DFDMAC: A Directional Full-duplex MAC Protocol for Millimeter Wave Networks

Shengbo Liu*, Liqun Fu†, Kaige Qu‡, Wen Wu*, Qiang Ye§, and Ning Zhang¶

*Frontier Research Center, Peng Cheng Laboratory, Shenzhen, China

†School of Informatics, Xiamen University, Xiamen, China

‡Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, Canada

§Department of Computer Science, Memorial University of Newfoundland, St.John's, Canada

¶Department of Electrical and Computer Engineering, University of Windsor, Windsor, Canada

Email: {liushb, wuw02}@pcl.ac.cn, liqun@xmu.edu.cn, k2qu@uwaterloo.ca, qiangy@mun.ca, ning.zhang@uwindsor.ca

***Abstract*—Millimeter wave (mmWave) communication has attracted extensive attentions in academia and industry owing to its multi-Gigabit data rate enabled by high available bandwidth at mmWave frequencies. Full-duplex (FD) has the potential to further improve the network performance via enabling simultaneous transmission and reception at the same mmWave band. However, the existing FD medium access control (MAC) protocols developed for the traditional omni-directional transmissions fail to support directional FD transmissions with beamforming in mmWave networks. In this paper, based on IEEE 802.11ad/ay, we present a directional FD MAC (DFDMAC) protocol design, which supports two-node and three-node directional FD mmWave transmissions. Specifically, three-node FD transmission can enable simultaneous uplink and downlink transmissions, or FD relaying transmission to overcome the blockage problem and increase mmWave coverage. Moreover, we design a busy-tone based mechanism to avoid the deafness and directional hidden-node problems in mmWave FD networks, and a power control based solution to improve the link throughput. Simulation results show that the proposed DFDMAC can significantly improve the network performance.**

I. INTRODUCTION

Millimeter wave (mmWave) communication is an attractive technology and capable of providing extremely high data rate to satisfy the increasing demands in wireless networking scenarios [1]–[3], benefiting from its abundant spectrum resource. In recent years, wireless full duplex (FD) communication is another promising technique for next-generation networking, which can enable simultaneous transmission and reception in the same frequency band [4]–[6]. Thus, introducing FD into the mmWave band can further improve the spectrum efficiency and increase the network capacity. The biggest challenge of implementing a mmWave FD system is broadband self-interference (SI), caused by the transmitted signal at the local receiving antenna. Some recent research has successfully overcome the SI problem at the mmWave band with novel designs at the antenna, analog and digital domains [6]–[8]. In order to fully exploit the potential of FD in general mmWave networks, the medium access control (MAC) protocol needs to be carefully redesigned.

Directional transmission based on beamforming technique using large antenna arrays is generally used in mmWave networks to overcome high path loss at mmWave band [1], [9], [10]. Furthermore, directional transmission using a narrow beam reduces the interference coverage, and hence improve the spatial reuse and network throughput, compared with omni-directional transmission used in sub-6 GHz networks. However, directional transmission disables the carrier sensing capability and thus brings some new challenges, such as deafness and directional hidden-node (HN) problems [11], [12]. Specifically, deafness problem occurs when the destinated receiver cannot reply as it is beamformed towards another direction, then the failed transmitter may continue to double its contention window, suffering unfair access and poor throughput. Since directional transmission can be sensed in only the covered direction, HN problem may happen when two nodes initiate transmissions to the same receiver simultaneously without sensing each other. In addition, mmWave signal is also prone to blockage problem, which means that mmWave signal can be easily blocked by physical objects. All these problems have may significantly degrade the performance of mmWave FD networks if not properly handled.

In the past decade, many MAC protocols were proposed to enable directional transmission and combat deafness and HN problems in mmWave networks [12]–[14]. In [13], the authors proposed a directional cooperative protocol to coordinate the uplink channel access among stations, but did not consider directional HN problem. In [14], the authors presented a novel MAC protocol using both directional and circular RTS/CTS packets and two network allocation vectors to overcome deafness, HN problems. In [12], the authors proposed a dual-sensing directional MAC protocol, in which a bust-tone based scheme was designed to solve deafness and HN problems. However, all the protocols fail to support directional FD transmissions. Moreover, FD can enable multiple directional transmission modes, making the MAC design and more challenging.

