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A NOVEL METHOD OF LOW INTERFERENCE UPLINK & DOWNLINK MAC PROTOCOL FOR FULL-DUPLEX WI-FI NETWORKS

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ABSTRACT

A Full-duplex MAC protocol provides a greater reception opportunities to clients with low interference and to reduce the interference between uplink and downlink transmissions at the AP. Full-duplex access points can potentially support simultaneous uplink and downlink flows. However, the atomic three-node topology, which allows simultaneous uplink and downlink, leads to inter-client interference. In this project, we propose a random-access medium access control protocol using distributed power control to manage inter-client interference in wireless networks with full-duplex capable access points that serve half-duplex clients. Our key contributions are two-fold. First, we identify the regimes in which power control provides sum throughput gains for the three-node atomic topology, with one uplink flow and one downlink flow. Second, we develop and benchmark PoCMAC, a full 802.11-based protocol that allows distributed selection of a three-node topology. The proposed MAC protocol is shown to achieve higher capacity as compared to an equivalent half-duplex counterpart, while maintaining similar fairness characteristics in single contention domain networks.

I. INTRODUCTION

Recent work has demonstrated in-band full duplex capability, i.e., the ability to transmit and receive simultaneously in the same band through self-interference cancellation using multiple antennas. In fact, the ability to suppress self-interference below the noise floor has been demonstrated, thereby enabling near-ideal full-duplex capability. To take advantage of full-duplex capability in a multi-node network, it is essential to have new medium access control (MAC) protocols, because full-duplex leads to new interference patterns compared to current half-duplex communication networks.

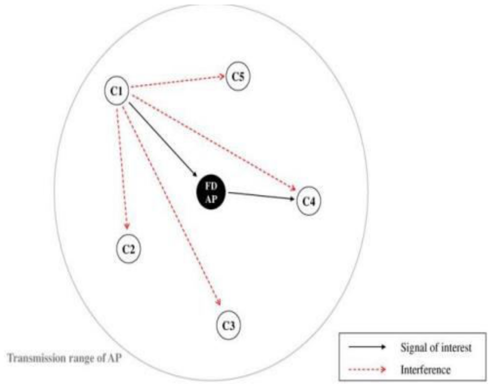

Fig.1.Uplink (C1→AP) and Downlink (AP→C4) Network with Full-DuplexAP and Half-Duplex Clients.

The key challenge for the full-duplex MAC is to coordinate multiple simultaneous transmissions, which are made possible by the new in-band full-duplex capability. Fig. 1 shows the key challenge of inter-client interference with simultaneous up/downlink in

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a network environment, when the uplink and downlink flows involve different clients. The gray circle in Fig. 1 denotes the transmission range of the full-duplex access point (AP). Assume that Client 1 (C1) wants to transmit a packet to the full-duplex AP, and that the full-duplex AP wants to transmit a packet to Client 4 (C4), as shown by the black line in the figure. In this case, the signal transmitted from C1can interferes with other clients, particularly C4, which intends to receive the signal from the AP. If C1 is located close to C4,and the signal transmitted from C1 is very strong, C4 cannot receive the signal transmitted from the AP owing to the inter client interference caused by the signal of C1. In this paper, we consider wireless networks in which an APis capable of full-duplex communication and clients only use half-duplex transmissions. To overcome the challenge of inter client interference shown in Fig. 1, we propose two concepts: distributed interference measurement to modulate access probabilities, and distributed power control to maximize the resulting throughput. First, we propose the use of a signal strength-based back-off mechanism to provide a higher reception opportunity to the client with a low inter-client interference. Using this mechanism, the client with the lowest inter-client interference has the smallest contention window size and is eventually selected to receive a downlink transmission from the AP. Second, to maximize the network throughput performance, we formulate an optimization problem for calculating the optimal transmit powers of the AP and client. The optimization problem is then solved as part of the proposed MAC protocol, namely, power controlled MAC (PoCMAC), to coordinate the uplink and downlink transmissions.

II. WIRELESS NETWORK MODEL WITH A SINGLE FULL-DUPLEX

Until very recently, the concept of transmission and reception in the same time and frequency domain (referred as full duplex (FD) technology) did not seem to be very promising. The primary reason of this was the overwhelming nature of the so called self-interference (SI), which is generated by the transmitter to its own collocated receiver. SI is a fundamental bottleneck in the progress of FD technology. Fortunately, with the recent advancements in the antenna and digital baseband technologies as well as the RF interference cancellation techniques, SI can be reduced close to the level of noise floor in low-power networks, e.g., cognitive radio networks and Wi-Fi networks. At the physical layer (PHY), considering a point-to-point link and perfect SI cancellation, FD transmission offers twice the spectral efficiency of half duplex (HD) transmission.

