324Mbps WLAN Equipment with MAC Frame Aggregation for High MAC-SAP Throughput

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***Abstract*— We developed a high speed wireless LAN prototype in the 5GHz band. Maximum transmission rate of the developed WLAN equipment was 324Mbit/sec using 6 multi-channels of 802.11a. We proposed a novel frame aggregation scheme to improve MAC efficiency. The proposed frame aggregation scheme had a feature of an adaptive aggregation size selection depending on the wireless channel conditions and application requirements. Throughput performance was obtained from simulation using a multiple station system with the proposed frame aggregation. A throughput of more than 150Mbit/sec was achieved with an evaluated system of 10 STAs. We also found that the measured throughput of more than 170Mbit/sec was achieved using the proposed frame aggregation.**

***Index Terms*— Wireless Networks, IEEE802.11, Frame Aggregation, performance evaluation**

I. INTRODUCTION

High reliability and data rate are required for multi-media access at home and at office using wireless local area network. The reliability is indispensable to maintain a constant bandwidth to serve broadband data such as HDTV (High Definition Television) and Video-on-Demand traffic. A data rate of more than 100Mbit/sec throughput is necessary in order to allow several users to gain access to the same access point (AP) of WLAN (Wireless LAN) simultaneously

In legacy WLAN [1], CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) was used for multiple accesses. However, QoS (Quality of Service) was not supported. Enhancing the QoS at the MAC (Medium Access Control) layer for supporting diversification of applications became the standard of Task Group e (TGe) [2] in Sept 2005.

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Throughput at the MAC service access point (SAP) was less than 30Mbit/sec even with 1500byte UDP data in legacy IEEE802.11a [3], although the PHY data rate was 54Mbit/sec. The low efficiency was due to the high MAC overhead using CSMA/CA.

Increasing the throughput to more than 100Mbit/sec at the MAC-SAP has been discussed for the standard at Task Group n (TGn) [4 - 6]. For the enhancement of the PHY data rate, MIMO (Multiple Input Multiple Output) and channel bundling have been proposed in TGn.

It was well known that the conventional IEEE802.11 MAC protocol was not enough to achieve improvement of throughput in accordance with increasing PHY data rate. Moreover, legacy IEEE802.11a systems limited the maximum length to 1500byte, because 1500byte was maximum length at Wired LAN.

The limitation of MAC throughput with legacy MAC protocol was evaluated by computer simulations. Table.1 shows the parameters of the simulation, which was defined in the IEEE802.11a standard. Figure.1 shows simulation results of the MAC-SAP throughput as a function of the PHY data rate. The horizontal axis is the PHY data rate. The vertical axis is the throughput at the MAC-SAP. Packet size of 500, 1000, and 1500 byte/packet were used. There was a limitation of throughput of 60Mbit/sec using the conventional MAC protocol, although the PHY data rate was increased.

TABLE 1. IEEE802.11a parameters

Parameter	Value
SIFS	16usec
DIFS	34usec
Slot time	9usec
PLCP preamble	16usec
SIGNAL	4usec
CWmin	15
CWmax	1023
MAC Header	28byte
ACK rate	6Mbit/sec

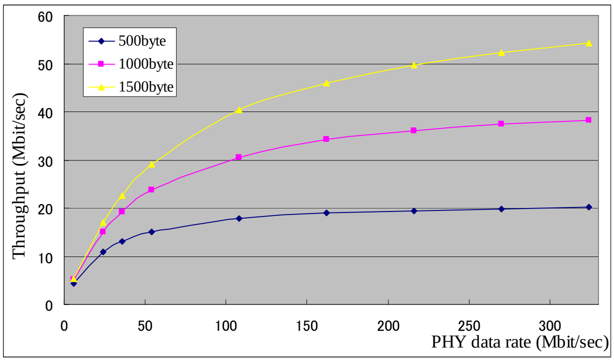

Figure 1. IEEE802.11 CSMA/CA Throughput Limit

In this paper, we present our development of the 324Mbit/sec WLAN equipment to alleviate these efficiency problems. We present both the implementation of the WLAN equipment and the construction of MAC layer architecture including the proposed frame aggregation. Instead of MIMO technology as proposed in IEEE802.11n, we use 6 channels bundling of IEEE802.11a. While channel bundling decreases the spectral efficiency, the developed equipment has the advantage of backward compatibility with IEEE802.11a. Furthermore, the developed MAC algorithms can also be used in a MIMO context.

