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Frame Length Optimization for In-Band Full-Duplex Wireless LANs

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***Abstract*—This paper proposes frame length optimization for wireless local area networks (WLANs) using an in-band full-duplex system that enables a WLAN access point and stations to transmit and receive frames at the same time on the same frequency channel. In in-band full-duplex WLANs, a primary sender which captures the channel transmits a frame to the intended receiver called a secondary sender and then the secondary sender transmits a frame reacting to the primary sender's transmission. The difference of time length of frames transmitted by the primary sender and the secondary sender wastes the frequency channel where more frames could be transmitted. The wasted time decreases the system throughput performance of the in-band full-duplex system. In order to solve this problem, we propose a scheme where the secondary sender adjusts the length of its frame to the length of the primary sender's frame by selecting frames used for frame aggregation properly. We evaluate the average delay, the average wasted time and the system throughput performance by computer simulations. The simulation results show that the proposed optimization reduces the delay by 49%, reduces the wasted time by 99.9% and improves the system throughput performance by 15% when the traffic is saturated.**

I. INTRODUCTION

IEEE 802.11 wireless local area networks (WLANs) have been widely used. As a result, the 2.4 GHz band for WLANs is heavily crowded and the 5 GHz band will become the same situation in the near future. Therefore the system throughput performance will be severely degraded due to heavy contention. An in-band full-duplex system is expected to be a key enabler for increasing wireless capacity. An in-band full-duplex system allows a node to transmit and receive frames simultaneously on the same frequency channel by canceling self-interference. The recent works [1], [2] reported that self-interference can be cancelled to be a negligible level and the in-band full-duplex system becomes applicable for WLANs. In IEEE 802.11ax task group for the next generation WLAN, the in-band full-duplex system is expected to be key enabler [3], [4]. WLAN applied the in-band full-duplex system, call in-band full-duplex WLANs, can theoretically double the system throughput of the WLANs without using another frequency channel compared to the conventional half-duplex WLANs.

Recent works proposed media access control (MAC) protocols for in-band full-duplex WLANs. The MAC protocols proposed in [5]–[7] are distributed control and busy tone base, and the protocols in [1], [8] are distributed control and request to send (RTS)/clear to send (CTS) base. The distributed MAC protocols for in-band full-duplex WLANs have wasted time. Fig. 1 illustrates in-band full-duplex communication having the wasted time. We call the node obtaining transmission opportunity a primary sender, and the intended receiver a secondary sender. If the secondary sender's frame is shorter than the primary sender's frame, there is wasted time where the transmission is operated by a half-duplex system. The system throughput performance decreases because the frequency channel is vacant in this wasted time. In the conventional works, such wasted time is not discussed or they assume that the same size frame and the same PHY rate are used, which could be different from transmission to transmission.

Fig. 1. Wasted time in in-band full-duplex communication.

In this paper, we propose frame length optimization in order to reduce the wasted time and improve the system throughput performance in distributed control. In the optimization, the secondary sender adjusts length of its own frame to that of the primary sender's frame by selecting and aggregating frames. By fully using the wasted time for in-band full-duplex transmission, the proposed scheme maximizes the system throughput of the in-band full-duplex WLANs. We evaluate the performance of the proposed scheme by computer simulations.

The remainder of this paper is organized as follows. Section II introduces related works, and section III describes system model and MAC protocol for in-band full-duplex WLANs. The frame length optimization is proposed in Section IV. In Section V, computer simulation results for the optimization are presented. Finally, in Section VI, we conclude this paper.

II. RELATED WORKS

A. *MAC Protocol for In-band Full Duplex WLANs*

Several MAC protocols for in-band full-duplex WLANs have been proposed. The MAC protocols proposed in [9], [10] are based on centralized control. In the MAC protocols, nodes send transmission request or length information of all frames the nodes wants to transmit, to a center node. The center node decides transmission nodes and order of transmission, and then the center node informs nodes of transmission schedule. However, the centralized control based MAC protocols are far from IEEE 802.11 standard which employs distributed mechanism called carrier sense multiple access with collision avoidance (CSMA/CA) .

