Adaptive Two-Level Frame Aggregation in IEEE 802.11n WLAN

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Abstract—In order to reduce the overhead of legacy WLANs, the IEEE 802.11n standard defines two aggregation schemes, i.e., A-MSDU and A-MPDU. In general, A-MPDU outperforms A-MSDU due to its selective retransmission capability. However, A-MPDU has a fundamental restriction on the minimum separation in time between the start of two consecutive subframes carried on the same A-MPDU. If such a gap is smaller than the minimum MPDU start spacing of the receiver, the sender should insert additional padding, thus resulting in throughput degradation. The main contribution of this paper is that we provide an adaptive aggregation scheme in which the sender conveys A-MSDUs within A-MPDUs in an adaptive manner, in order to resolve this potential problem in A-MPDU. Our analytical and simulation results demonstrate that the proposed scheme improves throughput performance over A-MPDU and A-MSDU by up to 280% and 19%, respectively.

Index Terms—IEEE 802.11n, WLAN, frame aggregation.

I. INTRODUCTION

Since the first IEEE 802.11 wireless local area network (WLAN) specification published in 1997, a series of amendments have been released in order to further improve the data rate at the physical (PHY) layer [1]. Nevertheless, compared to the underlying PHY rate, the MAC efficiency of IEEE 802.11 has been quite low due to the overheads of the MAC [2]. Accordingly, the IEEE 802.11n amendment has been developed with the goal of achieving more than 100 Mb/s throughput at the MAC Service Access Point (SAP) with 20 MHz channel bandwidth [3]. One way to meet such a goal is to employ frame aggregation, which is a simple and powerful method to increase MAC efficiency [5]. The IEEE 802.11n standard defines two aggregation schemes, namely, Aggregate MAC Service Data Unit (A-MSDU) and Aggregate MAC Protocol Data Unit (A-MPDU). Moreover, the emerging amendment, IEEE 802.11ac, also adapts these two aggregation schemes as its basic MAC technologies [4].

In this paper, we first point out that A-MPDU may suffer from severe throughput degradation due to the following intrinsic limitation: an IEEE 802.11n sender is not allowed to transmit more than one MPDU within a time interval called minimum MPDU start spacing, which is determined and announced by the receiver. This limitation can result in severe throughput degradation in certain situations, as explained in Section IV-A. In order to resolve this fundamental limitation of A-MPDU, we propose an effective frame aggregation architecture, which works in an adaptive manner based on

the PHY rate and payload size. Our analytical and simulation results show that the proposed scheme can improve throughput performance by as much as 280% over A-MPDU and 19% over A-MSDU, approximately, as shown in Section VI.

The rest of the paper is organized as follows: the two frame aggregation schemes in IEEE 802.11n are briefly described in Section II. Then, we summarize related work in Section III. In Section IV, we first explain the fundamental limitation of A-MPDU, and then present our proposed solution. We provide a throughput analysis of the proposed scheme along with that of A-MPDU and A-MSDU in Section V. Numerical evaluation of said analysis and simulation results are then presented in Section VI. Finally, our conclusion follows in Section VII.

II. IEEE 802.11N AGGREGATION SCHEMES

Based on its time sensitivity, the 802.11n MAC sublayer can be conceptually divided into two entities, namely, the upper and lower MACs. The upper MAC, which is basically a software part, takes care of the interaction with the upper layer such as IEEE 802.2 logical link control (LLC). The lower MAC, which is usually a hardware component, handles the interaction with the underlying PHY layer. Two frame aggregation schemes, A-MSDU and A-MPDU, are performed at upper and lower MACs, respectively:

1) A-MSDU: In this scheme, multiple MSDUs are aggregated into a single A-MSDU, which is then conveyed within a single MPDU. The maximum A-MSDU size is based on the capability of the receiver. Fig. 1 shows the frame format of the A-MSDU structure. All the subframes it carries should have the same sender and receiver addresses since they are conveyed in a single MPDU. However, the subframes are allowed to have different source and/or destination addresses, which are indicated in the subframe header. The padding bits are needed to make each subframe length a multiple of four bytes. As the unit for an acknowledgement is an MPDU, if any bit within an A-MSDU is corrupted at the receiver, the entire A-MSDU has to be retransmitted.