The developed WLAN equipment has the functions of adaptive modulation per channel, adaptive coding per channel, link adaptation, adaptive channel selection, and frame aggregation. We proposed a novel frame aggregation scheme for over 100Mbit/sec throughput at MAC-SAP. The optimal frame aggregation size for the PHY data rate was evaluated by computer simulation. It was shown quantitative results for the improvement of MAC-SAP throughput due to the proposed frame aggregation, as obtained from measurement result using the WLAN equipment.

II. Frame Aggregation

In this section, a comparison of 3 types of frame aggregation was described.

Figure 2 shows an example of frame format of PPDU aggregation method. The PPDU aggregation should be implemented in the PHY layer. A PHY SYNC header was placed before a SIGNAL field of the first MPDU. Subsequent PPDUs without PHY SYNC Header were continuously transmitted after RIFS (Reduce Inter frame Space) timing that is 0 < RIFS << SIFS. Data rate of each MPDU was independently defined in the SIGNAL field.

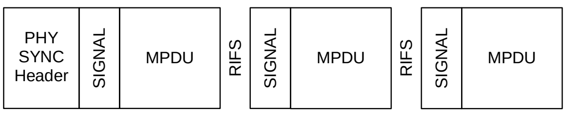

Figure 2. PPDU aggregation format

Figure 3 shows a frame format of MPDU aggregation method [5, 6]. The MPDU aggregation should be implemented between PHY and MAC layer. PHY has no knowledge of MPDU boundaries. A MPDU delimiter for marking the start point of each MPDU was placed before the MPDUs. Except when it was the last MPDU, padding octets were appended to make each section a multiple of 4 octets in length, if needed. The MPDU delimiter is 4 octets in length and consists of MPDU length, CRC, unique pattern.

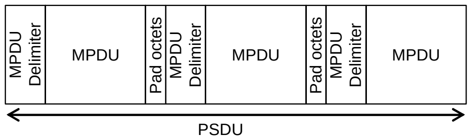

Figure 3. MPDU aggregation format

Figure 4 shows a format of MSDU aggregation method. The MSDU aggregation should be implemented in the MAC layer. MAC header and FCS (Frame Check Sequence) were attached for the whole frame. A Sub-frame header was placed in front of each MSDU in order to detect the starting points of the MSDUs. The QoS Control Field of MAC header included one bit to indicate using MSDU aggregation. Processing and implementation was relatively easy because MAC and PHY could operate on a single frame body.

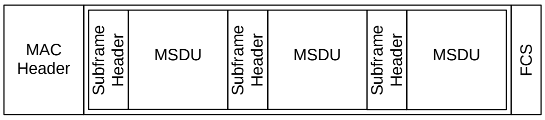

Figure 4. MSDU aggregation format

The summary of the comparison among 3 types of frame aggregation was listed in Table 2.

The PPDU aggregation and the MPDU aggregation had an advantage for implementation for multiple destination addresses. The PPDU aggregation and the MPDU aggregation were robust to transmission errors because a FCS was attached. Furthermore, the PPDU aggregation had an advantage for rate changes for each PPDU.

On the other hand, in order to implement MPDU and PPDU aggregation, MAC function should be changed itself for the addition of the aggregation function. An access procedure to receive “Acknowledge” packets from each destination should be redesigned for the frame aggregation with multiple destinations using the MPDU or the PPDU aggregation.

Efficiency of the MAC was the most important factor to design high speed WLAN equipment, because the processing speed of a MAC layer using CSMA/CA was a bottleneck for the data rate. Furthermore, complexity from legacy was important factor to ensure interoperability between proposed high speed WLAN equipment and legacy equipment.