Some works proposed distributed MAC protocols [1], [5]–[8]. In [5]–[7], MAC protocols leveraging busy tone are proposed. In the protocols, the primary sender that finishes backoff procedure first starts to transmit to the intended receiver. The receiver decodes the MAC header of the frame transmitted by the primary sender, and then the receiver as the secondary sender starts to transmit. At this time, if one of the two senders completes transmission earlier, a node in hidden terminal situation that cannot hear the remaining transmission may start to transmit and collide with the remaining transmission. In order to prevent this collision, the sender that completes transmission earlier uses busy tone. If the node in hidden terminal situation can hear the busy tone, the node does not start to transmit. In these MAC protocols, the time during which busy tone is sent is the wasted time.

In [1] and [8], a MAC protocol called FD-MAC is proposed. The FD-MAC is based on CSMA/CA with RTS/CTS which is defined in IEEE 802.11 standard and it is equipped with off the shelf WLAN devices. Moreover, the protocol has backward compatibility for conventional IEEE 802.11 standards. From a viewpoint of compatibility with IEEE 802.11, we use FD-MAC for our system model in this paper. The detail procedure of FD-MAC will be described in Section III-A .

B. *Self-Interference Cancelation*

In-band full-duplex WLANs have the self-interference problem. A node's transmission signal interferes with its own reception signal because both signals are simultaneous on the same frequency channel. Therefore self-interference has to be canceled so that frames are received correctly. For this purpose, a number of authors have studied in the self-interference cancellation. Bharadia et al. [2] shows that self-interference can be cancelled by 110 dB with one antenna using combination of analog and digital cancellation. If the transmit power is 20 dBm, the 110 dB cancellation is able to cancel self-interference to the noise floor around -90 dBm.

III. SYSTEM MODEL

This paper considers an IEEE 802.11n based WLAN where there are one access point (AP) and one station (STA) that use RTS/CTS-based MAC protocol detail of which is described in the next section. We assume that the AP and the STA can use the in-band full-duplex system and the self-interference is cancelled completely when the AP and the STA transmit and receive frames by the in-band full-duplex system. Moreover, in order to evaluate MAC layer performance, fading and shadowing are not considered. Therefore, frame losses occur only when the AP and the STA transmit RTS frames simultaneously.

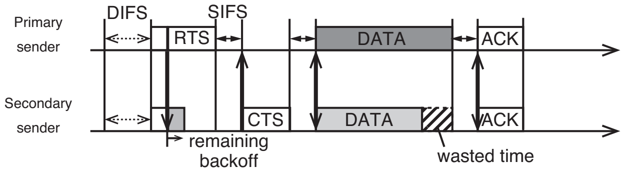

Fig. 2. Transmission procedure of FD-MAC [1].

A. *MAC Protocol*

In this paper, we use FD-MAC proposed in [1], [8]. Fig. 2 illustrates the transmission procedure of FD-MAC. It is based on CSMA/CA with RTS/CTS. First, the primary sender which finished the backoff period first sends an RTS frame. Receiving the RTS frame, the secondary sender sends a CTS frame back to the primary sender after short interframe space (SIFS) time that is defined by IEEE 802.11 standard. Then the primary sender starts to transmit data frames to the secondary sender and the secondary sender also starts to transmit data frames to the primary sender at the same time by using in-band full-duplex system if the secondary sender has data frames to the primary sender. Finally, receiving data frames correctly, the two senders exchange acknowledgement (ACK) frames by using in-band full-duplex system.

In FD-MAC, if one sender completes transmission earlier because frame length or PHY data rate are different between the primary sender and the secondary sender, the remaining transmission is operated by half-duplex transmission. The increase of the ratio of half-duplex transmission decreases the system throughput performance from the upper bound of the system throughput performance of the in-band full-duplex WLANs.

