Throughput Enhancement of IEEE 802.11 WLAN via Frame Aggregation

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Abstract- **The popular IEEE 802.11 WLAN is known to achieve relatively small throughput performance compared to the underlying physical layer (PHY) transmission rate. This is due mainly to the large overheads composed of medium access control (MAC) header, PHY preamble/header, backoff time, acknowledgement (ACK) transmission, and some inter-frame spaces (IFSs). Since these overheads are added to each frame transmission, the throughput degradation is relatively high when the small-size frames are transmitted. In this paper, we present a *frame aggregation* scheme, which can improve the throughput performance of IEEE 802.11 WLAN. By aggregating small-size frames into a large frame, we can reduce these overheads relatively. We propose a simple method to implement the frame aggregation into the real testbed using off-the-shelf IEEE 802.11 wireless LAN products via the device driver modifications. The performance of the frame aggregation is evaluated by both the numerical analysis and the actual measurements from the real testbed. According to the measurement results from the real testbed, the frame aggregation can improve the throughput performance of IEEE 802.11b WLAN by 2 to 3 Mbps, when multiple frames are aggregated.**

Index Terms – **IEEE 802.11 WLAN, throughput, frame aggregation**

I. INTRODUCTION

During the last few years, IEEE 802.11 Wireless LANs (WLANs) have become very popular among mobile users for the Internet access using their portable devices. Although the WLAN supports relatively lower data transmission rate than the high-speed wired networks, the number of users is dramatically growing today due to the mobility support and the low cost. The IEEE 802.11 specification was first approved in 1997, and the second revision was published in 1999 [1]. The initial IEEE 802.11 specification defined a single Medium Access Control (MAC) and three Physical Layers (PHYs), which provided PHY rates of 1 and 2 Mbps. In 1999, two new high-speed PHY specifications were additionally defined, namely, IEEE 802.11a [2] and IEEE 802.11b [3]. The IEEE 802.11a standard provides from 6 to 54 Mbps raw PHY transmission rates at the 5 GHz U-NII bands using the Orthogonal Frequency Division Multiplexing (OFDM) schemes, while the IEEE 802.11b standard provides 1, 2, 5.5 and 11 Mbps raw PHY transmission rates at the 2.4 GHz bands. The IEEE 802.11g, the state-of-the-art 2.4 GHz PHY, also supports up to 54 Mbps [4].

The throughput performance of the 802.11 WLAN is notoriously poor compared to the underlying PHY rates. For example, the practically achievable throughput using the 802.11a 54 Mbps transmission rate is about 25 Mbps. This is due mainly

to the MAC/PHY overheads such as MAC header, Physical Layer Convergence Protocol (PLCP) preamble/header, acknowledgement (ACK) transmission, and some Inter Frame Spaces (IFSs). These overheads are added to each frame transmission in a fixed manner. Therefore, the small-size frame transmission can make the throughput performance even worse. Apparently, reducing such fixed overheads could be one way to enhance the throughput performance of the 802.11 WLAN.

In this paper, we present a frame aggregation scheme to achieve a high-throughput and high-efficiency WLAN. With the frame aggregation, a transmitting station basically aggregates multiple packets from the higher layer into a single MAC frame, i.e., a single transmission unit, thus reducing the MAC/PHY overheads relatively. We also propose a simple method to implement the frame aggregation into the current WLAN devices with device driver modifications.

Recently, a new Task Group (TG), called TGn, was established within the IEEE 802.11 standardization Working Group (WG) with the goal of developing a Higher Throughput extension of the current WLAN standard. The main goal of this group is to achieve the throughput performance of over 100 Mbps, which is approximately 4 times higher than current IEEE 802.11a and IEEE 802.11g WLANs. For this purpose, different technologies at both PHY and MAC layers can be applied. The PHY approaches include multiple-input and multiple-output (MIMO) and channel bonding schemes. The proposed frame aggregation scheme is apparently one of the possible components in the future 802.11n MAC.

