MAC level Throughput comparison: 802.11ax vs. 802.11ac

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Abstract

In this paper we compare between the maximum Throughputs received in IEEE 802.11ax and IEEE 802.11ac in a scenario where a single user continuously transmits to another one. The comparison is done as a function of the Modulation/Coding scheme in use. In IEEE 802.11ax we consider two modes of operation where in one Acknowledgment frame up to 64 or 256 frames are acknowledged respectively. IEEE 802.11ax outperforms IEEE 802.11ac by at most 48% and 29% in unreliable and reliable channels respectively.

Keywords:IEEE 802.11ax;IEEE 802.11ac; Throughput; Single User;

1 Introduction

The latest IEEE 802.11-REVmc Standard (WiFi), created and maintained by the IEEE LAN/MAN Standards Committee (IEEE 802.11) [1] is currently the most effective solution within the range of Wireless Local Area Networks (LAN). Since its first release in 1997, the

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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 its 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 introduced recently [2]. IEEE 802.11ax is a six generation type of a WLAN in the IEEE 802.11 set of types of WLANs [3, 4] and it is a successor to IEEE 802.11ac [5]. Currently this project is at a very early stage of development and it is due to be publicly released in 2019. IEEE 802.11ax is predicted to have a top capacity of around 10 Gbps and a frequency of 2.4 and/or 5 GHz, and has the goal of providing 4 times the Throughput of IEEE 802.11ac.

In this paper we compare between the Throughputs of IEEE 802.11ax and IEEE 802.11ac in a scenario where one user continuously transmits in a single user (SU) operation mode to another user without collisions, using aggregation. In order to achieve the 4 times Throughput compared to IEEE 802.11ac, around 10Gbps, the IEEE 802.11ax addresses several new features.

The first feature extends by 4 times the IEEE 802.11ac OFDM symbols duration while preserving the IEEE 802.11ac Guard Interval (GI). In addition, two new Modulation/Coding schemes are introduced in IEEE 802.11ax, 1024 QAM 3/4 and 1024 QAM 5/6, MCS10 and MCS11 respectively. In order to support the above two new features the PHY Preamble in IEEE 802.11ax is longer than that in IEEE 802.11ac, as we show in Section 2.

Next, in this paper we focus in Two-Level aggregation, first introduced in IEEE 802.11n [6] and later extended in IEEE 802.11ac [5] and IEEE 802.11ax [2]. In order to increase the Throughput in IEEE 802.11ax the MAC acknowledgment window is extended to 256 MAC Protocol Data Units (MPDU) which extends the IEEE 802.11ac aggregation capability.

In this paper we verify what is the Throughput improvement achieved in IEEE 802.11ax following the above new features. In overall, the research on the performance of IEEE 802.11ax in various scenarios is in its first steps [7].

The paper is organized as follows: In Section 2 we describe in more details the new features of IEEE 802.11ax mentioned above and describe the transmission scenario over which we compare between IEEE 802.11ax and IEEE 802.11ac. 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. [8]. In Section 3 we analytically compute the Throughput of the transmission scenario described in Section 2 and in Section 4 we present the Throughputs of the protocols and compare between them. In Section 5 we analytically compute the PHY rates from which using a 256 MPDUs acknowledgment window size in IEEE 802.11ax is better than using a 64 MPDUs acknowledgment window size and finally Section 6 summarizes the paper. In the rest of the paper we denote IEEE 802.11ax and IEEE 802.11ac by 11ax and 11ac respectively.

2 Model

In this paper we consider the Single User (SU) operation mode in 11ax vs. that in 11ac. In this operation mode every transmitted PHY Protocol Data Unit (PPDU) is destined to one user only. As mentioned, there are several new features in 11ax compared to 11ac in the PHY and MAC layers in the SU operation mode. Assuming an OFDM based PHY layer, every OFDM symbol is extended from $3.2 \mu s$ in 11ac to $12.8 \mu s$ in 11ax. Since the same Guard Interval (GI) is added to every such symbol, the overhead in 11ax due to the GI is lower. Second, in 11ax there are two new Modulation/Coding schemes (MCSs), 1024 QAM 3/4 and 1024 QAM 5/6, MCS 10 and MCS 11 respectively, applicable for bandwidth larger than 20 MHz. The above two features enlarge the PHY rate of 11ax.

