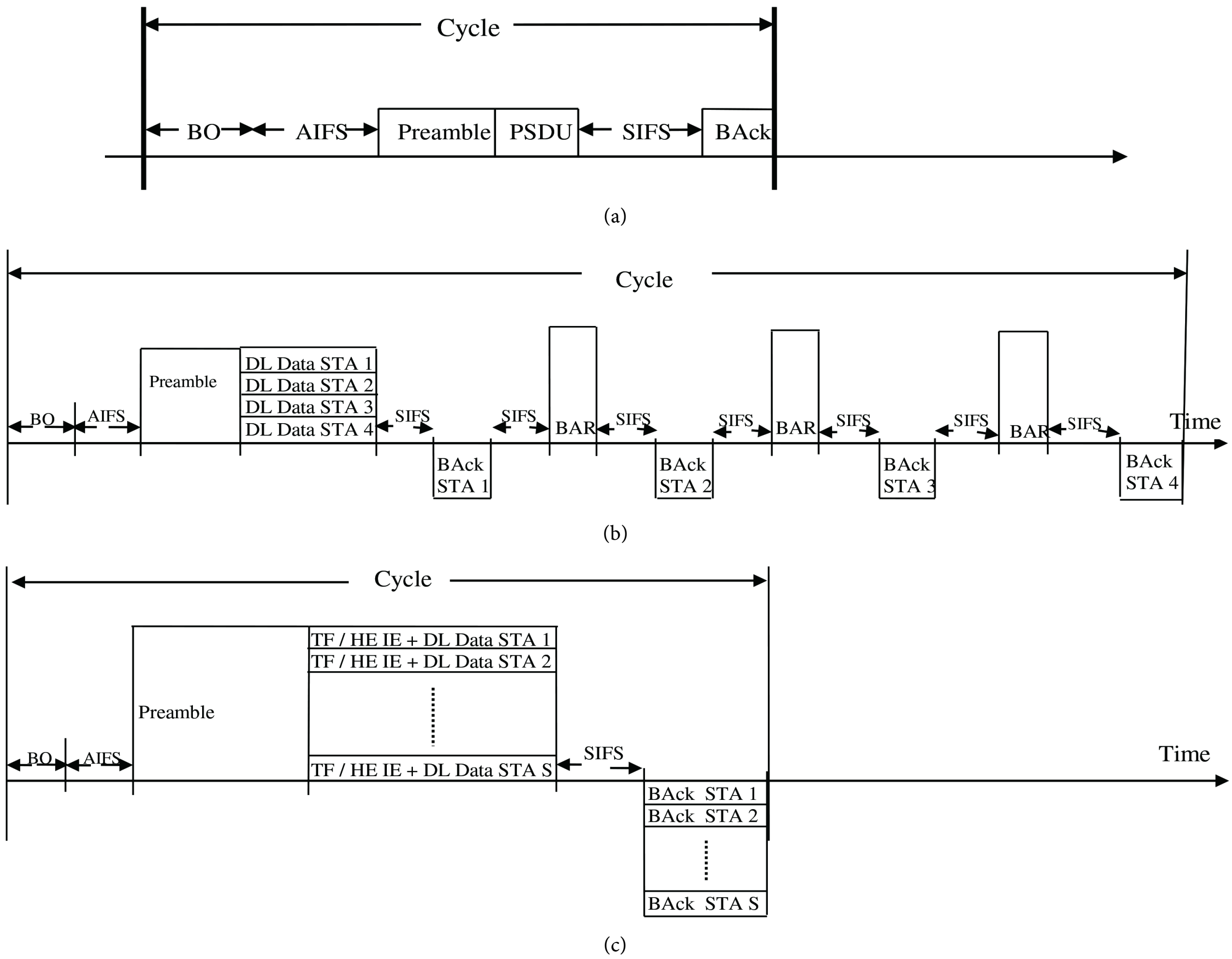

Figure 2. Transmissions from the AP to stations in Single User and Multi User modes in IEEE 802.11ac and in IEEE 802.11ax. (a) Un-scheduled SU transmission pattern in IEEE 802.11ac and IEEE 802.11ax from the AP to one station; (b) Scheduled MU transmission pattern in IEEE 802.11ac from the AP to 4 stations; (c) Scheduled MU transmission pattern in IEEE 802.11ax from the AP to S stations, $S = 4, 8, 16, 32, 64$.

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

2	2	6	6	2	8	4
Frame control	Duration ID	RA	TA	BA control	BA information	FCS

(a)

2	2	6	6	2	32	4
Frame control	Duration ID	RA	TA	BA control	BA information	FCS

(b)

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

(c)

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

(d)

Figure 3. The Block Ack (BAck), the Block Ack request (BAR) and the Trigger Frame (TF) frames' format. (a) The Block Ack (Back) Frame format (compressed) acknowledgeing up to 64 MPDUs; (b) The Block Ack (Back) Frame format (compressed) acknowledgeing up to 256 MPDUs; (c) The Block Ack Request (BAR) Frame format (compressed); (d) The Unicast Trigger Frame format (destined to one station).

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), Figure 2(b) and Figure 2(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. The notation $x \cdot MU_{AC}(4)$ stands for using the traffic pattern of Figure 2(b) x times in sequence, transmitting to x different groups of stations, each of 4 stations. Similarly, $m \cdot MU_{AX}(n)$ stands for using the traffic pattern of Figure 2(c) in a row, transmitting to m different groups of stations, each of n stations. n can receive the values of 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 5 GHz band, a 160 MHz 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.