Due to this attractive feature, FD technology is rapidly extending its applications in different wireless communications scenarios, especially, the ones with low transmission power and distance requirements. For instance, small cell networks, device-to device(D2D) communications, cognitive radio networks and multi-hop relaying are potential areas where FD technology can be practically feasible and implementable in the near future. This article first discusses the fundamental concepts, potential benefits, primary network topologies, and collision domains in FD transmission. Then it highlights the immediate challenges (both in the PHY and MAC layers) that need to be addressed in the design of FD-MAC protocols. A qualitative overview of the existing FD-MAC protocols is then provided. To this end, major issues and approaches for designing FDMAC are discussed. Finally, implications of FD technology on the resource and interference management aspects of cellular networks are highlighted.

A. System Model

We consider an in-band full-duplex wireless network that consists of an AP with full-duplex capability and multiple clients without full-duplex capability. Note that the AP is easily equipped with elaborate antenna techniques and signal Processing modules for self-interference cancellation while mobile

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clients with full-duplex capability are being incrementally deployed. Therefore, we consider a full-duplex wireless net work where the AP can simultaneously transmit and receive signals and the clients can either transmit or receive at a given instant in time. In this paper, a transmitter (TX) refers to the client transmitting signals to the AP, and a receiver (RX) refers to the client receiving signals from the AP. Fig. 2 shows the system model for a wireless network with a single full-duplex AP, one TX, and one RX. Note that the single AP is depicted as two separate components for transmitting and receiving signals. The full-duplex AP and TX transmit the signals XAP and XTX, and the RX and fullduplex AP receive the signals YRX and YAP, respectively.

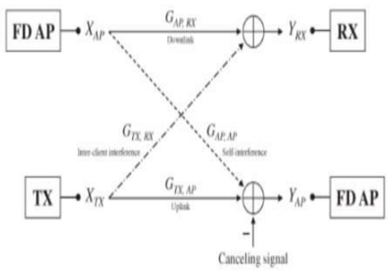

Fig.2. Wireless Network Model with a Single Full-Duplex AP (Separate Transmitting and Receiving Components), One Transmitter, and One Receiver.

Gimp is the channel gain from Client i to Client j. Because a full-duplex AP transmits and receives a signal simultaneously, the transmitted signal of the AP is fed back to the receiving RF chain of the AP, and it interferes with the signal reception at the AP. Thus, there exists a channel from the transmitting RF chain to the receiving RF chain of the AP, and this channel is modeled as the self-interference channel gain GAP, AP. The channel gains are modelled as complex Gaussian random variables with zero mean, and they are assumed to be constant over the duration of each transmission. As shown in Fig. 2, the canceling signal for self-interference cancellation in the full-duplex AP is modeled as τ · _GAP, AP· XAP, where GAP, APis the channel estimate of GAP, AP, and τ is a cancellation Coefficient. Here, τ is determined by the degree of self-interference cancellation, which depends on the analog and digital cancellation techniques for full-duplex communication. Note that the self-interference signal could be canceled by subtracting the canceling signal from the received signal [7].Then, the received signals YRX and YAP can be written as

$$\begin{aligned} Y_{RX} &= G_{AP,RX} \cdot X_{AP} + G_{TX,RX} \cdot X_{TX} + N_{RX}, \\ Y_{AP} &= G_{TX,AP} \cdot X_{TX} + G_{AP,AP} \cdot X_{AP} \\ &\quad - \tau \cdot \widehat{G}_{AP,AP} \cdot X_{AP} + N_{AP}, \end{aligned} \quad (1)$$

Where NRX and NAP are the white Gaussian noises at the R and AP, respectively, i.e., NRX CN (0, σ2RX) and NAP∼CN (0, σ2AP). For perfect self-interference cancellation, the canceling signal should be equal to GAP, AP· XAP, i.e., The AP already knows XAP, and what remains for perfect self interference. Cancellation is the accurate estimation of GAP, AP and its compensation with gain control. If the self interference cancellation is imperfect, GAP, AP· XAP − τ · _GAP, AP· X AP Can be a non-zero value. However, if the self-interference is very small compared to the received signal of the AP, we will consider it negligible and ignore it.

