IEEE 802.11ac: Enhancements for Very High Throughput WLANs

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***Abstract*—The IEEE 802.11ac is an emerging very high throughput (VHT) WLAN standard, targeted to achieve data rates of close to 7 Gbps for the 5 GHz band. In this paper, we introduce the key mandatory and optional PHY features, as well as the MAC enhancements of 802.11ac over the existing 802.11n standard in the evolution towards higher data rates. Through numerical analysis, we compare the MAC performance between 802.11ac and 802.11n over three different frame aggregation mechanisms, viz., aggregate MAC service data unit (A-MSDU), aggregate MAC protocol data unit (A-MPDU), and hybrid A-MSDU/A-MPDU aggregation. Our results indicate that 802.11ac with a configuration of 80MHz and single (two) spatial stream(s) outperforms 802.11n with a configuration of 40 MHz and two spatial streams in terms of maximum throughput by 28% (84%). In addition, we demonstrate that hybrid A-MSDU/A-MPDU aggregation yields the best performance for both 802.11n and 802.11ac devices, and its improvement is a function of the maximum A-MSDU size.**

I. Introduction

In recent years, the continued effort in pursuit of gigabit wireless communications has been most noticeable in the IEEE 802.11 WLAN [1]. For example in 2010, the Wireless Gigabit (WiGig) Alliance, formed by a consortium of industry leaders, has completed the first draft of the WiGig specification [2] that defines a unified architecture to enable tri-band communications over the frequency bands of 2.4, 5, and 60 GHz. The WiGig specification, which aims to achieve multi-gigabit wireless communication in the 60 GHz band, has since been contributed to the new 802.11ad amendment. It is built on the existing 802.11 standard where interoperability with the 2.4 and 5 GHz bands are based on the existing 802.11b/a/g/n and the upcoming 802.11ac standards.

In this paper, we focus on gigabit solution in the 5 GHz band where the emerging 802.11ac amendment [3] could provide a maximum PHY data rate of close to 7 Gbps. To be more specific, it promises MAC throughput of more than 500 Mbps for a single user scenario and aggregated MAC throughput of more than 1 Gbps for a multi-user scenario, both utilizing no more than 80 MHz of channel bandwidth. Consequently, 802.11ac is targeted at higher data rate services such as high-definition television, wireless implementation of high-definition multimedia interface (HDMI replacement), and lately the wireless display applications which according to the report in [4] could result in an expected shipment of 50 million wireless video devices in 2015. To the best of the authors' knowledge, this is one of the first studies to introduce the draft 802.11ac amendment and analyze its potential benefits in terms of MAC performance gains as compared to existing 802.11n devices over various frame aggregation mechanisms.

The remainder of this paper is organized as follows. Section II presents an overview of the key mandatory and optional PHY features together with the MAC enhancements of 802.11ac over the existing 802.11n standard. Section III provides the numerical analysis of 802.11ac and 802.11n MAC performances in terms of maximum throughput and MAC efficiency. Section IV compares the performance analysis between 802.11ac and 802.11n over various frame aggregation mechanisms. Finally, Section V concludes this paper with some directions for future work.

II. Overview of Key PHY Features and MAC Enhancements

In general, 802.11ac could be seen as a lateral extension of 802.11n in which the two basic notions of multiple input, multiple output (MIMO) and wider channel bandwidth, anchored in 802.11n [5], [6] are enhanced. The basic idea is that theoretical maximum PHY data rate can be linearly increased by a factor of the number of spatial streams (transmit/receive antennas) or channel bandwidth. In other words, PHY data rate can be doubled (quadrupled) by doubling the number of spatial streams or (and) channel bandwidth. Fig. 1 illustrates the key mandatory and optional PHY features, as well as the MAC enhancements introduced in 802.11ac. Note that the blocks in dashed lines represent the new PHY features and key MAC enhancements of 802.11ac in contrast to 802.11n at the time of writing.

