Performance Study of Frame Aggregation Mechanisms in the New Generation WiFi

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The new generation WiFi (Widely Fidelity), which is called 802.11ac, has the goal of reaching at least 1 Gbps on bands below 6 GHz. This is why, the standard has been extended with new features at both PHYsical (PHY) and Medium Access Control (MAC) layers level. One of the key features of MAC layer is the ability of aggregating frames in order to reduce temporal overheads that significantly harm the performance of 802.11 networks. Three forms of aggregation exist, namely Aggregate MAC Service Data Unit (A-MSDU), Aggregate MAC Protocol Data Unit (A-MPDU) and hybrid A-MSDU/A-MPDU Aggregation (A-hybrid). In this paper, we study the impact of Frame Aggregation Mechanisms (FAMs) for improving the overall throughput of 802.11ac networks. Furthermore, we highlight the need of PHY/MAC cross-layer communications for optimizing the wireless bandwidth utilization. Simulation results demonstrate the gains offered by the FAMs.

IEEE 802.11ac, Frame Aggregation Mechanisms, Physical Data Rates, Simulation and Performance Study.

1. INTRODUCTION

More than any time ever before, today technology has a significant impact on people's lives. The proliferation of slim, mobile, and portable devices such as notebooks, ultrabooks, tablets, and smartphones is a clear testament to the importance of wireless communications in modern society (Cordeiro et al. (2013)). The most notable example of wireless systems with data rates greater than 1 Gbps, includes the IEEE 802.11ac amendment to the base IEEE 802.11 standard (IEEE 802.11ac Standard (2013)). Several companies have announced products implementing this technology, with a few of those products already available, or soon to be available, to consumers (Cordeiro et al. (2013)). The data rates provided by IEEE 802.11ac can meet the needs of many applications, with replacement of Wired Digital Interface (WDI) cables arguably the most prominent new use of this technology. To this end, the IEEE 802.11ac Task Group (TGac) is working on an amendment that has the goal of reaching maximum aggregate network throughputs of at least 1 Gbps on bands below 6 GHz (Yazid et al. (2014)). Due to the significant rate increase achieved by 802.11ac, the term Very High Throughput (VHT) is also used in reference to this new amendment (Bejarano et al. (2013)).

Several key enhancements have been proposed to both the PHY and MAC layers of the IEEE 802.11ac standard in order to reach gigabit throughput rates (Charfi et al. (2013)). On the one hand, substantial modifications are required at the PHY layer in order to increase the PHY data rates (Ismail el. (2013)). On the other hand, the IEEE 802.11ac standard specifies the use of different Frame Aggregation Mechanisms (FAMs) at the MAC layer level in order to increase the channel utilization and MAC efficiency (Charfi et al. (2012)). The IEEE 802.11ac standard boasts better MAC layer efficiency through innovative mechanisms such as Frame Aggregation (FA) and Block Acknowledgment (ACK) (Yazid et al. (2015)). Three forms of aggregation exist, namely: Aggregate MAC Service Data Unit (A-MSDU), Aggregate MAC Protocol Data Unit (A-MPDU) and hybrid A-MSDU/A-MPDU Aggregation (A-hybrid). These involve aggregating several MPDU/MSDU frames (called sub-frames) into one larger frame, and as a result only require a single MAC layer header for it to be accepted by the PHY layer (Al-Adhami et al. (2012)). Thus, the laborious channel access of the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol is considerably reduced by the sharing of the PHY header and channel access mechanism among the MPDUs of the A-MPDU. Hence, the MAC layer efficiency is considerably improved (Redieteab et al. (2012)).

The main contribution of this paper is to analyze the potential benefits in terms of MAC throughput gains of IEEE 802.11ac WLANs over various Frame Aggregation Mechanisms and practical PHY data rates. In the same way, we highlight the need to cross-layer communications between the PHY and MAC layers in order to increase the efficiency of the wireless channel utilization. In addition, we demonstrate that hybrid A-MSDU/A-MPDU aggregation yields the best throughput for the IEEE 802.11ac WLANs.