The 160 MHz channel is divided in the MU mode into $\frac{S}{4}$ channels of $\frac{160 \cdot 4}{S}$ MHz each. S can be 4, 8, 16, 32 or 64. 4 Spatial Streams are defined in every channel and in every Spatial Stream the AP transmits to a different station. Notice for example that when $S = 64$ the AP transmits to 64 stations using 16 channels of 10 MHz each. For the case of $S = 4$ there is no need to divide the

160 MHz channel and 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 PPDUs' formats in use in the various transmission patterns of Figure 2.

In Figure 4(a) and Figure 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 μs. 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 μs [2]. 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 $4\ \mu\text{s} + X \cdot (7.2 - 4)\ \mu\text{s} = 4\ \mu\text{s} + X \cdot 3.2\ \mu\text{s}$.

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 μs.

In Figure 4(a) and Figure 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 μs. The MCS used in the HE-SIG-B field is the minimum between MCS4 and the one used for the data transmissions [2]. 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 μs for MCS0 and MCS1, and is 4 μs for MCS2-4 following section 29.3.9.8 in [2]. For MCS5-MCS11 it is 4μs 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

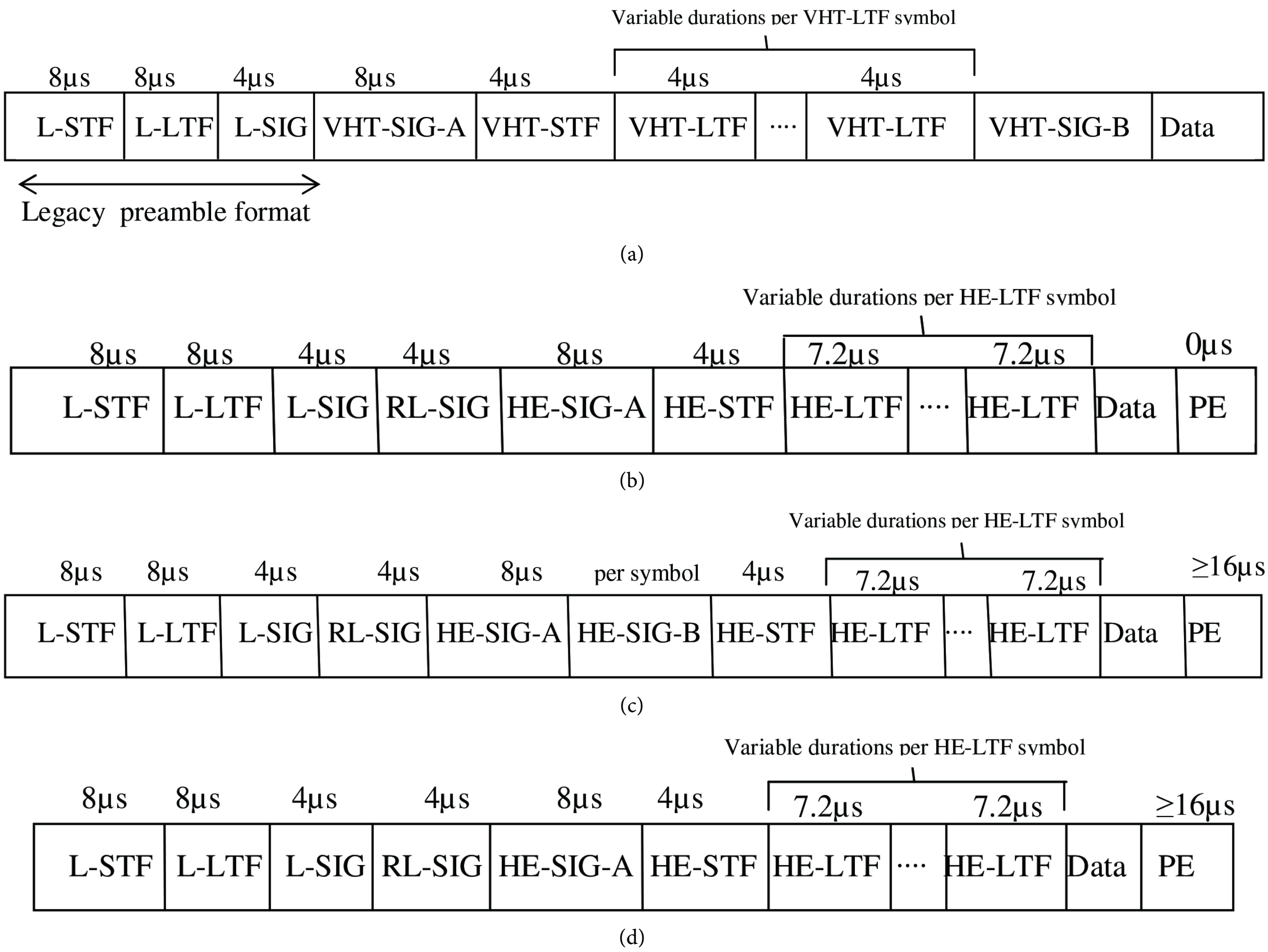

Figure 4. The PPDU formats in the SU and MU modes. (a) IEEE 802.11ac AP DL SU or DL MU-MIMO PPDU format; (b) IEEE 802.11ax AP DL SU PPDU format; (c) IEEE 802.11ax AP DL MU PPDU format; (d) IEEE 802.11ax STA UL MU PPDU format.

the PSDU additional time to move from a reception mode to a transmission mode. The largest duration of this field is 16μs which we assume in this paper.

3.5. Parameters' Values

In the appendix we show the PHY rates that are used in 11ac and 11ax in SU and MU, over the DL and UL and in the various MCSs.