The rest of the paper is organized as follows: A brief overview of IEEE 802.11 MAC and 802.11a PHY is presented in Section II. The concept and implementation method of the frame aggregation are presented in Section III. After evaluating the frame aggregation via the numerical analysis and the measurement results of the real testbed in Section IV, the paper concludes in Section V.

II. IEEE 802.11 OVERVIEW

A. IEEE 802.11 MAC

The IEEE 802.11 has two types of access schemes. One is the mandatory Distributed Coordination Function (DCF), and the other is the optional Point Coordination Function (PCF). In this paper, we only consider the DCF, since most commercial 802.11 devices are operating only with the DCF mode.

Fig. 1 shows the basic medium access mechanism of the DCF. When a station has a frame to transmit, it detects whether the medium is idle or not. If it detects that the medium is occupied by another station, it defers the frame transmission until the medium becomes available for the transmission. After the station detects that the medium is free for a certain period of time, which is the DCF Inter Frame Space (DIFS), it starts a back-off operation with a randomly-selected back-off count value. This random back-off count decreases by one for each idle slot time. When the back-off count becomes zero, the station transmits the frame. When the destination station receives this frame successfully, it transmits an ACK frame back to the source station. When the source station receives the ACK frame, the transmission operation of that frame is finally completed.

As shown in Fig. 1, in the IEEE 802.11, irrespective of the payload size, the overheads such as MAC header, FCS, PLCP preamble/header, ACK, and some IFSs are used per frame basis. These overheads become relatively large when the size of the payload is small. In the next section, we will explain how these overheads can affect the throughput performance.
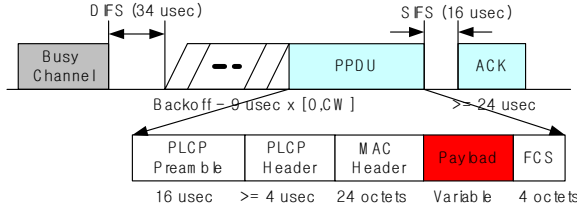

Fig. 1. Basic operation in DCF

B. Throughput Analysis

We can easily see how these overheads can affect the system throughput through a simple numerical analysis [7]. The following assumptions are made for the analysis. One sender and one receiver operate with the DCF mode. The sender always has frames to transmit. Each frame has a fixed-size payload. Finally, this throughput is determined at the Link Layer Control (LLC) Service Access Point (SAP), which is the interface between the MAC and its immediate higher-layer, i.e., the 802.2 LLC. In this analysis, we use 54Mbps for the data frame transmissions, and 24Mbps for the ACK transmissions. Channel errors are not considered in order to emphasize the impact of the overheads.

With the IEEE 802.11a, the transmission time of a data frame or MAC Protocol Data Unit (MPDU) with L-byte long payload at m Mbps PHY rate and the transmission time of the corresponding ACK frame at n Mbps PHY rate are given by

$$T_{data}^m(L) = tPLCPPreamble + tPCLPHeader + \left\lceil \frac{30.75 + L}{BpS(m)} \right\rceil * tSymbol,$$

and

$$T_{ack}^n = tPLCPPreamble + tPCLPHeader + \left\lceil \frac{16.75}{BpS(n)} \right\rceil * tSymbol,$$

respectively, where the number of bytes in a symbol at m Mbps PHY rate is given by

$$BpS(m) = m/2,$$

and the related parameters and corresponding values for the IEEE 802.11a PHY are listed in Table I.

Then, the throughput performance of the system, when the data frames are transmitted at m Mbps and the ACK frames are transmitted at n Mbps, is determined as follows:

$$T(m,n) = \frac{8 * L}{aDIFSTime + \overline{T}_{bk} + T_{data}^m(L) + aSIFSTime + T_{ack}^n} \quad \text{(bps)}$$

where the average backoff time is given by

$$\overline{T}_{bk} = \frac{CW\min}{2} * aSlotTime.$$

Table I. IEEE 802.11a PHY Characteristics

Parameters	Value	Comments
aSlotTime	9 usec	Slot time
aDIFSTime	34 usec	DIFS time
aCWmin	15	Min contention window size in unit of aSlotTime
tPLCPPreamble	16 usec	PLCP preamble duration
tPLCPHeader	4 usec	PLCP header duration (except the SERVICE field in case of 802.11a)
tSymbol	4 usec	OFDM symbol interval