The reminder of this paper is organized as follows: Section 2 presents the different mechanisms of Frame Aggregation introduced in the IEEE 802.11ac standard. Section 3 gives a review of existing studies on Frame Aggregation Mechanisms. Simulation results and performance analysis are presented in Section 4. Finally, our main conclusions are summarized in Section 5.

2. FRAME AGGREGATION MECHANISMS

There are three methods available to perform frame aggregation: Aggregate MAC Service Data Unit (A-MSDU), Aggregate MAC Protocol Data Unit (A-MPDU) and hybrid A-MSDU/A-MPDU Aggregation (A-hybrid) (Charfi et al. (2012)). The main distinction between an MSDU and an MPDU is that the former corresponds to the information that is imported to or exported from the upper part of the MAC layer from or to the higher layers, respectively. Whereas, the latter relates to the information that is exchanged from or to the PHY layer by the lower part of the MAC layer. Aggregate exchange sequences are made possible with a protocol that acknowledges multiple MPDUs with a single Block ACK (BA) in response to a Block ACK Request (BAR) (Skordoulis et al. (2008)).

2.1. Aggregate MSDU

The principle of the A-MSDU is to allow multiple MSDUs sent to the same receiver to be concatenated in a single MPDU. This definitively improves the efficiency of the MAC layer, specifically when there are many small MSDUs. For an A-MSDU to be formed, a layer at the top of the MAC receives and buffers multiple MSDUs. The A-MSDU is completed when the size of the waiting MSDUs reaches the maximal A-MSDU threshold (Charfi et al. (2013)).

In Figure 1, we describe a simple structure of an A-MSDU. Each MSDU consists of a MSDU header, which contains the Destination Address (DA), the Sender Address (SA) and the length of the MSDU, followed by the MSDU arrived from the Logical Link Control (LLC) layer and 0-3 bytes of padding. A major drawback of using A-MSDU is under error-prone channels. By compressing all MSDUs into a single MPDU with a single Frame Check Sequence (FCS), for any MSDUs that are corrupted, the entire A-MSDU must be retransmitted (Skordoulis et al. (2008)).

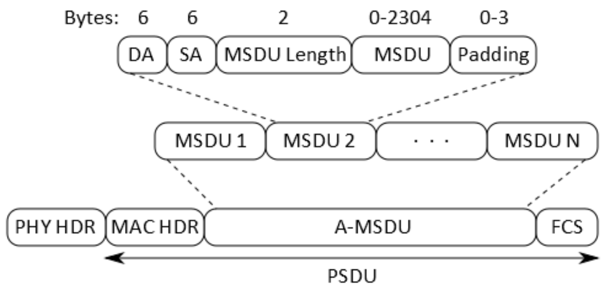

Figure 1: *Aggregate MSDU.*

2.2. Aggregate MPDU

The concept of A-MPDU aggregation is to join multiple MPDUs with a single leading PHY header. A key difference from A-MSDU aggregation is that A-MPDU operates after the MAC header encapsulation process. The utmost number of MPDUs that it can hold is 64 because a Block ACK bitmap field is 128 bytes in length, where each MPDU is mapped using two bytes (Charfi et al. (2012)). The basic structure is shown in Figure 2.

A set of fields, known as MPDU header is inserted before each MPDU and padding bits varied from 0-3 bytes are added at the tail. The basic operation of the MPDU header is to define the MPDU position and length inside the A-MPDU. The Cyclic Redundancy Check (CRC) field in the MPDU header is used to verify the authenticity of the 16 preceding bits. After the A-MPDU is received, a de-aggregation process is initiates. First it checks the MPDU header for any errors based on the CRC value. If it is correct, the MPDU is extracted, and it continues with the next MPDU till it reaches the end of the PHY Service Data Unit (PSDU). Otherwise, it checks every four bytes until it locates a valid MPDU header or the end of the PSDU. The delimiter has a unique pattern to assist the de-aggregation process while scanning for MPDU header (Skordoulis et al. (2008)).