To enable directional FD transmissions and overcome the aforementioned problems in mmWave networks, we propose a directional FD MAC (DFDMAC) protocol. To our best knowledge, the proposed DFDMAC is the first distributed MAC protocol for mmWave FD networks. Firstly, DFDMAC enables both two-node and three-node directional FD transmissions. If two nodes have packets for each other, two-node FD transmission can be enabled. If a receiver has s packet to transmit to a third node, three-node FD transmission can be enabled. For example, simultaneous uplink and downlink in a wireless local area network (WLAN) can be enabled by the three-node FD transmission. Moreover, three-node FD transmission can also be used to overcome blockage problem via enabling FD relay transmission around an obstacle. Secondly, DFDMAC uses out-of-band omni-directional busy-tone signals to identify each node's transmission, so as to solve deafness and directional HN problems. Thirdly, we formulate optimization problems for the three different FD transmission scenarios to maximize the link throughput using power control. Finally, we carry out extensive simulations and demonstrate that DFDMAC can greatly improve the network performance and solve the deafness and directional HN problems in mmWave FD networks.

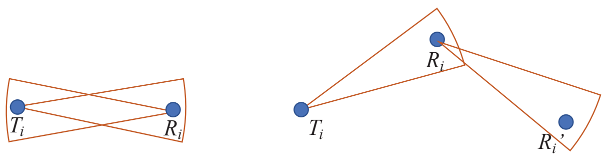
This paper's main contributions are:

- The first MAC protocol design supporting three types of directional FD transmissions in mmWave FD networks;
- A power control based solution that improves the link throughput of different FD transmission scenarios;
- A new busy-tone mechanism that overcomes deafness and directional HN problems in mmWave FD networks.

The rest of this paper is organized as follows. In Section II, we present system model and the optimization problem formulation. Section III provides detailed description on the proposed DFDMAC protocol, and simulation results are presented in Section IV. Finally, we conclude this paper in Section V.

II. SYSTEM MODEL

Consider an FD mmWave network, which consists of a set of FD link pairs $\mathbb{L} = \{l_i, 1 \leq i \leq |\mathbb{L}|\}$. The FD mmWave network can be either an ad hoc network or a wireless local area network (WLAN). With full-duplex capability, a transmitter can receive packets while transmitting to a node in the same mmWave band at the same time. Thus, FD mmWave communication has two kinds of FD transmissions, as shown in Fig. 1:



(a) (b)

Fig. 1. Two directional FD transmission modes: (a) Two-node directional FD transmission; (b) Three-node directional FD transmission.

- Two-node directional FD transmission: As shown in Fig. 1 (a), transmitter T_i wins the channel and initiates a primary directional transmission to receiver R_i, which also has a packet to directionally transmit to T_i, i.e., a secondary transmission. This two-node FD transmission is denoted by $l(T_i, R_i)$;
- Three-node directional FD transmission: Transmitter T_i wins the channel and initiates a primary directional transmission to the primary receiver R_i, which can enable a secondary transmission to a secondary receiver R_i', as shown in Fig. 1 (b). This three-node FD transmission is denoted by $l(T_i, R_i, R_i')$.

A. Antenna Model

We consider a widely used directional antenna model [12]. The antenna of a node has M highly directive and predefined beam sectors that totally cover $360°$ area, where $M = 2\pi/\theta$, and θ denotes the beamwidth in radians. When T_i transmits a signal to R_i using a transmitting beam sector, the transmitting antenna gain at T_i is given by

$$G_{T_i}^{Tx} = g(\phi_t) G_{T_i}^{max} \tag{1}$$

where $G_{T_i}^{max}$ denotes the maximum transmitting antenna gain of T_i [1], and $g(\phi_t)$ is given by

$$g(\phi_t) = \begin{cases} 1, & |\phi_t < \frac{\theta_{T_i}}{2}| \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

where ϕ_t denotes the center line of T_i's transmitting beam to the line pointing from T_i to R_i. Note that $g(\phi_t)$ is used to determine if R_i is located in the coverage of T_i's transmitting beam.