We define α as the suppression level of self-interference cancellation, and it cane expressed as

$$\alpha = \frac{|G_{AP,AP}|^2}{|G_{AP,AP} - \tau \cdot \widehat{G}_{AP,AP}|^2}. \quad (2)$$

For the successful reception of uplink and downlink transmissions, the minimum SINR of YRX and YAP should be higher than the SINR threshold γ. Although this model inherently guarantees only the minimum rate, it is possible that higher SINR will be achievable in some cases, and hence, higher rates can be utilized. Let Pr,i→j denote the received power at Client j due to the signal transmitted by Client i, and let Pr,SI denote the self-interference power for the AP. Pr,i→j and Pr, SIare given by

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$$P_{r,i\to j} = |G_{i,j}|^2 \cdot E\left(|X_i|^2\right) = |G_{i,j}|^2 \cdot P_{t,i},$$
$$P_{r,SI} = |G_{i,j}|^2 \cdot E\left(|X_{AP}|^2\right) = |G_{AP,AP}|^2 \cdot P_{t,AP}, \quad (3)$$

Where Pt,i is the transmit power of Client i. Thus, the SINRs of YRX and YAP can be expressed as

$$\mathrm{SINR_{RX}} = \frac{P_{r,AP\to RX}}{P_{r,TX\to RX} + N_{RX}},$$
$$\mathrm{SINR_{AP}} = \frac{P_{r,TX\to AP}}{\frac{P_{r,SI}}{\alpha} + N_{AP}}. \quad (4)$$

Then, the conditions for successful transmission from the AP To the RX and from the TX to the AP are respectively given By

$$\mathrm{SINR_{RX}} \geq \gamma,$$
$$\mathrm{SINR_{AP}} \geq \gamma. \quad (5)$$

In addition, from (5) and (6), we define the sum rate Rsum as the achievable sum rate of the uplink and downlink transmissions at the AP as follows.

$$\mathcal{R}_{sum} = \log_2(1+\mathrm{SINR_{Uplink}}) + \log_2(1+\mathrm{SINR_{Downlink}}), \quad (6)$$

Where SINR Uplink and SINR Downlink are the SINRs of the uplink and downlink transmissions, which correspond to SINRAPin (5) and SINRRX in (6), respectively.

III. POCMAC: FULL-DUPLEX MAC PROTOCOL

In this section, we describe our power-controlled MAC protocol (PoCMAC) for in-band full-duplex wireless networks. Before providing a detailed description of Po CMAC, we consider how to increase the sum rate of the uplink and downlink transmissions at the AP in a full-duplex wireless environment. Fig. 3 shows the sum rate of the wireless network, where AP and TX are located at (0, 0) and (−50, 0), respectively. The sum rate Rsum is computed with respect to the position of the RX, which changes within a 200 × 200 m region. Fig. 3(a) shows that Rsum is maximized when the RX is far from the TX and close to the AP. When the inter-client interference signal from the TX is weak and the signal from the AP is strong, the RX Fig. 3. Sum rate Rsum with respect to (a) the position of the RX and (b) RSS values at the RX for the signals from the AP and TX, when the AP and TX are located at (0, 0) and (−50, 0), respectively. (a) Position of RX. (b) RSS at RX for the signals from AP and TX. can have high SINR Downlink, and thus, Rsum becomes high. On the other hand, if the signal from the TX is strong, the RX cannot receive the signal transmitted by the AP because the signal from the TX is an inter-client interference signal at the RX. In this case, Rsum decreases.

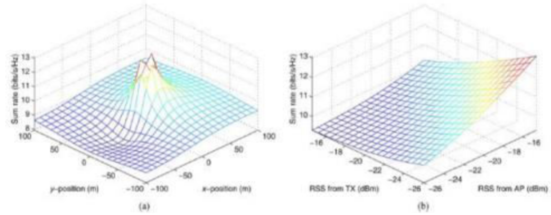

Fig.3. Sum rate Rsum with respect to (a) the position of the RX and (b) RSS values at the RX for the signals from the AP and TX, when the AP and TX are located at (0, 0) and (−50, 0), respectively. (a) Position of RX. (b) RSS at RX for the signals from AP and TX.

In Fig. 3(b), Rsumis redrawn with respect to the received signal strength (RSS)values at the RX. Depending on the position of the RX, the RSSvalues at the RX for signals from the AP and TX lie in the range of [−26,−15] Db m. Fig. 3(b) shows that Rsum is maximized when the RSS values from the AP and TX are the highest and lowest, respectively. The above numerical example is indicative of the following general result: when two transmitters, i.e., the AP and TX, are fixed, then the RX should be carefully selected from among multiple candidate clients because the sum rate of a full-duplex wireless network changes according to the position of the RX. Therefore, we propose a signal-strength based back-off mechanism for selecting the RX to achieve a low inter-client interference. In

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addition, if the AP transmits signals using the maximum transmit power, the strength of self-interference at the AP increases owing to the strong signal transmitted from the AP itself. As a result, the self interference signal is not sufficiently suppressed, and the AP cannot decode signals from the TX. If the TX transmits signals using the maximum transmit power, the RX undergoes strong inter-client interference from the TX and cannot receive signals from the AP. The above conclusion is our motivation for adapting the transmit powers of the AP and TX to maximize the sum capacity. In summary, PoCMAC includes (i) a contention-based receiver selection scheme to provide a higher reception opportunity to clients with low interference and (ii) a transmit power adjustment scheme for computing the optimal transmit powers of the AP and TX. PoCMAC needs to collect the channel gains, such as GTX,AP , GAP,RX, and GTX,RX, and these channel gains can be obtained when control frames are exchanged between the AP and clients. For example, the channel gain from the TX to the AP (GTX,AP) is obtained when theta transmits a control

