An Energy Efficient MAC
for Wireless Full Duplex Networks

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Abstract—**Full-duplex (FD) wireless communication is a key technology for enhancing the capacity of next-generation wireless networks. Previous studies have investigated FD wireless communication medium access control (MAC) schemes to double the existing network capacity. However, energy consumption and power saving mode (PSM) in wireless FD infrastructure networks have not been discussed extensively. Current implementations of 802.11 wireless infrastructure local area networks (WLANs) support PSM to extend the battery life of energy-limited mobile devices. In this paper, we propose a MAC protocol that supports PSM for wireless FD networks (FDPSM). FDPSM enables PSM for both half-duplex(HD)-capable clients and FD-capable clients in FD WLANs with FD-enabled access points (APs) by supporting not only bidirectional FD communication but also two-directional FD communication. In addition, FDPSM does not require any change in frame designs from the IEEE 802.11 standard. Simulation results show that the proposed method achieves a higher bit per energy than conventional FD communication. Thus, the proposed method facilitates energy-efficient wireless communication. Moreover, the request to send/clear to send (RTS/CTS) mechanism enhances the bit per energy. Specifically, the bit per energy achieved by FDPSM with RTS/CTS (FDPSM+) is approximately 10 times higher than that achieved by FDPSM when the data rate is 54 [Mbps] and the number of clients is 10.**

I. INTRODUCTION

Recent years have witnessed a proliferation of battery-powered mobile devices, e.g., smartphones, tablet devices, sensors, and laptops. Consequently, the demand for mobile traffic has been growing rapidly. Mobile data traffic has been increasing at an average annual rate of 65% and is expected to increase by 100 times over the next decade [1]. Therefore, it is necessary to achieve a high data rate under existing battery capacities and bandwidth limitations.

Current wireless communication schemes assume half-duplex (HD) wireless communication at a single frequency. In HD communications, when one node receives data from another node, it does not transmit data in order to avoid collision. Current HD communication schemes are approaching the Shannon limit of channel capacity. Full-duplex (FD) communication, which involves simultaneous transmission and reception, has the potential to double the throughput compared to that of HD communication. Figures 1 and 2 show examples of FD communication. Recent developments in physical layer technologies have enabled full-duplex wireless communication, which allows nodes to transmit and receive data at the same frequency and at the same time [2]–[5]. In reference [4], 110-dB self-interference cancellation and practical wireless

FD communication have been achieved. However, to fully exploit the potential of FD communication in wireless networks, an effective medium access control (MAC) protocol is required.

This paper focuses on a MAC protocol for wireless FD networks. MAC protocols for FD wireless LANs have been extensively researched in recent years [6]–[12]. Relay FD MAC protocol has been proposed [6], which enables multi-hop relay communication with full-duplex capabilities. In reference [7], a MAC design has been proposed for a wireless LAN with three nodes; one is an FD-capable access point (AP) while the other two are HD-capable user terminals (UTs). In reference [8], power-controlled MAC (PocMAC) has been proposed to avoid and reduce inter-user interference. Further, full-duplex multi-channel MAC (FD-MMAC) has been proposed to mitigate the hidden terminal problem in multi-channel scenarios by using busy tones [9]. In reference [10], an FD-MAC has been proposed for a wireless LAN comprising an FD-capable AP and HD-capable UTs. Carrier Sense Multiple Access/Collision Notification (CSMA/CN) has been proposed in [11], while request to send/full-duplex clear to send (RTS/FCTS) has been proposed in [12]. The RTS/FCTS mechanism supports both bi-directional and two-directional FD communication. Figure 1 shows an example of bi-directional FD communication; AP and client 1 (C1) transmit/receive data to/from each other. Figure 2 shows an example of two-directional FD communication; AP sends data to client 2 (C2), and client 1 (C1) sends data to AP. The above-mentioned studies [6]–[12] have shown that MAC designs are crucial for doubling the throughput in wireless FD LAN. However, these studies have not discussed energy consumption and power saving mode (PSM), which are defined in the 802.11 standard, in wireless FD LAN. PSM is necessary for extending the battery life of battery-powered mobile devices.