2.3. Hybrid A-MSDU/A-MPDU Aggregation

The hybrid aggregation as shown in Figure 3 comprises a blend of A-MSDU and A-MPDU over two stages. In the first stage, MSDUs received by MAC from the upper layer are buffered for a short time until A-MSDUs are formed according to their traffic identifier, destination, source, and the

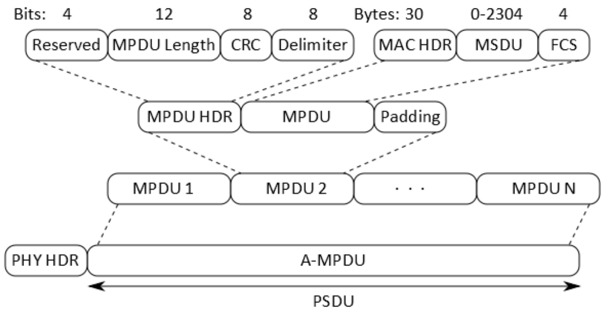

Figure 2: *Aggregate MPDU.*

maximum size of A-MSDU. The complete A-MSDUs and other non-aggregate MSDUs then enter the second stage to form an A-MPDU. Only complete A-MSDUs and MSDUs, not the fragments of A-MSDUs or MSDUs, could be contained in an A-MPDU. The entire aggregation scheme completes when A-MPDU is created (Wang et al. (2009)).

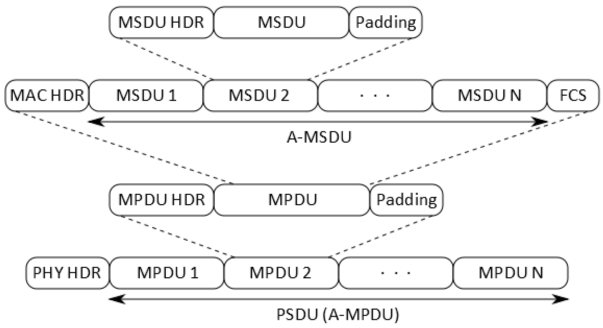

Figure 3: *Hybrid A-MSDU/A-MPDU aggregation.*

3. RELATED WORKS AND MOTIVATIONS

The Frame Aggregation Mechanisms, which are designed for improving channel utilization and MAC efficiency have received a large interest by the research community. In the field, Redieteab et al. (Redieteab et al. (2010)) proposed a new cross-layer aggregation scheme that increases throughput as a compromise between robustness to collisions and channel diversity exploitation in a WLAN multichannel context. Ong et al. (Ong et al. (2011)) compared the MAC performance between 802.11ac and 802.11n over three different frame aggregation mechanisms, and indicated that 802.11ac with a configuration of 80 MHz and single spatial streams outperforms 802.11n with a configuration of 40 MHz and two spatial streams in terms of throughput by 28%. Bellalta et al. (Bellalta et al. (2012)) proposed and evaluated a simple reference scheme covering the fundamental properties of frame aggregation and MU-MIMO transmission in order to demonstrate that the combination of both techniques is able to significantly improve the system performance. Cha et al. (Cha et al. (2012)) compared the performance of the two down-link user multiplexing schemes: MU-MIMO and frame aggregation in IEEE 802.11ac. The authors showed that, if each user's data stream has a similar length, the MU-MIMO scheme yields better average throughput. Whereas, if each user's data stream has a different length, the frame aggregation scheme outperforms the MU-MIMO scheme in terms of average throughput. Chung et al. (Chung et al. (2013)) proposed an aggregated MPDU using fragmented MPDUs with a compressed Block ACK mechanism for use in IEEE 802.11ac MU-MIMO transmission. The authors showed that, by allowing the use of fragmentation with the A-MPDU, the waste of medium resources in terms of meaningless A-MPDU padding can be eliminated.