A. Mandatory and Optional PHY Features

As depicted in Fig. 1, 802.11ac maintains most of the mandatory PHY features of 802.11n such as binary convolutional coding (BCC) for forward error correction, basic MIMO, modulation and coding schemes (MCSs) of 0 to 7, and regular guard interval of 800 ns. The key difference in these mandatory features is the support of 80 MHz channel bandwidth for an approximately twofold increase in data rate as compared to 802.11n where 40 MHz is the largest channel bandwidth. As a result, 802.11ac mandates only a single spatial stream instead of one or two spatial streams as specified

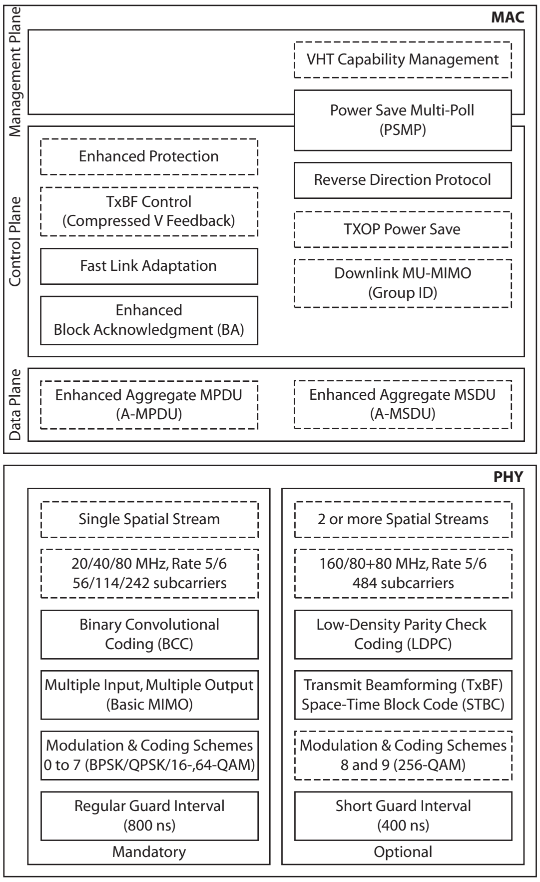


Fig. 1. Overview of key mandatory and optional PHY features of 802.11ac, and MAC enhancements.

in 802.11n. One reason for such change is that increasing the number of antennas often relates to higher cost. Hence, the modes that utilize more than one spatial streams are now optional in 802.11ac. This is due to the fact that the 80 MHz mode is seen as the lower cost alternative to increase PHY data rate as compared to 40 MHz mode with two spatial streams for example. In terms of optional features, 802.11ac defines the support of 160 MHz channel bandwidth for yet another twofold increase in data rate over the mandatory 80 MHz channel bandwidth. In addition, two new MCSs 8 and 9 are introduced based on 256-QAM with code rates of $3/4$ and $5/6$ for a further 20% and 33% improvements in data rate, respectively, when comparing to the highest MCS specified in 802.11n based on 64-QAM with a code rate of $5/6$.

In order to support wider channel bandwidths, 802.11ac defines its channelization for 20, 40, 80, and 160 MHz channels as shown in Fig. 2. For example, a 40 MHz transmission band is formed by two contiguous 20 MHz bands, whereas an 80 MHz transmission band is formed by two contiguous 40 MHz bands in which one of the 20 MHz bands is the primary channel and the rest are secondary channels. However, a 160 MHz transmission band is formed by both lower and higher 80 MHz bands which may be either contiguous or non-contiguous. Note that such a channelization structure implies that only a specific set of primary and secondary channels can

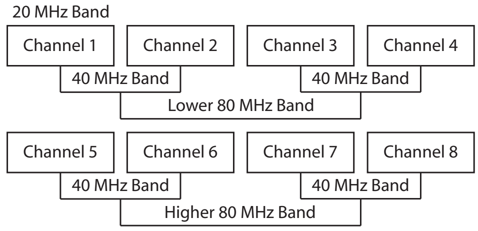


Fig. 2. Channelization concept in the draft IEEE 802.11ac standard.

be used to construct wider channel bandwidths.