The analysis results are shown in Fig. 2, in which the throughput performance is depicted as the size of the payload varies, when 54 Mbps and 24 Mbps are used for the data and ACK transmissions, respectively. Currently, a payload is transmitted via a single 802.11 MAC frame. As shown in the figure, the throughput performance is compromised as the payload size is reduced. We observe that small-size payloads achieve extremely small throughput. For example, using 100 byte payload only achieves about 5Mbps throughput over the 54Mbps link. Apparently, we desire that our system operates at the right upper side of this curve. In other words, we prefer large-size payloads.
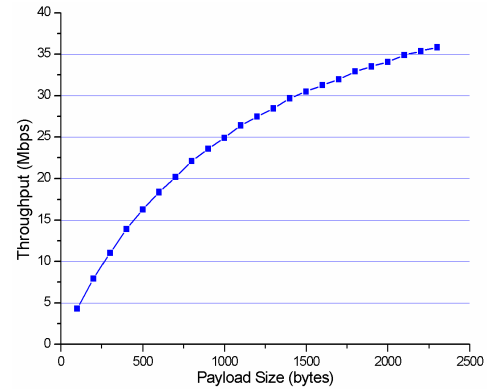

Fig. 2. Throughput performance vs. payload size

However, in reality, the IP packets, which are the payload in MAC sublayer, generated by different applications have various sizes. Unfortunately, according to the report from Cooperative Association for Internet Data Analysis (CAIDA) [8], the distribution of Internet packet sizes is dominated by small-size packets. More than half of the packets have the size of less than 200 bytes. Small-sized packets can degrade the throughput performance as we have seen above. Therefore, we apply a frame aggregation scheme in order to improve the throughput by reducing the fixed overheads relatively.
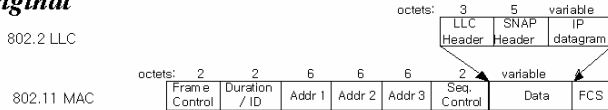
III. FRAME AGGREGATION

The frame aggregation scheme is a simple method to enhance the throughput performance of the 802.11 WLAN. The frame aggregation is literally to aggregate the multiple frames into a single MAC frame. By doing so, the impact of the fixed overheads on the throughput performance, which were analyzed earlier, is reduced relatively.

A. Implementation Issues

In this section, we present how we implement the frame aggregation in our testbed. Though the frame aggregation can be implemented in many different ways, we use a simple method, which can be implemented using the off-the-shelf WLAN devices. The task of the frame aggregation can be made simpler by performing frame aggregation above the MAC SAP, which lies between MAC and LLC. Therefore, in our implementation, modifications in the current MAC and PHY are not needed. Above the MAC SAP, we can aggregate multiple IP packets into a single chunk, and send it to the MAC as a single frame or more exactly MAC Service Data Unit (MSDU). Therefore, the MAC layer can deal with this aggregated frame as a normal MSDU.

Fig. 3 illustrates the original and modified frame formats and how we implement the frame aggregation with the current MAC architecture. The upper part of the figure shows the original frame format used in the current 802.11 system. The Data field consists of a single IP packet, LLC header, and Sub Network Access Protocol (SNAP) header [5]. When it is forwarded to the MAC layer, a MAC header and Frame Check Sequence (FCS), which is a CRC-32, are added to this data. The lower part of the figure shows how the frame aggregation is implemented into a real system without changing the current MAC. In our implementation, we aggregate several Ether-frames containing IP packets, and add some new fields such as a Count field and Size fields, which specify the number of aggregation packets and the size of each aggregated packet, respectively. This aggregated chunk is sent to MAC as a normal MSDU as explained above. Specific values are used in the Destination Service Access Point (DSAP) and Source SAP (SSAP), i.e., 0xdd, in order to indicate that the corresponding frame contains multiple aggregated packets, so that the receiving station can de-aggregate the frame after detecting these pre-defined DSAP/SSAP values.
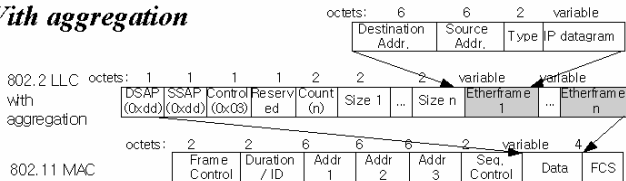

