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Efficient dynamic frame aggregation in IEEE 802.11s mesh networks

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SUMMARY

IEEE 802.11n could improve the network efficiency of WLAN by aggregating multiple frames into a single transmission. The frame aggregation technique especially benefits multi-hop transmissions that introduce enormous 802.11 medium access control (MAC) layer control overhead. This paper proposes a novel algorithm, namely *dynamic aggregation selection and scheduling* (*DASS*) algorithm, that can dynamically adopt the appropriate aggregation mechanism for IEEE 802.11s mesh network. The characteristics, benefits and the restrictions of three aggregation mechanisms, aggregate MAC service data units, aggregate MAC protocol data unit and aggregate physical protocol data unit, are investigated. Based on the channel condition, the quantity and the distribution of the frame arrivals, DASS could determine what aggregation mechanism to adopt and whether to wait for the next frame for aggregating transmissions. Simulation results demonstrate that the algorithm significantly increases the channel efficiency of the 802.11 MAC and further improves the overall throughput of the wireless mesh network by approximately 95%. Copyright © 2009 John Wiley & Sons, Ltd.

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KEY WORDS: frame aggregation; multi-hop; mesh networks; 802.11s

1. INTRODUCTION

With the increasing demand for real-time applications over wireless networks, IEEE 802.11n [1] is proposed to provide high-speed wireless access with maximum physical layer (PHY) data rate up to 600 Mbps. However, the 802.11 medium access control (MAC) layer control overhead, including the preamble, frame headers, carrier sense waiting time and the random backoff period, has limited the improvement of the user perceived throughput [2]. Especially with the high data

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rate in 802.11n, MAC control overhead frequently occupies the channel when transmitting small-size frames, e.g. control messages and voice-over-IP (VoIP) traffic. In other words, the channel utilization is deteriorated. To enhance the channel utilization and network efficiency, 802.11n adopts the *frame aggregation* mechanisms that aggregate several frames into one single transmission.

Frame aggregation is particularly essential in the wireless mesh network (WMN) due to the repeated MAC control overhead in transmitting frames over the multi-hop wireless backhaul links [3]. A WMN is composed of mesh portals (MPPs), mesh points (MPs), mesh access points (MAPs) and wireless stations (STAs) [4]. MPPs, MAPs and MPs communicate with one another via the wireless medium and form a wireless backbone network. Moreover, STAs associate with an MAP to communicate with the other STAs or access the Internet via the MPP. Because of the nature of the wireless communication, only one mesh entity can transmit frames at a time within a collision domain [5, 6]. Besides, traffic loads of different mesh entities in the WMN are unbalanced [7]. The traffic load of the mesh nodes near the MPP is relatively high so that those nodes may have more frames to aggregate than the others. Appropriately aggregating frames can significantly moderate the MAC control overhead in the WMN.

In this paper, we propose a novel algorithm, namely *dynamic aggregation selection and scheduling* (*DASS*), to maximize the bandwidth utilization and achieve a high-throughput and high-efficiency WMN. It could dynamically select the aggregation mechanism according to the bit error rate (BER), the communication type, the transmission category, the quantity and the distribution of frame arrivals in the transmission queue. Based on the analysis of the traffic history, we could calculate the expected number of frame arrivals within a certain time. Then, an appropriate waiting time is determined to aggregate incoming frames and send. We conduct extensive simulation to evaluate the throughput performance and the average delay of DASS. The results are to be compared with the fixed aggregation mechanisms.

The rest of this paper is organized as follows. Section 2 is dedicated to the related work. Section 3 provides an overview of the IEEE 802.11n frame aggregation mechanisms and 802.11s mesh networks. In Section 4, the DASS algorithm and its detailed operations are described. Section 5 presents the simulation results to evaluate the performance enhancement and provide proper configuration and parameters for DASS. Finally, Section 6 concludes this paper.

2. RELATED WORK

Wireless channel condition is commonly dynamic and error-prone. Transmission error can tremendously impact the performance of WLAN. Many literatures focus on modeling and analyzing the IEEE 802.11 CSMA/CA protocol. A two-dimensional Markov-chain is proposed to model the backoff behavior of saturated 802.11 WLAN by Bianchi [8]. Tay and Chua [9] propose a simple analytical model by using the average values for 802.11 WLAN. Yin *et al.* [10] analyze the throughput performance in error-prone channel and conclude that there could be an optimal frame size under a certain BER to achieve the maximum throughput. In [11] and [12], the analytical models are proposed to model frame aggregation of the CSMA/CA protocol. Furthermore, Kim *et al.* [13] and Kuppa and Dattatreya [14] focus on modeling IEEE 802.11n frame aggregation mechanisms. Their results also confirm that frame aggregation can enhance the throughput of WLAN.

Related work on adaptive frame aggregation schemes [15–18] aims to optimize the network performance by adjusting the aggregated frame size. The work in [15] leverages the 802.11e

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priority queues to schedule the frame aggregation. In [16] an cross-layered adaptive frame aggregation scheme for WMN is proposed. Zhang *et al.* [18] propose a prediction-based link-layer dynamic frame reassembling scheme 802.11-based WMN. However, these two schemes above only aggregate MAC service data units (A-MSDUs) to enhance the scalability of WMNs. The 802.11n frame aggregation mechanisms are not considered either. Lin and Wong [17] conduct a thorough study of the newly proposed A-MSDU and A-MPDU frame aggregation schemes in IEEE 802.11n. They propose a simple optimal frame size adaptation algorithm for A-MSDU and A-MPDU under error-prone channels. Nevertheless, they only focus on enhancements of 802.11n MAC protocol, whereas the characteristics of mesh networks are not concerned. Therefore, the proposed algorithm could be inapplicable to WMN.

These existing studies do not consider how to choose an appropriate aggregation mechanism corresponding to the quantity and the distribution of frame arrivals, the communication types and transmission categories. Moreover, in WMN, the characteristics of the traffic vary with the roles and the locations of the communication pairs. To the best of our knowledge, there is no previous work collaborating the 802.11n frame aggregation mechanisms and 802.11s WMN. In this paper, we not only model the frame aggregation of CSMA/CA protocol in an error-prone channel to estimate the throughput of a given frame size but the proposed DASS can also dynamically predict and change the 802.11n frame aggregation mechanism according to the characteristics of the communication between the 802.11s mesh entities.