IV. FRAME LENGTH OPTIMIZATION

In this section, we propose the frame length optimization on the secondary sender in order to reduce the wasted time. The optimization procedure is operated when the secondary sender receives the RTS frame and it should be completed until the data frame transmission is started.

When the secondary sender receives the RTS frame from the primary sender, the secondary sender knows the time length of a data frame which will be sent by the primary sender from a duration field of the RTS frame. The duration field value is calculated by the primary sender as following,

$$\text{duration value} = \text{SIFS} \times 3 + T_{\text{CTS}} + T_{\text{data}} + T_{\text{ACK}}, \quad (1)$$

where T_{CTS} is the time to transmit a CTS frame, T_{data} is the time to transmit a data frame, and T_{ACK} is the time to transmit an ACK frame. This value represent the time from the end of the transmission of the RTS frame to the end of the transmission of the ACK frame. The CTS frame and the ACK frame have proper length defined by IEEE 802.11. Therefore the secondary sender can know the time length by subtracting three SIFS time and the time to transmit a CTS frame, a data frame and an ACK frame from the value of the duration field.

Next, the secondary sender optimizes length of the frame to transmit based on the calculated frame length of the primary sender by following two steps. In the first, called step 1 aggregation, the secondary sender adjusts frame length coarsely, and in the second step, called step 2 aggregation, it adjusts finely. In the step 1 aggregation, the secondary sender selects m frames for aggregation in order from the top frame in its buffer. m is determined by the following optimization problem:

$$\arg\max_{m} \; L^{\mathrm{f}} = \sum_{i=1}^{m} L_i \tag{2}$$

$$\text{subject to} \qquad L^{\mathrm{p}} \geq \sum_{i=1}^{m} L_i, \tag{3}$$

where L^{f} is a sum of length of frames selected in the first step, L_i is a frame length of ith frame, and L^{p} is a length of frame, which will be sent by the primary sender. In the step 2 aggregation, the secondary sender selects a set of frames $\mathcal{F}^{\mathrm{s}}$ by solving following optimization problem:

$$\mathcal{F}^{\mathrm{s}} = \arg\min_{\mathcal{X}\subseteq\mathcal{F}} \; L^{\mathrm{p}} - L^{\mathrm{f}} - \sum_{i\in\mathcal{X}} L_i \tag{4}$$

$$\text{subject to} \qquad |\mathcal{X}| \leq n \tag{5}$$

$$L^{\mathrm{p}} - L^{\mathrm{f}} - \sum_{i\in\mathcal{X}} L_i \geq 0, \tag{6}$$

where $\mathcal{F}$ is a set of frames remaining in the secondary sender's buffer and n is the maximum number of frames used for the second step. The n is introduced to reduce the complexity of the optimization problem. Fig. 3 shows the example of the optimization on the secondary sender. In the step 1 aggregation, if $m + 1$ frames are aggregated into one frame, length of the frame exceed length of the primary sender's frame. At this time, m frames (from #1 to #m) are used in the first step. Then in the step 2 aggregation, the difference of length is filled with some frames no more than n chosen from among the residual frames (from #$m + 2$ to the bottom frame). The secondary sender aggregates the frames chosen in the two steps into one frame and transmits it to the primary sender.

The time required for the optimization mainly depends on the second step. The secondary sender has to end the optimization by the beginning of transmitting the data frame. Therefore the time the secondary sender can use for the optimization is at most sum of two SIFS time and T_{CTS}. Although the larger n enables to achieve less wasted time, it increases the complexity exponentially and increase the required time for solving the optimization problem.

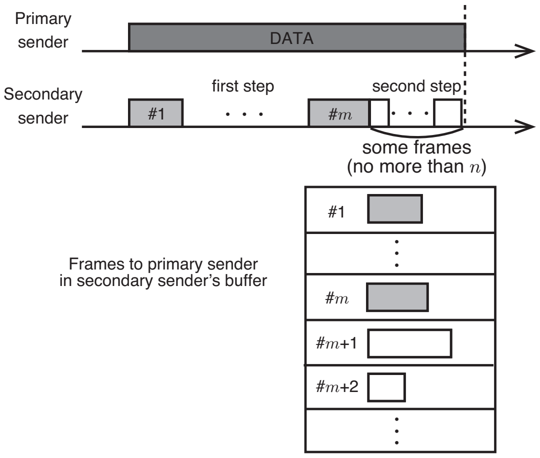

Fig. 3. How to optimize frame length on secondary sender.