The MSDU aggregation had the highest efficiency because of its small overhead. In order to implement MSDU aggregation, a convergence function was added in addition to the conventional MAC function. It meant that it was easy to maintain compatibility with legacy IEEE802.11 MAC functions.

TABLE 2. Aggregation Comparison

	PPDU	MPDU	MSDU
Multiple DA	Yes	Yes	No
Rate change for every DA	Yes	No	No
Efficiency	Low	Middle	High
Robust for Error	High	High	Low
Complexity from Legacy	High	High	Low

From the summary of features of each aggregation methods as described above, it was confirmed that the MSDU aggregation was the most suitable for the realization of high throughput WLAN equipment.

III. Simulation for Frame Aggregation

The MAC throughput as a function of the aggregation size was simulated using the Network Simulator 2 (NS2). The PHY and MAC parameters for the simulation are listed in Table 3. The offered load for the simulation was 200Mbit/sec. Constant UDP data was used. The UDP data sent from AP from a STA.

Figure 5 shows the throughput performances of frame aggregation compared with the performances without frame aggregation. The horizontal axis is the packet length. The vertical axis is the throughput at the MAC-SAP.

TABLE 3. Simulation parameters

	Simulation	Unit
Access	DCF	---
Data frame rate per channel	54	Mbit/sec/ Channel
Control frame rate per channel	24	Mbit/sec/ Channel
Slot Time	9	usec
DIFS	48	usec
SIFS	30	usec
CW min	15	---
CW max	511	---
Transmission Rate	324	Mbit/sec
Channel Number	6	Channels
Frame Aggregation	6	Packets
Packet Error Rate	Error Free	---

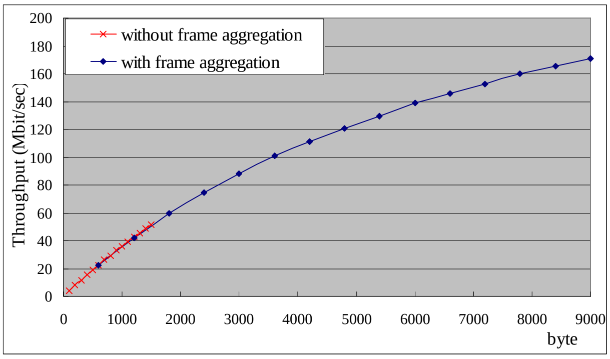

Figure 5. The throughput of frame aggregation

A maximum simulated throughput of more than 170Mbit/sec was obtained for the case of an aggregated frame size of 9000byte.

The throughput of a multiple STAs was evaluated using a computer simulation. Figure 6 shows the throughput at MAC as a function of station number. The PHY and MAC parameters for the simulation are listed in Table 3. The traffic parameter was constant for both uplink and down link UDP data. The evaluated system throughput of more than 150Mbit/sec was achieved for the case of 10 stations.

AP and STA use same procedure to obtain the transmission opportunity. The transmission opportunity of the total STA was relatively increased due to the randomization of CW (contention window). However the transmission opportunity of AP was relatively reduced due to the traffic of other STAs. Consequently, uplink traffic becomes the dominant traffic when the STA numbers is increased.

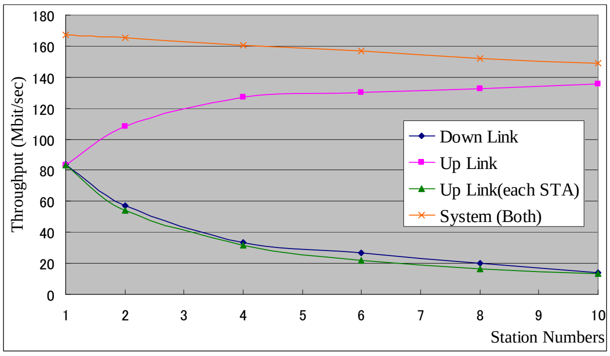

Figure 6. The throughput of multiple STAs

The optimal frame aggregation size for the PHY data rate was evaluated. MAC throughput as a function of aggregation size is shown in Figure 7. Table 4 lists parameters for throughput simulation. The horizontal axis is the number of frame aggregation at the Adaptive Frame Aggregation sub-layer. The vertical axis is the throughput at the MAC-SAP.