In this paper we focus in the Two-Level aggregation scheme, first introduced in IEEE 802.11n [6], in which several MPDUs are transmitted in a single PHY Service Data Unit (PSDU). Such a PSDU is denoted Aggregate MAC Protocol Data Unit (A-MPDU) frame. In Two-Level aggregation every MPDU contains several MAC Service Data Units (MSDU). 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 multiply of 4 bytes together with the SubHeader field. Every MPDU is also rounded to an integral multiply 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 1048575 bytes and this limit is removed in 11ax. In both 11ac and 11ax the transmission time of the PPDU (PSDU and its Preamble) is limited to $\sim 5.4 ms$ ($5400 \mu s$) due to L-SIG (one of the legacy Preamble’s fields) duration limit [1].

In this paper we also assume that all the 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.
In Figure 1 we show the PPDU formats in 11ax and 11ac in parts (A) and (B) respectively. In the 11ax PPDU format there are HE-LTF fields, the number of which equals to the number of Spatial Streams (SSs) in use. In this paper we assume that each such field is of the shortest length possible, i.e. $7.2\mu s$. In the PPDU format of 11ac there are the VHT-LTF fields, the number of which equals again to the number of SSs, and each is $4\mu s$. Notice that in SU mode and when using the same number $S$ of SS, the Preamble in 11ax is longer than that in 11ac by $S \cdot (7.2 - 4) = S \cdot 3.2\mu s$.

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 so we assume that it does not present, i.e. it is of length $0\mu s$.

We also assume a UDP like traffic where the AP continuously transmits Data MSDUs to a station, and the station responds with the BAck control frame. A transmission of a PPDU from the AP followed by a BAck control frame from the station is denoted Transmission Cycle and such a cycle repeats itself continuously, as shown in Figure 2. We also assume the
compressed BAck frame format and consider two cases: in one case the AP transmits up to 64 MPDUs in every A-MPDU frame and so the BAck frame is 32 bytes long. It contains 8 bytes, i.e. 64 bits, each acknowledging one MPDU. In the second case, that is relevant to 11ax only, the AP can transmit up to 256 MPDUs in an A-MPDU frame and so the BAck frame is 56 bytes long, containing 32 bytes for acknowledging MPDUs. The BAck frame is transmitted in legacy mode using a 24 Mbps PHY rate. Therefore, its transmission times are 31µs and 39µs in the above two cases respectively.

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 successfully at the destination. We assume a model where these probabilities are independent from bit to bit [9].

3 Throughput computation

Let $X$ be the number of MPDU frames in an A-MPDU frame, numbered 1, ..., $X$, and $Y_i$ be the number of MSDUs in MPDU number $i$.

Also, let $O_P = AIFS + BO + Preamble + SIFS + BAck$, $O_M = MPDUDelimiter + MacHeader + FCS$, $Len = 4 \cdot \lceil \frac{L_{DATA}+14}{4} \rceil$ and $C_i = 8 \cdot 4 \cdot \lceil \frac{O_M+Y_i \cdot Len}{4} \rceil$.

Then, the Throughput in both 11ax and 11ac is given by Eq. 1 [8]:

$$Thr = \frac{8 \sum_{i=1}^{X} Y_i \cdot L_{DATA} \cdot (1 - BER)^{C_i}}{O_P + TSym \left\lfloor \frac{\sum_{i=1}^{X} C_i + 22}{TSym - R} \right\rfloor}$$

(1)

$TSym$ is the length of an OFDM symbol and every transmission must be of an integral number of OFDM symbols. The additional 22 bits in the denomination are due to the SERVICE and TAIL fields that are added to every transmission by the PHY layer conv. protocol [1].

The function in Eq. (1) is not continuous and so it is difficult to find the optimal $X$ and $Y$. However, in [8] it is shown that if one neglects the rounding in the denomination 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 the transmission time of the PPDU does not enable to transmit the same number of MSDUs in all the MPDUs.

If one neglects the rounding of the denomination of Eq. (1) the received Throughput for every $X$ and $Y$ is as large as that received in Eq. (1). The difference depends on the size of
the denomination.

We therefore use the result in \[8\] 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 5.4 ms on the transmission time of the PPDU (PSDU+Preamble). In case where 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 denomination of any of the maximum Throughputs is around 1000 \(\mu s\). Neglecting the rounding in the denomination reduces its size by at most 13.6 \(\mu s\) in 11ax and 4 \(\mu s\) in 11ac. Thus, the mistake in the received maximum Throughputs is in the order of at most 1.4%.