It is clear that, the frame aggregation and block acknowledgement are the most important MAC mechanisms proposed in the new generation IEEE 802.11ac WLANs standard for achieving a very high throughput. This is due to their efficiency of reducing the temporal overheads caused mainly by the PHY and MAC headers, inter-frame spacing, backoff timer and frame ACK. However, non of the existing studies has been devoted to evaluate the performance level and quantify the throughput gains offered by the frame aggregation mechanisms. This is why, we dedicate this work to separately study how each frame aggregation mechanism allows increasing the overall throughput in an IEEE 802.11ac WLAN. In the same way, we identify, for the first time in the literature, some issues risen to the use of frame aggregation mechanisms with practical physical data rates. These drawbacks should be taken into account, in order to enhance the IEEE 802.11ac WLAN.

4. SIMULATION RESULTS AND ANALYSIS

In this section, we analyze the impact of the MAC layer to increase the overall throughput in the VHT IEEE 802.11ac WLAN. Especially, we study how the frame aggregation mechanisms allow enhancing the utilization of the scarce wireless bandwidth and improving the achievable throughput in an IEEE 802.11ac WLAN. Furthermore, we highlight the need to cross-layer communications between the PHY and MAC layers to accommodate the use of the different frame aggregation mechanisms according to the offered physical data rates.

In order to analyze the gains of the different frame aggregation mechanisms over several physical data rates in an IEEE 802.11ac WLAN, we have implemented the IEEE 802.11ac frame aggregation mechanisms in a custom-made simulator written in C++ programming language under Linux operating system. The values of parameters used to obtain the simulation results are given in Table 1.

Table 1: *802.11ac PHY and MAC Parameters.*

Parameter	***Numerical value***
Signal propagation delay	1 μs
DIFS	34 μs
SIFS	16 μs
Slot time	9 μs
Minimum PHY hdr time	40 μs
Maximum PHY hdr time	68 μs
Minimum CW	32
Maximum CW	1024
Maximum MAC hdr size	36 bytes
Maximum MPDU size	11454 bytes
ACK length	14 bytes
Block-ACK length	64 bytes
Maximum MSDU size	2304 bytes

The goal of the following obtained simulation results is to show the relation existing between the data rates (offered by the PHY layer) and frame aggregation mechanisms (available at MAC layer level), allowing an efficient use of the scarce wireless bandwidth while improving the achievable throughput in an IEEE 802.11ac WLAN. Therefore, our analysis is organized as follows:

- Firstly, we study the bandwidth utilization rate according to various physical data rates without applying frame aggregation. The objective of this study is to show that, increasing the physical data rate does not increase systematically the bandwidth utilization. So, the frame aggregation is required for increasing the bandwidth utilization and MAC efficiency.

- Secondly, we evaluate the first existing frame aggregation scheme, which is the A-MSDU aggregation. So, we quantify the achievable throughput with the A-MSDU aggregation scheme according to the A-MSDU length. With the A-MSDU aggregation, we already note the benefit gain of the frame aggregation in an IEEE 802.11ac WLAN.

- Thirdly, we evaluate the second frame aggregation scheme, which is the A-MPDU aggregation. This scheme offers greater length to the aggregated frame, up to 64 MPDUs in the same A-MPDU, where the payload length of each MPDU does not exceed 2304 bytes. Several simulation results will be given according to the number of MPDUs with different MPDU lengths and physical data rates.

- Fourthly, we report on the third and last frame aggregation scheme, which is the hybrid A-MSDU/A-MPDU aggregation. This scheme allows the same maximum number of MPDUs as in A-MPDU aggregation. However, in the hybrid aggregation, a single MPDU can encapsulate several MSDUs, conditioned by the size of MPDU which does not exceed 4095 bytes.

- Finally, we give a comparative study between the maximum throughput reached with the different frame aggregation mechanisms in an IEEE 802.11ac WLAN according to the network size.