3. OVERVIEW OF FRAME AGGREGATION AND 802.11s WMNs

3.1. Frame aggregation mechanisms

Frame aggregation can be performed at different sub-layers [1]. Figure 1 illustrates the three major frame aggregation mechanisms—(1) *A-MSDU*, in which multiple MAC service data units (MSDUs) can be aggregated into a single MAC protocol data unit (MPDU) with a single MAC header; (2) *aggregate MPDU* (*A-MPDU*), which aggregates a number of MPDU to form a PHY service data unit (PSDU), (3) *aggregate PHY protocol data unit* (*A-PPDU*), which concatenates multiple PSDUs together and adds a PHY header.

Figure 2 illustrates the frame format of an A-MSDU that aggregates multiple MSDUs destined to the same destination and transmits them via a single MPDU. Because all MSDUs are concatenated into a single MPDU with a single frame control sequence (FCS), corruption of one subframe results in the failure of the entire A-MSDU. In 802.11n, A-MSDU increases the maximum frame transmission size from 2304 bytes to 7935 bytes. When there are many small MSDUs in the transmission queue, aggregating these small MSDU could significantly reduce the MAC control overhead. Thus, the channel efficiency could be improved.

The MPDUs that are physically transmitted to the same receiver could be aggregated into the A-MPDU. As shown in Figure 3, A-MPDU intends to concatenate the MPDUs to eliminate the PHY header followed by each MPDUs. The delimiter in each A-MPDU subframe assists the recovery of the A-MPDU when one or more received delimiters are with error. The value of the Duration/ID field in the MAC headers of all the MPDUs in the A-MPDU should be the same. In 802.11n, the maximum number of subframes it could hold is 64 and the maximum size is increased to 64*k* bytes.

Figure 4 depicts the format of an A-PPDU. A-PPDU concatenates multiple PSDUs with a common preamble to improve channel utilization. A-PPDU allows multiple frames to be sent to

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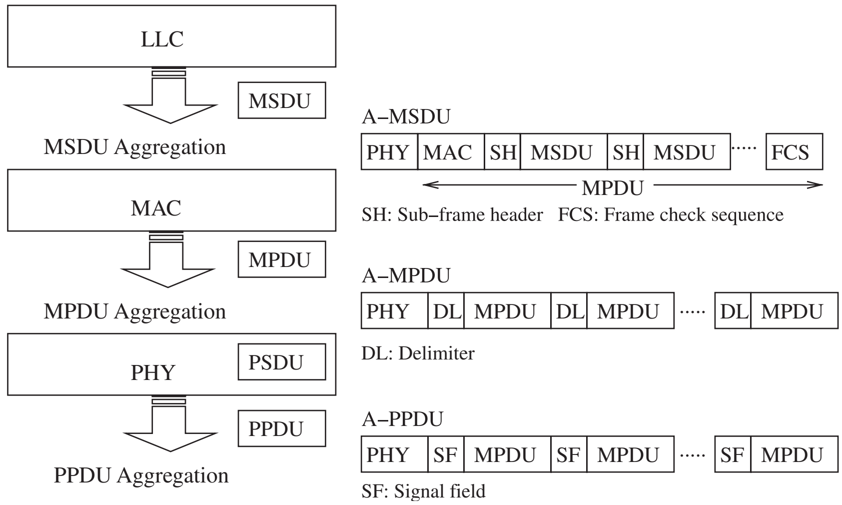

Figure 1. Layers of WLAN interface.

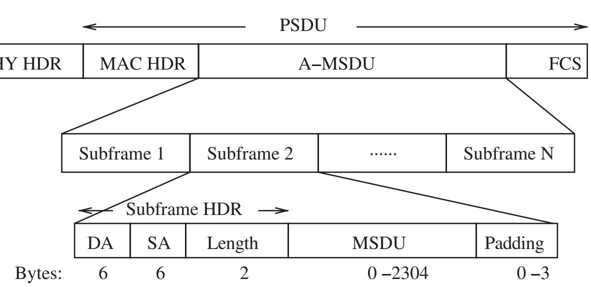

Figure 2. The frame format of an A-MSDU.

different destination addresses in one single medium access. Different PSDUs within the A-PPDU are separated by a Physical Layer Convergence Procedure (PLCP) signal field.

The comparison among the three frame aggregation mechanisms is summarized in Table I [19]. A-MSDU has the characteristics of the highest network efficiency because there is no additional MAC control overhead for each MSDU. However, MSDUs are restricted to a single pair of source and destination endpoints and traffic class. A-MSDU is also vulnerable to transmission errors owing to that the payload of an A-MSDU is merely protected by a single cyclic redundancy check. A-MPDU and A-PPDU have the advantage of aggregating frames destined to multiple destination addresses. Moreover, each frame within the A-MPDU or A-PPDU is individually attached with an FCS that can ensure the correctness of frame transmission. Thus, A-MPDU and A-PPDU are relatively robust to the transmission error. A-PPDU has another advantage that the PPDUs destined to different destination addresses may adopt different transmission rates with different modulations.

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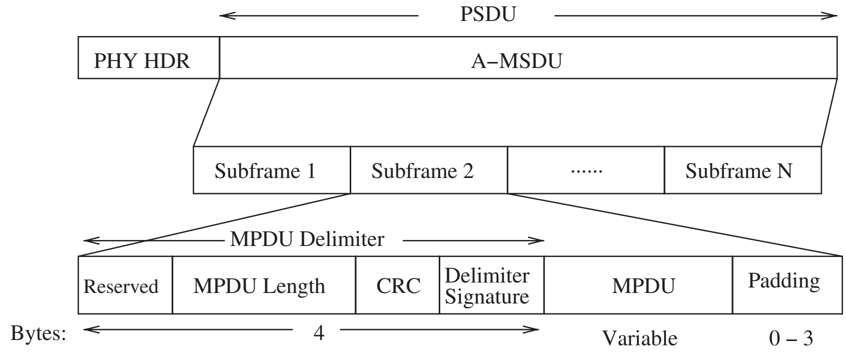

Figure 3. The frame format of an A-MPDU.