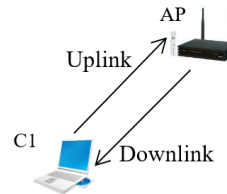In this paper, we propose PSM for wireless FD LANs

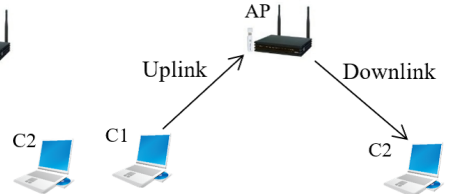Fig. 1. Bidirectional FD communication

Fig. 2. Two-directional FD communication

(FDPSM) that reduces energy consumption while enhancing the energy efficiency of data transmission. In addition, we discuss the energy efficiency of data communication in wireless infrastructure FD LANs. We define the "bit per energy" [bit/J] for measuring energy efficiency. Further, we perform computer simulations, the results of which show that the proposed method achieves higher bit per energy than conventional FD communication. Thus, the proposed method facilitates energy-efficient wireless communication. Moreover, the RTS/CTS mechanism enhances the bit per energy. Specifically, the bit per energy achieved by FDPSM with RTS/CTS (FDPSM+) is approximately 10 times higher than that achieved by FDPSM when the data rate is 54 [Mbps] and the number of clients is 10.

The remainder of this paper is organized as follows. Section II introduces the current PSM in the MAC layer of the IEEE 802.11 standard. Section III describes the bit per energy of wireless FD networks. Section IV presents FDPSM and FDPSM+. Section V discusses the evaluation of the proposed methods. Finally, Section VI concludes the paper.

II. POWER SAVING MODE IN THE IEEE 802.11 STANDARD

In this section, we introduce PSM in the IEEE 802.11 standard. In the MAC layer, the IEEE 802.11standard supports two power modes: active mode (AM) and PSM [13]. Clients can select one of the two modes. For example, when a laptop is plugged into a socket, it operates in AM; however, when it is disconnected from the socket and runs on battery, it switches to PSM. In AM, a client is always active and is ready to transmit/receive data at any time. In contrast to AM, PSM enables clients to be in two different states: "awake" and "sleep." PSM is defined for reducing the power consumption of battery-powered clients. In the awake state, a client turns on its transceiver to be ready for communication, whereas in the sleep state, the client turns off its transceiver and cannot transmit/receive any data over radio frequencies.

An AP keeps its transceiver on to serve its clients. The AP buffers packets to be sent to PSM clients and sends the buffered packets after the beacon notification. In every beacon period, the AP transmits a beacon frame that contains a traffic indication map (TIM). The TIM represents the buffered packets of all PSM clients. In the IEEE 802.11 standard PSM, each client usually stays in the sleep state and wakes up periodically to listen for selected beacon frames with its own fixed wakeup interval.

Figure 3 shows the IEEE 802.11 standard PSM; client 1 is in PSM and client 2 is in AM. In Fig. 3, client 1 wakes up to listen for a beacon frame. Then, the AP sends a beacon frame that contains the TIM to the clients. The TIM indicates that the packet to be sent to client 1 is buffered. After receiving the beacon frame, client 1 replies with the power saving polling frame (PS-Poll). Finally, AP sends data to client 1, and client 1 replies by sending the acknowledgement frame (ACK). Finally, client 1 returns to the sleep state. In contrast to downlink traffic, all clients can transmit uplink data to AP at any time.
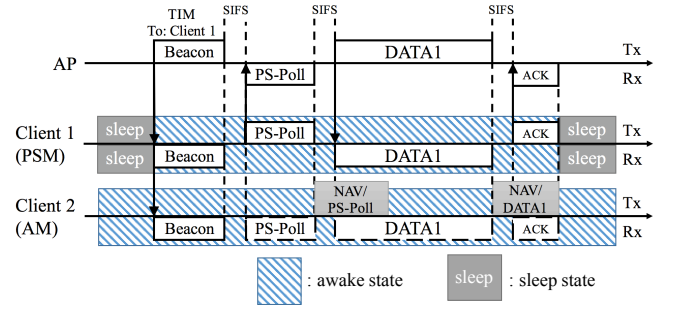

Fig. 3. IEEE 802.11 standard Power Saving Mode (PSM)

III. BIT PER ENERGY OF WIRELESS FD NETWORKS

In this section, we consider an energy model of 802.11 wireless FD networks. In reference [14], an FD energy model was developed on the basis of the 802.15.4 chipset. However, no energy model is available for 802.11-based wireless FD networks. We develop the energy model of FD networks in order to evaluate their energy consumption and energy efficiency.