V. SIMULATION EVALUATION

A. Simulation Details

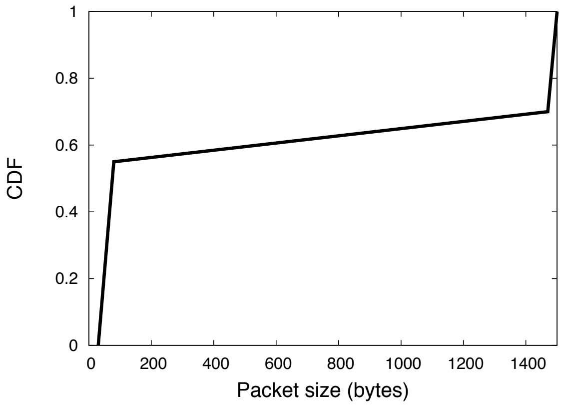

Fig. 4. Packet size distribution used in simulations.

In this section, we evaluate the performance of the proposed frame length optimization by using computer simulations. In the simulation, there are one AP and one STA. Both of them are compatible with the in-band full-duplex system where self-interference can be canceled completely, and they transmit all frames by using the in-band full-duplex system as long as a secondary sender has a frame to send. All frames are received correctly except that RTS frames collide by transmitting RTS frames at the same time. Data frames arrive at each node followed Poisson's distribution with rate λ (frames per second). λ_{AP} is the frame arrival rate of the AP and λ_{STA} is that of the STA. λ_{AP} is fixed to 10^5 where the AP always has sufficient number of frames to send. The reason is that, in the real usage of WLANs, downlink traffic, which is transmitted by the AP, is much larger than uplink traffic, which is transmitted by the STA [11]. The packet size generated by the traffic follows a simplified distribution shown in Fig. 4, which is derived from the packet size distribution [11]. Aggregate MAC service data unit (A-MSDU) aggregation is used for frame

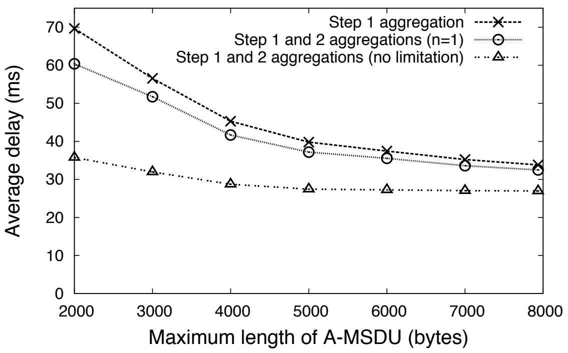

Fig. 5. Average delay vs. maximum length of A-MSDU when λ_{AP} and λ_{STA} are 10^5.

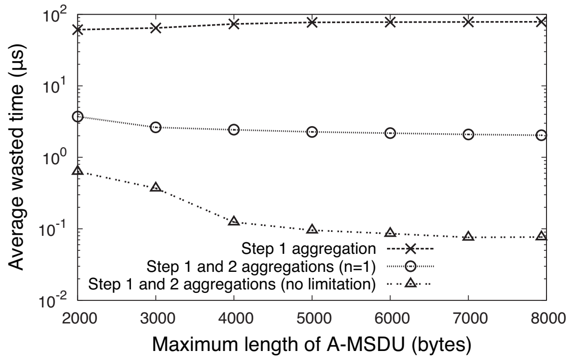

Fig. 6. Average wasted time vs. maximum length of A-MSDU when λ_{AP} and λ_{STA} are 10^5.

transmission. The PHY data rate is 65 Mbit/s. The buffer size of the AP and the STA is 200 kbytes. The details on MAC layer are based on IEEE 802.11n [12]. Simulation time is 5 min. In this simulation, we evaluate the average wasted time of each transmission, the system throughput performance and the average delay which are defined as a duration from when a frame stored in the buffer to when the frame is received by a receiver. We compared the performance with the step 1 and 2 aggregations with the performance with the step 1 aggregation. Our simulation programs are developed in C language. We confirmed that the simulation results of our programs are in good agreement with those of QualNet in the conventional CSMA/CA with RTS/CTS.