B. MAC Enhancements

802.11n introduces, as a pivotal part of its MAC enhancements, two different kinds of frame aggregations comprising of A-MSDU and A-MPDU in order to improve its MAC efficiency. It is also possible to combine both A-MSDU and A-MPDU which is referred as hybrid A-MSDU/A-MPDU aggregation hereinafter. Readers are referred to [7] for a detailed description of these three frame aggregation mechanisms. On the other hand, the key MAC enhancements of 802.11ac are centered around its capability of multi-channel operations. In particular, the 802.11ac supports enhanced A-MSDU and A-MPDU in which the maximum A-MSDU size and PHY convergence procedure (PLCP) service data unit (PSDU) length are increased from 7935 to 11426 bytes and 65535 to 1048576 bytes, respectively to further improve its MAC efficiency along with the higher PHY data rates.

Further, owing to its multi-channel capability, 802.11ac supports enhanced protection in which the RTS/CTS handshake mechanism is modified to support static or dynamic bandwidth reservation and carry the channel bandwidth information. The idea is that both RTS and CTS frames are transmitted by VHT STA using the non-high-throughput (non-HT) duplicate PLCP protocol data unit (PPDU) upon successful clear channel assessment. Accordingly, the duplication of a 20 MHz non-HT transmission in every adjacent 20 MHz channel of a wider channel bandwidth provides backward compatibility with legacy devices. In this way, legacy STAs could decode the RTS and CTS frames and update their network allocation vector to prevent hidden terminal problem, which will escalate with the multi-channel operations of 802.11ac, on the secondary channels of a VHT STA. Additionally, the channel bandwidth information in the RTS and CTS frames together with the 802.11ac channelization will enable neighboring VHT STAs to gain knowledge of the VHT STA's secondary channels.

The 802.11ac also provides support of VHT capabilities such as transmit beamforming (TxBF) control with sounding protocol and compressed beamforming (V) feedback, downlink multi-user, multiple input, multiple output (MU-MIMO), and transmission opportunity (TXOP) power save through its VHT Capabilities Info field of the management frame. The sounding protocol is necessary for TxBF and MU-MIMO as the beamformer needs to acquire explicit channel state information in order to derive a steering matrix that could be used to optimize the reception at one or more beamformees.

The downlink MU-MIMO transmissions can be organized in the form of MU-TXOP to facilitate the sharing of TXOP where AP can perform simultaneous transmissions to multiple receiving STAs by using the group ID. Note that MU-TXOP requires at least a single STA, regardless of its access category (AC), to receive traffic from the AC that successfully obtained the TXOP instead of the original EDCA requirement where only transmission originating from the AC that won the TXOP is allowed. Finally, TXOP power save is introduced so that non-AP VHT STA could enter power save mode when it ascertains that it is not the intended recipient during that TXOP by filtering based on the RXVECTOR parameter of group ID or partial AID.

III. Numerical Analysis

In order to understand the key benefits of 802.11ac, a theoretical analysis for both 802.11n and 802.11ac is carried out. This numerical analysis serves to compare their MAC performance in terms of maximum throughput and MAC efficiency by considering the following four scenarios:

- 40 MHz channel with 2×2 MIMO
- 80 MHz channel with single input, single output (SISO)
- 80 MHz channel with 2×2 MIMO
- 160 MHz channel with SISO

The following assumptions are made in the numerical analysis:

- Point-to-point transmission of one transmitter and one receiver operating with the EDCA mode (single AC).
- Transmitter always has frames to send, and each frame has a fixed payload size.
- Ideal (error-free) wireless channel conditions.
- Mandatory binary convolutional coding (BCC) is used.
- Space-time block code (STBC) is not used.
- Regular guard interval (GI) is used.
- Fragmentation is not used. Hence, the compressed form of the block acknowledgment (BA) bitmap is used.
- HT-mixed PPDU format is considered in 802.11n for backward compatibility.

The motivation of the above assumptions is to focus our study on the effect of overheads on different frame aggregation mechanisms, and hence contentions and channel errors are not considered. Although we mainly focus on the mandatory features, this analysis can be easily extended to accommodate other optional features. Note that in error-prone channels, the maximum throughput and MAC efficiency values are expected to be lower than those being presented.

