FFD: A Fragmentation-based Full-Duplex MAC Protocol for Asymmetric IEEE 802.11 WLANs

Yen-Da Chen†, Jie-Min Cao‡, I-Ju Chen‡, and Kuei-Ping Shih‡

†Department of Computer Information and Network Engineering, Lunghwa University of Science and Technology, Taiwan
‡Department of Computer Science and Information Engineering, Tamkang University, Taiwan
Email: †ydchen@mail.lhu.edu.tw, ‡kpshih@mail.tku.edu.tw

***Abstract*—In-band full-duplex (IBFD) technology allows a wireless device transmitting and receiving packets at the same time and on the same frequency. The advantage of using IBFD in wireless local area networks (WLANs) is to increase channel utilization and therefore achieve higher throughput. However, due to the asymmetric hardware capability and DATA length between AP and stations, the channel wastage problem and collision problem may happen, which will degrade network throughput. As a result, a Fragmentation-based Full-Duplex MAC protocol, named FFD MAC, is proposed in the paper. FFD cannot only enhance the channel utilization but also increase network throughput for asymmetric IBFD WLANs. Simulation results conducted by OMNET++ simulator show that FFD MAC performs much better than the related work in terms of network throughput as well as the transmission delay.**

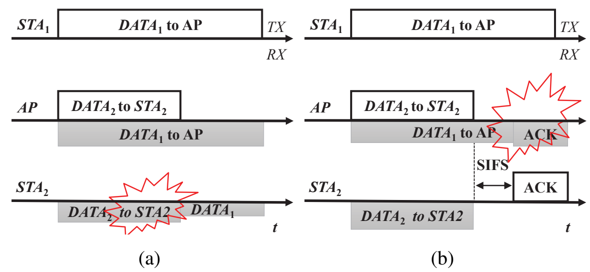

Fig. 1. The concept of (a) Inter-Station Interference, and (b) DATA-ACK collision problems for IBFD WLANs.

I. Introduction

Full-Duplex (FD) wireless communication, which allows a wireless station (STA) transmitting and receiving packets at the same time, has been recognized as an important transmission technology in wireless local area networks (WLANs). FD communication can double the network capacity with respect to traditional half-duplex transmission. However, due to the self-interference problem (SIP), the FD communication cannot serve well in the same frequency, where the reception of an incoming signal will collide with its own transmitting signal. Recently, thanks to the development of the self-interference cancellation technique, FD communication can be further extended to be used at the same frequency without SIP and is so-called in-band full-duplex (IBFD) communication.

Some IBFD MAC protocols [1], [2] assume that Access Point (AP) operates in FD transmission, but STAs are only equipped with Half-Duplex (HD) radios because of hardware constraints and legacy of the previous IEEE 802.11 standard. Therefore, to support the coexistence of FD AP and HD STAs, the IBFD wireless transmission is designed to as that FD AP is able to simultaneously transmit and receive DATA from different STAs. Unfortunately, as shown in Fig. 1(a), to double network capacity is not easily achieved in FD AP because the signal from the transmitting HD STA (STA_1) may collide with another HD STA (STA_2) while it is receiving data from AP. This collision problem is termed as Inter-Station Interference Problem (ISIP) [3].

Recently, ISIP is able to be alleviated efficiently thanks to the capture effect phenomenon [4] or modulation and coding scheme [5]. The detail of the capture effect will be further introduced in the next section. However, due to the variable DATA rate and DATA size, the transmission time of uplink may be longer than that of the downlink. As shown in Fig. 1(b), suppose STA_1 has DATA to AP, and AP also has data to STA_2. When AP finishes its transmission first, STA_2 will immediately replay ACK frame to confirm the transmission after an SIFS period. One can see that the time that STA_2 replies the ACK frame overlaps with that of the uplink transmission. In this case, the ACK frame may interfere with the DATA received by AP. This collision problem is termed as the DATA-ACK collision problem.

In [2], the authors proposed an FD MAC protocol, named A-Duplex MAC protocol, to avoid the DATA-ACK collision. The concept of A-Duplex protocol is that AP immediately transmits a busy tone signal after its DATA transmission to ensure that the two transmissions from AP and STA_1 can finish at the same time. Therefore, the ACK transmission will not overlap with the DATA transmission, and then the DACK-ACK collision can be avoided. However, busy tone transmission will degrade the channel utilization. In fact, during the period of the busy tone transmission, AP is able to transmit to another HD STA without causing ISIP. As a result, the paper proposes a Fragmentation-based Full-Duplex MAC protocol, named FFD MAC protocol, which can not only avoid ISIP but also alleviate the channel wastage problem for IBFD WLANs.