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$$\mathrm{CW}_{\mathrm{RSSB,i}} = \left\lfloor \omega_\alpha - \omega_\beta \cdot \log_2\left(1 + \frac{P_{r,AP\to i}}{P_{r,TX\to i}}\right)\right\rfloor , \tag{7}$$

where ωα and ωβ are the constants for a linear mapping fromlog2

$$1 + Pr,\ AP\longrightarrow I \tag{8}$$

$$Pr,\ TX\longrightarrow I \tag{9}$$

to an integer value for the contention window in the range of [0,CWmin]. Note that the value oflog2

$$1 + Pr,\ AP\longrightarrow I, \tag{10}$$

Pr, TX→I may change owing to various factors in wireless network environment. A high Pr, AP→I Pr, TX→I implies that Client i has a high RSS from the AP and low inter-client interference by the TX; therefore, we

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use the CWRSSB,i of Client i for providing a higher reception probability to the client with a high RSS from the AP and low inter-client interference. Thus, CWRSSB,i decreases as Pr,AP→I Pr,TX→I increases, and as a result, the probability that the client with a small contention window size can access the wireless channel first, increases. Using the RSSB contention mechanism to determine the receiver, PoCMAC enables the candidate client that can maximize full-duplex capability to have a higher probability of receiving the downlink transmission from the AP. During this contention, collisions among candidate clients may occur if more than two clients choose the same back-off number. In this case, PoCMAC fails to select the RX for downlink transmission, and the TX that successfully transmitted RTS to and received CTS from the AP performs the half-duplex uplink transmission.

B. Transmit Power Adjustment

After the RX is determined by the RSSB contention mechanism, the AP calculates the optimal transmit powers for itself and the TX using the information about the received powers from the TX and RX, the inter-client interference from the TX to the RX, and the self-interference in the AP. This transmit power adjustment scheme can reduce the inter client interference and prevent collisions at the RX. In Section II, we stated the conditions required for successful uplink and downlink transmissions in (7) and (8), i.e., for successful transmissions, the SINR of the uplink and downlink transmissions should be higher than the SINR threshold γ. From Section II, the conditions can be rewritten as

$$\mathrm{SINR}_{\mathrm{Uplink}} = \frac{|G_{TX,AP}|^2 \cdot P_{t,TX}}{\frac{|G_{AP,AP}|^2}{\alpha} \cdot P_{t,AP} + N_{AP}} \geq \gamma,$$
$$\mathrm{SINR}_{\mathrm{Downlink}} = \frac{|G_{AP,RX}|^2 \cdot P_{t,AP}}{|G_{TX,RX}|^2 \cdot P_{t,TX} + N_{RX}} \geq \gamma. \quad (11)$$

The transmit power control that determines the transmit powers of the AP and TX should 1) facilitate successful simultaneous uplink and downlink transmissions, and 2) enable each transmission to achieve the maximum SINR value. Fig. 4 shows the feasible region and optimal point of transmit powers with respect to the transmit power of the AP and TX. The blue line is the upper bound that satisfies (11), and the green line is the lower bound that satisfies (12). The gray-shaded area is the feasible region that simultaneously satisfies both (11) and (12), i.e., the transmit powers of the AP and TX in the region ensure the feasibility of simultaneous uplink and downlink transmissions. Within the feasible region, we need to find the optimal transmit powers of the AP and TX to maximize the SINR values of the uplink and downlink transmissions. Therefore, we formulate an optimization problem for the transmit powers of the AP and Texas follows

$$P^*_{t,i} = \arg\max_{P_{t,i}} \left(\min\left(\mathrm{SINR}_{\mathrm{Uplink}}, \mathrm{SINR}_{\mathrm{Downlink}}\right)\right)$$
$$\text{subject to} \quad \begin{array}{l} \mathrm{SINR}_{\mathrm{Uplink}} \geq \gamma \\ \mathrm{SINR}_{\mathrm{Downlink}} \geq \gamma\,, \ \text{for } i \in \{AP, TX\}. \\ 0 \leq P_{t,i} \leq P_{max} \end{array} \quad (12)$$

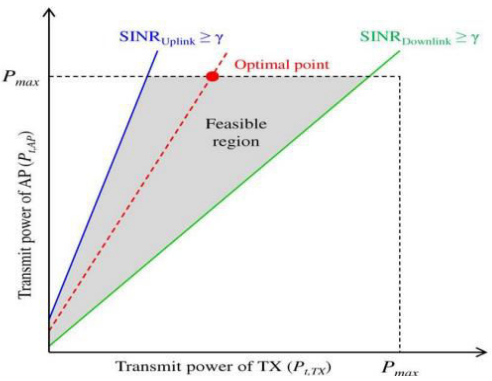

Fig.4. Feasible Region and Optimal Point To Satisfy Conditions (11) and (12) with Respect To the Transmit Powers of the AP and TX.