The list of system parameters and their notations used in the following numerical analysis can be found in Table I. Note that the number of space-time streams N_{STS} is equal to the number of spatial streams N_{SS} when STBC is not used as stated in [3] and [5]. Without loss of generality, the maximum throughput (MTP) with RTS/CTS protection for A-MSDU, A-MPDU, and hybrid A-MSDU/A-MPDU aggregation can be derived by extending from the work of [8] as shown in (1) overleaf. Further note that the HT-mixed and VHT PPDU formats used in our analysis for 802.11n and 802.11ac, respectively, are shown in Fig. 3. Finally, the MAC efficiency η_{MAC} which is the normalized throughput can be written as

TABLE I
System parameters of 802.11n and 802.11ac.

System Parameters	Notations	802.11n	802.11ac
Slot time	T_{SLOT}	9 μs	
SIFS duration	T_{SIFS}	16 μs	
DIFS duration	T_{DIFS}	34 μs	
Propagation delay	τ	$<<$ 1 μs	
STBC is not used	m_{STBC}	1	
Number of BCC encoders	N_{ES}	1	1–2
PHY data rate	R_{DATA}	27, 270 Mbps	29.3 – 780 Mbps
Non-HT/legacy short training sequence duration	T_{L-STF}	8 μs	
Non-HT/legacy long training sequence duration	T_{L-LTF}	8 μs	
Regular GI symbol interval	T_{SYM}	4 μs	
Non-HT/legacy SIGNAL field duration	T_{L-SIG}	4 μs	
HT SIGNAL field duration	T_{HT-SIG}	8 μs	-
HT short training field duration	T_{HT-STF}	4 μs	-
First HT long training field duration	$T_{HT-LTF-1}$	4 μs	-
Second, or more, HT long training field duration	$T_{HT-LTFs}$	4 μs	-
Number of HT long training fields	N_{LTF}	Equation (20-22) of [5]	-
VHT SIGNAL A field duration	$T_{VHT-SIG-A}$	-	8 μs
VHT short training field duration	$T_{VHT-STF}$	-	4 μs
VHT long training field duration	$T_{VHT-LTF}$	-	4 μs
VHT SIGNAL B field duration	$T_{VHT-SIG-B}$	-	4 μs
Number of VHT long training fields	N_{VHTLTF}	-	Table 22-10 of [3]
Minimum CW size	CW_{min}	15	
Average backoff time	T_{BO}	$CW_{\min}.T_{SLOT}/2$	
TXOP Limit	$TXOPLimit$	0	
Length of service bits	L_{SER}	16 bits	
Length of tail bits	L_{TAIL}	$6.N_{ES}$ bits	
Number of data bits per symbol	N_{DBPS}	108, 1080	117 – 3120
MAC header size including 32 bit FCS	L_{MAChdr}	34 bytes	
MAC payload size	L_{PLD}	1500 bytes	
MAC ACK frame size	L_{ACK}	14 bytes	
MAC RTS frame size	L_{RTS}	20 bytes	
MAC CTS frame size	L_{CTS}	14 bytes	
MAC compressed BAR frame size	L_{BAR}	24 bytes	
MAC compressed BA frame size	L_{BA}	32 bytes	
MAC overheads associated with frame aggregation	L_{FA_OH}	16 – 40 bytes	

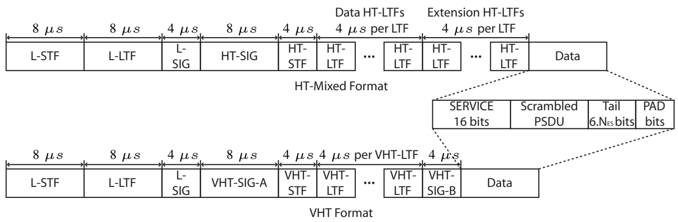


Fig. 3. PPDU formats of 802.11n and 802.11ac.

$$\eta_{MAC} = \frac{MTP}{R_{DATA}} \tag{2}$$

where R_{DATA} is the PHY data rate.