The rest of this paper is organized as follows. Section II formally describes the capture effect phenomenon. The concept

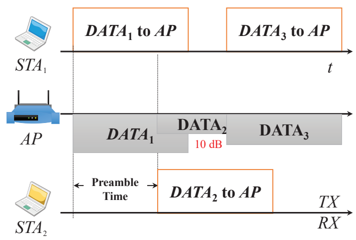

Fig. 2. An example to illustrate the capture effect.

of FFD MAC is proposed in Section III as well. Simulation results are presented in Section IV. Finally, Section V concludes the paper.

II. PRELIMINARIES

In the early version of radio technology, if multiple signals are transmitted from different STAs over a shared channel at the same time, the collision may happen at the receiver. Therefore, to alleviate this collision problem, the capture effect mechanism is born. The capture effect is a phenomenon that the receiver can demodulate the stronger signal if two signals received simultaneously.

Two cases are considered below to further illustrate the capture effect. As shown in Fig. 2, both STA_1 and STA_2 have packets to AP. The first case is that the target signal is transmitted early. Suppose STA_1 transmits first, and STA_2 also starts transmitting to AP after a preamble period passing. If the received signal of $DATA_1$ is greater than that of $DATA_2$, AP is able to decode $DATA_1$ successfully. Conversely, the second case is that the target signal is transmitted later. As shown in Fig. 2, the transmission time of $DATA_3$ is later than that of $DATA_2$. If the received signal of $DATA_3$ is 10 dB stronger than that of $DATA_2$, $DATA_3$ can be received correctly by AP.

Basically, it is easier to decode the target signal in case 1. As a result, the target signal will be transmitted later to avoid ISIP in the proposed FFD MAC protocol.

III. FRAGMENTATION-BASED FULL-DUPLEX (FFD) MAC PROTOCOL

Channel wastage problem and Inter-Station interference problem are two challenges in designing IBFD MAC protocols. Therefore, to overcome these two challenges, two ideas are proposed in FFD MAC protocol for IBFD WLANs. Firstly, to alleviate channel wastage problem, AP is allowed to transmit multiple DATAs to the same or different HD STAs in one IBFD transmission process when the transmission time of the uplink is longer than that of the downlink. However, it is difficult for AP to transmit multiple DATAs before an uplink DATA transmitting if the previous capture effect schemes directly apply to this asymmetric transmission time scenario for preventing ISIP. As a result, the second idea to avoid ISIP in FFD MAC is that the uplink DATA will be fragmented into multiple segments, and each segment uplink DATA will be transmitted after a downlink DATA transmitting. Take Fig. 3 as an example to further illustrate FFD MAC protocol in detail.

STA_1 has DATA to AP, and AP also intends to transmit to STA_2, STA_3, and STA_4, respectively. Assume that STA_1 wins the contention followed by IEEE 802.11 DCF, and then broadcasts a RTS frame after DIFS period. If channel is free for reception and transmission, AP will broadcast a Full-Duplex CTS (FCTS) control frame to confirm the IBFD transmission. From duration field in the RTS frame, the length of $DATA_1$ is available for AP. Then AP can decide how many DATAs ($DATA_2$, $DATA_3$, and $DATA_4$) can be transmitted in one IBFD transmission and attaches receiver ID and duration information in the FCTS frame. After FCTS, AP directly starts DATA transmissions in turn.

On the other hand, due to fragmentation, the transmission time of $DATA_1$ will be extended. A slight modification is needed for the duration field in the RTS frame. Therefore, a new control frame (FRTS) is proposed in FFD MAC protocol to correct the NAV information. The duration in FRTS is set to

$$\begin{aligned} &T_{DATA_2} + T_{DATA_3} + T_{DATA_4} + T_{SIFS} + \\ &\quad 4 * T_{ACK} - 2 * T_{Preamble} - T_{FRTS}, \end{aligned} \tag{1}$$

where $T_{Preamble}$ is the preamble time. T_{DATA_2}, T_{DATA_3}, T_{DATA_4}, T_{FRTS} and T_{ACK} are the transmission time of $DATA_2$, $DATA_3$, $DATA_4$, FRTS, and ACK, respectively.

Finally, after FRTS, STA_1 also starts $DATA_1$ transmission as shown in Fig. 3.

IV. PERFORMANCE EVALUATIONS

To verify the effectiveness of the proposed FFD MAC protocol, A-Duplex MAC [2] and CSMA based half-duplex MAC protocol are simulated and compared. The simulations are conducted by the OMNeT++ [6]. The simulation is the random topology, where one AP and some STAs around it. The general simulation settings are shown in Table I.

TABLE I
SIMULATION SETTINGS.