Fig. 3. Frame format of the original and frame aggregation operations

In order to define the proposed scheme along with the existing standard specifications, we can introduce a new sub-layer called Aggregation Sub-layer. This sub-layer is located between LLC and MAC. Moreover, this sub-layer works transparently to both LLC and MAC. Therefore, the introduction of a new sub-layer does not affect the existing MAC and LLC layers.

IV. PERFORMANCE EVALUATION

A. Theoretical Evaluation

In this section, we evaluate the throughput enhancement by the frame aggregation. First, Fig. 4 shows the theoretical throughput results with frame aggregation, where each curve is normalized with the corresponding PHY transmission rate. In this analysis, three transmission rates are used, namely, 6, 24, and 54 Mbps. For each transmission rate, the throughput performance curves of with and without frame aggregation are depicted. Moreover, we assumed that the sender generates fixed-size frames fast enough to be aggregated up to the maximum MSDU size, which is 2304 bytes. For example, if the frame size is 700 bytes, sender can aggregate up to 3 frames. Each pair of curves with and without frame aggregation for each transmission rate is merged when the size of the frame is larger than 1152 bytes, because the frames cannot be aggregated due to the maximum MSDU size.
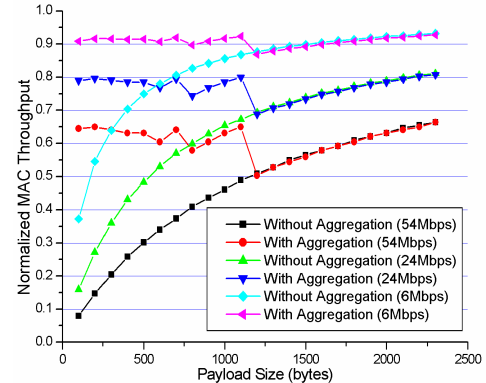

Fig. 4. Normalized throughput performance with and without Frame aggregation

A few observations from Fig. 4 are as follows. First, the maximum normalized MAC throughput differs among different transmission rates. The maximum normalized MAC throughput is about 90% for 6 Mbps, while the maximum relative MAC throughput is less than 70% for 54 Mbps. This disparity in the maximum achievable normalized throughput can be explained by noticing that the time for the actual data transmission is relatively shorter when the PHY transmission rate is higher. Second, the effectiveness of the frame aggregation is high when the frame size is small. We can easily indicate this observation from the slope of the original curve without the frame aggregation. For each transmission rate, the slope of the curve is large when the frame size is small. Therefore, the throughput enhancement becomes larger when more small-sized frames are aggregated. Third, the effectiveness of the frame aggregation is high when higher transmission rate is used. For 6 Mbps

transmission rate, the slope of the curve is drastically decreased as the frame size increases. On the other hand, for 54 Mbps transmission rate, the slope decreasing rate is very low. This observation indicates that for the higher transmission rate, the amount of throughput enhancement gained by the frame aggregation is maintained relatively wider range of payload size.

We also analyze the throughput gain with the frame aggregation considering the wireless channel errors, where the throughput gain is defined as the throughput with aggregation minus the throughput without aggregation. We use the channel error analysis found in [6] and [7]. Followings are the assumptions we made in the analysis. An ideal rate-adaptation is used in order to maximize the throughput performance for a given channel condition. Therefore, the station always selects the best transmission rate. For the error performance analysis, we assume the hard-decision Viterbi decoding with AWGN at the receiver.