4 Throughput comparison between IEEE 802.11ax and IEEE 802.11ac

In Figures 3, 4, 5, 6 we show the maximum Throughputs of 11ax and 11ac for four different channel’s conditions: BER= 0, \(10^{-7}\), \(10^{-6}\), \(10^{-5}\) respectively. Every figure contains results for 3 different sizes \(L_{\text{DATA}}\) of MSDUs: \(L_{\text{DATA}} = 64, 512\) and 1500 octets in parts (A), (B) and (C) respectively. There are results for 11ac, with 64 MPDUs in every A-MPDU frame, for 11ax with 64 MPDUs in every A-MPDU frame and for 11ax with 256 MPDUs in every A-MPDU frame. The last two flavors of 11ax are denoted 11ax/64 and 11ax/256 respectively.

First notice that in every figure the Throughput is shown as a function of the MCSs in the x-axis. In every MCS 11ax and 11ac enable different PHY rates and so the comparison criteria is the Throughput of the two protocols in every MCS in use. Also notice that MCS 10 and MCS 11 are not possible in 11ac and so 11ac does not have results for these MCSs. In 11ac the PHY rates for MCS0-MCS9 are 234, 468, 702, 936, 1404, 1872, 2106, 2340, 2808 and 3120 Mbps respectively, assuming a 160MHz channel, 4 SSs and a 0.8 \(\mu s\) Guard Interval. In 11ax the PHY rates for MCS0-MCS11 are 288, 576, 864, 1152, 1729, 2305, 2594, 2882, 3458, 3843, 4323 and 4803 Mbps respectively.

In all the figures the performance of 11ax is better than that of 11ac. This is due to the larger PHY rates that 11ax enables in every MCS compared to 11ac. For BER=0
11ax/256 outperforms 11ac by 29% and in BER = $10^{-5}$ the improvement reaches 48%. When comparing between 11ax/64 and 11ax/256 one can see that for BER = 0 11ax/256 outperforms 11ax/64 only for MCSs higher than MCS2. On the other hand in the case of BER = $10^{-5}$ 11ax/256 outperforms 11ax/64 starting from MCS0. The reason for this difference is as follows: for BER = 0 it is worth to transmit MPDUs with as much MSDUs as possible. Thus, not many MPDUs are transmitted when the maximum Throughput is received and the limiting parameter on the Throughput is the limit on the PPDU transmission time. Therefore, is small PHY rates, i.e. small MCSs, 11ax/256 has no advantage over 11ax/64. Only when the PHY rates increase, the limit of 64 MPDUs in 11ax/64 begins to be significant and 11ax/256 begins to outperform 11ax/64. When BER = $10^{-5}$ it is worth to transmit short MPDUs because the failure probability of an MPDU increases with its length. In small PHY rates the limiting parameter is now the number of MPDUs and not the limit on the PPDU’ transmission times. Therefore, 11ax/256 outperforms 11ax/64 also in small indexed MCSs.

Notice that 11ax/256 outperforms 11ac in BER = $10^{-5}$, in percentage, more than in BER=0. The main overhead incurred in the transmissions is $O_p$. In BER=0 MPDUs are large with relatively many MSDUs. On the other hand in BER = $10^{-5}$ MPDUs are short in order to keep on large transmission success probabilities. More MPDUs in BER = $10^{-5}$ are therefore more significant than in BER=0 and so is the relative improvement in Throughput between 11ax/256 and 11ac.

5 Acknowledgment window size analysis

One can conclude from the results in Section 4 two findings: First, as the BER is smaller, 11ax/256 outperforms 11ax/64 from larger PHY rates. Second, the MCS from which
Figure 4: Comparison between the maximum Throughputs of 802.11ax and 802.11ac in the Two-level aggregation scheme, single user operation mode and different length MSDUs. BER=10^{-7}.

Figure 5: Comparison between the maximum Throughputs of 802.11ax and 802.11ac in the Two-level aggregation scheme, single user operation mode and different length MSDUs. BER=10^{-6}.
Figure 6: Comparison between the maximum Throughputs of 802.11ax and 802.11ac in the Two-level aggregation scheme, single user operatopm mode and different length MSDUs. BER=10\(^{-5}\).

11ax/256 outperforms 11ax/64 is not dependent on the MSDU size. We want to investigate these phenomena further.