2) A-MPDU: In the A-MPDU scheme, multiple MPDUs are aggregated into a single A-MPDU, which is, in turn, delivered to the PHY layer as a single Physical Layer Service Data Unit (PSDU). It is then processed as a single Physical Layer Protocol Data Unit (PPDU) ready to be sent to the channel. Fig. 2 shows the frame format of an A-MPDU. All
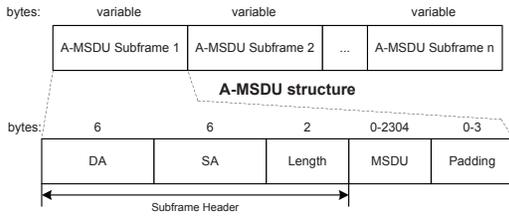
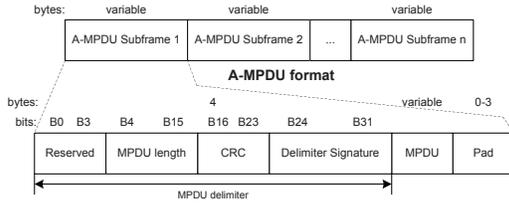Fig. 1: Frame structure of A-MSDU.

Fig. 2: Frame structure of A-MPDU.

the subframes have the same sender and receiver addresses, and each subframe is preceded by an MPDU delimiter such that the structure of the A-MPDU can usually be recovered even when one or more MPDU delimiters are received with errors. As already mentioned, in the 802.11 MAC, the unit for an acknowledgement is an MPDU. Hence, each subframe within an A-MPDU should be individually acknowledged. As multiple MPDUs are transmitted within a single PPDU, the usage of the Block Ack (BA) is needed for the A-MPDU scheme.

III. RELATED WORK

Most of the studies on frame aggregation in IEEE 802.11n can be classified into the following two categories: performance analysis, and optimal frame size and aggregation method selection. The studies in the first category typically present an analytical model for describing the operation and performance of the two 802.11n frame aggregation schemes. For example, in [8], a simulation-based performance comparison of the maximum throughput of the aggregation methods is presented. Note that the two-level aggregation evaluated in [8] is similar to our scheme, but here we have applied it to solve the identified limitation in A-MPDU aggregation. An analytical study of the A-MSDU and A-MPDU schemes is performed in [9] while the authors in [10] propose a transmission queue model of an 802.11n station employing frame aggregation. Similarly, an analytical model to evaluate the throughput performance based on an enhanced discrete-time Markov chain is presented in [11]. As for the other category, in [14] the authors propose a frame size adaptation algorithm for A-MPDU aggregation that combines it with fragmentation of large MSDU. The authors also introduce an analytical model to determine the optimal size of each aggregated fragment. The idea of combining fragmentation with A-MPDU aggregation is also presented in [13]. In addition, a simple scheduling algorithm that decides which

aggregation option to use is proposed in [12]. As we can see, there is a wealthy body of research on the subject of frame aggregation in 802.11n. However, to our best knowledge, no previous work has explicitly studied the receiver capability-induced performance degradation in A-MPDU. Moreover, our proposed aggregation scheme can be combined with these existing methods to further improve throughput performance.

IV. PROPOSED AGGREGATION ARCHITECTURE

In this section, we first point out that A-MPDU as defined in the 802.11n standard has an intrinsic limitation on throughput performance when the receiver has low capability in terms of deaggregation, that is, when it is not able to decode A-MPDU subframes whose start times are too close to each other. In particular, this performance degradation can be exacerbated either when the aggregated subframe size is small or when the underlying PHY rate is high. Next, in order to resolve such a limitation, we propose a simple and practically efficient aggregation architecture.

A. Limitation of A-MPDU Performance

When using A-MPDU aggregation, a transmitting station is not allowed to transmit more than one A-MPDU subframe within the time limit defined by a parameter called `Minimum MPDU Start Spacing`,[1] or t_{MMSS}, which depends on the receiver's capability. In order to satisfy this limit, the number of bytes between the start of two consecutive A-MPDU subframes needs to be equal to or greater than $L_{min} = t_{MMSS} \cdot r/8$, where t_{MMSS} is in μs, and r is the PHY data rate in Mb/s. If the number of bytes between the start of two consecutive A-MPDU subframes is less than L_{min}, one or more "dummy" MPDU delimiters (i.e., delimiters without a subsequent MPDU) need to be added so as to satisfy the timing requirement. We can easily expect that using MPDU delimiters will degrade throughput performance.