A. Energy Model of FD-Capable Nodes

There is no readymade FD-capable radio communication system. Therefore, we define an energy model for FD-capable nodes. First, we define 4 types of node states: sleep, transmission, reception, and FD. The sleep, transmission (Tx), and reception (Rx) states are node states of the IEEE 802.11 standard [13]. We add an FD (TxRx) node state to the 802.11 standard. Figure 4 shows a circuit model of an FD-capable node. The FD-capable node consists of a controller (CTRL), transmission circuit (Txc), receive circuit (Rxc), and canceller (cancel). Table I specifies the relation between the node states and the power supply of each circuit.

The energy consumptions of the sleep state (P_{sleep}), Tx state (P_{Tx}), Rx state (P_{Rx}) and TxRx state (P_{TxRx}) are given by

$$
\begin{aligned}
P_{\text{sleep}} &= & P_{\text{CTRLoff}} \ [\text{W}] \\
P_{\text{Tx}} &= & P_{\text{CTRL}} + P_{\text{Txc}} \ [\text{W}] \\
P_{\text{Rx}} &= & P_{\text{CTRL}} + P_{\text{Rxc}} \ [\text{W}] \\
P_{\text{TxRx}} &= P_{\text{CTRL}} + P_{\text{Txc}} + P_{\text{Rxc}} + P_{\text{cancel}} \ [\text{W}]
\end{aligned}
$$

when P_{CTRL}, P_{Txc}, P_{Rxc}, and $P_{\text{canceller}}$ are the energy consumption of the controller (CTRL), transmitter circuit (Txc), receiver circuit (Rxc), and canceller (cancel), respectively. In addition, the controller consumes energy (P_{CTRLoff}) even when it is turned off.

B. Bit per Energy

We propose "bit per energy" as a benchmark unit of energy efficiency of communication. First, we show the average power consumption of wireless FD communication. The average power consumption of the FD-capable node is

$$
P_{avg.} = \frac{\sum_{s \in S} P_s T_s}{\sum_{s \in S} T_s} \ [\text{W}]
$$

TABLE I
RELATION OF NODE STATES AND POWER SUPPLY OF CIRCUITS

Node states	CTRL	Tx circuit	Rx circuit	Canceller
Sleep	OFF	OFF	OFF	OFF
Tx	ON	ON	OFF	OFF
Rx	ON	OFF	ON	OFF
TxRx	ON	ON	ON	ON

Fig. 5. FDPSM: Bidirectional FD case
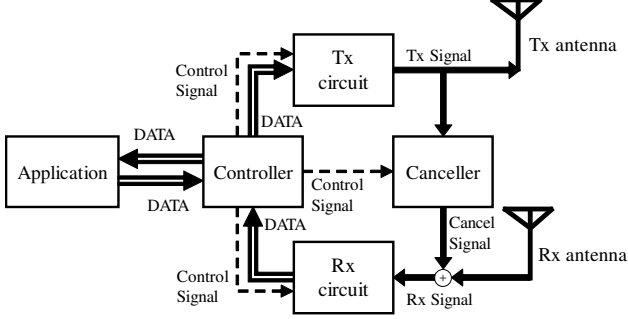
Fig. 4. Full-duplex capable node

Fig. 6. FDPSM: Two-directional FD case

where S is defined as $S = \{\text{sleep, Tx, Rx, TxRx}\}$, and T_s is the duration of each node state. Then, the throughput of the FD capable node is

$$Th = \frac{C(T_{\text{Tx}} + T_{\text{Rx}} + 2 \cdot T_{\text{TxRx}})}{\sum_{s \in S} T_s} \text{[bps]}$$

where C denotes the capacity of the physical layer. In the FD state (TxRx), nodes are able to transmit and receive at the same time. Therefore, the physical layer capacity is doubled.

Finally, we define the bit per energy (BPE), which is benchmark of energy consumption, as

$$\text{BPE} = \frac{Th}{P_{avg.}} \text{[bps/W = bits/J]}.$$

Bit per energy is a benchmark for measuring energy efficiency of transmission. A higher bit per energy indicates higher energy efficiency of wireless communication.

