FuPlex: A Full Duplex MAC for the Next Generation WLAN

(Invited Paper)

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***Abstract*—IEEE 802.11 wireless local area network (WLAN) has been increasingly developed over several decades. It requires four times throughput improvement in the next generation WLAN. Thus, researchers focus on the co-frequency co-time full duplex technology, which makes the devices transmit and receive packets simultaneously and theoretically doubles the throughput. Some existing works proposed several media access control (MAC) protocols on the assumption that all nodes have full duplex capability. However, it is more practicable that only AP possesses full duplex capability whereas STAs have no full duplex capability in the early stage of introducing full duplex technology into the next generation WLAN. In this paper, a simple and compatible full duplex MAC protocol named FuPlex is proposed. The design details of FuPlex, including primary access, secondary access and data transmission, are introduced. Simulation results show that FuPlex improves the throughput to 150% compared with legacy IEEE 802.11 MAC protocol.**

I. Introduction

IEEE 802.11 wireless local area network (WLAN) is being deployed worldwide and lighting up our daily lives [1] [2]. The ever-increasing wireless traffic requires higher transmission capacity for the next generation WLAN. IEEE 802.11ax was approved in March 2014 to design a brand new amendment for the next generation WLAN [3]. IEEE 802.11ax requires four times throughput improvement in dense deployment scenarios compared with the current IEEE 802.11 WLAN. However, simply increasing the bandwidth for higher throughput will no longer be available since the spectrum resource is increasingly scarce. Therefore, new wireless communication technologies are needed to improve the spectrum efficiency in the next generation WLAN.

To achieve the objective mentioned above, co-frequency co-time full duplex technology has been propounded as a promising technology by enabling the devices to transmit and receive data packets at the same time and at the same frequency. It significantly improves the spectral efficiency of the wireless communication link, theoretically double. Most researchers paid attention to the physical layer implementation of full duplex technology, i.e. self-interference cancellation technologies [4]–[9]. However, full duplex technology cannot directly be adopted for the next generation WLAN without supportive medium access control (MAC) protocol. Therefore, it is necessary to study full duplex MAC protocol for the next generation WLAN.

There are some existing works focusing on the full duplex MAC protocol design. Singh et. al. [10] proposed ContraFlow based on the traditional IEEE 802.11 MAC protocol, i.e. distributed coordination function (DCF). When any node receives a data packet for itself, it may also send another packet simultaneously. In other words, full duplex transmission enabled by ContraFlow only occurs when a node receives a data packet and has data packets for other nodes at the same time. FD-MAC [11] also adopts DCF as its channel access mechanism. Unlike ContraFlow, in FD-MAC whenever a node transmits a data packet, other nodes including the receiver could send a data packet to the sender, i.e. only the transmitting node could leverage full duplex technology to receive and transmit packets at the same time. Janus [12] is a centralized MAC protocol with AP scheduling. AP needs to firstly collect the interference and service information of STAs, and then broadcasts the scheduling information of the available full duplex transmission and the rate selection for STAs.

All the full duplex MAC protocols mentioned above are proposed on the same assumption that all the nodes, including AP and STAs, have full duplex capability. But this assumption is impracticable in the upcoming next generation WLAN because WLAN is considered and designed as a simple and low cost wireless network. Thus, in the early stage of the next generation WLAN, it is more likely that AP has full duplex capability but STAs have no full duplex capability. Therefore, the current full duplex MAC protocols may not suitable. Specifically, in ContraFlow, when STAs receive packets, they cannot send packets to establish full duplex transmission since STAs have no full duplex capability. In FD-MAC, when a STA sends a data packet at first , no full duplex transmission could occur since STAs are not able to receive a data packet while transmitting. Besides, because of the centralized character, Janus is difficult to be compatible with the legacy IEEE 802.11 WLAN. To the best of our knowledge this paper is the first work focusing on the scenario that only AP has full duplex capability and STAs have no full duplex capability. In this paper a simple and compatible full duplex MAC protocol named FuPlex for the next generation WLAN is proposed. In FuPlex, each node follows channel access mechanism in IEEE 802.11 DCF to ensure better compatibility with legacy WLAN, and the full duplex transmission is established and implemented during data transmission in IEEE 802.11 DCF. Thus, FuPlex not only leverages full duplex technology to achieve higher throughput, but also has good compatibility with legacy IEEE 802.11 WLAN.