Figure 4. The frame format of an A-PPDU.

Table I. Comparisons of frame aggregation mechanisms [19].

	A-MSDU	A-MPDU	A-PPDU
MAC control overhead	Low	Middle	High
Network efficiency enhancement	High	Middle	Low
Multiple destination addresses	No	Yes	Yes
Robustness for transmission error	Low	High	High
Rate change for different destination	No	No	Yes

3.2. IEEE 802.11s mesh networks

IEEE 802.11s defines the mesh networking using the IEEE 802.11 MAC/PHY layers that support layer-2 path selection protocols and data forwarding over multi-hop topologies. Figure 5 illustrates the architecture of a mesh network.

Based on the roles of the mesh entities and the transmission behaviors, we first consider three types of communication pairs and four categories of transmission in the WMN. The peer-to-peer communication among the wireless mesh nodes could be classified into three types, including M(A)P-to-M(A)P, MAP-to-STA and STA-to-MAP. In addition, in WMN, the receiver of a peer link might not be the destination of the frame. Thus, frames to different destinations could be aggregated into one single frame. There are four transmission categories for an aggregated frame in this multi-hop environment, namely single destination single receiver (SDSR), multiple destination single receiver (MDSR), multiple destination multiple receiver (MDMR) and single destination multiple receiver (SDMR).[‡] According to the characteristics of the communication pair and the

‡SDMR is also named the multi-path issue.

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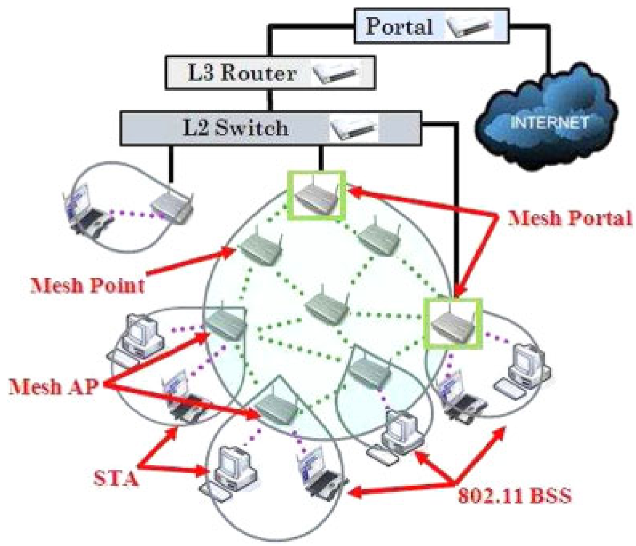

Figure 5. IEEE 802.11s mesh networks architecture.

Table II. The adaptive frame aggregation mechanisms among different transmission pairs.

	MP-to-MP				STA-to-MAP		MAP-to-STA	
	SDSR	MDSR	SDMR	MDMR	SDSR	MDSR	SDSR	MDMR
A-MSDU	○				○		○	
A-MPDU	□	○			□	○	□	
A-PPDU	△	△	○	○	△	△	△	○

○: Most suitable, □: Replaceable but less efficient, △: Replaceable but inefficient.

transmission category, the corresponding suitable aggregation mechanisms can be determined. For example, A-PPDU is suitable for the MDMR case because it is the only applicable aggregation mechanism for multiple destinations and receivers. A-PPDU is not suggested for the STA-to-MAP case because the MAP is the only receiver in this case. But multiple STAs may associate with one MAP at the same time. Therefore, A-PPDU could be adopted by an MAP to aggregate the frames destined to different STAs, i.e. MAP-to-STA.

The usage of a frame aggregation mechanism varies with the roles of the communication pair. Table II shows the usage of the aggregation mechanisms in different communication scenarios. A-MSDU reduces the most MAC control overhead. In the aspect of the network efficiency enhancement, A-MSDU is the most suitable aggregation mechanism for all the SDSR cases. However, A-MSDU is restricted to the SDSR case. Also, if the BER is high, the user could choose A-MPDU rather than A-MSDU to prevent the entire A-MSDU from corruption. For the MDSR cases, A-MPDU could improve more network efficiency than A-PPDU because of the saved control overhead. Although A-PPDU eliminates the least MAC and PHY overhead and is not suggested if A-MSDU and A-MPDU are applicable, it is the only choice for the cases of multiple receivers, i.e. SDMR and MDMR.

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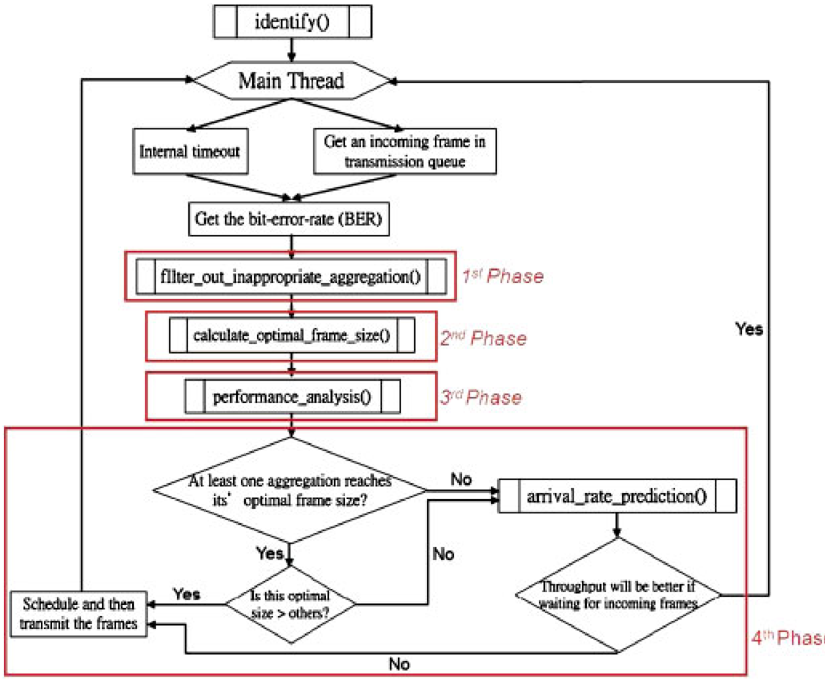

Figure 6. The flow chart of the DASS algorithm.