The optimization problem attempts to maximize the minimum SINR of the uplink and downlink transmissions while satisfying the SINR constraints. To effectively solve this max-min optimization problem, (13) is rewritten as a linear programming problem by introducing a new variable K. Then, the linear programming problem for (13) can be expressed as follows.

$$P^*_{t,i} = \arg\max_{P_{t,i}} \mathcal{K}$$

$$\text{subject to} \quad \begin{array}{l} \text{SINR}_{Uplink} \geq \mathcal{K} \\ \text{SINR}_{\text{Downlink}} \geq \mathcal{K} \\ \mathcal{K} \geq \gamma \\ 0 \leq P_{t,i} \leq P_{max} \end{array}, \text{ for } i \in \{AP, TX\}. \tag{13}$$

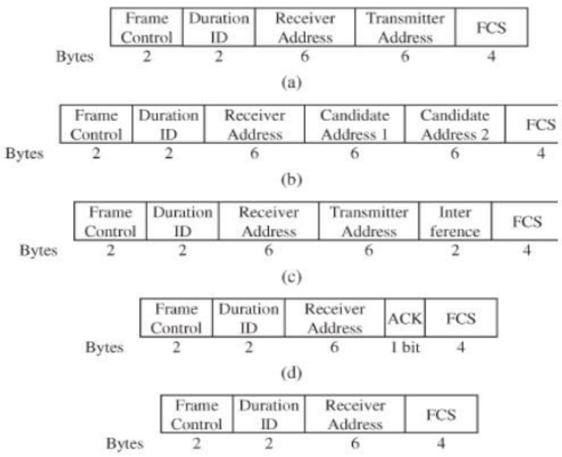

Fig.5. Control Frame Structures. (a) RTS. (b) CTS Uplink (CTS-U). (c) CTS Downlink(CTS-D). (d) ACK Uplink (ACK-U). (e) ACK-Downlink (ACK-D).

To maximize K, which is a quantity dependent on SINR Uplink and SINR Downlink, the optimal solution should make SINR Uplink and SINR Downlink equal to each other. Then, the inequality SINR constraints can be expressed as a function of K as follows:

$$\text{SINR}_{\text{Uplink}} = \frac{|G_{TX,AP}|^2 \cdot P_{t,TX}}{\frac{|G_{AP,AP}|^2}{\alpha} \cdot P_{t,AP} + N_{AP}} = \mathcal{K}$$

$$\text{SINR}_{\text{Downlink}} = \frac{|G_{AP,RX}|^2 \cdot P_{t,AP}}{|G_{TX,RX}|^2 \cdot P_{t,TX} + N_{RX}} = \mathcal{K} \tag{14}$$

$$P_{t,AP} = \frac{\mathcal{K} N_{RX} \left(|G_{TX,AP}|^2 + \mathcal{K}|G_{TX,RX}|^2\right)}{|G_{TX,AP}|^2 |G_{AP,RX}|^2 - \frac{\mathcal{K}^2}{\alpha}|G_{TX,RX}|^2 |G_{AP,AP}|^2},$$

$$P_{t,TX} = \frac{\mathcal{K} N_{AP} \left(|G_{AP,RX}|^2 + \frac{\mathcal{K}}{\alpha}|G_{AP,AP}|^2\right)}{|G_{TX,AP}|^2 |G_{AP,RX}|^2 - \frac{\mathcal{K}^2}{\alpha}|G_{TX,RX}|^2 |G_{AP,AP}|^2}. \tag{15}$$

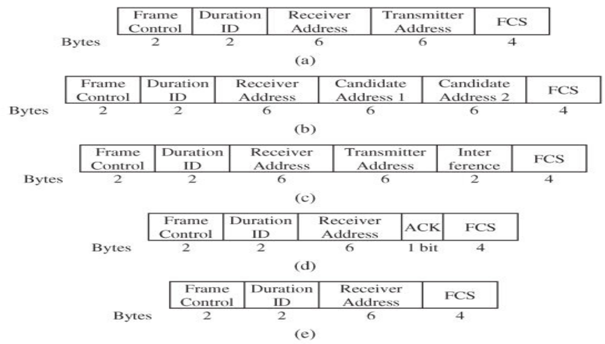

Fig. 5. Control frame structures. (a) RTS. (b) CTS-Uplink (CTS-U). (c) CTS Downlink (CTS-D). (d) ACK-Uplink (ACK-U). (e) ACK-Downlink (ACK-D).