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The contributions of this paper can be summarized as follows:

- This paper proposes a full duplex MAC protocol named FuPlex for the next generation WLAN on the assumption that only AP possesses full duplex capability, which adapts to the evolution of WLAN and has good compatibility.
- The simulation results demonstrate that FuPlex can improve throughput up to 150% compared with the IEEE 802.11 DCF in dense deployment scenarios.

The rest of this paper is organized as follows. In Section II, the design principles and overview of FuPlex are introduced. Then in Section III, the design details of FuPlex are described. Performance evaluation based on simulation is presented in Section IV to validate the performance of FuPlex. This paper is summarized in Section V.

II. The Overview of FuPlex

The overview design of FuPlex is proposed in this section according to the demand of the next generation WLAN.

A. Design Principles

1) Only APs possess full duplex capability

Researchers express great interests in full duplex technology due to its advantage of theoretically doubling the spectrum efficiency. However, full duplex technology, on the other hand, will increase the complexity and cost of devices. Consequently, to implement full duplex technology only in AP is a relatively efficient and low-cost way in the upcoming next generation WLAN. Thus, the full duplex link should be an asymmetric link which consists of three nodes and two single links. As shown in Fig. 1, STA_1 receives packets from AP, while STA_2 transmits packets to AP. Thus, AP simultaneously receives packets from STA_2 and transmits packets to STA_1.

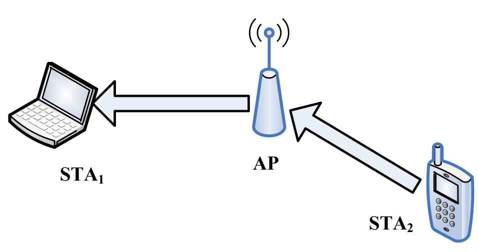


Fig. 1. Asymmetric full duplex link.

2) Compatibility with legacy WLAN

For the design of the next generation IEEE 802.11 standards, compatibility must be considered. Therefore, the full duplex MAC protocols for the next generation WLAN should follow the basic framework of IEEE 802.11 MAC protocol to possess better backward compatibility with IEEE 802.11a/b/g/n/ac [13] [14], e.g. the full duplex MAC protocols should be DCF-based.

B. FuPlex Overview

The overview design of the full duplex transmission for the next generation WLAN consists of two transmission procedures as shown in Fig. 2. The transmission procedure started at first refers to as the primary transmission procedure, and the later transmission procedure is denoted as the secondary transmission procedure. Primary transmission procedure consists of primary access, primary data transmission and primary acknowledgement (ACK) transmission, while secondary transmission procedure consists of secondary access, secondary data transmission and secondary ACK transmission. The definitions used in this paper is summarized in Table I.

TABLE I. Definitions in this paper

Definitions	Description
Full Duplex Transmission	A dual transmission using full duplex technology, including primary transmission procedure and secondary transmission procedure
Primary Transmission Procedure	The firstly starting transmission procedure, including primary access, primary data transmission and primary ACK transmission
Secondary Transmission Procedure	The later transmission procedure, including secondary access, secondary data transmission and secondary ACK transmission
Primary Access	The channel access mechanism in primary transmission procedure
Secondary Access	The channel access mechanism in secondary transmission procedure
Primary Data Transmission	The data transmission in primary transmission procedure
Secondary Data Transmission	The data transmission in secondary transmission procedure
Primary ACK Transmission	The ACK transmission in primary transmission procedure
Secondary ACK Transmission	The ACK transmission in secondary transmission procedure
Primary Sender	The sender in primary transmission procedure
Primary Receiver	The receiver in primary transmission procedure
Secondary Sender	The sender in secondary transmission procedure
Secondary Receiver	The receiver in secondary transmission procedure

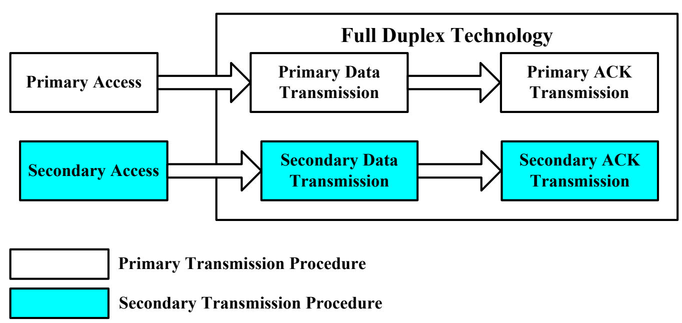


Fig. 2. The full duplex transmission in FuPlex.