4. DASS ALGORITHM

This section details the concepts and procedures of the proposed DASS algorithm. The DASS algorithm decides which aggregation mechanism to employ and when to transmit the frames. The expected quantity and distribution of the frame arrivals in the transmission queue are evaluated. Based on the prediction of the frame arrivals, DASS dynamically selects the preferable frame aggregation mechanism and schedules the transmission to achieve a high-throughput and high-efficiency mesh network.

4.1. Overview of the algorithms

There are four phases in the proposed DASS algorithm. In the first phase of DASS, each aggregation point filters out the inappropriate aggregation mechanisms before transmission. In the latter phases of DASS, the channel quality, the quantity, distribution and the expected arrival rate of the incoming frames are measured and evaluated. Based on these factors, DASS algorithm determines: (1) which aggregation mechanism to adopt and (2) when to send the aggregated frame out. The operations of the algorithm are depicted in Figure 6 and elaborated in the following subsections.

4.2. Detailed operations of DASS

4.2.1. First phase: *filtering out inappropriate aggregation mechanisms.* When a mesh node joins a mesh network, DASS identifies the current role of the node in the mesh. Through the identification,

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DASS can filter out the inappropriate aggregation mechanisms in the first phase before each transmission. In this paper, every STA is supposed to follow the 802.11 standard to have only one link to its associated MAP in the Basic Service Set (BSS). Thus, if a transmitter is an STA, DASS will not consider A-PPDU to aggregate the frames because multiple receivers, MDMR, will not happen to such a transmission.

4.2.2. Second phase: getting the optimal frame size. In the second phase, DASS analyzes the optimal frame size for the available aggregation mechanisms. We adopt Lin and Wong's analytical model [17] that extends the model from Bianchi [8] to compute the optimal frame size under error-prone channels. In their analytical model, N mobile stations are assumed to exist in the WLAN. In mesh networks, the BSS traffic and the mesh forwarded traffic compete for the same channel that can only be occupied by one channel access at a time. Thus, N is redefined as the number of all mesh nodes which can sense each other within the same collision domain. The wireless channel is assumed to be with a bit-error-rate (BER) of P_b, which can be measured through an incoming frame. The minimum contention window size is W and the maximum backoff stage is m. Because the size of an aggregated frame is large, the request-to-send/clear-to-send (RTS/CTS) access scheme is enabled all the time. Moreover, the control frames are transmitted at the basic rate, which is much more robust in combating errors than the data frames transmitted at the data rate. To simplify the analysis, the analytical model does not consider the frame error for control frames and preambles.

In [8, 17], a virtual time slot system is adopted to model the state of the queuing system. Each virtual time slot represents the interval between two consecutive countdown of backoff timers by non-transmitting stations.

From [17], the transmission probability τ in a virtual time slot is

$$\tau = \frac{2(1-2p)}{(1-2p)(W+1)+pW(1-(2p)^m)} \tag{1}$$

where p is the conditional probability that an unsuccessful transmission happens in a time slot. p can further be expressed as

$$p = 1-(1-(1-(1-\tau)^{(N-1)}))(1-p_{\mathrm{e}}) \tag{2}$$

where p_{e} denotes the conditional error probability that an error happens after a successful RTS/CTS exchange in the time slot.

The probability of an idle slot is

$$P_{\mathrm{idle}} = (1-\tau)^N \tag{3}$$

The transmission probability for a time slot is

$$P_{\mathrm{tr}} = 1-P_{\mathrm{idle}} = 1-(1-\tau)^N \tag{4}$$

Thus, the conditional probability for a non-collided transmission is

$$P_s = \frac{N\tau(1-\tau)(N-1)}{P_{\mathrm{tr}}} \tag{5}$$

The probability that the transmission fails not due to collisions but transmission errors is

$$p_{\mathrm{err}} = P_{\mathrm{tr}} P_s p_{\mathrm{e}} \tag{6}$$

Similarly, the probability for a successful transmission without collisions and transmission errors is

$$P_{\text{succ}} = P_{\text{tr}} P_s (1 - p_{\text{e}}) \tag{7}$$

The saturated network throughput can be derived as

$$S = \frac{E_{\text{p}}}{E_{\text{t}}} \tag{8}$$

where E_{p} is the number of bits of payload that are successfully transmitted in a virtual time slot. E_{t} denotes the expected time length of a virtual time slot. E_{t} can be expressed as

$$E_{\text{t}} = T_{\text{idle}} P_{\text{idle}} + T_{\text{c}} P_{\text{tr}} (1 - P_s) + T_{\text{e}} p_{\text{err}} + T_{\text{succ}} P_{\text{succ}} \tag{9}$$

where $T_{\text{idle}}, T_{\text{c}}$ and T_{succ} are the lengths of the idle, collision and successful virtual time slot. T_{e} is the virtual time slot length for an error transmission sequence. T_{idle} is the default empty slot time of the system.

The average delay of channel access is then derived as

$$d = N \frac{L_{\text{p}}}{S} \tag{10}$$

where L_{p} is payload length of the aggregated frame.

In this paper, we only consider the uni-directional case in [17]; the equations for $T_{\text{c}}, T_{\text{succ}}, T_{\text{e}}$ and E_{p} are

$$T_{\text{c}} = \text{RTS} + \text{EIFS} \tag{11}$$

$$T_{\text{succ}} = \text{RTS} + \text{CTS} + \text{DATA} + \text{BACK} + 3\text{SIFS} + \text{DIFS} \tag{12}$$

$$T_{\text{e}} = \text{RTS} + \text{CTS} + \text{DATA} + \text{EIFS} + 2\text{SIFS} \tag{13}$$

For A-MSDU, p_{e} and E_{p} can be obtained by

$$p_{\text{e}} = 1 - (1 - P_b)^L \tag{14}$$

$$E_{\text{p}} = (L - L_{\text{hdr}})(1 - p_{\text{e}}) \tag{15}$$

where L is the aggregated MAC frame size and L_{hdr} is the total length including MAC header and FCS.