This throughput degradation will become more severe with small subframe sizes because of the increased padding ratio. According to [6], the packet size distribution of the Internet is bimodal at 40 bytes and 1,500 bytes with around 40% and 20% of total packets, respectively. Moreover, about 60% of the Internet packets are smaller than 500 bytes. Consequently, the performance degradation of A-MPDU imposed by t_{MMSS} will become more severe in practice due to small frame sizes.

B. Proposed Aggregation Scheme

From the observations described in the previous section, we can conclude that the conventional A-MPDU scheme alone is insufficient in terms of throughput enhancement. Moreover, A-MPDU is performed at the lower MAC, which is usually a hardware-based structure. Hence, in order to support A-MPDU, additional hardware is required to support the mechanism to insert dummy MPDU delimiters.

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[1]This is a three-bit subfield in the A-MPDU Parameters field within the HT Capabilities information element, which indicates the minimum time between the start of two adjacent MPDUs within an A-MPDU, measured at the PHY SAP [3].
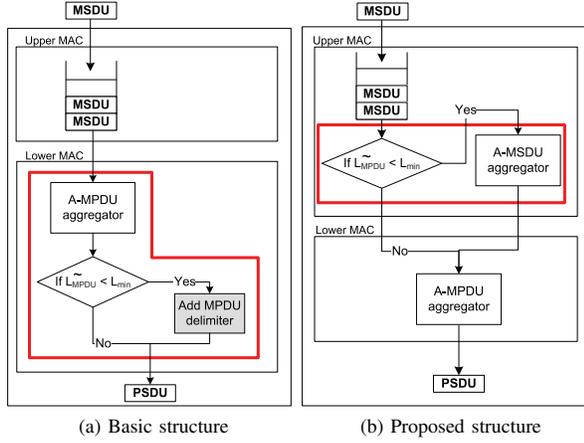
(a) Basic structure (b) Proposed structure

Fig. 3: Comparison between the basic and proposed structures. $\tilde{L}_{\text{MPDU}}$ is the A-MPDU subframe size before inserting dummy MPDU delimiters, as explained in Section IV-A.

In order to resolve this drawback of the conventional A-MPDU, we propose an adaptive, two-level aggregation architecture when A-MPDU is used. Specifically, when the lower MAC is expected to use additional MPDU delimiters, our scheme employs A-MSDU aggregation at the upper MAC, while at the lower MAC A-MPDU is always used. With the proposed architecture, the hardware structure of the lower MAC becomes simpler. Fig. 3 compares the proposed aggregation scheme and the basic one. In the proposed scheme, when the upper MAC detects that the size of an MSDU is less than L_{min}, it performs A-MSDU aggregation in order to make the MPDU size larger than L_{min}. With this mechanism, additional dummy MPDU delimiters are no longer needed. Moreover, under the basic structure, the lower MAC needs to perform a comparison procedure in order to decide whether it will add additional MPDU delimiters or not. However, with the proposed structure, the comparison routine is carried out only at the upper MAC, which is basically a software component. Consequently, by the proposed architecture, the hardware structure of a station can become simpler.

V. PERFORMANCE ANALYSIS

In this section, in order to evaluate the performance of different aggregation schemes, we analyze the maximum throughput performance under an error-free environment. In this analysis, we consider the following three scenarios in which a single or multiple PPDUs are acknowledged by a BA, depending on the type of aggregation that a PPDU conveys:

- (Case 1) A-MSDU: An A-MSDU is conveyed in a single PPDU, with multiple PPDUs being acknowledged by a BA.
- (Case 2) A-MPDU: A PPDU carries an A-MPDU consisting of multiple MPDUs. Each PPDU is acknowledged by a BA.
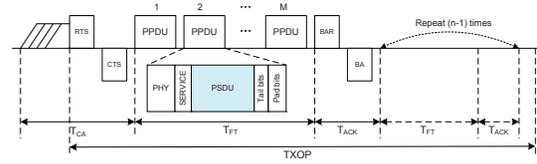

Fig. 4: Frame exchange structure for the block acknowledgement scenario.