1) Primary transmission procedure

In order to possess better compatibility with legacy IEEE 802.11 MAC protocol, primary access adopts the traditional IEEE 802.11 DCF for channel access mechanism. Since all nodes compete to access channel following IEEE 802.11 DCF, the primary transmission procedure could be initiated by AP, or by a STA.

2) Secondary transmission procedure

After primary sender completes its primary access, secondary sender could access channel by secondary access mechanism. The secondary sender could be the AP in the current basic set service (BSS) if the primary sender is a STA, or a STA if the primary sender is the AP. Thus, there are totally two types of full duplex transmission: AP initiated full duplex transmission and STA initiated full duplex transmission. For the AP initiated full duplex transmission, the secondary sender should be a STA except for the primary receiver STA. On the other hand, for the STA initiated full duplex transmission, the secondary sender is the AP. Since the primary access employs IEEE 802.11 DCF to compete for channel resource, the main challenge for the full duplex MAC protocol design is how to implement secondary access.

3) Interference in full duplex transmission

It is important in full duplex transmission that the primary receiver successfully receives packets from the primary sender under the acceptable interference from the secondary sender, and the secondary receiver successfully receives packets from the secondary sender under the acceptable interference from the primary sender. For instance, in Fig. 3(a) the primary receiver STA_2 not only receives a data packet from AP, but also suffers from the interference from STA_1. In this case, AP needs to adopt self-interference cancellation technology to cancel the self-interference. Similarly, in Fig. 3(b), when the full duplex transmission is initiated by STA_2, STA_1 could both receive a data packet from AP and suffer interference from STA_2, and it is also necessary for AP to cancel the self-interference. Therefore, interference in full duplex transmission should be considered carefully and thoughtfully. Since the self-interference cancellation technology is fully studied [4]–[9], the main problem of full duplex transmission is to control the interference between two STAs involved in full duplex transmission so that primary transmission procedure and secondary transmission procedure can coexist.

III. The Design Details of FuPlex

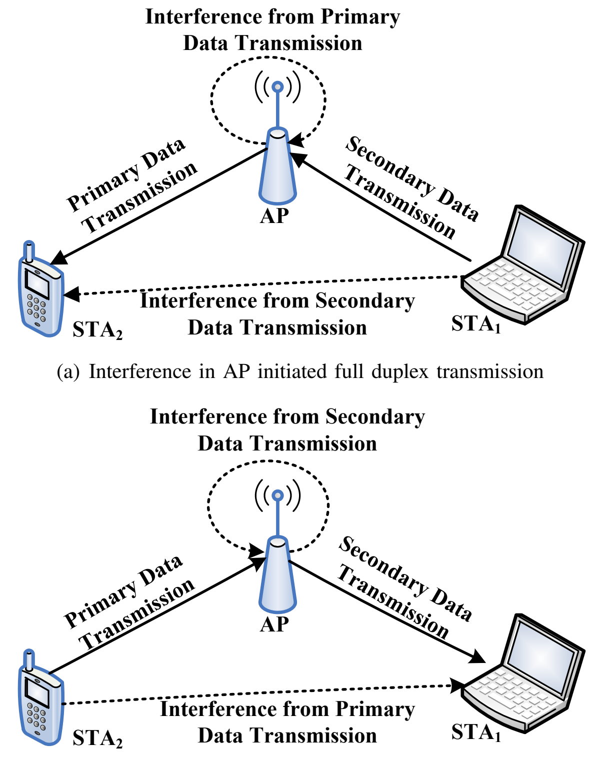
This section provides the design details of FuPlex for the next generation WLAN according to the overall design consideration as described in Section II.

A. MAC Procedure

The procedure of FuPlex is illustrated in Fig. 4, including the procedure of AP initiated full duplex transmission in Fig. 4(a) and the procedure of STA initiated full duplex transmission in Fig. 4(b):

1) AP and STAs detect the channel according to the carrier sensing procedure defined in IEEE 802.11 DCF. After the channel has been idle for distributed inter-frame space (DIFS), AP and STAs start backoff procedure obeying the rules given in IEEE 802.11 DCF.