For A-MPDU, error occurs when all the sub-frames become corrupted. Thus, we have

$$p_{\text{e}} = \prod_i (1 - (1 - P_b)^{L_i}) \tag{16}$$

$$E_{\text{p}} = \sum_i (L_i - L_{\text{subhdr}})(1 - P_b)^{L_i} \tag{17}$$

Table III. Notations of the third phase of DASS.

$\text{Endpoint}_{i,j}$	The set of frames which are destined to the endpoint i with the TID equals to j, where $0\leqslant j\leqslant 7$
$f(x, \text{BER})$	The goodput function that is defined by divide the optimal aggregated frame size
$f(x, \text{BER})$	x to the duration of sender successfully transmitting the frame under the BER
$D_{\text{buffered}}(i, j)$	The amount of the buffered data for $\text{Endpoint}_{i,j}$
Rr_m	The set of the traffic that will be transmitted to the same receiver m
$D_{\text{Rr}}(m)$	The amount of the buffered data for Rr_m
$T_{\text{Max}-\text{MSDU}}$	The current maximum throughput using A-MSDU
$T_{\text{Max}-\text{MPDU}}$	The current maximum throughput using A-MPDU
$T_{\text{Max}-\text{PPDU}}$	The current maximum throughput using A-PPDU

where i is from 1 to the total number of aggregated sub-MPDUs and L_i is the size for the ith sub-MPDU. L_{subhdr} is the total size of each sub-MPDU's delimiter, header and FCS.

To summarize, according to the given aggregation method and the frame size, DASS can evaluate the expected network throughput S and the average access delay d from Equation (8) and (10). According to the value of S, the optimal aggregated frame size can be derived.

4.2.3. Third phase: *performance evaluation.* After getting the optimal frame size of available aggregation mechanisms, the third phase of DASS intends to select an aggregation mechanism with the largest throughput improvement for the mesh node.

In the second phase, one can observe that the optimal aggregated frame size varies with BER. Since a mesh node may have more than one neighbor, it is necessary to consider the diverse BER between different communication peers. To explain the third phase of DASS, we take an example that a mesh has a certain number of frames destined to the endpoint i with TID equals j. Table III defines the notations used in this phase.

When frames are enqueued in the transmission queue, DASS, based on the available aggregation mechanisms, shall, respectively, compute the maximum throughput. All of the frames in the transmission queue are classified according to destination address and TID value.

For A-MSDU, frames could only be aggregated when their destination and TID value are the same. BER measured between the communication pair along with the accumulative size of the frames, x, could then be used as the input of $f(x, \text{BER})$ to calculate the corresponding throughput. We repeat this procedure for each set of aggregated frames, $\text{Endpoint}_{i,j}$. The maximum throughput of the transmission queue under A-MSDU is then obtained. Note that different set of aggregated frames may have the same maximum throughput. The expected maximum throughput can be formulated as

$$T_{\text{Max}-\text{MSDU}} = \max_{i,j}\{f(D_{\text{buffered}}(i, j), \text{BER})\} \tag{18}$$

For A-MPDU, the frames with the same receivers can be aggregated. Via routing information, each mesh node can classify all the frames in transmission queue according to the next-hop receivers. In A-MPDU, frames can be aggregated as long as having the same receiver. Each mesh node might determine the concatenatability of individual nodes according to the routing information. In a similar way, the maximum throughput of the transmission queue can be obtained. Note that as in A-MSDU, different set of concatenatable frames may have the same maximum

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throughput as

$$T_{\mathrm{Max-MPDU}} = \max_{m}\{f(D_{\mathrm{Rr}}(m), \mathrm{BER})\} \tag{19}$$

A-PPDU has no restrictions on concatenation. The maximum throughput is computed in a similar way, except that it is the maximum among all possible frame aggregations as

$$T_{\mathrm{Max-PPDU}} = f\left(\sum_{i}\sum_{j=0}^{7} D_{\mathrm{Buffered}}(i,j), \mathrm{BER}\right) \tag{20}$$

Through the comparison among the three maximum throughput values $T_{\mathrm{Max-MSDU}}$, $T_{\mathrm{Max-MPDU}}$ and $T_{\mathrm{Max-PPDU}}$, DASS can determine the aggregation mechanism and proceed to the next phase.

4.2.4. Fourth phase: *scheduling packets.* In the second stage, different BER values bring different optimal aggregated frame sizes of the corresponding aggregation mechanisms. The optimal aggregated frame size is called the ideal value. Afterward, through the third stage, we can estimate the maximal throughput of the different aggregation mechanisms and determine which aggregation mechanism to adopt. Comparing the ideal values with the accumulative amount of frames, there are three possible situations.

The first situation is that the current amount of frames is greater than the ideal value. If the amount of frames is greater than the ideal value, the frames will be aggregated to a size close but smaller than the ideal value. For A-MSDU, the selection strategy is first-in-first-out (FIFO). On the other hand, for A-MPDU and A-PPDU, the selection depends on the QoS classes. The frames with the higher QoS type have the higher priority to be sent. If the frames are with the same QoS type, DASS selects the frames that have traversed more hop-counts before arriving the current aggregation point. This selection strategy aims to minimize the variation of the end-to-end latency among all frames.

The second situation is that the amount of frames is equal to the ideal value. When the amount of frames is equal to ideal value, the only choice is to aggregate these frames and then transmit it.

The third situation, which is the most complicated, is that the amount of frames is less than the ideal value. When the amount of frames is less than the ideal value, DASS, based on the past traffic, predicts the arrival rate of the same set of frames. According to the past 16 frame arrivals, DASS could estimate the frame arrival rate by dividing the accumulative amount of frames to the time duration of the past 16 frames. The expected arrival rate, R_{Predict}, is formulated as

$$R_{\mathrm{Predict}}(i,j) = \frac{16L_{\mathrm{p}}}{\sum_{k=1}^{16} A_k} \tag{21}$$

where L_{p} is the payload length of the aggregated frame and A_k is the inter-arrival time between frame_k and frame_{k+1}.