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

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 $[0, \cdots, CW_{\min} - 1]$. 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 μs 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].

4. Throughput Analysis

Let X be the number of MPDU frames in an A-MPDU frame, numbered $1,\cdots,X$, and Y_i is the number of MSDUs in MPDU number *i*. Let $MacHeader$, $MpduDelimiter$ and FCS be the length, in bytes, of the MAC Header, MPDU Delimiter and FCS fields respectively, and let $O_M = MacHeader + MpduDelimiter + FCS$. Let L_{DATA} be the length, in bytes, of the MSDU frames. Also, let $Len = 4 \cdot \left\lceil \frac{L_{DATA} + 14}{4} \right\rceil$ and $C_i = 8 \cdot 4 \cdot \left\lceil \frac{O_M + Y_i \cdot Len}{4} \right\rceil$. 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 Equation (1) [20] where BER is the Bit Error Rate:

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

where:

$$\begin{aligned} T(DATA) &= TSym_{DL} \cdot \left\lceil \frac{\sum_{i=1}^{X} C_i + 22}{TSym_{DL} \cdot R_{DL}} \right\rceil \\ T(BAck) &= TSym_{UL} \cdot \left\lceil \frac{(30 \times 8) + 22}{TSym_{UL} \cdot R_{UL}} \right\rceil \end{aligned} \quad (2)$$

The term $BO(average)$ 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.

$T(DATA)$ and $T(BAck)$ are the transmission times of the data A-MPDU frames and BAck frames respectively. $T(BAck)$ 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.

R_{DL} and P_{DL} are the PHY rate and preamble used over the DL respectively while R_{UL} and P_{UL} are similarly defined for the UL (see **Figure 4**). $TSym_{DL}$ is the length of the OFDM symbol used over the DL and similarly $TSym_{UL}$ is defined for the Uplink. The conv. protocol [1] used by the PHY layer has an overhead of 22 bits which are added in the numerators of $T(DATA)$ and $T(BAck)$.

The term in Equation (1) is not continuous, so it is difficult to find the optimal X and $Yi(s)$, *i.e.* the values for X and $Yi(s)$ that maximize the throughput. However, in [20] it is shown that if one neglects the rounding in the denominator of Equation (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 Equation (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 Equation (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, $1 \le X \le 64$ (also $1 \le X \le 256$ for 11ax) and for every Y, $1 \le Y \le Y_{\max}$, what is the received throughput such that $Y_{\max}$ 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 μs. Neglecting the rounding in the denominator reduces its size by at most $2\times13.6\ \mu s$ in 11ax and $2\times4\ \mu s$ 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 Equations (3)-(6) and their derivation can be found in [20].

The throughput of 11ac for the traffic pattern in **Figure 2(b)** is given in Equation (3):

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

where:

$$\begin{aligned} T(DATA) &= TSym_{DL}\cdot\left\lceil\frac{\sum_{i=1}^{X}C_i+22}{TSym_{DL}\cdot R_{DL}}\right\rceil \\ T(BAck) &= TSym_{UL}\cdot\left\lceil\frac{(30\times8)+22}{TSym_{UL}\cdot R_{UL}}\right\rceil \\ T(BAR) &= TSym_{UL}\cdot\left\lceil\frac{(24\times8)+22}{TSym_{UL}\cdot R_{UL}}\right\rceil \end{aligned} \quad (4)$$

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 Equation (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 Equation (5):

$$Thr_{AX} = \frac{S \cdot \sum_{i=1}^{X} 8 \cdot Y_i \cdot L_{DATA} \cdot (1-BER)^{C_i}}{AIFS + BO(average) + P_{DL} + T'(DATA) + PE + SIFS + P_{UL} + T'(BAck) + PE} \quad (5)$$

where:

$$T'(DATA) = TSym_{DL} \cdot \left\lceil \frac{\sum_{i=1}^{X} C_i + ((O_M + 72) \cdot 8) + 22}{TSym_{DL} \cdot R_{DL}} \right\rceil$$
$$T'(BAck) = TSym_{UL} \cdot \left\lceil \frac{(30 \times 8) + 22}{TSym_{UL} \cdot R_{UL}} \right\rceil \quad (6)$$

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 $19 \le X \le 64$. For $1 \le X \le 18$ 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 $(X \times 4 \times 8)$. 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 Equation (5). S is either 4, 8, 16, 32 or 64, the number of stations to which the AP transmits simultaneously.

Again, the terms in Equation (3) and Equation (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.

We verified the analysis results of 11ax by simulation using the *ns*3 simulator [23]. The analysis and simulation results match perfectly since there is not any stochastic process in our transmission models. Therefore, we do not consider the simulation results 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 optimal number of 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 Equation (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:

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

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 μs in our case. Then, the following approximation on the relation between X and Y can be written:

$$T = \frac{X \cdot 8 \cdot (Y \cdot len + O_M)}{R_{DL}} + P_{DL} \tag{8}$$

or:

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

In Equation (8) and Equation (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 Equation (7) by the term in Equation (9) and receive:

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

Notice that the denominator of Equation (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:

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

The optimal Y, Y_{OPT}, is given in Equation (12):

$$Y_{OPT} = \frac{O_M \cdot \left(\sqrt{1 - \frac{4}{8 \cdot O_M \cdot \ln(1-BER)}} - 1 \right)}{2 \cdot Len} \tag{12}$$