2) When a node, i.e. primary sender, completes the backoff procedure, it sends a request to send (RTS) packet to start primary transmission procedure, and then the primary receiver replies a clear to send (CTS) packet. In addition, nodes in the same BSS could measure the channel state information (CSI) during the RTS/CTS exchange.



(a) Interference in AP initiated full duplex transmission

(b) Interference in STA initiated full duplex transmission

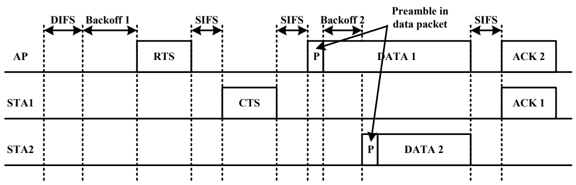
Fig. 3. Interference in two types of full duplex transmission.

3) After receiving the CTS packet, the primary sender firstly sends a data packet to the primary receiver. In AP initiated full duplex transmission, the STAs except for the primary receiver STA start secondary backoff procedure to compete for the secondary access, and the winner of the secondary access could directly transmit a data packet to the secondary receiver. While in STA initiated full duplex transmission, AP can use scheduling algorithm to select an appropriate STA as the secondary receiver according to buffer state information and historical transmission information of STAs. Moreover, the secondary sender has to receive the preamble of the data packet sent in the primary data transmission to acquire its duration.

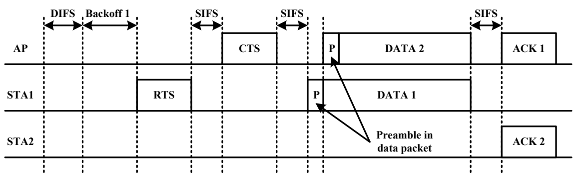
4) The secondary sender needs to adjust (e.g. add some padding) its data transmission duration to make sure that both primary data transmission and secondary data transmission complete at the same time. Then the primary receiver and the secondary receiver simultaneously reply ACK to their senders. Thus, we highlight that full duplex technology is used both in data transmission period and ACK transmission period.

B. Primary access

In order to ensure better compatibility with legacy IEEE 802.11 WLAN, IEEE 802.11 DCF is employed as primary access mechanism for the FuPlex nodes, i.e. the nodes adopting FuPlex protocol. In other words, both legacy nodes and FuPlex nodes use the same rules to compete for channel resource. Thus, the fairness between FuPlex nodes and legacy nodes is guaranteed. In fact the primary transmission procedure and the secondary transmission procedure are independent from

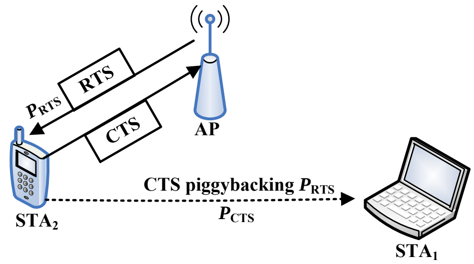


(a) AP initiated full duplex transmission

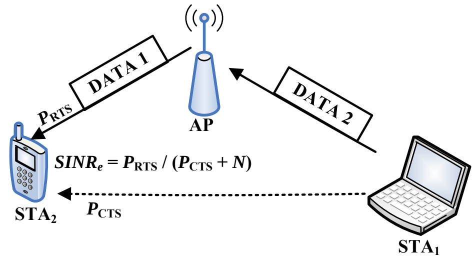


(b) STA initiated full duplex transmission

Fig. 4. The procedure of FuPlex.



(a) CSI measurement in AP initiated full duplex transmission



(b) Estimation of $SINR_e$

Fig. 5. The procedure of CSI measurement and the estimation of $SINR_e$.

the STAs' view except for the interference effect. The self-interference cancellation technology is able to cancel the self-interference existing in AP when it transmits packet and receives packet simultaneously, while CSI measurement during primary access is adopted to control interference between STAs.