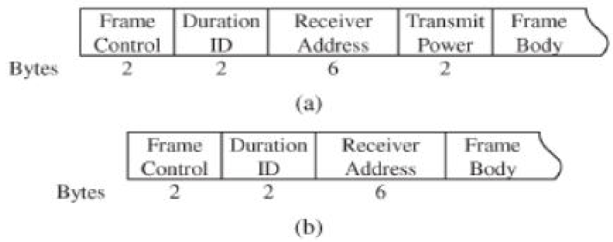

Fig.6. Header of DATA Frame for AP and Client. (a) Header of AP (HA).(b) Header of Client (HC).

C. Description of PoCMAC

We have proposed the RSSB contention scheme for receiver selection and the transmit power adjustment scheme to compute the optimal transmit powers of the AP and TX. In this section, we describe newly designed frame structures and detailed procedures of the TX, RX, and AP for performing both schemes in PoCMAC.

1. Frame Structures

PoCMAC uses five types of control frames and two types of DATA frame headers, as shown in Figs. 5 and 6. The five control frames are RTS, CTS-Uplink(CTS-U), CTSDownlink (CTS-D), ACK-Downlink (ACK-D),and ACKUplink (ACK-U), and the two types of DATA frame headers are the header of the AP (HA) and the header of the client (HC). Among these control frames and DATA frame headers, RTS, ACK-D, and HC

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have the same structures asRTS, ACK, and the DATA frame headers of the IEEE 802.11standard, respectively. The frame structures of CTS-U, CTS-D,ACK-U, and HA are newly designed in this study.

- The CTS-U frame is transmitted by the AP after it receives an RTS frame from a client. This frame gives permission to perform the uplink DATA transmission to the client. In addition, using the CTS-U frame, the AP informs the candidate clients that it wants to transmit the DATA frame.
- The number of RX candidates that can be listed in The CTS-U frame is set to M. The AP can simply Choose M clients to which the first M frames in its transmission queue belong 1. The AP designates multiple candidates forth RX to exploit the diversity of receivers. If only a single client were allowed to be listed as an RX candidate and it happened to be close to the TX, it would not be possible to successfully receive the DATA frame from the AP owing to strong interference from the TX. The CTS-D frame is transmitted by the candidate client that wins the RSSB contention after the AP broadcasts CTS-U frame. The CTS-D frame sent by a candidate client informs the AP and the other RX candidates that it has been selected as the RX that is to receive a DATA frame from the AP. Note that if a client overhears the CTS-U frame, it knows which client has been nominated as the RX. This frame includes the address of the winning candidate and the inter-client interference information, which is the received power of the RTS frame transmitted from the TX. If the RX cannot overhear the RTS frame from the TX and cannot measure the signal strength from the TX, the interference field is filled with zeroes.
- The ACK-U frame is transmitted by the AP after completing the uplink DATA reception from the TX. If the AP successfully receives the uplink DATA frame, it transmits the ACK-U frame with the ACK field set to —1‖; otherwise, it transmits the ACK-U frame with the ACK field set to—0.‖ The AP always transmits the ACK-U frame regardless of the success status of the uplink DATA frame. This is done to inform all the clients that the transmission period has ended.
- The TX can confirm the success of its own uplink DATA transmission via the ACK field in the Accurate transmitted from the AP, and the other clients can detect the completion of the transmission period via the ACKU frame transmitted from the AP.
- The HA frame is the header of the DATA frame transmitted by the AP. Unlike the HC frame of the DATA frame transmitted by the clients, the HA frame has a field that stores information on the transmit power to be used when the TX transmits the DATA frame. When the AP transmits the DATA frame to the RX, the TX can overhear the HA frame of this DATA frame and identify the transmit power calculated by the AP. Then, the TX starts its own uplink DATA transmission to the AP with the instructed transmit power.

2. Proposed PoCMAC

Using the control frames and headers, the AP collects the inter-client interference information from the RX, calculates the transmit powers for itself and theta based on the collected information, and then informs theta of the transmit power for the uplink DATA transmission. Fig. 7 shows an example of the operation of the TX, RX, an dap. During the first transmission period, C1 wins the contention against C3 and C5, and C1 is the TX that transmits to the AP. The AP broadcasts a CTS-U control frame, which is an acknowledgement to C1, and includes the information that it wants to transmit a DATA frame to C2 or C4. From the contention Contention for the receiver selection, which has been described in Section III-B, C4 is determined as the RX, and it then transmits CTS-D frame with the inter-client interference information to the AP. Using the estimated and collected information, the AP calculates the optimal transmit powers for the TX and itself, and then, it starts a downlink DATA transmission that is used to inform the TX of its transmit power. Then, C1 can start an

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uplink DATA transmission with the instructed transmit power. Finally, C4 transmits an ACK-D frame to the AP, and the AP also transmits an ACK-U frame to C1. The next transmission period will start after a distributed inter-frame space (DIFS).The detailed procedures of the TX, RX, and AP under the proposed PoCMAC protocol are described as follows.