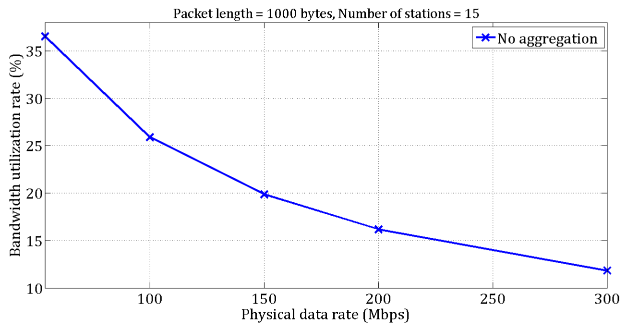

Figure 4: *Bandwidth utilization versus data rate.*

In Figure 4, we study the bandwidth utilization according to the physical data rate without using the frame aggregation. Therefore, we have used a middle MPDU length (1000 bytes), an average network size (15 stations), and we have varied the physical data rate from 50 Mbps to 300 Mbps. We observe from the Figure 4 that, the bandwidth utilization is decreasing with the increase of physical data rate; the greater the used physical data rate, the lower the bandwidth utilization rate. We note that, with a physical data rate of 54 Mbps, the bandwidth utilization rate is 37%. The bandwidth utilization decreases to 12%, when the physical data rate reaches 300 Mbps. This is mainly due to the PHY and MAC headers which harm the bandwidth utilization and the achievable throughput of IEEE 802.11 WLANs. By enabling new features (like wider channels and MU-MIMO transmission) at the PHY layer, it is true that, the physical data rate is highly increased. However, as we have shown in Figure 4, the channel bandwidth is less and less utilized. This can be explained by the fact that the physical data rates are only used to transmit the payload of the 802.11 frame (the useful data). However, the PHY and MAC headers are always transmitted by using the physical basic rate, which is very low compared to the physical data rates. This is why, when increasing the physical data rate, the time duration spent to transmit the PHY and MAC headers becomes larger and larger compared to the time duration spent to transmit the frame payload. Consequently, the channel bandwidth is less utilized.

So, increasing the data rate at the PHY layer does not systematically increase the bandwidth utilization and MAC efficiency. Thereby, the frame aggregation and block acknowledgment are required at MAC layer level in order to share among several frames the overheads mainly generated by the PHY and MAC headers, and inter-frame spacing.

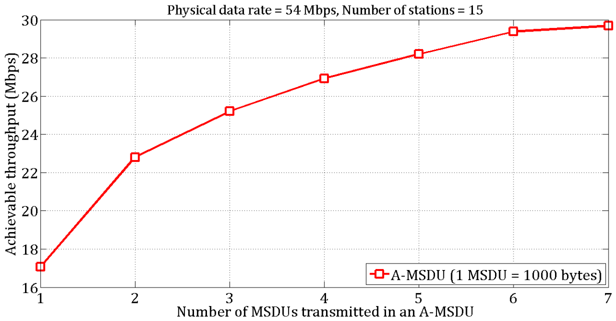

Figure 5: *Throughput versus A-MSDU length.*

In Figure 5, we analyze the achievable throughput in an IEEE 802.11ac WLAN, when using the A-MSDU frame aggregation mechanism at the MAC layer level, according to the number of MSDU frames aggregated in an A-MSDU frame. Therefore, we have fixed the PHY data rate at 54 Mbps, the network size at 15 stations, and we have varied the number of MSDUs in an A-MSDU frame from 1 to 7 (i.e., we have varied the length of the A-MSDU frame from 1000 bytes to 7000 bytes). We observe from Figure 5 that, the larger the A-MSDU frame length, the greater the achievable throughput in the IEEE 802.11ac WLAN. We remark that, with an A-MSDU frame of 1000 bytes the achievable throughput is 17 Mbps, it increases to 30 Mbps with an A-MSDU frame of 7000 bytes. In terms of channel bandwidth, by enabling the A-MSDU aggregation at MAC layer level, the bandwidth utilization increases from 32% to 56% when the A-MSDU frame length increases from 1000 bytes to 7000 bytes. This significant improvement level, in terms of achievable throughput and bandwidth utilization, is provided by the A-MSDU frame aggregation mechanism which allows several MSDU frames to be transmitted with the same PHY and MAC headers during one channel access. Thereby, the overheads caused by the PHY and MAC headers, inter-frame spacing and channel access time, are shared among several MSDU frames. This is why, by enabling the A-MSDU aggregation, the overheads are significantly reduced and the amount of transmitted useful data is highly increased.