By computing the frame arrival rate, we could estimate whether the aggregation of the frames of $\mathrm{Endpoint}_{i,j}$ could improve the throughput. The expected throughput of transmitting the aggregated buffered data, $\mathrm{Th}_{\mathrm{Buffered}}$, is

$$\mathrm{Th}_{\mathrm{Buffered}} = f(D_{\mathrm{Buffered}}(i,j), \mathrm{BER}) \tag{22}$$

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Assuming that T_{Waiting} is the waiting time for the incoming frames, the total incoming frame sizes could be calculated by the frame arrival rate as

$$D_{\mathrm{Future}}(i,j) = R_{\mathrm{Predict}}(i,j)\cdot T_{\mathrm{Waiting}} \tag{23}$$

Then we could calculate the predicted throughput of transmitting the aggregated frame after waiting T_{Waiting} seconds. The equations of the expected throughput of the three aggregation methods, namely $\mathrm{Th}_{\mathrm{Predict\_A-MSDU}}$, $\mathrm{Th}_{\mathrm{Predict\_A-MPDU}}$ and $\mathrm{Th}_{\mathrm{Predict\_A-PPDU}}$ are derived as

$$\mathrm{Th}_{\mathrm{Predict\_A-MSDU}} = \frac{\min(D_{\mathrm{Buffered}}(i,j)+D_{\mathrm{Future}}(i,j), 7935)}{\dfrac{D_{\mathrm{Buffered}}(i,j)+D_{\mathrm{Future}}(i,j)}{f(D_{\mathrm{Buffered}}(i,j)+D_{\mathrm{Future}}(i,j), \mathrm{BER})}+T_{\mathrm{Waiting}}} \tag{24}$$

$$\mathrm{Th}_{\mathrm{Predict\_A\text{-}MPDU}} = \frac{\min(\sum_{j=0}^{7}(D_{\mathrm{Buffered}}(i,j)+D_{\mathrm{Future}}(i,j)), 64k)}{\dfrac{\sum_{j=0}^{7}(D_{\mathrm{Buffered}}(i,j)+D_{\mathrm{Future}}(i,j))}{f(\sum_{j=0}^{7}(D_{\mathrm{Buffered}}(i,j)+D_{\mathrm{Future}}(i,j)), \mathrm{BER})}+T_{\mathrm{Waiting}}} \tag{25}$$

$$\mathrm{Th}_{\mathrm{Predict\_A\text{-}MPDU}} = \frac{\sum_i\sum_{j=0}^{7}(D_{\mathrm{Buffered}}(i,j)+D_{\mathrm{Future}}(i,j))}{\dfrac{\sum_i\sum_{j=0}^{7}(D_{\mathrm{Buffered}}(i,j)+D_{\mathrm{Future}}(i,j))}{f(\sum_i\sum_{j=0}^{7}(D_{\mathrm{Buffered}}(i,j)+D_{\mathrm{Future}}(i,j)), \mathrm{BER})}+T_{\mathrm{Waiting}}} \tag{26}$$

Afterward, DASS compares the $\mathrm{Th}_{\mathrm{Buffered}}$ with $\mathrm{Th}_{\mathrm{Predict}_*}$ ($\mathrm{Th}_{\mathrm{Predict}_*}\in\{\mathrm{Th}_{\mathrm{Predict\_A-MSDU}}$, $\mathrm{Th}_{\mathrm{Predict\_A-MPDU}}$, $\mathrm{Th}_{\mathrm{Predict\_A-MPDU}}\}$) to decide whether the MAC should wait for the more frames for aggregation or not. If $\mathrm{Th}_{\mathrm{Predict}_*}>\mathrm{Th}_{\mathrm{Buffered}}$, DASS triggers an internal timer with timer length equal to T_{Waiting}. Then, the MAC suspends the transmission and waits for the frame arrivals before the timer runs out. If the amount of the follow-up frames is larger than the maximum size of the aggregated frame, DASS stops the timer and orders the MAC to transmit the frames with the corresponding frame aggregation mechanism. If $\mathrm{Th}_{\mathrm{Predict}_*}\leqslant\mathrm{Th}_{\mathrm{Buffered}}$, the MAC will immediately aggregate the frames in the transmission queue and send out.

5. SIMULATION RESULTS

This section verifies the performance of DASS through the extensive simulations with the ns-2 [20] simulator. Section 5.1 first describes the simulation environment. Moreover, Section 5.2 elaborates the simulation results. The throughput performance under infinite and steady backlog, the accuracy of prediction for frame arrival rate and the comparisons between different selection strategies are presented.

5.1. Simulation environment

In the simulation, we set up an infrastructure service area that includes 8 MPs, 8 MAPs and 10–30 STAs. To simulate the IEEE 802.11n MAC, we set the basic rate to 54 Mbps to transmit the management frames, whereas the data frame are transmitted with 144.44 Mbps [1]. Based on the 802.11n, all entities operate over a 20 MHz channel with the same modulation coding scheme.

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Table IV. Simulation parameters.

Parameter	Value
Basic rate	54 Mbps
Data rate	144.44 Mbps
PLCP preamble	16 µs
PLCP header	48 bits
PLCP rate	6 Mbps
MAC header	192 bits
FCS (Frame check sequence)	32 bits
Time slot	9 µs
Sub-frame header in A-MSDU	14 Bytes
Delimiter in A-MPDU	4 Bytes
Duration of signal field in A-PPDU	4 µs
RIFS (Reduced inter frame space)	2 µs
SIFS (Short inter frame space)	16 µs
DIFS (Data inter frame space)	34 µs
Size of ACK frame	14 Bytes
Size of block ACK frame	32 Bytes

These devices are placed over a distance of 50 m with line of sight (LOS) communications. Each STA generates traffic with a predefined rate. These sources have no timeout values specified and they might have different TID. To simulate the real-time traffic, all the data packets pass down to the MAC layer are 100 bytes in length. The BER varies from 0 to 10^{-3}. The simulation time is 10 s. The detailed MAC parameters used in the simulation are shown in Table IV.