3. TX Side

- All clients that want to transmit a DATA frame perform a back-off mechanism.
- The client that wins the contention transmits a RTS frame with an initial transmit power to the AP and waits for a CTS-U frame from the AP. (3-1) If the client that transmitted the RTS frame receives the CTS-U frame, it is confirmed as the TX and waits for the HA of the DATA frame. (3-2) The other clients set a network allocation vector(NAV) until the end of this transmission period, and defer their transmission.
- As soon as the TX receives the HA of the DATA frame from the AP, it starts an uplink DATA transmission with the transmit power specified in the received HA frame.
- After completing the uplink DATA transmission, theta waits for an ACK-U frame from the AP. (6-1) After receiving the ACK-U frame, if the acknowledgement bit of the ACK-U frame is ―1‖, the Tacna verify that the uplink DATA transmission was successful, and then return to the initial state. (6-2) Otherwise, the TX returns to the initial state for retransmission.

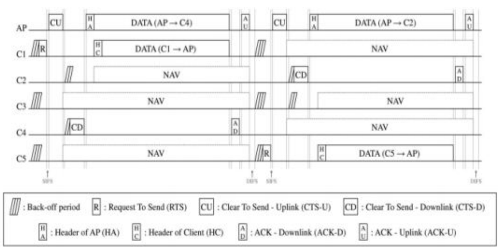

Fig.7. Operation Example of the Full-Duplex AP and Clients. (1st Transmission Period: C1-TX, C4-RX/2nd Transmission Period: C5-TX, C2-RX).

4. RX Side

- All clients that do not want to transmit a DATA frame to the AP, or that lose the contention, continue to overhear the RTS frame transmitted from other clients or wait for a CTS-U frame from the AP.
- After the clients overhear the CTS-U frame from the AP, they can identify the clients that are nominated as the RX candidates. (3-1) If the client is one of the candidates for the RX, it performs the RSSB contention mechanism. (3-2) Otherwise, it sets an NAV until the end of this transmission period, and waits until all the transmissions are completed.
- The client that wins the contention among the candidates transmits a CTS-D frame, including the information on the inter-client interference from theta, and waits for the HA of the DATA frame.
- (5-1) If the client that transmitted the CTS-D frame receives the HA frame of the DATA frame, the client is considered to be the RX and starts the downlink DATA reception.
- (5-2) The other clients set an NAV until the end of this transmission period, and wait until all the transmissions are completed.
- (6-1) If the downlink DATA reception is successful, theRX transmits an ACK-D frame to the AP.
- (6-2) Otherwise, the RX does not transmit the ACKDframe to the AP.
- After overhearing an ACK-U frame from the AP, theRX returns to the initial state.

5. AP Side

- The AP waits for an RTS frame from clients that want to transmit a DATA frame.
- After receiving the RTS frame, the AP selects a client as the TX, transmits a CTS-U frame including the address of the TX and the addresses of the RX candidates to which the AP wants to transmit the DATA frame, and waits for a CTS-D frame.
- After receiving the CTS-D frame, the AP can calculate the optimal transmit powers for the AP andTX; then, it starts the

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transmission of HA, which includes the transmit power obtained for the TX,with the transmit power obtained for itself.

- During the transmission of the HA, the AP start self interference cancellation to receive the DATA frame from the TX and stabilizes interference nulling for the receiving signal.
- After transmitting the HA and stabilizing the interferencenulling, the AP continues the downlink DATA transmission to the RX and starts the uplink DATA reception from the TX.
- After transmitting and receiving the DATA frames simultaneously, the AP aits for an ACK-D frame from the RX.
- (7-1) If the ACK-D frame is received, the AP can determine that the downlink DATA transmission was successful, and then, it transmits an ACK-U frame with _1‘ acknowledgement bit.
- (7-2) Otherwise, the AP determines that the downlink DATA transmission has failed, and then, it transmits the ACK-U frame with _0‘ acknowledgement bit.
- After transmitting the ACK-U frame, the AP returns to the initial state. Note that the AP starts the downlink DATA transmission tothe RX earlier than the uplink DATA transmission from the TX.There are two reasons for this. First, the AP has to notify theta of the optimal transmit power using an HA frame of the downlink DATA frame before the TX starts the uplink DATA transmission to the AP. Second, for effective selfinterference cancellation, the AP needs to nullify the selfinterference caused by the signal that the AP is transmitting.