Notice that by Equation (9) we can now write the optimal X, X_{OPT}, as:

$$X_{OPT} = \frac{R_{DL} \cdot (T - P_{DL})}{8 \cdot O_M \left(\frac{\left(\sqrt{1 - \frac{4}{8 \cdot O_M \cdot \ln(1 - BER)}} - 1 \right)}{2 \cdot Len} + 1 \right)} \tag{13}$$

Notice that we look for an integer Y_{OPT} and that Y_{OPT} must be at least 1. Therefore, Equation (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 Len, $Len =$ 1516, 528 and 80 bytes for MSDUs of lengths 1500, 512 and 64 bytes respectively. For all three cases we receive that $Y_{OPT} = \frac{653}{Len}$. For $Len =$ 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

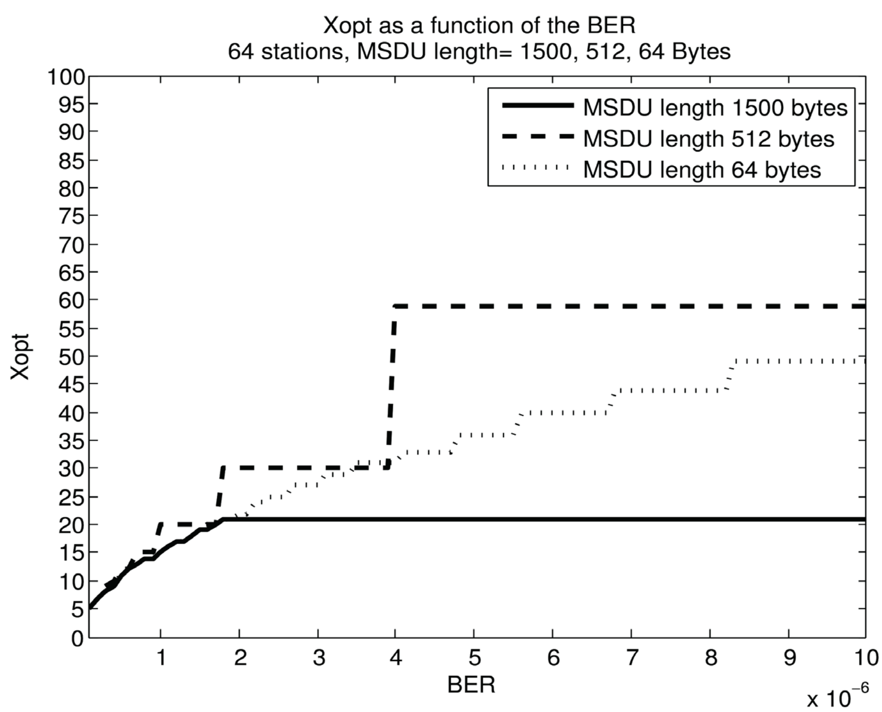

Figure 5. X_{OPT} as a function of the BER and MSDU length, 64 stations, in IEEE 802.11ax.

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 $BER = 0$ Equation (7) becomes:

$$Thr = \frac{S \cdot X \cdot Y \cdot 8 \cdot L_{DATA}}{O_p + P_{DL} + \frac{X \cdot 8 \cdot (Y \cdot Len + O_M)}{R_{DL}}} \tag{14}$$

and one needs to optimize the function:

$$\frac{Y}{8 \cdot (Y \cdot Len + O_M)} \tag{15}$$

which reveals that in every MPDU it is worthwhile to contain the maximum number of MSDUs, Y_{MAX}, which is $\left\lfloor \frac{11454 - O_M}{Len} \right\rfloor$.

Therefore:

$$X_{OPT} = \frac{R_{DL} \cdot (T - P_{DL})}{8 \cdot \left(\left\lfloor \frac{11454 - O_M}{Len} \right\rfloor \cdot Len + O_M \right)} \tag{16}$$

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

For MSDUs of 1500, 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. Throughputs' 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 checked what is the best transmission scheduling strategy, the best MCS and the best A-MPDU frame structure. In doing so we checked for every number S of stations all the applicable scheduling strategies, e.g. for 64 stations and 11ac these are $64 \cdot SU_{AC}(1)$ and $16 \cdot MU_{AC}(4)$, Figure 2(a) and Figure 2(b) respectively, and $64 \cdot SU_{AX}(1)$, $16 \cdot MU_{AX}(4)$, $8 \cdot MU_{AX}(8)$, $4 \cdot MU_{AX}(16)$, $2 \cdot MU_{AX}(32)$ and $MU_{AX}(64)$, Figure 2(c), for 11ax.

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 $BER = 0, 10^{-6}, 10^{-5}$.

There are three sets of results shown in Figure 6, Figure 7 and Figure 8. In Figure 6 we assume MSDUs of 1500 bytes and show the maximum throughputs received in every transmission flavor. For MSDUs of 64 and 512 bytes the results are the same. In Figure 7 we assume different MCSs and show their influence on the throughputs received in the various scheduling flavors of 11ax. We show results for $MU_{AX}(4)$ and $MU_{AX}(64)$ only. Notice that the maximum throughput received among the MCSs is the one shown in Figure 6. Figure 7 also considers the influence of using 64 or 256 MPDUs in an A-MPDU and of using MU-MIMO or OFDMA over the UL. In Figure 8 we consider three values of the *BER*, $0, 10^{-6}$ and 10^{-5} and show their influence on the received throughput for 4 and 64 stations and different numbers of MPDUs in an A-MPDU frame.