Parameter	Value
Traffic Model	CBR
Uplink DATA Length	1500 Bytes
RTS, FRTS	20 Bytes
CTS, ACK	14 Bytes
FCTS	Dynamic
DATA Rate	54 Mbps
Base Rate	12 Mbps
Channel Bandwidth	20 MHz

Fig. 4 illustrates the comparisons of network throughput among HD CSMA based, A-Duplex, and FFD MAC protocols in terms of the different number of stations. Due to AP with the full duplex ability, we can see that A-Duplex MAC and FFD MAC protocols always have better throughput than HD CSMA based MAC protocol. In addition, FFD MAC performs the best in all cases because of that the an extra busy tone signal is needed in A-Duplex MAC protocol to avoid Inter-Station

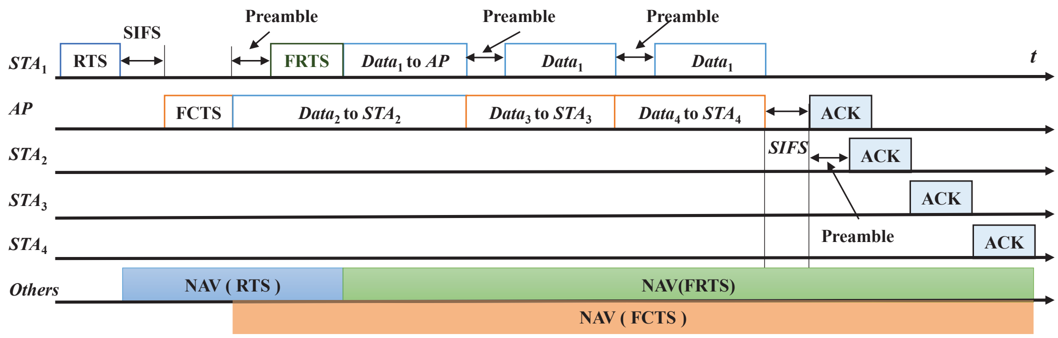

Fig. 3. The concept of FFD MAC protocol.

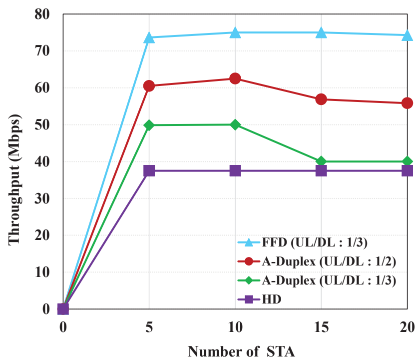

Fig. 4. The comparisons of network throughput among CSMA based, A-Duplex, and FFD MAC protocols in terms of different number of stations.

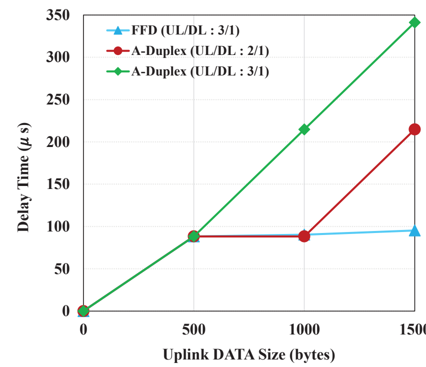

Fig. 5. The comparisons of packet delay between A-Duplex, and FFD MAC protocols in terms of the different uplink DATA lengths.

Interference Problem. It is worth mentioning that the longer length of downlink DATA is, the better of throughput gets. Note that the throughput of A-Duplex MAC and FFD MAC do not improve apparently with the number of STAs increasing because of that the contention among STAs becomes seriously.

Fig. 5 shows the comparisons of packet delay between A-Duplex, and FFD MAC protocols in terms of the different DATA length in downlink transmission. We can observe that the packet delay of A-Duplex MAC protocol is always higher than that of FFD MAC protocol because of that multiple DATA can be transmitted in one channel competition. Nevertheless, no matter in downlink or uplink, as the DATA length increasing, the channel competition increasing, and then packet delay also becomes seriously.

V. Conclusions

In the next-generation wireless networks, In-Band Full-Duplex is a key wireless technology to improve the network performance. However, the signal from the transmitting STA may collide with another STA in receiving. Hence, two collision problems, Inter-Station Interference Problem (ISIP) and ACK collision problem, furthermore, channel wastage problem may happen. As a result, a Fragmentation-based Full Duplex (FFD) MAC protocol is proposed in this paper not only to prevent ISIP and ACK collision problems but also to increase network performance without channel wastage problem. Simulation results show that FFD outperforms against other protocols in network throughput and transmission delay.

Acknowledgement

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