When the AP starts the downlink DATA transmission, it can accurately estimate the gain of its own self-interference if there are no other signals. With this estimate, it begins the self-interference cancellation, and the self-interference is then cancelled out and stabilized at the noise level. This approach, which makes the A transmit before receiving, can cancel the self-interference more effectively than in the opposite case [16]. When the length of DATA frames for the uplink and downlink transmissions is the same, two transmissions cannot be simultaneously terminated owing to the delayed uplink transmission. Even though the uplink transmission is delayed for the transmission time of theHC frame, the delay is around 2 μs when the data transmission rate is 54 Mbps; because it is shorter than a short inter-frame space (SIFS) time, collisions due to the transmission of the AD frame do not occur.

IV. SIMULATION RESULTS

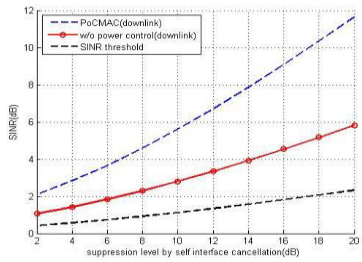

FIG8 SINR of Uplink And Downlink Transmission

The SINR Uplink and SINR Downlink of PoCMAC increase linearly as α increases. Because the SINR threshold is 6 dB, simultaneous uplink and downlink transmissions are possible when α exceeds around 60 dB. However, when α is lower than 60 dB, the AP under PoCMAC cannot sufficiently suppress the self-interference.

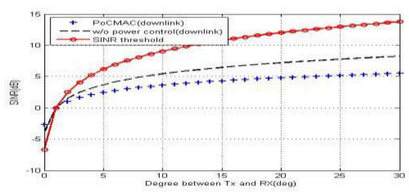

FIG 9 SINR OF Uplink And Downlink Transmission (Contd)

SINR Uplink and SINR Downlink with respect to the distance between the TX and the RX when the suppression level of self-interference cancellation is 70 dB. In the case of full-duplex without power control, SINR Uplink does not change as the distance

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between the TX and the RX increases, because it is not affected by the position of the RX.

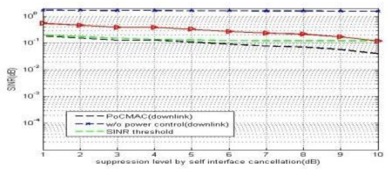

FIG10 Simulation for Average Throughput

The throughput is saturated after α is greater than 65 dB. When α is greater than 65 dB, the throughput performance levels off because the AP already uses its maximum transmit power and the self interference is sufficiently suppressed with the high value of α. PoCMAC without the RSSB contention mechanism shows a lower throughput performance than that with the RSSB contention mechanism.

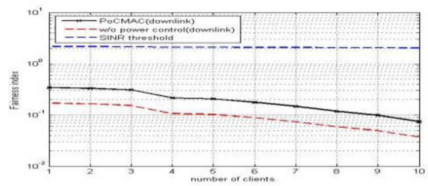

FIG 11 Simulation For Fairness

The throughput fairness with respect to the number of clients when α is 60 dB. As the number of clients increases, the average inter-client interference between clients increases because the distance between clients becomes shorter. PoCMAC achieves a better fairness performance in throughput among clients than the other schemes.

V. CONCLUSION

We proposed a full-duplex MAC protocol to provide greater reception opportunities to clients with low interference and to reduce the interference between uplink and downlink transmissions at the AP. For a given uplink transmission from a client to the AP, a client that can achieve high SINR in spite of the simultaneous uplink transmission may have a greater chance of being selected as the downlink client under the proposed RSSB contention mechanism. To maximize the uplink and downlink SINRs, an optimization problem was formulated; When the RX is located in 30 random positions. (a) Changes of received powers for uplink and downlink transmissions by PoCMAC. (b) CDF of inter client interference. The optimal solution of which determines the transmit power of the AP and the uplink client. We defined control frames and header structures to implement our protocol, PoCMAC. The performance of PoCMAC was evaluated under various simulation configurations with regard to the SINR, throughput, and fairness. In addition, SDR-based experiments with WARP were performed in a real wireless communication environment. The simulation and experiment results confirmed the excellent performance of PoCMAC Full-duplexing will be one of the main candidate technologies for future wireless communication systems to exploit spectrum and this will practically enable applications such as cognitive radios. We believe that the maximum gain due8to full-duplexing can only be achieved through a smart FDMAC protocol that jointly addresses the physical layer and MAC layer aspects. In this paper, we have highlighted the major challenges that need to be considered in designing smart FD-MAC protocols. The possible approaches to solve these challenges have been discussed. Also, the interference management challenges that arise in cellular networks due to the adoption of FD technology have also been discussed.

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