In Figures 6, 7 and 8, we analyze the achievable throughput in an IEEE 802.11ac WLAN, by enabling the A-MPDU frame aggregation mechanism at MAC layer level, according to the number of MPDU frames in an A-MPDU frame (from 1 MPDU to 64 MPDUs), with different MPDU frame lengths (1000 bytes and 2000 bytes), and over various physical data rates (54 Mbps, 100 Mbps and 150 Mbps).

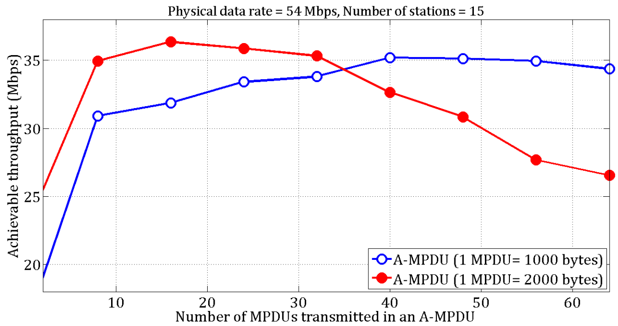

Figure 6: *Throughput versus A-MPDU length over a data rate of 54 Mbps.*

We remark from Figure 6 that, the achievable throughput with the A-MPDU aggregation increases, at the beginning, with the increase of the number of MPDU frames in an A-MPDU frame, for both MPDU frame lengths 1000 bytes and 2000 bytes. However, when the number of MPDU frames exceeds 40 MPDUs and 16 MPDUs respectively for the MPDU frame lengths of 1000 bytes and 2000 bytes, the achievable throughput decreases along the increase of the number of MPDU frames. This degradation in more remarkable in case of MPDU frame length of 2000 bytes, where the throughput increases first from 26 Mbps (with 1 MPDU) to 37 Mbps (with 16 MPDUs), then it decreases to 27 Mbps (with 64 MPDUs). Through these results, we show for the first time in the literature that, with a specific value of physical data rate (54 Mbps, for example), there is an optimum length of the A-MPDU frame which allows the IEEE 802.11ac WLAN to achieve the maximum throughput. Beyond of this A-MPDU length, the achievable throughput will decrease with the increase of A-MPDU length. Traditionally, we think that, increasing the amount of transmitted data means automatically an increase of the achievable throughput. Here, we prove that, for a given physical data rate, the best achievable throughput in an IEEE 802.11ac WLAN is conditioned by an optimum A-MPDU length. Before reaching this A-MPDU length, there is a problem of overheads which harm the throughput. But, after this value, there is an other problem which is the collision time that becomes more and more important with the increase of the A-MPDU length.