Fig. 5 and Fig. 6 show the throughput gain via the frame aggregation, when 100-byte and 500-byte frames are aggregated, respectively. For example, in Fig. 5, the lower, middle, and upper curves indicate the throughput gain when five, ten, and twenty 100-byte frames are aggregated, respectively. In Fig. 6, the lower and upper curves indicate the throughput gain when two and four 500-byte frames are aggregated respectively. As shown in both figures, the throughput gain is gradually decreased as the distance between a transmitter and a receiver increases, or equivalently as the PHY transmission rate decreases. Specially, it should be noted that for the original frame size of 500 bytes, as found in Fig. 6, the throughput gain with the lowest transmission rate is virtually zero. This is actually consistent with the tendency found in Fig. 4. It is interesting that there are some minus throughput gain regions in both figures when the distance is larger than 42 meters and the lowest rate is used. Generally, the frame error rate (FER) increases as the size of the frame increases. The increasing FER can shrink the transmission range. When more frames are aggregated, the station has the smaller transmission range.

In both figures, we also find that the curves are overlapping in some region where the lower transmission rate is used. This observation implies that there is a trade off between the number of aggregated frames and the throughput gain. Over-aggregated frames may decrease the throughput gain, because the throughput degradation due to the increased FER is larger than the throughput enhancement due to aggregate the frames. As we have learned from Fig. 4, the throughput enhancement due to the frame aggregation is small at the lower transmission rate. Therefore, the number of aggregated frames should be carefully determined when the low (especially, the lowest or 6 Mbps) transmission rate is used, or the distance between the transmitter and the receiver is far.

We conclude the followings from the analytical performance evaluation: (1) the frame aggregation can remarkably improve the throughput in general; (2) the throughput gain could be marginal or even negative when the lowest transmission rate is used for the frame transmission; and (3) frames should not be aggregated when the receiver is around the boundary of the transmission range with the lowest PHY transmission rate.
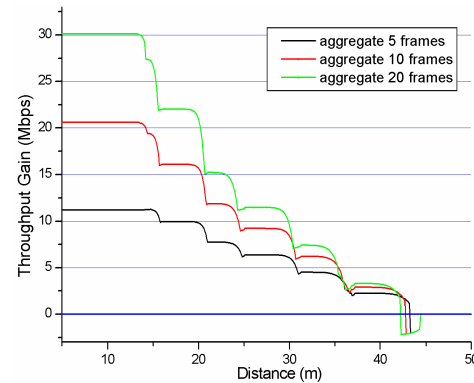

Fig. 5. Throughput gain via frame aggregation when aggregating 100 byte frames; channel error is considered.
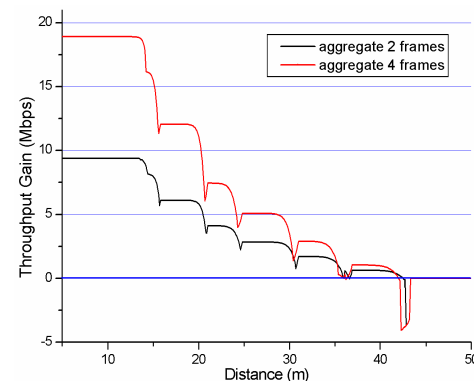

Fig. 6 Throughput gain via frame aggregation when aggregating 500 byte frames; channel error is considered.

B. Measurement Results

In this section, we present the throughput enhancement based on the measurements from the real testbed implementation. When we implemented our testbed, IEEE 802.11a system was not available due to the frequency restriction in our country, Korea. Therefore, we have implemented the frame aggregation using the IEEE 802.11b devices. Though we have used the 802.11b for the implementation, the general trend of the throughput results will be still valid irrespective of the underlying PHY since proposed scheme affects the MAC efficiency, which is the same for any IEEE 802.11 PHY.

In our implementation, we modify the device drivers of both access point (AP) and station in order to perform the frame (de)-aggregation [9]. In the presented measurements, we use three entities; a traffic generator, an AP, and a station. The AP is located between the traffic generator and wireless station, where the AP and traffic generator are connected via the Ethernet. In our implementation, the AP aggregates the frames when it has the multiple frames in its buffer at the transmission attempt. Therefore, our implementation does not delay the frame transmission intentionally for the frame aggregation.