IV. POWER SAVING MODE FOR WIRELESS FD NETWORKS

In this paper, we propose PSM for wireless FD networks (FDPSM). FDPSM reduces the energy consumption of battery-powered mobile devices by adapting PSM to wireless FD networks. FDPSM supports not only bidirectional wireless FD communication but also two-directional wireless FD communication. More specifically, FDPSM requires no change in frame design from the IEEE 802.11 standard.

A. FDPSM

FDPSM allows clients to mostly remain in the sleep state. Clients wake up to listen for beacon frames with a fixed wakeup interval. The difference between PSM of the IEEE 802.11 standard and FDPSM is that clients also buffer uplink packets in the latter. The clients send the buffered uplink packets after receiving a beacon frame through the FD handshake mechanism.
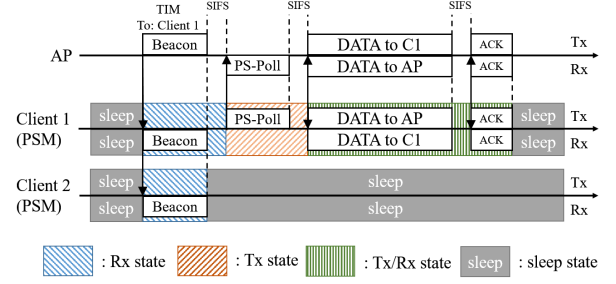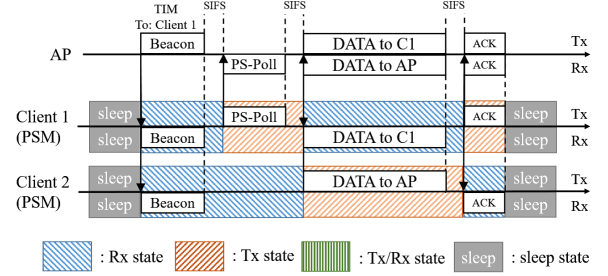
Figure 5 shows the bidirectional FD case in the FDPSM MAC design. In this situation, client 1 has buffered packets but client 2 has no buffered packet before receiving a beacon frame. The TIM contained in the beacon frame informs the clients that there is a buffered frame for client 1. Then, client 2 returns to the sleep state, because it has nothing to do. After replying with the PS-Poll frame, client 1 transmits data to AP and receives data from AP simultaneously.

FDPSM also support two-directional FD communication. In two-directional FD communication, the AP transmits and receives data in different directions. Figure 6 shows two-directional FD communication in FDPSM-capable wireless networks. Client 2 has a buffered packet but client 1 has no buffered packet before receiving a beacon frame. The TIM informs the clients that there is a buffered frame for client 1. Client 1 replies by sending PS-Poll to AP. Then, client 2 sends data to AP; AP transmits data (to client 1) and receives data (from client 2) at the same time. Thus, the clients are not required to have FD capability.

In addition, the frames that are used in FDPSM, namely Beacon, PS-Poll, Data, and ACK, have the same frame design as the frames used in the IEEE 802.11 standard. Clients having no FD capability can also exist in an FDPSM network. Further details about the client operation in FDPSM are presented in **Algorithm 1**. A **while** loop is executed in every beacon interval.

B. FDPSM with RTS/CTS (FDPSM+)

Figure 7 shows the collision problem in FDPSM. In this situation, client 1 and client 2 have a buffered packet before receiving a beacon frame. The TIM informs the clients that there is a buffered frame for client 1. Client 1 replies with PS-Poll to AP. Then, client 1 and client 2 send data to AP and the data frames collide. When data frames collide, additional

Algorithm 1 Client Operation in FDPSM
1: **while** do
2:     Wake up to enter awake state
3:     Receive a Beacon Frame
4:     **if** TIM informs that buffered packets to the client exist **then**
5:         Reply with PS-Poll Frame
6:         **if** Buffered packets to AP exit in the client **then**
7:             Receive a packet from AP and Transmit a packet to AP at the same time
8:             Reply ACK and receive ACK from AP
9:         **else**
10:             Receive a packet from AP
11:             Reply ACK
12:         **end if**
13:     **else**
14:         **if** Buffered packets to AP exist in the client **then**
15:             Wait for the duration of "SIFS + PS-Poll + SIFS"
16:             Transmit the packet to AP
17:             Receive ACK from AP
18:         **end if**
19:     **end if**
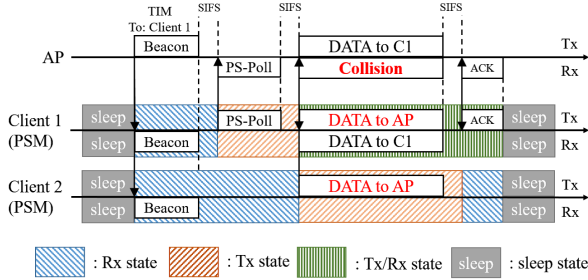20:   Return to sleep state
21: **end while**