5.2. Simulation results

5.2.1. Throughput enhancement. First, we discuss the throughput enhancement by adopting the DASS algorithm. The simulation is carried out with the saturated traffic of 10–30 STAs. We compare the throughput improvement of DASS with those of the hybrid without waiting and single frame aggregation schemes. For the purpose of comparison, a simple hybrid frame aggregation scheme that transmits frames immediately after selecting a suitable frame aggregation mechanism is elaborated. Figure 7 shows the throughput improvement by adopting various frame aggregation schemes under the saturated traffic. The results showed that the hybrid aggregation sc heme apparently outperforms the other single aggregation schemes. Moreover, DASS still has better throughput improvement than the simple hybrid frame aggregation scheme. This could be because an STA might send an A-MSDU aggregated frame to its associated MAP, but, in DASS, the associated MAP might wait for more frames to use A-MPDU or A-PPDU for a larger aggregated frame and better throughput. Comparing with the case without any frame aggregation, DASS could enhance the overall throughput by 92%. Another phenomenon we have observed is that the degree of throughput improvement decreases slightly with an increase in the number of STAs. The reason is that when the channel is completely saturated, the time wasted on a CSMA/CA random backoff and the probability of collisions might be raised with an increase in contention for bandwidth. The contention and retransmission then deteriorate the throughput.

Next, we discuss the importance of the waiting mechanism in DASS, especially when the traffic load is not saturated. We conduct the simulation with the unsaturated traffic and 10–30 STAs. Figure 8 presents the throughput improvement for the various frame aggregation schemes.

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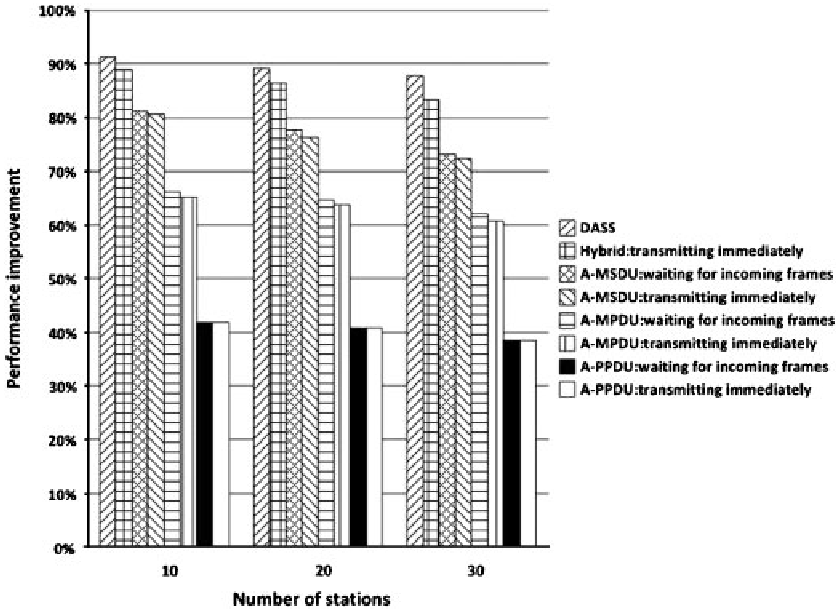

Figure 7. Throughput improvement by adopting frame aggregation schemes under the saturated traffic.

The simulation results show that the degree of throughput improvement of DASS, which enables the waiting strategy, apparently outperforms those schemes without the waiting mechanism. Comparing with the case with no frame aggregation, DASS could enhance the overall throughput by 95%. However, please note that, different from the former experiment, the channel is not saturated in this experiment. The degree of throughput improvement increases as the number of STAs increases. Therefore, channel utilization is increased when the traffic load was getting saturated.

5.2.2. Accuracy of prediction of frame arrival rate. Through the prediction of frame arrivals, DASS can analyze and decide whether to wait for the follow-up frames to aggregate to seek better throughput. The results in Section 5.2.1 demonstrate that adopting the waiting mechanism can further enhance the degree of throughput improvement. However, how many previous frames should the DASS algorithm consider for the prediction of the frame arrivals? In this section, an experiment is designed to observe the success rate, which is defined as

$$\text{Success rate} = \frac{\text{Counts of improved throughput}}{\text{Counts of waiting}} \tag{27}$$

Table V lists the success rate of the waiting strategy versus the number of past frames observed. Because the traffic of STAs is more stable than the other entities, the success rate in the STAs is relatively high and approaches to 92.53%. Moreover, the success rate of each aggregation point commonly decreases when the number of the referred past frames increases. The degree of degradation is especially severe and evident for the STAs. This phenomenon is caused by the *On–Off* behavior of the wireless traffic flow. If the frames generated from the STAs are transmitted continuously without any interruption caused by contention or transmission error, the success rate

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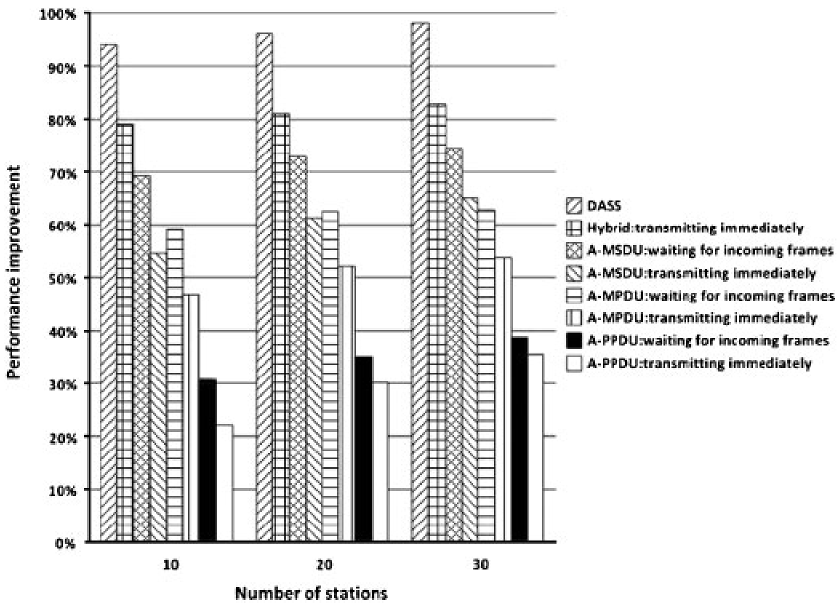

Figure 8. Throughput improvement by adopting frame aggregation schemes under the unsaturated traffic.

Table V. Success rate of the waiting strategy of the mesh entities.