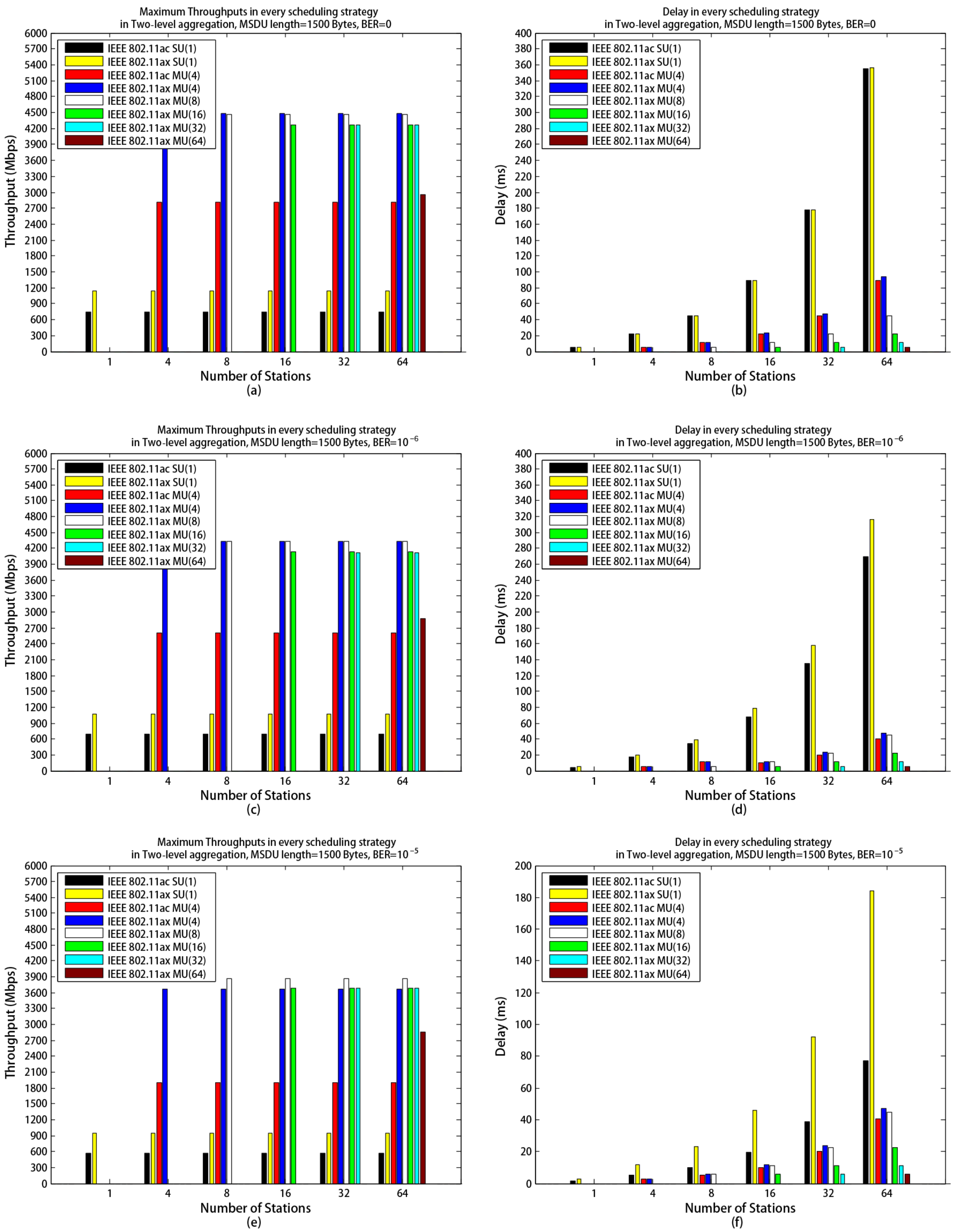

Figure 6. Maximum throughputs and corresponding access delays in Single User and Multi User in IEEE 802.11ac and IEEE 802.11ax.