When R_i receives a signal from T_i with a receiving beam sector, the receiving antenna gain at R_i is given by

$$G_{R_i}^{Rx} = g(\phi_r) G_{R_i}^{max}, \tag{3}$$

where $G_{R_i}^{max}$ denotes the maximum receiving antenna gain of R_i, and $g(\phi_r)$ is given by

$$g(\phi_r) = \begin{cases} 1, & |\phi_r < \frac{\theta_{R_i}}{2}| \\ 0, & \text{otherwise} \end{cases} \tag{4}$$

where ϕ_r denotes the center line of R_i's receiving beam to the line pointing from R_i to T_i. We use $g(\phi_r)$ to determine if T_i is located in the coverage of R_i's receiving beam.

B. Transmission Model AND PROBLEM FORMULATION

According to IEEE 802.11ad MAC protocol, a transmitter directionally transmits all kinds of packets, including the RTS, CTS, DATA, and ACK frames. Assume that a transmitter T_i wins the channel and knows which beam to use for transmitting an RTS frame. However, as a potential receiver does not know the direction of a coming packet, it always listens to the channel omni-directionally. After receiving the RTS frame, the receiver chooses a best beam sector to respond to the transmitter with a CTS frame. After exchanging of control packets, i.e., RTS and CTS frames, the directional transmissions of DATA and ACK frames start.

[1]The maximum antenna gain is closely related to number of antenna arrays, angle of arrival and angle of incidence of beams [11], [15]. In this paper, $G_{T_i}^{max} = \frac{2\pi}{\theta_{T_i}}$.

We consider the widely used Friss transmission model for mmWave signal propagation. Specifically, the path-gain from transmitter T_i to receiver R_i is given by

$$G(T_i, R_i) = G_0 d(T_i, R_i)^{-\alpha} e^{-c_o d(T_i, R_i)}. \tag{5}$$

where $d(T_i, R_i)$ is the Euclidean distance between T_i and R_i, and G_0 denotes the reference path loss gain of mmWave signal at the distance of 1 meter, α denotes the path-loss exponent, and c_0 denotes the attenuation factor due to the oxygen absorption loss ($c_0 = 0.0037/m$ in [15]). When T_i transmits to R_i, the received signal strength at R_i is given by

$$P(T_i, R_i) = P_{T_i}^{Tx} G_{T_i}^{Tx} G_{R_i}^{Rx} G(T_i, R_i) \tag{6}$$

where $P_{T_i}^{Tx}$ is the transmit power.

In mmWave networks, a node can successfully decode the received signal only if the signal-to-interference-plus-noise ratio (SINR) is above a given threshold. Note that the SINR conditions of successful transmissions of two-node FD link and three-node FD link in different transmission scenarios are different. Furthermore, three-node FD link pair can enable two types of FD transmissions. Next, we analyze the successful transmission conditions for different FD transmission scenarios.

1) Two-node Directional FD Transmission: A two-node directional FD link $l(T_i, R_i)$ is successful if the following two conditions are satisfied:

$$SINR_{R_i} = \frac{P_{T_i}^{Tx} G_{T_i}^{Tx} G_{R_i}^{Rx} G(T_i, R_i)}{I_{R_i}^{SI} + I_s + n_0} \geq \gamma_{R_i} \tag{7}$$

$$SINR_{T_i} = \frac{P_{R_i}^{Tx} G_{R_i}^{Tx} G_{T_i}^{Rx} G(R_i, T_i)}{I_{T_i}^{SI} + I_s + n_0} \geq \gamma_{T_i} \tag{8}$$

where $P_{R_i}^{Tx}$ is the transmit power, γ_{T_i} and γ_{R_i} denote the SINR thresholds which ensure that T_i and R_i successfully receive the intended DATA frame, $I_{T_i}^{SI}$ and $I_{R_i}^{SI}$ denote the residual SI at T_i and R_i, respectively, I_{SI} denotes the self interference, n_0 is the background noise, and I_s denotes the interference from other links. Let β_{N_i} be the SI cancellation level at N_i. The residual SI at N_i is given by