In AP initiated full duplex transmission, STAs could measure the CSI during the procedure of RTS/CTS exchange as illustrated in Fig. 5(a). When STA_2 receives the RTS packet from AP, it measures the receiving power P_{RTS} and piggybacks P_{RTS} on the CTS packet. Thus, once STA_2 sends the CTS packet, the other STAs could measure the receiving power P_{CTS} and obtain the piggybacked P_{RTS}. P_{RTS} indicates the receiving power of STA_2 for those packets sent by AP. P_{CTS} indicates both the receiving power of STA_2 for those packets sent by STA_1 and the receiving power of STA_1 for those packets sent by STA_2 on the assumption that CSI is reversible [15] [16]. Therefore, STA_1 could estimate the signal to interference and noise ratio (SINR) of DATA1 received by STA_2 if STA_1 sends DATA2 to AP simultaneously as shown in Fig. 5(b), and the estimated SINR is calculated as

$$SINR_e = \frac{P_{RTS}}{(P_{CTS} + N)}, \tag{1}$$

where N is the power of noise. We define $SINR_T$ as the minimal SINR value for primary receiver to successfully receive data packet. The STAs are allowed to perform secondary access if and only if the estimated $SINR_e$ is equal to or larger than $SINR_T$. In summary, when a STA receives a CTS packet, it checks the receiver address of the CTS packet. If the receiver of the CTS packet is the AP of the current BSS, the STA measures the receiving power P_{CTS} and obtains the P_{RTS} piggybacked in CTS, and then estimates the $SINR_e$. If the estimated $SINR_e$ is not less than $SINR_T$, the STA could perform secondary access.

In STA initiated full duplex transmission, AP can use scheduling algorithm to select an appropriate STA as the secondary receiver. Thus, there is no extra CSI measurement procedure in primary access. In other words, the primary access in STA initiated full duplex transmission is as same as the channel access in IEEE 802.11 DCF.

C. Secondary access

Secondary backoff mechanism is employed for secondary access in AP initiated full duplex transmission. When AP sends data packet to the primary receiver STA, the other STAs except for the primary receiver STA need to receive the preamble of data packet sent by AP to get the data transmission duration from the L-SIG field [13]. Those STAs whose estimated $SINR_e$ are not less than $SINR_T$ start their secondary backoff procedures. To lower the possible interference to primary data transmission, the STAs with higher estimated $SINR_e$ should have higher priority for secondary access. Thus, it is assumed that contention window in secondary access (denoted as CW_S) and $1/SINR_e$ is in linear relationship [17]. The STAs performing secondary backoff calculate the CW_S value by Eq. (2) in [18]

$$\frac{1}{SINR_e} : \frac{1}{SINR_T} = CW_S : CW_{S-Max}, \tag{2}$$

where CW_{S-Max} is the maximal value of CW_S. After that, these STAs randomly choose a backoff counter from $[0, CW_S]$, and then start secondary backoff procedure respectively. Once a STA completes backoff process and sends a data packet to the AP, the other STAs sense the increase of power on the channel and determine that the channel is busy until the full duplex transmission completes. An example of secondary backoff procedure is illustrated in Fig. 6.

In STA initiated full duplex transmission, since AP has all the downlink data packets to STAs, it is easy for AP to select a STA as the secondary receiver. Thus, centralized scheduling in AP is adopted as the secondary access mechanism. At first AP randomly chooses a STA as the secondary receiver and then records the ACK information. If AP receives ACK from secondary receiver STA, it indicates that this STA can establish full duplex transmission with the current primary sender STA together, and these two STAs are named as *coupling STAs* for

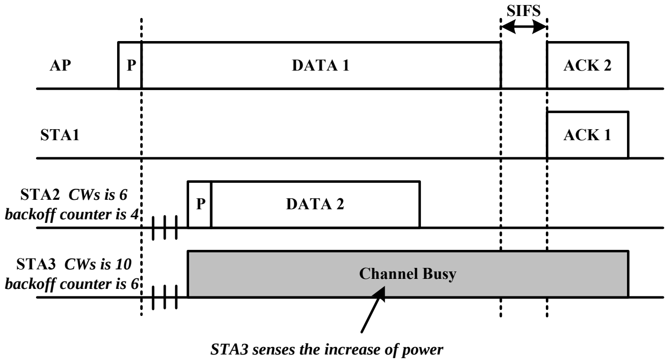


Fig. 6. When AP sends DATA1 to STA_1, STA_2 and STA_3 need to receive the preamble of DATA1 to get the transmission duration of DATA1. The estimated $SINR_e$ of STA_2 and STA_3 are both higher than $SINR_T$, and then STA_2 and STA_3 start secondary backoff procedure independently. According to Eq. (2), CW_S of STA_2 and STA_3 are 6 and 10 respectively. Then STA_2 selects 4 as the backoff counter, and STA_3 selects 6 as the backoff counter. Therefore, STA_2 completes backoff process after four time slots, and sends DATA2 to AP. Meanwhile, STA_3 senses the increase of power on the channel and realizes that other STAs have started secondary data transmission. Thus, STA_3 determines that the channel is busy until the full duplex transmission completes.

full duplex transmission. Thus, AP could use the information of coupling STAs for more efficient scheduling.