In Figures 7 and 8, we illustrate the achievable throughput by applying the A-MPDU aggregation scheme on IEEE 802.11ac network over 100 Mbps and 150 Mbps, respectively. We note on both Figures 7 and 8 that, the throughput increases with the increase of the number of MPDU frames in an A-MPDU frame, for both MPDU frame lengths 1000

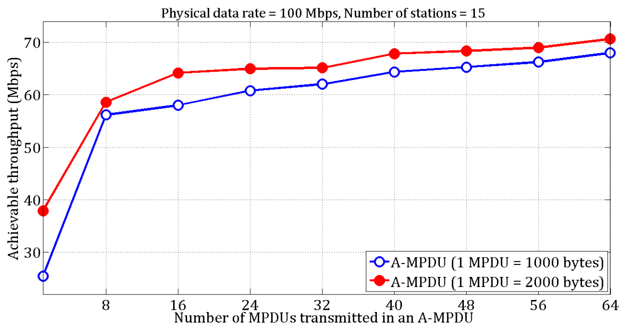

Figure 7: *Throughput versus A-MPDU length over a data rate of 100 Mbps.*

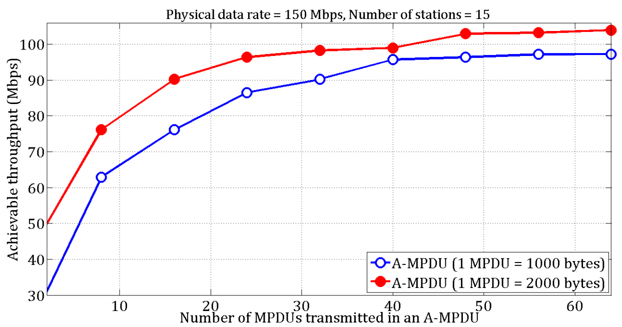

Figure 8: *Throughput versus A-MPDU length over a data rate of 150 Mbps.*

bytes and 2000 bytes. The maximum achievable throughputs with the maximum length of A-MPDU frame (64 MPDU frames of 2000 bytes for each of them) over the physical data rates 100 Mbps and 150 Mbps, are respectively 71 Mbps and 104 Mbps. This significant improvement, in terms of achievable throughput, is due to the collision time of the A-MPDU frame which is significantly reduced when using high data rates at the PHY layer level. So, when the length of the MAC frame is large, it is necessary to increase the data rate at the PHY layer in order to reduce the collision time and consequently to improve the achievable throughput. However, there is a limit that the physical data rate should not exceed. Otherwise, the channel bandwidth will be less utilized because of temporal overheads. This why, with the physical data rate of 100 Mbps, the rate of bandwidth utilization is 71%. It is decreased to 69% with the physical data rate of 150 Mbps. Therefore, for a given length of MAC frame, there is an optimum physical data rate which reduces the collision time and minimizes the temporal overheads. Consequently, the achievable throughput is improved and the bandwidth utilization is enhanced.

In Figures 9, 10 and 11, we evaluate the A-MSDU/A-MPDU hybrid frame aggregation scheme according to the number of MPDU frames in an A-MPDU frame, where each MPDU frame encapsulates an A-MSDU