Fig. 7. FDPSM: Collision Problem

power is consumed after the collision; this reduces the energy efficiency of data transmission (bit per energy). We propose FDPSM with RTS/CTS (FDPSM+) to overcome the collision problem.

Figures 8 and 9 show the MAC design of FDPSM+; the former shows the bidirectional case, while the latter shows the two-directional case. FDPSM+ overcomes the collision problem by using RTS/CTS. After replying with the PS-Poll frame, clients that want to send data to the AP send the RTS frame to the AP. The AP replies with the CTS frame to the client that wins the RTS contention. Then, that client sends data to the AP.

When RTS frames collide, no client can transmit data to the AP. However, clients can decide to return to the sleep state or enter the Rx state to reduce energy consumption. Figure 10, which shows the RTS collision case in FDPSM+, indicates that FDPSM+ can extend the sleep duration in comparison with FDPSM (Fig. 7). In addition, the frames that are used in FDPSM+, i.e., Beacon, PS-Poll, Data, ACK, RTS, and CTS,
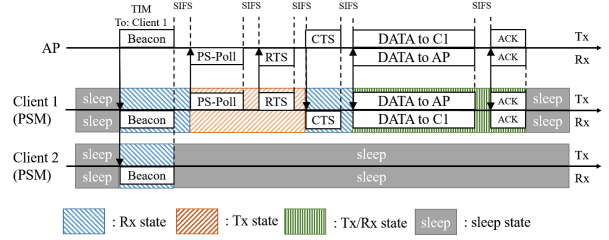

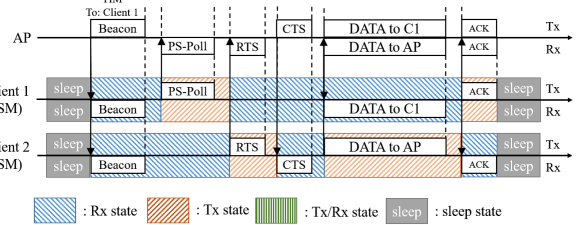Fig. 8. FDPSM+: Bidirectional FD case

Fig. 9. FDPSM+: Two-directional FD case

have the same frame design as the frames used in the IEEE 802.11 standard.

V. PERFORMANCE EVALUATION

We performed computer simulations to confirm the basic performance of FDPSM and FDPSM+.

A. Evaluation Environment

The topology of the evaluation environment comprised one AP and N clients. All the clients were included in the AP service areas, and we assumed that there is no hidden terminal problem. We set the data link layer frame length as in [13]. Table II summarizes the frame lengths: DATA is 1500 [byte]; RTS is 20 [byte]; CTS is 14 [byte]; ACK is 14 [byte]; Beacon is 278 [byte]; PS-Poll is 20 [byte]; SIFS is 16 [μs]. The base rate was 6 [Mbps], and the data rates were 6 and 54 [Mbps].

Further, we set the power consumption of the circuits as defined in Section III.

Table III summarizes the power consumption of each circuit: P_{CTRLoff} is 2.00 [mW]; P_{CTRL} is 4.95×10^1 [mW]; P_{Txc} is 7.76×10^2 [mW]; P_{Rxc} is 4.46×10^2 [mW]. We set the power consumption of each circuit as in [15]. There is no off-the-shelf FD canceller circuit; therefore, we cannot set a static value for the power consumption of the FD canceller circuit. Therefore, the power consumption of the canceller (P_{cancel}) was defined

TABLE II
FRAME LENGTH

Frame	Length
DATA	1500 [byte]
RTS	20 [byte]
CTS	14 [byte]
ACK	14 [byte]
Beacon	278 [byte]
PS-Poll	20 [byte]
SIFS	16 [μs]