B. Simulation Results of Delay, Wasted Time and System Throughput Performance

1) vs. Maximum A-MSDU Length: First we evaluate a case where the maximum A-MSDU length is changed from 2000 bytes to 7935 bytes. In this case, λ_{STA} is fix to 10^5. Fig. 5 shows the average delay as a function of the maximum length of A-MSDU. As shown in the figure, the step 1 and 2 aggregations with $n = 1$ decrease the delay by 13%, and the step 1 and 2 aggregations without limitation decrease by 49%, compared with the step 1 aggregation. The reason why the step 1 and 2 aggregations without limitation achieve much higher delay performance is that many small frames are used for adjusting frame length in order to adjust frame length finely and the delay of small frames is largely decreased.

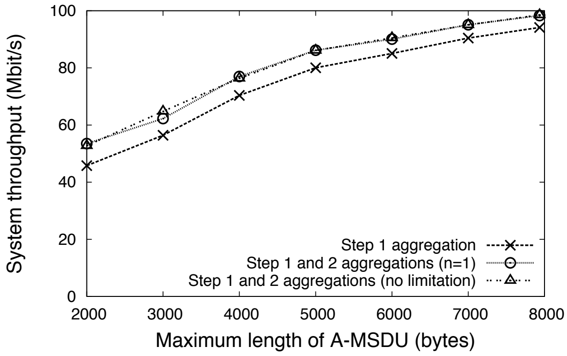

Fig. 7. System throughput vs. maximum length of A-MSDU when λ_{AP} and λ_{STA} are 10^5.

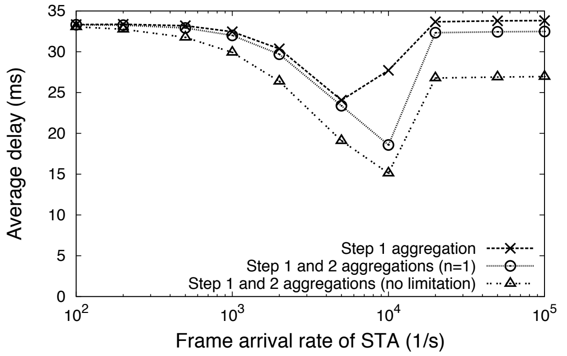

Fig. 8. Average delay vs. frame arrival rate of STA when maximum length of A-MSDU is 7935 bytes.

Fig. 6 shows the average wasted time as a function of the maximum length of A-MSDU. As shown in the figure, the step 1 and 2 aggregations with $n = 1$ decrease the wasted time by 97%, compared with the step 1 aggregation. Moreover, the step 1 and 2 aggregations without limitation decrease the wasted time by 96% compared with the step 1 and 2 aggregations with $n = 1$. The step 1 and 2 aggregations achieve much shorter average wasted time than the step 1 aggregation.

Fig. 7 shows the system throughput improvement as a function of the maximum length of A-MSDU. The step 1 and 2 aggregations with $n = 1$ increase the system throughput performance by 15% when A-MSDU is 2000 bytes. However, the step 1 and 2 aggregations without limitation bring only a little improvement against the step 1 and 2 aggregations with $n = 1$. This is because even the step 1 and 2 aggregations with $n = 1$ can reduce the average wasted time less than $4\,\mu s$ which is a orthogonal frequency division multiplexing (OFDM) symbol size and the secondary sender cannot increase the frame size even if the wasted time becomes small. Considering required time for solving optimization problem mentioned in Section IV, n should be 1 in this case.