IV. Performance Comparison

The analytical framework presented in the previous section is employed as a basis to analyze the performance comparison between 802.11ac and 802.11n in context of the four scenarios considered in Section III. Note that scenario 1 is based on the 802.11n HT-mixed PPDU format while scenarios 2 – 4 are based on the 802.11ac VHT PPDU format as shown in Fig. 3.

Accordingly, Figs. 4 – 6 illustrate the MTP and η_{MAC} of the four scenarios in which the characteristics of the three different frame aggregation mechanisms, viz., A-MSDU, A-MPDU, and hybrid A-MSDU/A-MPDU aggregation are also examined. The frame aggregation parameters are based on 802.11n and kept the same for 802.11ac to enable a uniform comparison. In particular, the maximum A-MSDU size is 7935 bytes and the maximum PSDU length or A-MPDU size is 65535 bytes. However, the maximum A-MSDU size is restricted to 4095 bytes for hybrid A-MSDU/A-MPDU aggregation.

It is clear from Figs. 4 and 5 that A-MSDU outperforms A-MPDU in terms of average MTP and η_{MAC} by 14% per aggregated frame for all the four scenarios. Although it has

$$MTP=\begin{cases}\frac{8N_{AF}.L_{PLD}}{T_{DIFS}+T_{BO}+T_{RTS}+T_{CTS}+T_{DATA}+3T_{SIFS}+T_{BA}+4\tau}, & if\ A-MSDU\\ \frac{8N_{AF}.L_{PLD}}{T_{DIFS}+T_{BO}+T_{RTS}+T_{CTS}+T_{DATA}+4T_{SIFS}+T_{BAR}+T_{BA}+5\tau}, & otherwise\end{cases}, \tag{1a}$$

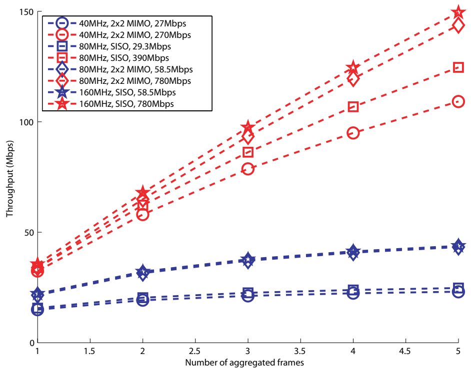
$$N_{AF}=\begin{cases}N_{A\_MSDU}, & A-MSDU\\ N_{A\_MPDU}, & A-MPDU\\ N_{A\_MSDU}.N_{A\_MPDU}, & A-MSDU/A-MPDU\end{cases}, \tag{1b}$$

$$T_{DATA}=T_{PHY}+T_{SYM}.N_{SYM}, \tag{1c}$$

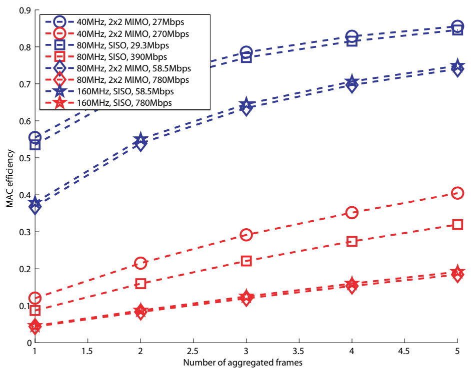
$$T_{PHY}=\begin{cases}T_{LEG\_PREAMBLE}+T_{L-SIG}+T_{HT\_PREAMBLE}+T_{HT-SIG}+T_{SIG-EXT}, & HT-mixed\\ T_{LEG\_PREAMBLE}+T_{L-SIG}+T_{VHT-SIG-A}+T_{VHT\_PREAMBLE}+T_{VHT-SIG-B}, & VHT\end{cases}, \tag{1d}$$