TABLE III
ENERGY CONSUMPTION OF CIRCUITS

	Energy Consumption
P_{CTRLoff}	2.00 [mW]
P_{CTRL}	4.95×10^1 [mW]
P_{Txc}	7.76×10^2 [mW]
P_{Rxc}	4.46×10^2 [mW]
P_{cancel}	0 - 100 [mW]
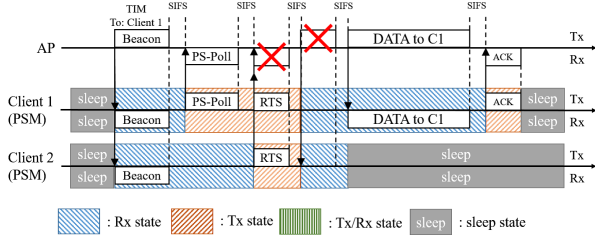
Fig. 10. FDPSM+: RTS collision case

(a) 6 Mbps

(b) 54 Mbps

Fig. 12. Throughput vs. Number of Clients

(a) 6 Mbps

(b) 54 Mbps

Fig. 11. Bit per Energy vs. Number of Clients

(a) 6 Mbps

(b) 54 Mbps

Fig. 13. Bit per Energy vs. Uplink Packet Arrival Rate at Each Client
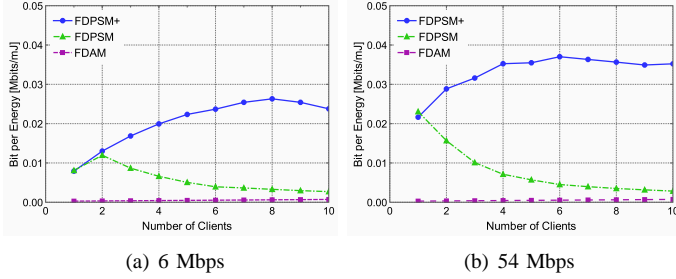
as a variable in the range of 0 - 100 [mW]. There are two types of FD cancellers: passive and active [5]. The former consumes very little energy but achieves low cancellation performance, whereas the latter consumes more energy and achieves higher cancel performance.

We compared the following three approaches to evaluate the performance of FDPSM.

1) FD in Active Mode (FDAM)
   FDAM is a simple FD MAC scheme. When a packet arrives at each node from the data link layer, the nodes will transmit at the same moment. Sometimes, the uplink data traffic involves collisions. FDAM is an energy efficiency benchmark for PSM in wireless FD networks.
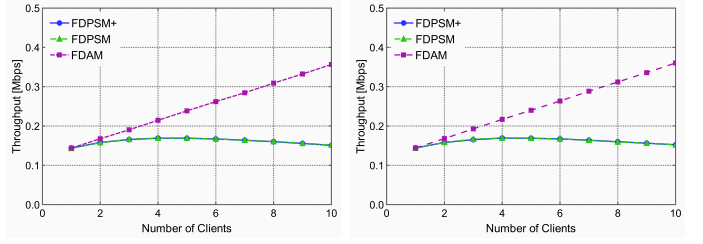
2) FDPSM
   FDPSM is the proposed method that supports PSM in wireless FD networks. The results show the importance of PSM for energy-efficient data transmission in FD WLANs.

3) FDPSM with RTS/CTS (FDPSM+)
   FDPSM+ is an improved version of FDPSM. In contrast to FDPSM, FDPSM+ uses the RTS/CTS mechanism to avoid collisions. The results show the effect of the RTS/CTS scheme.

B. Bit per Energy vs. Number of Clients

First, we evaluated the bit per energy by varying the number of clients (N) in the network in order to show the basic energy efficiency performance of FDPSM. Figure 11 shows the bit per energy when the number of clients varies from 1 to 10. The downlink packet arrival rate is 10 [packets/s], the power consumption of the canceller (P_{cancel}) is 0 [mW], the data rates are 6 and 54 [Mbps], the uplink packet arrival rate from each client is 2 [packets/s], and the beacon interval is 100 [ms]. The horizontal axis represents the number of clients, while the vertical axis represents the bit per energy [Mbits/mJ].