TABLE 4.Simulation parameters

Parameter	Value
SIFS	16usec
DIFS	34usec
Slot time	9usec
PLCP preamble	16usec
SIGNAL	4usec
CWmin	15
CWmax	1023
MAC Header	28byte
Channel Number	2 channels
Data Rate	54Mbit/sec per channel
ACK rate	6Mbit/sec
PER	Error Free

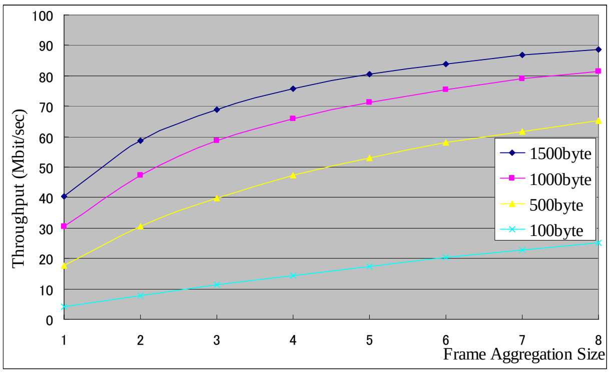

Figure 7. The throughput saturation

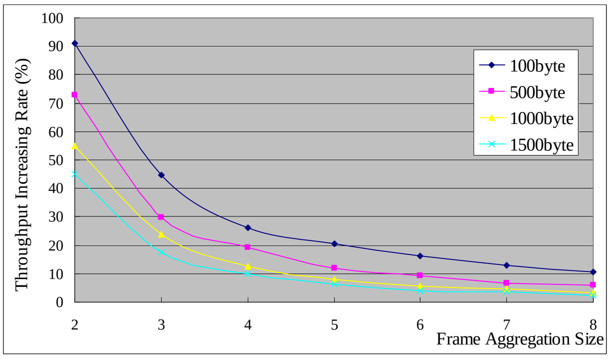

Figure 8. The throughput increasing rate

The PHY data rate was 108Mbit/sec, i.e., bundling two IEEE802.11a channels. Maximum throughput was evaluated to be more than 90Mbit/sec at the frame aggregation size of 10 with a 1500byte packet length from the LLC layer. Saturation of throughput was evaluated in the case of any packet frame size.

Figure 8 shows the increase of throughput as a function of aggregation size. The increasing rate at 1500byte packet size was over 40% at a frame aggregation size of less than 3. Frame aggregation was thus highly effective in improving MAC efficiency.

On the other hand, the throughput increasing rate at 1500byte was less than 10% at an aggregation number of more than 4. The efficiency of frame aggregation showed no additional improvements for frame aggregation sizes of more than 4.

Based on the above result, we have defined the optimal frame aggregation size depending on packet length at the 10% throughput increasing point.

IV. HIGH SPEED WIRELESS LAN PROTOTYPE

We developed high speed WLAN equipment using 5GHz frequency band as shown in Figure 9 [7 - 13]. The maximum transmission rate of the prototype is 324Mbit/sec. The developed equipment is backward compatible with legacy IEEE802.11a.

The channel structure of the PHY was designed by IEEE802.11a channel binding to achieve the bandwidth of 120MHz, corresponding to 6 channels.


Figure 9. The developed high speed Wireless LAN Unit

A. Dynamic Channel Assign and Link Adaptation

Figure 10 shows the channel structure with the features of Dynamic Channel Assign and Link Adaptation. The transmission rates of each channel were independently selected to be up to 54Mbit/sec, based on the propagation and interference conditions of each channel.

Furthermore duplicate ACK frames were transmitted at every used channel with same transmission rate to adjust to the same transmission time. Originator acknowledged when received one of ACK frames from recipient.