In the following analysis we use the above mentioned approximation from [8] where we neglect the rounding in the denomination of Eq. 1 and assume that all the MPDUs contain the same number of MSDUs. We also neglect the rounding of the MPDU size and the addition of the 22 bits in the denomination. Following this approximation Eq. 1 turns out to be Eq. 2:

\[
Thr = \frac{8 \cdot X \cdot Y \cdot L_{DATA} \cdot (1 - BER)^8 \cdot (O_M + Y \cdot Len)}{O_P + \frac{8 \cdot X \cdot (O_M + Y \cdot Len)}{R}}
\]  

(2)

Notice from Eq. 2 that given a number \( Y \) of MSDUs in an MPDU, it is worthwhile to contain as many MPDUs as possible in the A-MPDU frame, up to the limit on the PPDU transmission time.

### 5.0.1 Reliable channel, BER=0

Let MCS\(_C\) be the MCS from which 11ax/256 outperforms 11ax/64. For BER=0 it is possible to compute MCS\(_C\) accurately. Recall that \( O_M \) is the sum of the lengths of the MAC Header, MPDU Delimiter and FCS fields in bytes. Also recall that \( Len = 4 \cdot \lceil \frac{L+14}{4} \rceil \), let \( P_r \) be the length of the Preamble in \( \mu s \) (64.8\( \mu s \) in our case), \( R \) be the PHY rate and \( T \) be the limit on the transmission time of the PPDU (5400 \( \mu s \) in our case). Finally, let \( Y_{max} = \lceil \frac{11454 - O_M}{Len} \rceil \) be the maximum possible number of MSDUs per MPDU frame. For BER=0 it is most efficient
to include $Y_{\text{max}}$ MSDUs per MPDU frame and as many MPDUs in the A-MPDU frame up to the limit $T$. Then, one receives the following equation for 11ax/64 assuming that the PHY rate enables to transmit 64 MPDUs of $Y_{\text{max}}$ MSDUs each: $T = \frac{64 \cdot (O_M + Y_{\text{max}} \cdot \text{Len})}{R} + P_r$. The largest PHY rate the enables the transmissions of up to 64 MPDUs is $R = \frac{64 \cdot (O_M + Y_{\text{max}} \cdot \text{Len})}{T - P_r}$.

For $L_{\text{DATA}} = 1500$ bytes ($\text{Len} = 1516$ bytes) it turns out that $R = 1021 \text{ Mbps}$. Neglecting the rounding of $Y_{\text{max}}$ one receives that $R = \frac{64 \cdot 1154.5 \cdot 8}{T - P_r}$ which, independently of $L_{\text{DATA}}$, equals 1099 Mbps for $T = 5400 \mu s$ and $P_r = 64.8 \mu s$. The range 1021-1099 Mbps falls between MCS2 and MCS3 i.e. 11ax/256 outperforms 11ax/64 starting from $MCS_C = MCS_3$ for any MSDU length $L_{\text{DATA}}$ up to 1500 bytes. In Figure 3 the difference between 11ax/64 to 11ax/256 in MCS3 is too small to be noticed, however from MCS4 the difference is noticeable.

### 5.0.2 Unreliable channel, BER>0

For positive BERs the optimal number of MSDUs per MPDU is not necessarily $Y_{\text{max}}$. Therefore, we use the following approximation. Given that it is worthwhile to transmit as long PPDU as possible, then let $X_{\text{opt}}$ and $Y_{\text{opt}}$ be the number of MPDUs and the number of MSDUs per MPDU respectively in the optimal A-MPDU, i.e. the A-MPDU that achieves the largest Throughput. Then, Eqs. 3 and 4 can give a relation between $X_{\text{opt}}$ and $Y_{\text{opt}}$:

$$T = \frac{X_{\text{opt}} \cdot (Y_{\text{opt}} \cdot \text{Len} + O_M)}{R} + P_r \tag{3}$$

Or:

$$Y_{\text{opt}} = \frac{R \cdot T - R \cdot P_r - X_{\text{opt}} \cdot O_M}{X_{\text{opt}} \cdot \text{Len}} \tag{4}$$

Using Eqs. 3 and 4 the search for the optimal A-MPDU can consider only the number $X$ of MPDUs and the number $Y$ of MSDUs per MPDU that maintain Eq. 4. Eq. 2 can therefore be re-written as:

$$\text{Thr} = \frac{8 \cdot X \cdot \left(\frac{R \cdot T - R \cdot P_r - X \cdot O_M}{X \cdot \text{Len}}\right) \cdot L_{\text{DATA}} \cdot (1 - BER)^{8 \cdot \left(\frac{R \cdot T - R \cdot P_r - X \cdot O_M}{X \cdot \text{Len}}\right) \cdot \text{Len}}}{O_P - P_r + T} \tag{5}$$