2) vs. Frame Arrival Rate of STA: Next, we evaluate a case where the frame arrival rate of the STA λ_{STA} is changed from 10^2 to 10^5. In this case, the maximum A-MSDU length is fixed

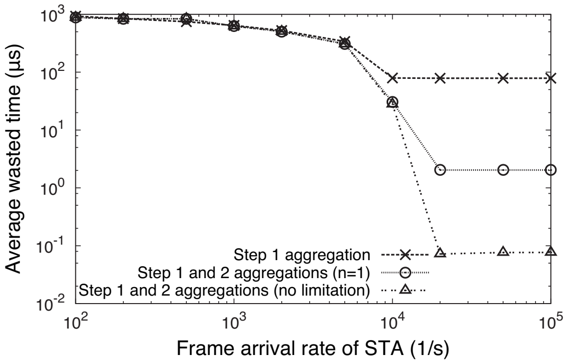

Fig. 9. Average wasted time vs. frame arrival rate of STA when maximum length of A-MSDU is 7935 bytes.

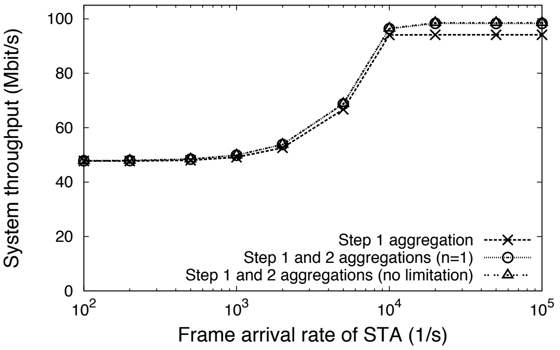

Fig. 10. System throughput vs. frame arrival rate of STA when maximum length of A-MSDU is 7935 bytes.

to 7935 bytes. Fig. 8 shows the average delay as a function of the frame arrival rate of the STA λ_{STA}. The step 1 and 2 aggregations with $n = 1$ and without limitation reduce the delay by 33% and 45%, respectively, compared with the step 1 aggregation.

Fig. 9 shows the average wasted time as a function of the frame arrival rate of the STA λ_{STA}. The step 1 and 2 aggregations with $n = 1$ reduce the wasted time by 97% compared with the step 1 aggregation when $\lambda_{\mathrm{STA}} \geq 2 \times 10^4$. In addition, the step 1 and 2 aggregations without limitation reduce by 96% compared with the step 1 and 2 aggregations with $n = 1$.

Fig. 10 shows the system throughput performance as a function of the frame arrival rate of the STA λ_{STA}. The system throughput improvement by the step 1 and 2 aggregations with $n = 1$ and without limitation are almost same, and they increase the system throughput performance by 4.7%, compared with the step 1 aggregation when $\lambda_{\mathrm{STA}} \geq 2 \times 10^4$.

When the STA has saturated traffic, the step 1 and 2 aggregations reduce the delay and the wasted time, and improves the system throughput performance. When the STA has non-saturated traffic, however, there is not a large effect. When the STA with a small offered load becomes a secondary sender, the secondary sender does not have many frames in its buffer. Therefore, the frame length of the secondary sender can not become the same length as the length of frame transmitted by primary sender and the wasted time decreases the system throughput performance.

VI. CONCLUSION

In this paper, we proposed the frame length optimization for in-band full-duplex WLANs. In the optimization, the secondary sender knows time length of the primary sender's frame from an RTS frame transmitted by the primary sender, and then adjust length of its own frame by selecting frames properly. The simulation results show that the proposed optimization reduces the delay and the wasted time, and improves the system throughput performance. Especially, when the maximum A-MSDU length is short and the STA has saturated traffic, the proposed optimization brings the large improvement of the system throughput performance. In addition, even if the maximum number of frames used for adjusting frame length is one, the system throughput performance is improved enough. Our future work includes a mechanism for increasing the system throughput performance in non-saturated case where STAs do not have many frames in their buffer.

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