- (Case 3) A-MSDU embedded in A-MPDU: This is our proposed scheme where each PPDU is also acknowledged by a BA.

In order to compare the achievable throughput of different aggregation schemes, we design a common frame exchange structure for all three cases as shown in Fig. 4. The frame exchange structure consists of the following three phases: channel access, frame transmission, and acknowledgement, whose durations are T_{CA}, T_{FT}, and T_{ACK}, respectively. T_{CA} consists of the average backoff time, RTS/CTS frame transmission time, and a couple of short interframe spaces as shown in Fig. 4. The frame transmission (T_{FT}) and acknowledgement (T_{ACK}) phases are repeated n times up to the transmission opportunity (TXOP) time duration, T_{TXOP}. In addition, T_{FE} denotes the total time duration for a series of frame transmission and acknowledgement phases[2]. We assume that the size of an MSDU is fixed to L_{MSDU} for all aggregation schemes. In all the cases we use compressed BA. Note that in Case 1, Block Ack Request (BAR)/BA sequences as shown in Fig. 4 are used while in Cases 2 and 3, BAR is omitted (i.e., implicit BAR).

With these notations, the throughput can be expressed as

$$Throughput = L_{\text{DATA}}/(T_{\text{FE}} + T_{\text{CA}}), \quad (1)$$

where L_{DATA} denotes the total amount of the payload delivered during a TXOP. In the following sections, we calculate L_{DATA} and T_{FE} for each of the three cases.

1) Case 1: As shown in Fig. 4, multiple PPDUs are acknowledged by a BA in this scenario. First, the length of an A-MSDU subframe and an A-MSDU are, respectively, given as

$$L_{\text{A-MSDU subframe}} = L_{\text{MSDU}} + L_{\text{A-MSDU subframe header}}, \quad (2)$$

and

$$L_{\text{A-MSDU}} = L_{\text{A-MSDU subframe}} \cdot N_{\text{A-MSDU subframe}}, \quad (3)$$

where $L_{\text{A-MSDU subframe header}}$ is the length of the A-MSDU subframe header of 14 bytes plus padding and $N_{\text{A-MSDU subframe}}$ is the number of A-MSDU subframes in one A-MSDU.[3]

Now, the transmission time for one PPDU, i.e., T_{PPDU}, can be calculated by

$$T_{\text{PPDU}} = T_{\text{PHY}} + \frac{8 \cdot (L_{\text{MAC overhead}} + L_{\text{A-MSDU}})}{BpS(\text{MCS index})} \cdot T_{\text{symbol}}, \quad (4)$$

[2]In Fig. 4, T_{FE} can be calculated by n $\cdot$ $(T_{\text{FT}} + T_{\text{ACK}})$.

[3]The number of A-MSDU subframes in one A-MSDU, $N_{\text{A-MSDU subframe}}$, can be calculated by $\lfloor$Maximum A-MSDU length$/L_{\text{A-MSDU subframe}}\rfloor$, where the maximum A-MSDU length is either 3,869 or 7,965.

where T_{PHY} is the transmission time of the PHY layer overhead, i.e., preamble and PLCP header, and $L_{MAC\ overhead}$ is the length of the MAC overhead in bytes. In addition, $BpS\,(\text{MCS index})$ is the number of bits per OFDM symbol for the transmission rate referred to as the MCS index and T_{symbol} is the time duration of one OFDM symbol.

Then, the frame transmission time and the frame exchange time are given as follows:

$$T_{FT} = M \cdot (T_{PPDU} + T_{SIFS}), \tag{5}$$

and

$$T_{FE} = n \cdot \{T_{FT} + T_{ACK}\}, \tag{6}$$

where M is the number of MPDUs acknowledged by the following BA, which is equal to the number of PPDUs in the case of A-MSDU. Here, T_{ACK} is the transmission time for BAR and BA plus two SIFS duration. The series of PPDUs and following BAR/BA exchanges are repeated until TXOP time duration. In addition, n is the repetition number of the series of PPDUs and BAR/BA exchange, calculated by $\lfloor (T_{TXOP} - T_{RTS/CTS})/(T_{FT} + T_{ACK}) \rfloor$, where $T_{RTS/CTS}$ denotes the time for Request to Send and Clear to Send (RTS/CTS) frame transmission.[4]