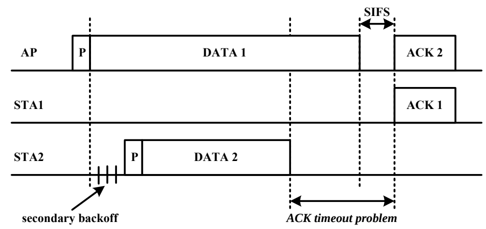
D. Data transmission

After receiving the preamble of the data packet in the primary data transmission, the secondary sender could get the transmission duration of the data packet. The secondary sender needs to select a proper data packet to make sure that secondary data transmission should not complete later than the primary data transmission. However, if the secondary sender completes data transmission earlier than the primary sender does, the *ACK timeout problem* occurs in FuPlex due to the ACK mechanism in IEEE 802.11 DCF. In AP initiated full duplex transmission, if the secondary sender STA completes data transmission earlier than AP does, AP cannot reply ACK to secondary sender STA immediately since it is sending a data packet to primary receiver. And in STA initiated full duplex transmission, if AP completes data transmission earlier than the primary sender STA does, AP could not receive ACK from secondary receiver STA since it is receiving a data packet from primary sender STA. Thus, ACK timeout problem may happen in both AP initiated full duplex transmission and STA initiated full duplex transmission. For instance, the ACK timeout problem mentioned above is described in Fig. 7.

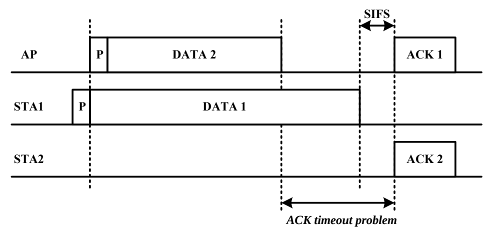
To solve the ACK timeout problem, secondary sender could add some padding in its data packet to make sure that the secondary data transmission and primary data transmission complete simultaneously. In addition, to take full advantage of full duplex technology and further reduce the signaling overhead, the primary receiver and the secondary receiver simultaneously reply ACK to their senders. Thus, full duplex technology is used both in data transmission and ACK transmission.

IV. Performance evaluation

In order to evaluate the performance of proposed full duplex MAC protocol, a simulation platform is built based



(a) AP firstly sends DATA1 to STA_1. Then, after finishing the secondary backoff procedure, STA_2 sends DATA2, and completes data transmission earlier than AP does. Since AP is sending DATA1, it cannot reply ACK to STA_2 immediately. Therefore, STA_2 considers that the reception of ACK is failed after a specific time.



(b) STA_1 sends DATA1 to AP at first. Then, AP sends DATA2 to STA_2, and completes data transmission earlier than STA_1 does. Since AP is receiving DATA1, it cannot receive ACK from STA_2 at the same time. Thus, AP considers that the reception of ACK is failed after a specific time.

Fig. 7. The ACK timeout problem in FuPlex.

on NS2 [19]. The details of FuPlex as described above are implemented in this simulation platform. The simulation scenarios is in a single BSS, i.e. there are only one AP and some STAs around it. We assume that a packet could be successfully received only if the receiving SINR of this packet is not less than the $SINR_T$. The parameters used in simulations are shown in Table II.

TABLE II. Simulation Parameters

Parameters	Value in Simulation
Preamble Duration	20us
Physical Rate	6Mbps
$SINR_T$	3.16dB
CW_{min}	15
CW_{max}	1023
CW_{S-Max}	15
DIFS	34us
SIFS	16us
Slot Time	9us

A. The number of STAs vs. Throughput

Fig. 8 depicts throughput comparison of FuPlex and traditional IEEE 802.11 DCF under saturated traffic as the number of STAs increases. It shows that FuPlex always delivers a higher throughput than IEEE 802.11 DCF does since full duplex transmission is employed. FuPlex improves the throughput to 150% compared with the IEEE 802.11 DCF.