Notice that the denominator of Eq. 5 is constant because we use the outcome that it is most efficient that the transmission time of the PPDU will be the largest possible.
To find the largest Throughput we derive Eq. 5 according to $X$ and find that the optimal $X$ is the single positive solution of a quadratic equation, which reveals that Eq. 5 is unimodal. The optimal $X$, $X_{opt}$, is given by Eq. 6:

$$X_{opt} = \frac{R \cdot (T - P_r) \cdot \ln(1 - BER) \cdot O_M}{2} \cdot (1 - \sqrt{1 - \frac{4}{O_M \cdot \ln(1 - BER)}})$$

(6)

If we now substitute the parameters in Eq. 6 by the values we use in this paper, and using $BER = 10^{-7}, 10^{-6}, 10^{-5}$ we get that $X_{opt} = 0.0991 \cdot R, 0.3117 \cdot R, 0.9678 \cdot R$ respectively. $X_{opt}$ does not depend on the MSDU size but it is a function of the PHY rate $R$. If we look for the PHY rates for which $X_{opt} > 64$, i.e. $11ax/256$ outperforms $11ax/64$, we get the following PHY rates 645, 205, 66 Mbps respectively. This means that the corresponding $MCS_C$'s are $MCS_2$, $MCS_0$, $MCS_0$ respectively, as is shown in Figures 4-6 respectively. Notice that by the above it turns out that the $MCS_C$'s do not depend on the MSDUs’ sizes, as it is also observed from Figures 4-6.

6 Summary

A comparison between the maximum Throughputs of IEEE 802.11ax and IEEE 802.11ac in a single user operation mode is performed, in a scenario where one user transmits continuously to another user using Two-Level aggregation. Concerning IEEE 802.11ax two flavors are considered, using acknowledgment windows of 256 and 64 MPDUs respectively.

IEEE 802.11ax outperforms IEEE 802.11ac by 48% and 29% in unreliable and reliable channels respectively. Also, a detailed analysis comparing between the two flavors of IEEE 802.11ax is given.

This paper is one of the first to evaluate the performance of IEEE 802.11ax and more are expected to come for other scenarios such as the multi user operation mode.
References

[1] IEEE P802.11-REVmc\textsuperscript{TM}/D5.2, IEEE Standard for Information Technology - Telecommunications and Information Exchange between Systems - Local and Metropolitan Area Networks - Specific Requirements. Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, IEEE, New York, (March 2016)

[2] IEEE Std. 802.11ax\textsuperscript{TM}/D0.1, IEEE Standard for Information Technology - Telecommunications and Information Exchange between Systems - Local and Metropolitan Area Networks - Specific Requirements. Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specific requirements. IEEE, New York, (2016)

[3] IEEE 802.11ax: Next Generation Wireless Local Area Networks, 10th Int. Conf. on Heterogeneous Networking for Quality, Security and Robustness (QSHINE), (2014) 77-82

[4] IEEE 802.11ax: High-efficiency WLANs, IEEE Wireless Communications, 23(1) (2016) 38-46

[5] IEEE Std. 802.11ac\textsuperscript{TM}-2013, IEEE Standard for Information Technology - Telecommunications and Information Exchange between Systems - Local and Metropolitan Area Networks - Specific Requirements. Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specific requirements. Amendment 4: Enhancements for Very High Throughput for Operation in Bands below 6 GHz, IEEE, New York, (2013)

[6] IEEE Std. 802.11\textsuperscript{T}M - 2012, Standard for Information Technology - Telecommunications and Information Exchange between Systems - Local and Metropolitan Area Networks - Specific Requirements. Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, IEEE, New York, (2012)

[7] An OFDMA based Concurrent Multiuser MAC for Upcoming IEEE 802.11ax, IEEE Wireless Comm. and Networking Conf. (WCNC) (2015) 136-141

[8] O. Sharon, Y. Alpert, MAC level Throughput comparison: 802.11ac vs. 802.11n, Physical Communication Journal 12 (2014) 33-49

[9] J. Lemmon, Wireless link statistical bit error rate model, Technical Report 02-934, U.S. Dept. of Commerce, June, (2002)