Finally, the total amount of delivered payload can be expressed as

$$L_{DATA} = L_{MSDU} \cdot N_{A\text{-MSDU subframe}} \cdot M \cdot n. \tag{7}$$

2) Case 2: In this case, as well as in Case 3, $M = 1$ since each PPDU conveying a number of MPDUs is acknowledged by a single BA. Let L_{MPDU} be the length of an MPDU, which is given as $L_{MAC\ overhead} + L_{MSDU}$. Here, for notational simplicity, let L_{MPDU} denote the length of an MPDU plus any possible padding, which is used to make the subframe length a multiple of four bytes. In addition, let $\tilde{L}_{MPDU} = L_{MPDU\ del} + L_{MPDU}$, where $L_{MPDU\ del}$ denotes the length of an MPDU delimiter. Then, the length of an A-MPDU subframe is given as

$$L_{A\text{-MPDU subframe}} = \begin{cases} \tilde{L}_{MPDU}, & \text{if } \tilde{L}_{MPDU} \geq L_{min}; \\ \tilde{L}_{MPDU} + L_{del}, & \text{otherwise.} \end{cases} \tag{8}$$

Here, $L_{del} = L_{MPDU\ del} \cdot N_{MPDU\ del}$, where $N_{MPDU\ del}$ is the number of MPDU delimiters, which can be calculated as $N_{MPDU\ del} = \lceil (L_{min} - \tilde{L}_{MPDU})/L_{MPDU\ del} \rceil$.

Now, the length of an A-MPDU can be obtained as

$$L_{A\text{-MPDU}} = L_{A\text{-MPDU subframe}} \cdot N_{A\text{-MPDU subframe}}, \tag{9}$$

where
$$N_{A\text{-MPDU subframe}} = \min\left\{ \left\lfloor \frac{\text{Maximum A-MPDU length}}{L_{A\text{-MPDU subframe}}} \right\rfloor, M_{max} \right\},$$
and M_{max} is the maximum number of MPDUs that one BA can acknowledge, i.e., 64.

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[4]In this case, $M = 64$ is assumed since it is the maximum number of MPDUs that can be acknowledged by a single BA. If a TXOP is fully utilized, the last T_{FT} may include fewer PPDUs, but we do not consider such a possibility for simplicity.

The transmission time for one PPDU, T_{PPDU}, can be calculated as follows:

$$T_{PPDU} = T_{PHY} + \frac{8 \cdot L_{A\text{-MPDU}}}{BpS(\text{MCS index})} \cdot T_{symbol}. \tag{10}$$

Hence, the frame exchange time, T_{FE} in this case can be obtained in a similar manner to (6) by putting (10) into (5) with $M = 1$. Finally, the total amount of the delivered payload in this case is given as

$$L_{DATA} = L_{MSDU} \cdot N_{A\text{-MPDU subframe}} \cdot n. \tag{11}$$

3) Case 3: In this case, a single PSDU consists of one A-MPDU, which contains multiple A-MPDU subframes. Each A-MPDU subframe consists of one MPDU delimiter and an MPDU, which is an A-MSDU in this case. The length of an A-MSDU is given as

$$L_{A\text{-MSDU}} = L_{A\text{-MSDU subframe}} \cdot N_{A\text{-MSDU subframe}}. \tag{12}$$

In this case, $N_{A\text{-MSDU subframe}}$ can be calculated by $\lfloor x/L_{A\text{-MSDU subframe}} \rfloor$, where x is the minimum value between the Maximum A-MSDU length (3,869 or 7,965 bytes) and the maximum MPDU length in an A-MPDU subframe (4,095 bytes).