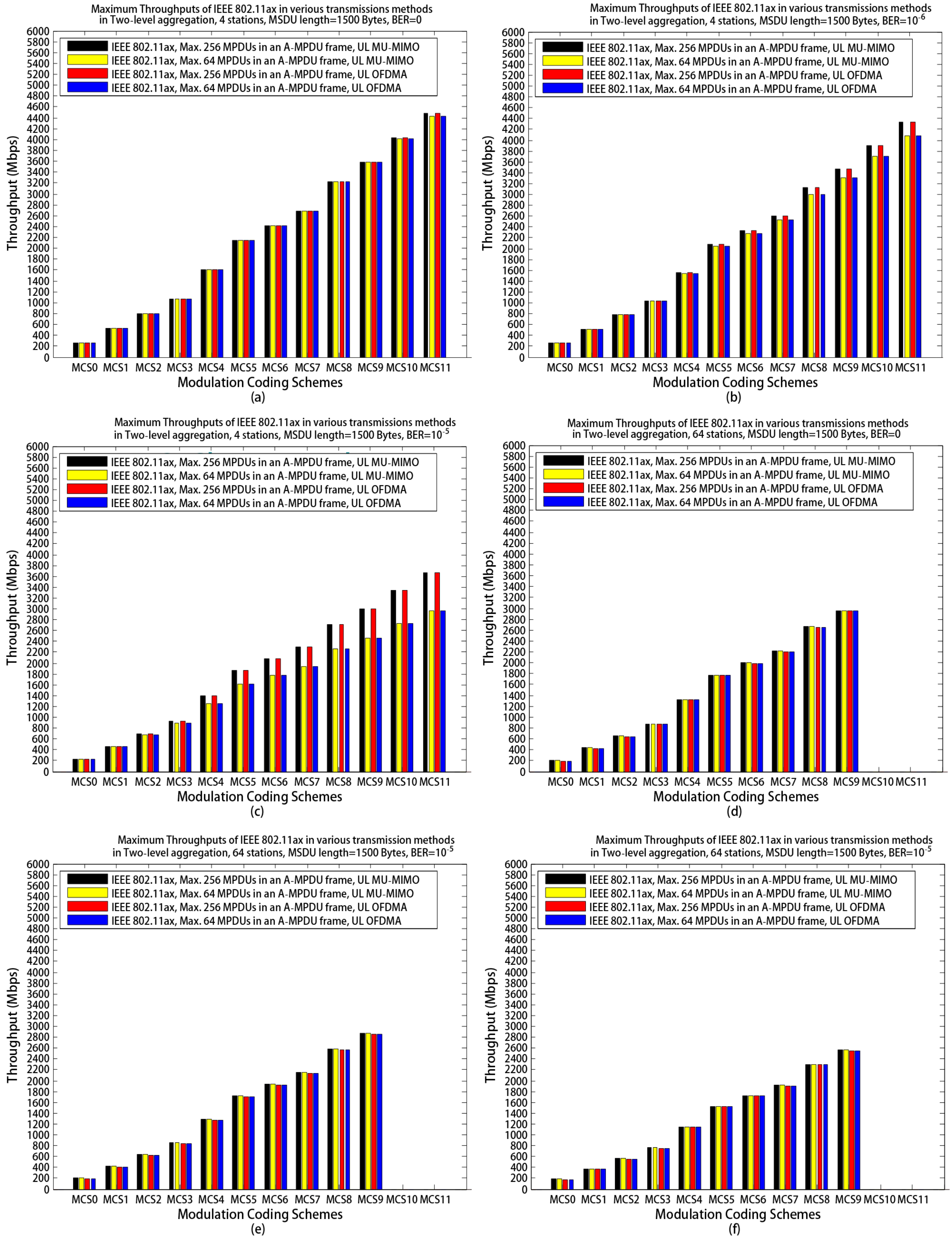

Figure 7. The throughputs of the various transmissions methods in IEEE 802.11ax for Multi User when transmitting simultaneously to 4 and 64 stations.

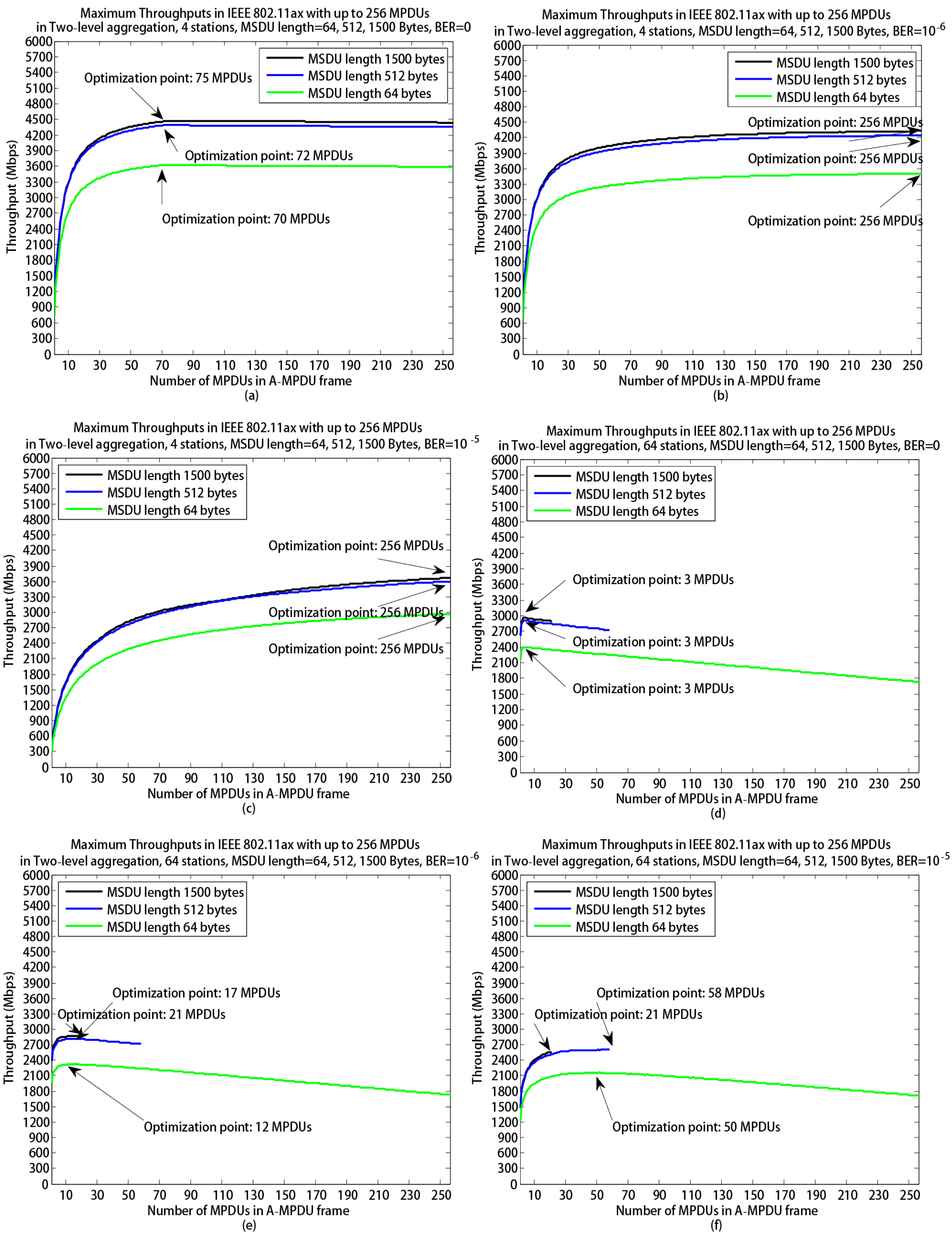

Figure 8. The throughputs vs. the number of MPDUs in A-MPDU frames in IEEE 802.11ax Multi User for 4 stations in MCS11 and 64 stations in MCS9.