	STA	MAP	MP
Generating traffic	Yes	No	No
Traffic load	Low	Middle	High
Success rate—past 16 frames (%)	92.53	82.74	89.6
Success rate—past 32 frames (%)	93.25	83.42	89.87
Success rate—past 64 frames (%)	86.8	81.78	88.72
Success rate—past 128 frames (%)	82.73	79.35	86.64

should converge to a fixed value gradually with the increase in the number of the referred past frames. Figure 9 illustrates the average throughput of DASS when referring to different numbers of the previous frames. Based on the success rate observed in Table V, the throughput of referring to the past 16 and 32 frames is relatively better when the prediction of frame arrival rate is more precise. In other words, the wasted waiting time caused by the unsuccessful prediction degrades the throughput.

5.2.3. Comparisons between different selection strategies. In this section, we discuss the selection strategies that come up when there are sufficient frames from different sets of traffic, $\text{Endpoint}_{i,j}$, to be aggregated at the same time. The experiment compares five selection strategies in terms of average latency and throughput. Specifically, the hop-count-based strategy depends on the hop count traversed from the source to the current aggregation point. A frame with more hop count has a higher priority for aggregation. The propagation-delay-based strategy first aggregates the frames

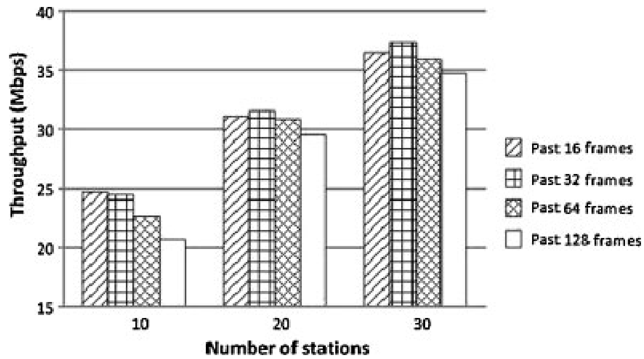

Figure 9. Throughput comparison of referring different numbers of the past frames.

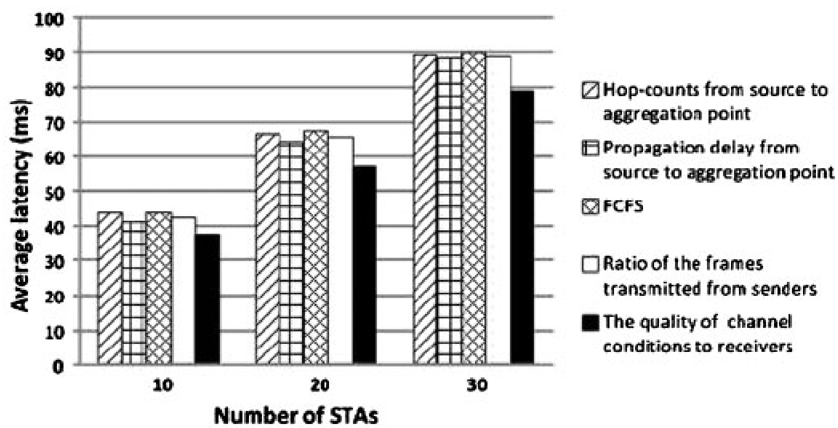

Figure 10. Comparison on the average latency among the different selection strategies.

with more propagation delay from the source to the current aggregation point. Moreover, for the First Come First Served (FCFS) strategy, DASS simply aggregates the frames in the manner of FCFS. Also, the ratio-based strategy selects the frames from the set of traffic that has the largest amount. Finally, the channel-quality-based strategy selects the frames that possess the best channel quality between the receiver and the current aggregation point. Please note that the strategies for different purposes can be mixed to seek for better performance. For example, we could combine the propagation-delay-based and the channel-quality-based strategies.

Figures 10 and 11 present the comparisons of the average latency and the throughput performance for the five selection strategies. In Figure 10, based on the channel quality between the aggregation point and the receiver to select the aggregated queue would decrease the average latency most. Therefore, the throughput performance is also largely improved as shown in Figure 11. Note that the channel quality here is exactly the BER value measured in the second stage of DASS. Besides, we observe that the variance of the average latency for different frame selection strategies is not

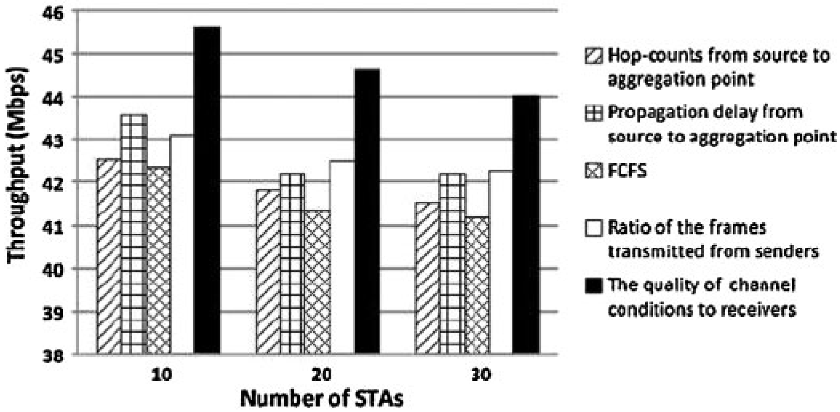

Figure 11. Comparison on the average throughput among the different selection strategies.

significant. Analyzing the variation of the latency, we could find that the variance of latency for the FCFS strategy is the highest, whereas the propagation-delay-based strategy is the lowest.

6. CONCLUSIONS

Frame aggregation mechanisms are introduced to resolve the fundamental problem of existing IEEE 802.11 MAC overhead. This paper proposes the DASS algorithm that dynamically adopts an appropriate aggregation mechanism according to the characteristics of communications to maximize the bandwidth utilization. It also eases the throughput degradation drawn by multi-hop transmissions in the WMNs. Simulation results demonstrate that DASS could improve the overall throughput of 802.11s mesh network by 95% compared with the case with no aggregation. It is also suggested that DASS should refer the past 16 or 32 frames for the prediction of the frame arrivals. Moreover, the channel-quality-based selection strategy could reduce latency most and significantly enhance the throughput. Overall, DASS is an innovative algorithm that collaborates the 802.11n frame aggregation mechanisms to achieve a high-throughput and high-efficiency WMN.

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