B. The traffic rate vs. Throughput

Fig. 9 illustrates the throughput for FuPlex compared with IEEE 802.11 DCF protocol in two scenarios with different

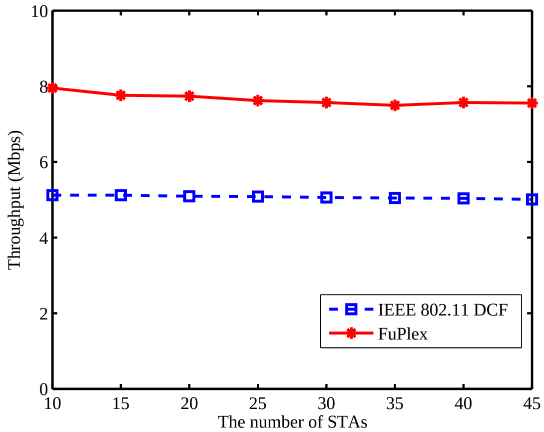


Fig. 8. The number of STAs vs. throughput under saturated traffic.

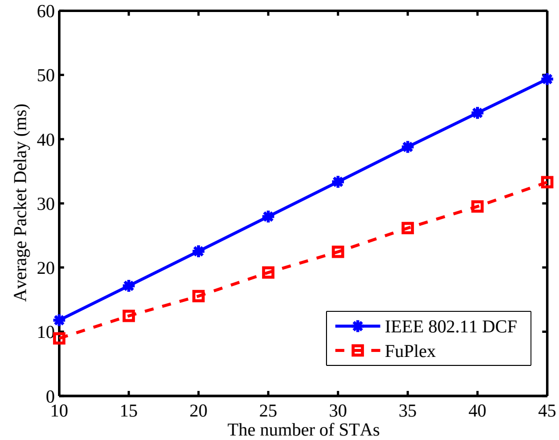


Fig. 10. The number of STAs vs. average packet delay.

STA number. Constant bit rate (CBR) traffic is employed in our simulation scenarios. We can observe that the throughput with FuPlex is equal to that with IEEE 802.11 DCF in light traffic load, and is larger than that with IEEE 802.11 DCF in heavy traffic load since there are more opportunities for FuPlex to establish full duplex transmission under heavy traffic load. In a word, FuPlex is more suitable for heavy traffic load scenarios than IEEE 802.11 DCF, which evidently benefits the next generation WLAN.

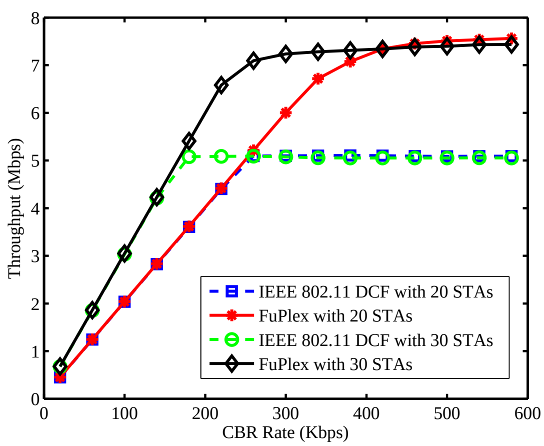


Fig. 9. The traffic rate vs. throughput.

C. The number of STAs vs. Average packet delay

In Fig. 10, the average packet delay is compared between FuPlex and IEEE 802.11 DCF, where the CBR traffic rate is 80Kbps. The packet delay of FuPlex is always lower than that of IEEE 802.11 DCF since AP and STAs have more opportunities to transmit data packet in FuPlex. In addition, with the number of STAs increasing, the average packet delay of FuPlex increases relatively slowly compared with that of IEEE 802.11 DCF since more STAs means more opportunities to use full duplex transmission.

V. Conclusion and Future Work

This paper proposes a simple and compatible full duplex MAC protocol named FuPlex for the upcoming next generation WLAN on the assumption that only AP possesses full duplex capability. FuPlex not only improves the throughput by using full duplex technology, but also possesses better backward compatibility with legacy IEEE 802.11 MAC protocol. Simulation results show that the FuPlex protocol has advantage of higher throughput, lower packet latency and especially improving the throughput to 150% compared with that in IEEE 802.11 DCF in dense deployment scenarios. In the future work we will focus on the optimization algorithm of backoff contention window based on SINR.

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