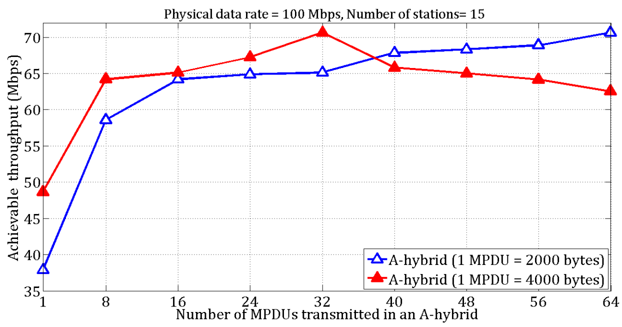

Figure 9: *Throughput versus A-hybrid length over a data rate of 100 Mbps.*

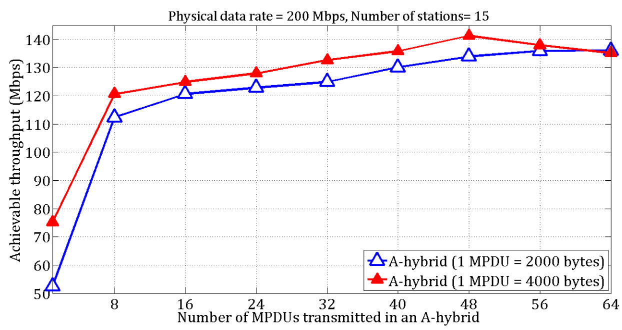

Figure 10: *Throughput versus A-hybrid length over a data rate of 200 Mbps.*

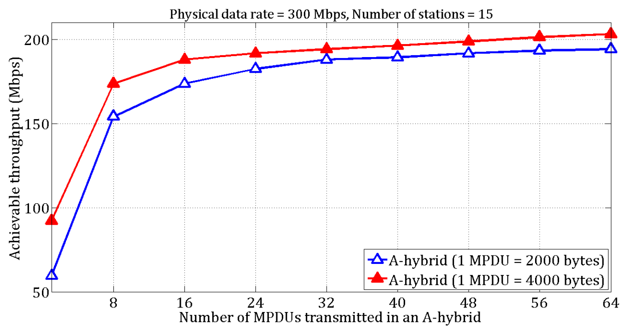

Figure 11: *Throughput versus A-hybrid length over a data rate of 300 Mbps.*

frame. The achievable throughput is given for two MPDU frame lengths: 2000 bytes and 4000 bytes, and over three different physical data rates: 100 Mbps, 200 Mbps and 300 Mbps.

From Figure 9, we note that, with a MPDU frame length of 4000 bytes and over a physical data rate of 100 Mbps, the maximum throughput of the hybrid frame aggregation is reached with 32 MPDUs. In Figure 10, we show that, although the physical data rate used is high (200 Mbps), the achievable throughput decreases when the number of MPDU frames exceeds 48 frames. So, when the hybrid frame aggregation scheme is enabled at the MAC layer level, it is required to employ the very high data rate available at the PHY layer level in order to achieve a very high throughput in the IEEE 802.11ac

WLAN. This is why, we note on Figure 11 that, over the physical data rate of 300 Mbps, the achievable throughput does not decrease whatever the length of the A-MPDU frame.

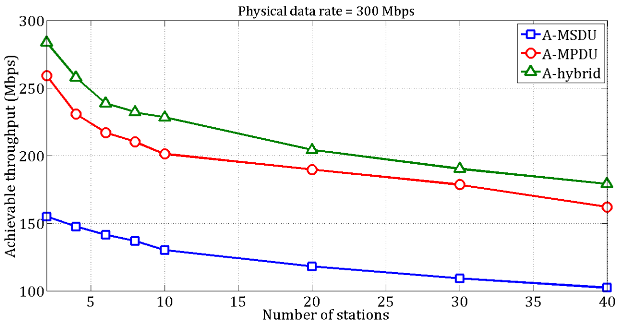

Figure 12: *Throughput variation according to the network size.*

In Figure 12, we compare the maximum achievable throughput by the different frame aggregation schemes in the IEEE 802.11ac WLAN according to the network size. Therefore, we have fixed the physical data rate to 300 Mbps, and we have used the maximum length of each frame aggregation scheme. Through this figure, we show clearly that, the hybrid frame aggregation scheme provides the best bandwidth utilization and MAC efficiency in the IEEE 802.11ac WLAN over a physical data rate of 300 Mbps.

5. CONCLUSION

In this paper, we are interested at presenting and studying the Frame Aggregation Mechanisms introduced in the IEEE 802.11ac standard for very high throughput WLANs. Indeed, Frame Aggregation Mechanisms allow enhancing MAC efficiency and bandwidth utilization. The presented simulation results show that, the Frame Aggregation Mechanisms are required at MAC layer level for reducing temporal overheads and consequently increasing the achievable throughput and bandwidth utilization. However, when the length of the aggregated MAC frame is very large, it is necessary to use a higher physical data rate in order to reduce the collision time of this aggregated frame. Thereby, we have identified, for the first time in the literature, the need to cross-layer communications between the PHY and MAC layers for accommodating the use of the different Frame Aggregation Mechanisms over the available physical rates.

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