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 A2 in the appendix 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 $MU_{AX}(32)$.

Notice also that for all stations 11ax outperforms 11ac due to larger PHY rates and simultaneous transmissions of BAck 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 results for the access delay. The relation between the access delays is similar to that between the number of stations to which the AP transmits simultaneously, because the cycles are about the same in length. Notice that the access delay criteria is important to real-time streaming applications such as voice conferencing or video conferencing/chat.

In Figure 6(c) and Figure 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 5.596 ms compared to 5.583 ms 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 5.5 ms. 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 5.5 ms, 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 Figure 7(a) and Figure 7(c) we show the results for $MU_{AX}(4)$ for $BER = 0$ and $BER = 10^{-5}$ respectively. In Figure 7(d) and Figure 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 bandwidth channels.

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 [24].

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 A2). However, rounding $T'(BAck)$ to an integral number of OFDM symbols of 14.4 μ (12.8 μs + 1.6 μs 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 how the number of MPDUs in A-MPDU frames has influence on the throughput. We consider $MU_{AX}(4)$ and $MU_{AX}(64)$ when using MCS11 and MCS9 respectively, assume MSDUs of 64, 512 and 1500 bytes and $BER = 0, 10^{-6}, 10^{-5}$. The results for $MU_{AX}(4)$ are shown in Figure 8(a), Figure 8(b) and Figure 8(c). In Figure 8(a) $BER = 0$ and in such a case it is efficient to transmit large MPDUs and 72 such MPDUs are possible for all sizes of MSDUs. If a larger number of MPDUs is used, a smaller number of MSDUs can be transmitted due to the limit of 5.484 ms on the PPDU transmission time, and a smaller throughput is received. Figure 8(c) shows the results for $BER = 10^{-5}$. In such a BER short MPDUs are efficient and thus it is possible to transmit 256 MPDUs.

The results for $MU_{AX}(64)$ are shown in Figure 8(d), Figure 8(e) and Figure 8(f). In the case of 64 stations the PHY rates are smaller compared to the case of 4 stations. For $BER = 10^{-5}$ only 21 and 58 MPDUs of a single MSDU are possible for MSDUs of 512 and 1500 bytes respectively. For $BER = 0$ larger MPDUs are efficient and for all MSDUs' sizes 3 MPDUs yield the maximum throughput. Notice that for MSDUs of 64 bytes it is possible to transmit 256 MPDUs, each containing one MSDU. However, 50 MPDUs yield the optimal throughput since several MSDUs are transmitted in an MPDU, with a reduced overhead compared to 256 MPDUs.

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.

IEEE 802.11ax 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 throughout, 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, *i.e.* $BER = 10^{-5}$.

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Appendix

In this appendix we show two tables containing PHY rates. In Table A1 we show the PHY rates and the preambles used in 11ac and 11ax in SU mode and in the various MCSs. In Table A2 we show the PHY rates and the preambles used in 11ac 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].

Table A1. 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.

	1		2		3		4	
	SU DL data transmission rate in 11ax		SU DL data transmission rate in 11ac		UL BAck transmission rate in 11ax		UL BAck transmission rate in 11ac	
MCS	PHY Rate (Mbps) GI = 0.8 μs	Preamble (μs)	PHY Rate (Mbps) GI = 0.8 μs	Preamble (μs)	PHY Rate (Mbps)	Preamble (μs)	PHY rate (Mbps)	Preamble (μs)
	1 station IEEE 802.11 ax		1 station IEEE 802.11 ac					
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