Fig. 7 and Fig. 8 show the throughput enhancement results when the traffic generator transmits fixed-size packets via UDP and TCP, respectively. For the UDP scenario, the traffic generator generates the UDP packets at the fixed rate, which is 8

Mbps, in order to overload the WLAN link. In case of the TCP, the packet transfer rate is determined at the highest rate which the TCP allows. This kind of situation is found in the real world when a large file is transferred via the FTP. The line labeled as "theoretical" is from the analysis for the 802.11b, based on the one for the 802.11a found in Section II.B. It should be noted that the throughput of the TCP is smaller than that of UDP due to the incurring overheads of the TCP connection management and TCP ACK transmissions. As shown in Fig. 7 and Fig. 8, the frame aggregation can improve the throughput performance in both UDP and TCP cases. If the packet size is larger than 1300 bytes, the throughput is almost same as that of original scheme since no frame aggregation occurs due to maximum MSDU size, i.e., 2304 bytes. If the packet size is smaller than that, we can observe some throughput enhancement since some of these packets are aggregated. The throughput enhancement is about 2 to 3 Mbps.
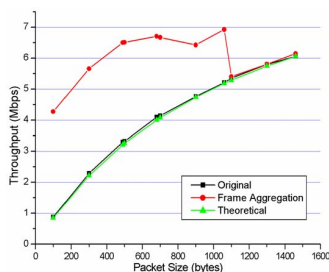

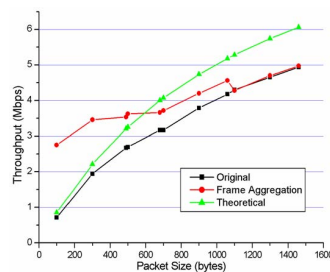Fig. 7. Throughput enhancement via frame aggregation in case of UDP traffic

Fig. 8. Throughput enhancement via frame aggregation in case of TCP traffic

In both scenarios, the shapes of throughput performance curves in case of the frame aggregation are not the same as the curve in Fig. 4 for the small-size packet, since in our implementation, the AP does not wait until it aggregates the packets up to the maximum MSDU size. Though we do not delay the frame transmission in our implementation, the throughput enhancement is high enough to show the utility of the frame aggregation scheme.

V. CONCLUSION AND FUTURE WORK

In this paper, we have presented a frame aggregation scheme in order to reduce the MAC/PHY overheads of the IEEE 802.11 WLAN by aggregating multiple packets into a single MAC frame. The analysis and the measurement results from the real implementation demonstrate that the frame aggregation is a good way to improve the efficiency of 802.11 MAC. The measurement results show that the throughput performance can be improved by 2 to 3 Mbps using the frame aggregation in the IEEE 802.11b WLAN PHY.

We have also proposed that the frame aggregation can be performed above the MAC SAP very easily with simple device driver modifications. This might be beneficial to the current system venders to make high performance products without any hardware (or MAC IC) change. We are currently proposing this scheme to the IEEE 802.11 standardization working group in order to incorporate this scheme into the emerging IEEE 802.11n standard for the high-throughput WLAN.

We are planning to evaluate the utility of the frame aggregation by considering more realistic traffic situations because depending on the traffic pattern, the actual gain could vary. The practical maximum packet size is about 1500 bytes, which is bounded by the maximum size of Ethernet frame, while the maximum MSDU of IEEE 802.11 is 2304 bytes. Since there are also many small packets, small packets can be aggregated with the 1500 byte packet as well. Therefore, the frame aggregation could be effective under the realistic traffic pattern.

Our current frame aggregation works when the frames are transmitted to the same receiver. For example, a station can aggregate all the packets since the receiver of all the frames from a station is the AP. Note that in the 802.11 infrastructure-based WLAN, a station communicates with its AP only. On the other hand, the AP can aggregate the packets destined to the same stations only under our current scheme. We are planning to develop a way to aggregate multiple packets destined to different stations in order to increase the chance of the aggregation. Using the existing multicast frames can be a possible candidate approach. However, it has some inherent problem since the multicast frame transmissions are not reliable due to the lack of the frame retransmission mechanism. We will be tackling this problem in the future.

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