At the time of T0, the transmitter sent Data frame using Channel (CH) 1 with the transmission rate of 54Mbit/sec, CH2 with 54Mbit/sec, CH3 with 24Mbit/sec, CH4 with 36Mbit/sec, and CH6 with 54Mbit/sec. CH5 was not used due to interference conditions from others. At the time of T1, the receiver send ACK frame using the CH1, CH2, CH3, CH4, CH6 with same data rate. At the time of T2, the transmitter send Data frame using every channel with updating data rate based on Link Adaptation (CH2, CH3).

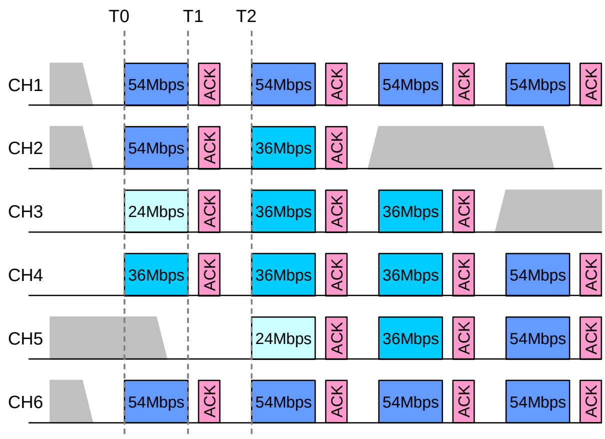

Figure 10. Dynamic Channel Assign and Link Adaptation

Figure 11 shows the implemented Link Adaptation that uses a closed loop. We extended Feedback field for every frame data and control frame to convey feedback information. The SIGNAL Field included one bit to indicate using closed loop link adaptation and frame extension.

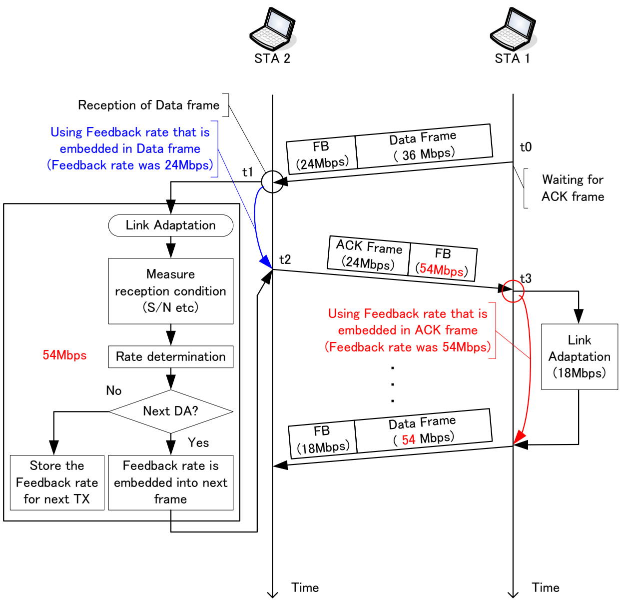

Figure 11. Implemented link adaptation sequence using one channel (image)

At the time of t0, STA1 transmitted Data frame using 36Mbit/sec which included Feedback (FB) rate of 24Mbit/sec. At the time of t1, STA2 received Data frame and estimated optimal transmission rate from STA1 to STA2 using received Data frame. At the time of t2, STA2 transmitted ACK frame using 24Mbit/sec that was informed by STA1 in previous Data frame. The estimated feedback rate of 54Mbit/sec was embedded in the feedback field of ACK frame. At the time of t3, STA1 received ACK frame and started to estimate the optimal transmission rate from STA2 to STA1 using received ACK frame. At the time of t4, the embedded feedback rate in the previous ACK frame was used for Data frame transmission from STA1 to STA2.

The transmission rates of each channel were independently selected to be up to 54Mbit/sec, based on the propagation and interference conditions of each channel.

B. The designed MAC layer structure

Figure 12 shows a block diagram of the designed MAC layer structure. The designed MAC layer has adaptive frame aggregation on the sub-layer for the MSDU frame aggregation. In the sub-layer, frames from the LLC layer are aggregated to a single frame for the same destination address.