While the frame exchange time, T_{FE}, can be obtained in the same manner as in Case 2, the length of an MPDU and an A-MPDU subframe are, respectively, given as

$$L_{MPDU} = L_{MAC\ overhead} + L_{A\text{-MSDU}}, \tag{13}$$

and

$$L_{A\text{-MPDU subframe}} = L_{MPDU\ del} + L_{MPDU}. \tag{14}$$

Consequently, the total amount of the delivered payload can be obtained as

$$L_{DATA} = L_{MSDU} \cdot N_{A\text{-MSDU subframe}} \cdot N_{A\text{-MPDU subframe}} \cdot n. \tag{15}$$

VI. Performance Evaluation

In this section, we evaluate the performance of the proposed scheme compared with that of conventional aggregation mechanisms via analysis based on the derivations in the previous section and NS3 simulation [15]. In order to focus on the performance of frame aggregation, we first consider a very simple one-to-one network topology with a single source operating under saturated traffic conditions, which is transmitting data to a single destination over an ideal wireless channel without any interference or errors. In addition, we assume that the stations work under a HT-mixed mode, which defines the structure of the HT preamble, its components and duration [3]. We use the following parameters: $t_{MMSS} = 16\ \mu s$, TXOP duration = 8,160 μs, Maximum A-MPDU length = 65,535 bytes, and Maximum A-MSDU length = 7,935 bytes, where these last two values correspond to the maximum values defined in the standard [3]. When A-MPDU is used, we also make sure that its maximum time duration is no greater than 10 ms [3].

Fig. 5 and 6 show the throughput performance of each aggregation scheme with MCS = 31 (260 Mb/s) and 15
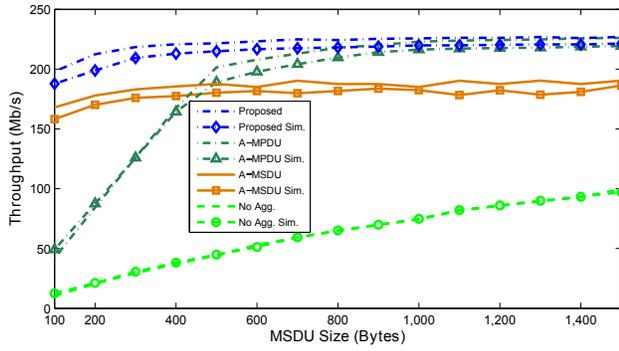
Fig. 5: Throughput comparison for a one-to-one scenario with PHY rate = 260 Mb/s.
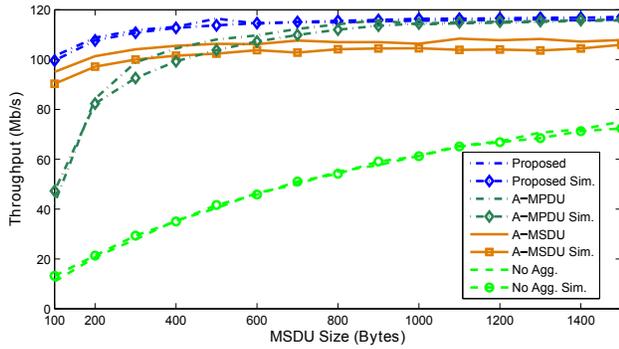

Fig. 7: Throughput comparison for a one-to-one scenario with different MCS indices.

Fig. 6: Throughput comparison for a one-to-one scenario with PHY rate = 130 Mb/s.
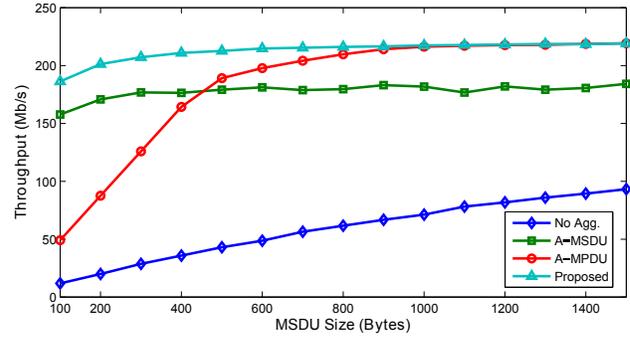
Fig. 8: Throughput comparison for a 10-station scenario with PHY rate = 260 Mb/s.