Table A2. 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		2		3		4		5	
	DL MU data transmission rate in 11ax		UL MU-MIMO BAck transmission rate in 11ax		UL OFDMA BAck Transmission rate in 11ax		DL MU-MIMO data transmission rate in 11ac		UL BAck transmission rate in 11ac	
MCS	PHY Rate (MBps) GI = 0.8 µs	Preamble (µs)	PHY Rate (MBps) GI = 1.6 µs	Preamble (µs)	PHY Rate (MBps) GI = 1.6 µs	Preamble (µs)	PHY Rate (MBps) GI = 0.8 µs	Preamble (µs)	PHY Rate (MBps)	Preamble (µs)
			4 stations IEEE 802.11 ax					4 stations IEEE 802.11 ac		
0	72.1	72.8	68.1	64.8	16.3	64.8	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
2	216.2	68.8	204.2	64.8	48.8	64.8	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
4	432.4	68.8	408.3	64.8	97.5	64.8	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
6	648.5	68.8	612.5	64.8	146.3	64.8	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
8	864.7	68.8	816.7	64.8	195.0	64.8	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
10	1080.9	68.8	1020.8	64.8	243.8	64.8	N/A	N/A	N/A	N/A
11	1201.0	68.8	1134.2	64.8	270.8	64.8	N/A	N/A	N/A	N/A
			8 stations IEEE 802.11 ax					4 stations IEEE 802.11 ac		
0	36.0	76.8	34.0	64.8	8.1	64.8	58.5	48.0	48.0	20.0
1	72.1	76.8	68.1	64.8	16.3	64.8	117.0	48.0	48.0	20.0
2	108.1	72.8	102.1	64.8	24.4	64.8	175.5	48.0	48.0	20.0
3	144.1	72.8	136.1	64.8	32.5	64.8	234.0	48.0	48.0	20.0
4	216.2	68.8	204.2	64.8	48.8	64.8	351.0	48.0	48.0	20.0
5	288.2	68.8	272.2	64.8	65.0	64.8	468.0	48.0	48.0	20.0
6	324.3	68.8	306.3	64.8	73.1	64.8	526.5	48.0	48.0	20.0
7	360.3	68.8	340.3	64.8	81.3	64.8	585.0	48.0	48.0	20.0
8	432.4	68.8	408.3	64.8	97.5	64.8	702.0	48.0	48.0	20.0
9	480.4	68.8	453.7	64.8	108.3	64.8	780.0	48.0	48.0	20.0
10	540.4	68.8	510.4	64.8	121.9	64.8	N/A	N/A	N/A	N/A
11	600.4	68.8	567.1	64.8	135.4	64.8	N/A	N/A	N/A	N/A
			16 stations IEEE 802.11 ax					4 stations IEEE 802.11 ac		
0	17.2	84.8	16.3	64.8	8.1	64.8	58.5	48.0	48.0	20.0
1	34.4	84.8	32.5	64.8	16.3	64.8	117.0	48.0	48.0	20.0
2	51.6	76.8	48.8	64.8	24.4	64.8	175.5	48.0	48.0	20.0
3	68.8	76.8	65.0	64.8	32.5	64.8	234.0	48.0	48.0	20.0
4	103.2	72.8	97.5	64.8	48.8	64.8	351.0	48.0	48.0	20.0
5	137.6	72.8	130.0	64.8	65.0	64.8	468.0	48.0	48.0	20.0
6	154.9	72.8	146.3	64.8	73.1	64.8	526.5	48.0	48.0	20.0
7	172.1	72.8	162.5	64.8	81.3	64.8	585.0	48.0	48.0	20.0
8	206.5	72.8	195.0	64.8	97.5	64.8	702.0	48.0	48.0	20.0
9	229.4	72.8	216.7	64.8	108.3	64.8	780.0	48.0	48.0	20.0
10	258.1	72.8	243.8	64.8	N/A	N/A	N/A	N/A	N/A	N/A
11	286.8	72.8	270.8	64.8	N/A	N/A	N/A	N/A	N/A	N/A

Continued

	1		2		3		4		5	
	DL MU data Transmission rate in 11ax		UL MU-MIMO BAck transmission rate in 11ax		UL OFDMA BAck transmission rate in 11ax		DL MU-MIMO data transmission rate in 11ac		UL BAck transmission rate in 11ac	
MCS	PHY Rate (MBps) GI = 0.8 µs	Preamble (µs)	PHY Rate (MBps) GI = 1.6 µs	Preamble (µs)	PHY Rate (MBps) GI = 1.6 µs	Preamble (µs)	PHY Rate (MBps) GI = 0.8 µs	Preamble (µs)	PHY Rate (MBps)	Preamble (µs)
	32 stations IEEE 802.11 ax						4 stations IEEE 802.11 ac			
0	8.6	104.8	8.1	64.8	1.7	64.8	58.5	48.0	48.0	20.0
1	17.2	104.8	16.3	64.8	3.3	64.8	117.0	48.0	48.0	20.0
2	25.8	84.8	24.4	64.8	5.0	64.8	175.5	48.0	48.0	20.0
3	34.4	84.8	32.5	64.8	6.7	64.8	234.0	48.0	48.0	20.0
4	51.6	80.8	48.8	64.8	10.0	64.8	351.0	48.0	48.0	20.0
5	68.8	80.8	65.0	64.8	13.3	64.8	468.0	48.0	48.0	20.0
6	77.4	80.8	73.1	64.8	15.0	64.8	526.5	48.0	48.0	20.0
7	86.0	80.8	81.3	64.8	16.7	64.8	585.0	48.0	48.0	20.0
8	103.2	80.8	97.5	64.8	20.0	64.8	702.0	48.0	48.0	20.0
9	114.7	80.8	108.3	64.8	22.2	64.8	780.0	48.0	48.0	20.0
10	129.0	80.8	121.9	64.8	N/A	N/A	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	N/A	N/A
	64 stations IEEE 802.11 ax						4 stations IEEE 802.11 ac			
0	3.8	136.8	3.5	64.8	0.8	64.8	58.5	48.0	48.0	20.0
1	7.5	136.8	7.1	64.8	1.7	64.8	117.0	48.0	48.0	20.0
2	11.3	100.8	10.6	64.8	2.5	64.8	175.5	48.0	48.0	20.0
3	15.0	100.8	14.2	64.8	3.3	64.8	234.0	48.0	48.0	20.0
4	22.5	88.8	21.3	64.8	5.0	64.8	351.0	48.0	48.0	20.0
5	30.0	88.8	28.3	64.8	6.7	64.8	468.0	48.0	48.0	20.0
6	33.8	88.8	31.9	64.8	7.5	64.8	526.5	48.0	48.0	20.0
7	37.5	88.8	35.4	64.8	8.3	64.8	585.0	48.0	48.0	20.0
8	45.0	88.8	42.5	64.8	10.9	64.8	702.0	48.0	48.0	20.0
9	50.0	88.8	47.2	64.8	11.1	64.8	780.0	48.0	48.0	20.0
10	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
11	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A