Figure 11 shows that both FDPSM and FDPSM+ achieve higher bit per energy than FDAM. In particular, FDPSM+ achieves the highest bit per energy. On the other hand, when the data rate is 6 [Mbps] and the number of clients is greater than 2, the bit per energy of FDPSM decreases. In addition, when the data rate is 54 [Mbps] and the number of clients is 10, the bit per energy achieved by FDPSM+ is approximately 10 times higher than that achieved by FDPSM. This is because the bit per energy of FDPSM decreases as the number of clients increases when the data rate is 54 [Mbps]. In FDPSM, data frames collide more frequently as the number of clients increases. By contrast, FDPSM+ reduces the power consumption by avoiding data collision through the RTS/CTS mechanism.

C. Throughput vs. Number of Clients

The throughput of the proposed method is possibly low when the packet arrival rate is high, because of the wakeup interval scheme for power saving. Therefore, in order to evaluate the throughput reduction caused by the wakeup interval, we measured the throughput by varying the number of clients from 1 to 10, as shown in Fig. 12. The downlink packet arrival rate is 10 [packets/s], the power consumption of the canceller (P_{cancel}) is 0 [mW], the data rates are 6 and 54 [Mbps], the uplink packet arrival rate from each client is 2 [packets/s], and the beacon interval is 100 [ms]. The parameter vales are the same as those stated in Section V-B. The horizontal axis represents the number of clients, while the vertical axis represents the throughput [Mbps].

Figure 12 shows that FDAM achieves the highest throughput, with a linear increase in the throughput. FDPSM and FDPSM+ cannot achieve high throughput because of their interval-based uplink data transmission mechanism.

D. Bit per Energy vs. Packet Arrival Rate

The bit per energy is expected to decrease as the uplink packet arrival rate increases. Figure 13 shows the bit per energy when the uplink packet arrival rate from each varies from 1 to 10 [packets/s]. The number of clients is 4, the downlink packet arrival rate is 10 [packets/s], the power consumption of the canceller (P_{cancel}) is 0 [mW], the data rates are 6 and 54 [Mbps], and the beacon interval is 100 [ms]. The horizontal axis represents the packet arrival rate, while the vertical axis represents the bit per energy [Mbits/mJ].

Figure 13 shows that FDPSM+ achieves the highest bit per energy. Specifically, the bit per energy achieved by FDPSM+ is approximately 8 times higher than that achieved by FDPSM when the number of clients is 4 and the packet arrival rate is 4 [packets/s]. In FDPSM, the data frames collide more frequently as the packet arrival rate increases. FDPSM+ reduces the power consumption by avoiding data collision through the RTS/CTS mechanism.

E. Bit per Energy vs. Canceller Energy Consumption

In Sections V-B, V-C and V-D, we assumed that the canceller for FD communication does not consume energy. However, the energy consumption of the canceller is expected to be greater than 0 when we use an active canceller. In order to evaluate how the canceller energy consumption affects the energy efficiency, we measured the bit per energy by varying the power consumption of the canceller (P_{cancel}) from 0 to 100 [mW].

The number of clients is 4, the downlink packet arrival rate is 10 [packets/s], the uplink packet arrival rate from each client is 2 [packets/s], the data rates are 6 and 54 [Mbps], and the beacon interval is 100 [ms].

The simulation results show that the energy efficiency of wireless FD communication is virtually unaffected by the energy consumption of the canceller, because the duration of the sleep state (in FDPSM+ and FDPSM) or the duration of the Rx state (in FDAM) is dominant.

The clients power their canceller only for bidirectional FD communication. The percentage of bidirectional FD communication in wireless radio communication was approximately only 2% in this simulation, because in FDPSM and FDPSM+, bidirectional FD communication occurs when only one client sends a data/RTS frame to the AP and the TIM conveys the information that there is a buffered frame for the client that sends data/RTS frame. The low percentage of bidirectional FD communication causes little effect of varying energy consumption of canceller on energy efficiency.

VI. Conclusion

In this paper, we proposed PSM for wireless FD networks (FDPSM). FDPSM increases energy efficiency by allowing clients to mostly remain in the sleep state. In addition, we proposed FDPSM with RTS/CTS (FDPSM+) in order to overcome energy efficiency degradation due to data collision. The performance evaluation results showed that FDPSM and FDPSM+ reduce energy consumption and achieve a high bit per energy, which is a measurement benchmark for energy efficiency. Demonstrations of FDPSM and FDPSM+ are currently underway. Further, FDPSM and FDPSM+ are not able to deal with data fragmentation. Therefore, we are now considering about the methods to overcome data fragmentation.

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