(130 Mb/s), respectively. For comparison, we also include the case of no aggregation. We first observe that the analytical and simulation results (denoted by "Sim." on the figures) match pretty well across all the range of MSDU sizes, thus confirming the validity of our analysis in the previous section. Then, it can be observed that the performance of the proposed scheme combines the advantages of A-MSDU and A-MPDU aggregations. The former yields more even throughput performance across different payload sizes. In general, A-MSDU is more efficient terms of throughput than A-MPDU due mainly to MAC header overhead. In our case, however, its throughput is lower than that of the A-MPDU scheme for large payload sizes, because the Maximum A-MSDU length is much smaller than that of A-MPDU. The A-MPDU performance, in turn, suffers severe degradation when the MSDU size is small due to additional dummy MPDU delimiters, while it exceeds that of A-MSDU for large payload sizes.

From the discussion in Section IV-A, we know that when the size of the A-MPDU subframe is smaller than L_{min}, the transmitter needs to add dummy MPDU delimiters, which may severely degrade the throughput performance. For example, in Fig. 5, L_{min} = 520 bytes and, consequently, the A-MPDU throughput becomes significantly low for any payload size less than L_{min}. The proposed scheme, on the other hand,
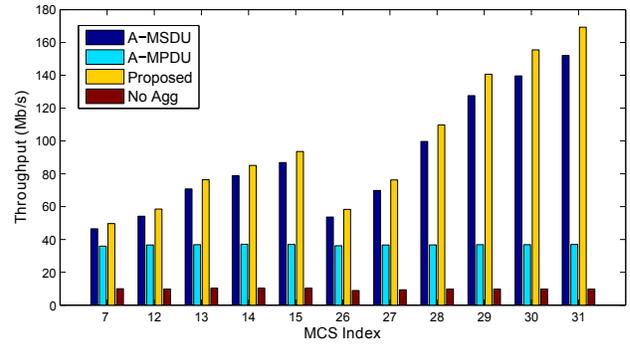
shows much better performance for such small MSDU sizes. Its throughput improvement over A-MPDU and A-MSDU is as high as around 280% and 19%, respectively, with a payload of 100 bytes, according to simulation results in Fig. 5. Furthermore, the throughput performance of the proposed scheme is as high as that of the A-MPDU scheme for large MSDU sizes. It should be also noted that the gap between A-MPDU and A-MSDU for small MSDU sizes is larger with 260 Mb/s compared with that with 130 Mb/s since more MPDU delimiters are added for A-MPDU in this case.

The proposed scheme improves the throughput performance particularly with high PHY rate and/or small payload size. Fig. 7 shows the throughput performance of each aggregation scheme for different MCS indices, obtained by simulation, when the payload size is 100 bytes. We can see that the proposed scheme outperforms conventional aggregation mechanisms in all cases, especially when compared with A-MPDU. Furthermore, the difference becomes more significant as the PHY rate increases, as predicted. The proposed scheme's throughput is even 11% higher than that of A-MSDU approximately, for the highest MCS.

We now proceed to evaluate each aggregation scheme in a network with multiple stations via NS3 simulation. We have randomly placed 10 stationary stations on a circle of 5 meter radius around an AP, with no interference or hidden nodes.

The stations are saturated and send UDP traffic at a constant rate to the AP, where the aggregate throughput was measured. The channel's large-scale fading follows the path loss model used by the standardization group that developed the 802.11n standard [16], while the small-scale Rayleigh fading model is based on Jakes' fading model with a Doppler velocity of 0.1 m/s. The PHY rate is 260 Mb/s while the other parameters are the same as those used previously. Fig. 8 shows the aggregate throughput of the four aggregation mechanisms considered. The tendencies and behavior observed previously in the one-to-one scenario are seen again in this case, with the proposed scheme being able to overcome the A-MPDU limitation when the MSDU size is small. As expected, the throughput of all aggregation schemes is reduced due to the channel errors and collisions. However, given the configuration of this network scenario, it is clear that the number of errors in the channel is small and so is the throughput degradation.

VII. CONCLUSION

In this paper, we have identified a potential limitation of the IEEE 802.11n A-MPDU aggregation scheme, which may cause significant throughput degradation when the transmitter sends small frames at high PHY rates. In order to resolve this limitation, we have proposed a simple, yet practically efficient aggregation scheme, which combines A-MPDU and A-MSDU in an adaptive manner. Our analytical and simulation results have shown that the proposed aggregation scheme can significantly enhance the throughput performance over the conventional schemes. As part of the future work, we plan to extend our analysis to consider an erroneous channel and obtain new simulation results under such conditions.

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