The designed MAC layer has an adaptive frame distribution sub-layer at the bottom of the MAC layer. In this sub-layer, the aggregated frame is distributed to each PHY channel module. The frames, distributed to each PHY module, are adjusted to the same length of OFDM symbols for individual PHY data rate.

In addition to 2 sub-layers, the designed MAC layer has the frame aggregation control and the frame distribution control at the MAC layer.

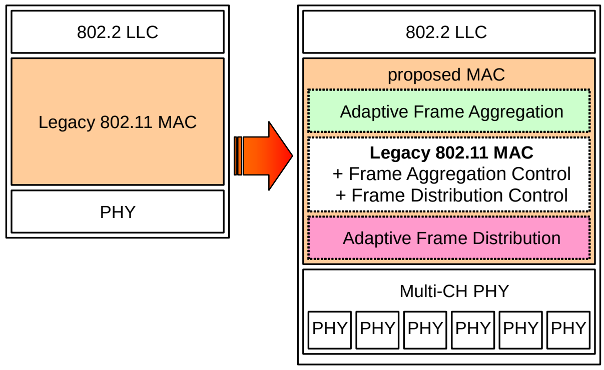

Figure 12. The designed MAC layer structure

C. The Proposed Adaptive Frame Aggregation Sub-layer

Figure 13 shows block diagram of the proposed adaptive frame aggregation sub-layer. The sub-layer includes a frame aggregation unit for transmission and frame de-aggregation unit for reception.

Several memories are placed in the frame aggregation unit to allow individual destination addresses in the aggregation frames simultaneously. The maximum aggregation length is limited by the summation of symbol lengths of each channel as determined from the individual data rates. The aggregation length is controlled depending on the PHY data rate determined by link adaptation, and the application requirement is determined by the acceptable delay.

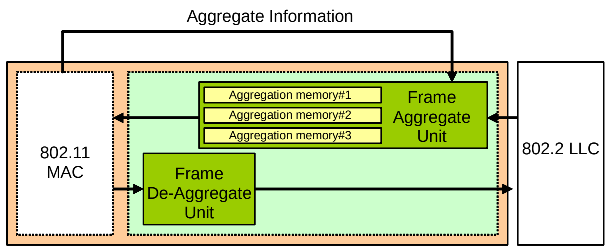

Figure 13. The Adaptive Frame Aggregation Sub Layer (Image)

Figure 14 shows the procedure of the proposed adaptive frame aggregation and the adaptive frame distribution. For example, the adaptive frame aggregation sub-layer aggregates 2 frames into one MPDU. The adaptive frame distribution sub-layer distributes a MPDU to a 3 PHY-channels module with the same OFDM symbol length. In this case, the PHY data rate is 54Mbit/sec at CH #1, 48Mbit/sec at CH #2 and 24Mbit/sec at CH #3. The number of bytes in the symbol of CH#1, CH#2 and CH#3 are 27, 24 and 12, respectively. The MPDU is distributed to each PHY channel depending on the number of bytes in the symbol. In order to adjust the number of OFDM symbols, appropriate pad bytes are inserted to the end of each PHY frame.

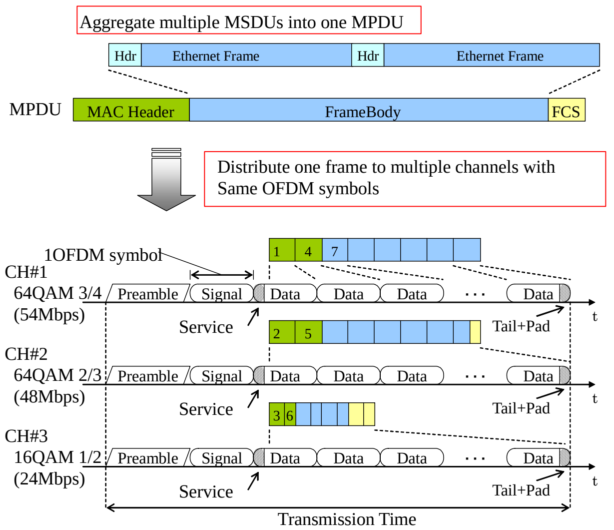

Figure 14. Adaptive Frame Distribution Sub Layer

D. Measurement Results

The MAC throughput as a function of the aggregation size was measured. We measured the throughput at the MAC-SAP using Smart Bit. The prototypes were connected through an attenuator with an RF cable as shown in Figure 15. The received power of 6 multi channels at sub-rack #2 was -37.1dBm with the attenuator level at 42dB.