$$\begin{cases}T_{LEG\_PREAMBLE}=T_{L-STF}+T_{L-LTF}\\ T_{HT\_PREAMBLE}=T_{HT-STF}+T_{HT-LTF1}+(N_{LTF}-1)\,T_{HT-LTFs}\\ T_{VHT\_PREAMBLE}=T_{VHT-STF}+N_{VHTLTF}.T_{VHT-LTF}\end{cases}, \tag{1e}$$

$$N_{SYM}=\begin{cases}m_{STBC}\times\left\lceil\frac{8[N_{A\_MSDU}(L_{PLD}+L_{FA\_OH})+L_{MAChdr}]+L_{SER}+L_{TAIL}.N_{ES}}{m_{STBC}.N_{DBPS}}\right\rceil, & A-MSDU\\ m_{STBC}\times\left\lceil\frac{8N_{A\_MPDU}(L_{PLD}+L_{FA\_OH}+L_{MAChdr})+L_{SER}+L_{TAIL}.N_{ES}}{m_{STBC}.N_{DBPS}}\right\rceil, & A-MPDU\\ m_{STBC}\times\left\lceil\frac{8N_{A\_MPDU}(L_{PLD}.N_{A\_MSDU}+L_{FA\_OH}+L_{MAChdr})+L_{SER}+L_{TAIL}.N_{ES}}{m_{STBC}.N_{DBPS}}\right\rceil, & A-MSDU/A-MPDU\end{cases}. \tag{1f}$$

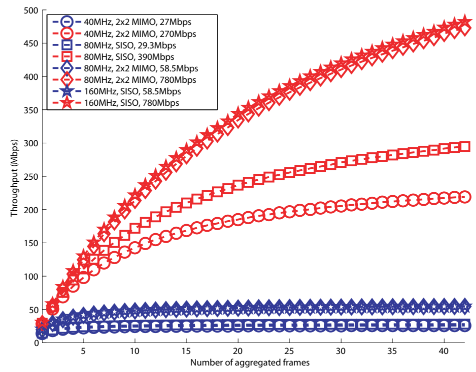


(a) MTP.

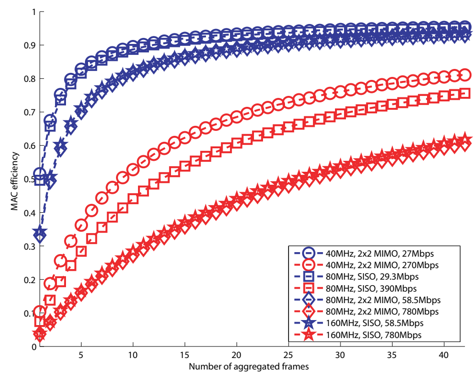


(b) η_{MAC}.

Fig. 4. MTP and η_{MAC} of four considered scenarios with A-MSDU.



(a) MTP.

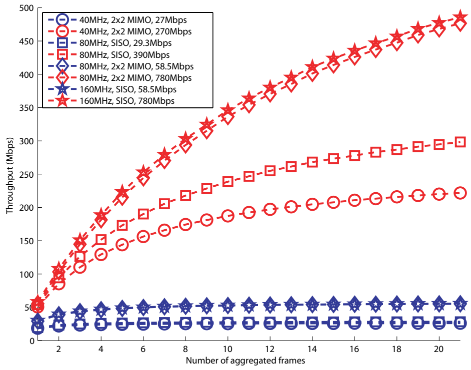


(b) η_{MAC}.

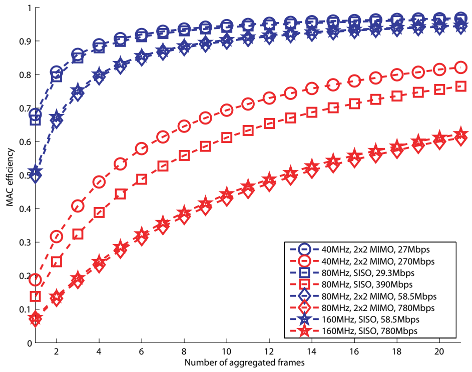
Fig. 5. MTP and η_{MAC} of four considered scenarios with A-MPDU.

the least overheads as shown in Fig. 7 as compared to the other two frame aggregation mechanisms, it does not achieve the highest MTP and η_{MAC}. This is due to the fact that such aggregation is limited by the maximum A-MSDU size of 7935 bytes that the receiver can process, which limits the maximum number of aggregated frames per PHY overhead. It is also worth noting that A-MSDU is more prone to channel error as it is transmitted within a single MPDU. This implies that the entire A-MSDU has to be retransmitted if any bits within the A-MSDU are erroneously received.

On the other hand, although A-MPDU has higher overheads, it offers a long-term improvement of at least twofold in terms of average MTP and η_{MAC} as compared to A-MSDU for all the four scenarios. This is a direct consequence of larger



(a) MTP.



(b) η_{MAC}.

Fig. 6. MTP and η_{MAC} of four considered scenarios with hybrid A-MSDU/A-MPDU aggregation.

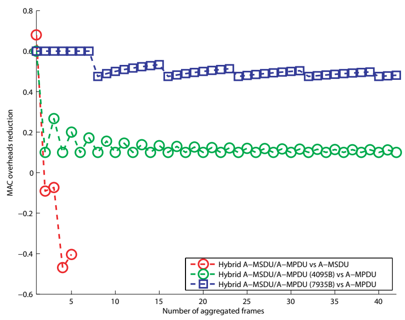


Fig. 7. Reduction in MAC overheads with hybrid A-MSDU/A-MPDU aggregation.

maximum A-MPDU size of up to 65535 bytes. Thus, it can aggregate more frames per PHY overhead, which improves the MTP and η_{MAC}. It is important to note that a maximum of 64 MPDUs may only be aggregated due to the limitation of the BA frame [5]. Additionally, it is more robust to channel errors as compared to A-MSDU as each MPDU within an A-MPDU has its own delimiter and FCS. Therefore, only the MPDU in error needs to be retransmitted.

Finally, it is evident from Fig. 7 that the hybrid A-MSDU/A-MPDU aggregation results in moderate overheads per MSDU frame which comes in between A-MSDU and A-MPDU. Specifically, it attains 12% reduction in MAC overheads on average as compared to A-MPDU, and such reduction improves to 51% with the increase of maximum A-MSDU size from 4095 to 7935 bytes. As a result, Figs. 5 and 6 show that hybrid A-MSDU/A-MPDU aggregation achieves a further improvement of 2.5% for both average MTP and η_{MAC} as compared to A-MPDU for all the four scenarios. Clearly, hybrid A-MSDU/A-MPDU aggregation could be used to reduce MAC overheads by prior MSDU aggregations, and it may be useful for scenarios where consecutive small MSDUs are required to be transmitted. For example, the use of A-MPDU would lead to the increase of MAC overheads as more BA frames need to be generated for longer TXOP due to the limit of 64 MPDUs per BA frame. A similar situation may arise with larger packets but are transmitted at higher data rates of 802.11ac. In fact, hybrid A-MSDU/A-MPDU aggregation could be used to mitigate the limitation of 64 MPDUs in the current BA mechanism. To this end, it is also worth to mention that scenarios with higher PHY data rates has lower η_{MAC} in general as the PHY overheads are relatively larger when MAC data frame can be transmitted over a shorter time duration.

V. Conclusion and Future Work

In this paper, we demonstrate that 802.11ac with a configuration of 80MHz and single (two) spatial stream(s) outperforms 802.11n with a configuration of 40 MHz and two spatial streams in terms of maximum throughput by 28% (84%). In addition, our performance analysis illustrates that different frame aggregation mechanisms could achieve different maximum throughput and MAC efficiency for the same given scenario in which hybrid A-MSDU/A-MPDU aggregation yields the best performance for both 802.11n and 802.11ac devices. Our analysis also suggests that operation in the 160 MHz channel bandwidth might not be immediately attractive given the fact that its maximum throughput does not scale well with the bandwidth increment. Furthermore, additional signaling would most likely be required to protect transmissions in the 160 MHz channel.

For future work, we planned to investigate the effects of overlapping basic service set and error-prone channels on multi-channel operations with our network-level simulator.

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