The PHY and MAC parameters for the measurement are listed in Table 5. Figure 16 shows the throughput performances of frame aggregation compared with the performances without frame aggregation. The horizontal axis is the packet length. The vertical axis is the throughput at the MAC-SAP.

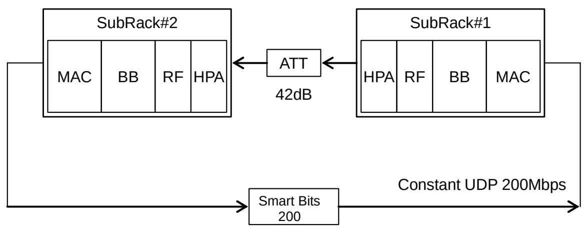

Figure 15. Test System

As shown in Figure16, the maximum throughput was measured to be more than 170Mbit/sec in the case of frame aggregation size of 9000byte.

The measurement results were similar to the simulation results with and without frame aggregation, respectively. The result without frame aggregation was less than 60Mbit/sec although the PHY data rate was 324Mbit/sec.

It was confirmed that the legacy MAC procedure was a bottleneck to increase the MAC-SAP throughput and that the proposed frame aggregation scheme had a good performance to increase the throughput of high speed wireless LAN equipments.

TABLE 5. Prototype Parameters

	Prototype	Unit
Access	DCF	---
Measurement time	60	Sec
Data frame rate per channel	54	Mbit/sec/ Channel
Control frame rate per channel	24	Mbit/sec/ Channel
Slot Time	9	usec
DIFS	48	usec
SIFS	30	usec
CW min	15	---
CW max	511	---
Application (Downlink)	Constant UDP 200Mbps	---
Transmission Rate	324	Mbit/sec
Channel Number	6	Channels
Frame Aggregation	6	Packets
Packet Error Rate	Error Free	---

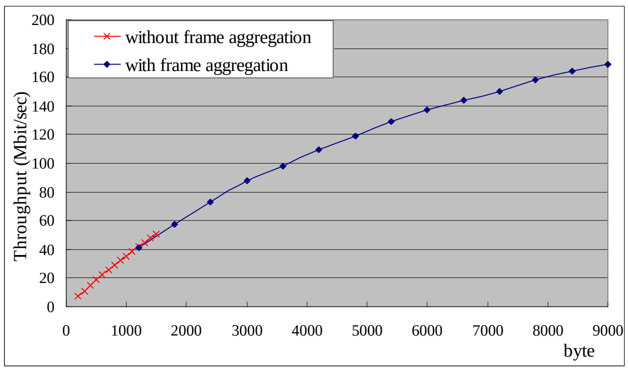

Figure 16. Frame Aggregation measurements result

V. CONCLUSION

We have developed a high speed WLAN equipment in the 5GHz spectrum. The developed WLAN equipment has a data rate of 324Mbit/sec using 6 PHY channels of IEEE802.11a. We have proposed an adaptive frame aggregation to improve the MAC efficiency.

Throughput performance was simulated in a multiple station scenario with the proposed frame aggregation. A system throughput of 150Mbit/sec was achieved using an evaluation system of 10 stations.

The MAC throughput as a function of aggregation size was both simulated and measured. It was found that a measured throughput of more than 170Mbit/sec was successfully achieved using the proposed frame aggregation in our equipment. It was proven that the proposed frame aggregation provides an effective alternative to achieve high throughput in a situation of high PHY data rates.

ACKNOWLEDGMENT

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