$$I_{N_i}^{SI} = P_{N_i}^{Tx} \beta_{N_i}. \tag{9}$$

In practical networks, transmission time of T_i's DATA frame can be different from R_i's, caused by different payload sizes, channel conditions, SI cancellation, etc. To maximize the FD link throughput via adjusting the transmit power at T_i and R_i, we formulate the following optimization problem

$$\max_{P_{T_i}^{Tx}, P_{R_i}^{Tx}} \frac{L_{T_i} + L_{R_i}}{\max(\frac{L_{T_i}}{r_{T_i}}, \frac{L_{R_i}}{r_{R_i}})}$$
$$s.t. \begin{cases} r_{T_i} = f(SINR_{R_i}) \\ r_{R_i} = f(SINR_{T_i}) \\ P_{T_i}^{min} \leq P_{T_i}^{Tx} \leq P_{T_i}^{max} \\ P_{R_i}^{min} \leq P_{R_i}^{Tx} \leq P_{R_i}^{max} \end{cases} \tag{10}$$

where L_{T_i} and L_{R_i} denote the payload size in T_i's and R_i's DATA frames, respectively, function $f(SINR)$ is used to derive the highest channel rate that the given SINR can support, $P_{T_i}^{min}$ and $P_{T_i}^{max}$ denote the minimum and maximum transmit power supported by T_i.

2) Three-node Directional FD Transmission: For three-node directional FD link pair $l(T_i, R_i, R_i')$, there are two cases. In case 1, T_i and R_i send different DATA frames to R_i and R_i', respectively. The conditions that guarantee the successful transmission are given by

$$SINR_{R_i} = \frac{P_{T_i}^{Tx} G_{T_i}^{Tx} G_{R_i}^{Rx} G(T_i, R_i)}{I_{R_i}^{SI} + I_s + n_0} \geq \gamma_{R_i} \tag{11}$$

$$SINR_{R_i'} = \frac{P_{R_i}^{Tx} G_{R_i}^{Tx} G_{R_i'}^{Rx} G(R_i, R_i')}{P_{T_i}^{Tx} G_{T_i}^{Tx} G_{R_i'}^{Rx} G(T_i, R_i') + I_s + n_0} \geq \gamma_{R_i'}. \tag{12}$$

Similarly, to improve the link throughput and channel utilization, we formulate the following optimization problem

$$\max_{P_{T_i}^{Tx}, P_{R_i}^{Tx}} \frac{L_{T_i} + L_{R_i}}{\max(\frac{L_{T_i}}{r_{T_i}}, \frac{L_{R_i}}{r_{R_i}})}$$
$$s.t. \begin{cases} r_{T_i} = f(SINR_{R_i}) \\ r_{R_i} = f(SINR_{R_i'}) \\ P_{min}^{Tx} < P_{T_i}^{Tx} < P_{max}^{Tx} \\ P_{min}^{Tx} < P_{R_i}^{Tx} < P_{max}^{Tx} \end{cases}. \tag{13}$$

In case 2, R_i receives a DATA frame from T_i and meanwhile, amplifies and forwards the frame to R_i' without decoding. The condition that guarantees the successful transmission is given by

$$SINR_{R_i'} = \frac{P_{T_i}^{Tx} G_{T_i}^{Tx} G_{R_i}^{Rx} G(T_i, R_i) A_{R_i} G_{R_i}^{Tx} G_{R_i'}^{Rx} G(R_i, R_i')}{A_{R_i}(I_{R_i}^{SI} + I_s + n_0) G_{R_i}^{Tx} G_{R_i'}^{Rx} G(R_i, R_i') + I_s + n_0}$$
$$\geq \gamma_{R_i'} \tag{14}$$

where A_{R_i} denotes the amplifying factor at R_i, given by

$$A_{R_i} = \frac{P_{R_i}^{Tx}}{P_{T_i}^{Tx} G_{T_i}^{Tx} G_{R_i}^{Rx} G(T_i, R_i) + I_{SI} + I_s + n_0}. \tag{15}$$

Similarly, to maximize the throughput of the FD relay link, we formulate the following optimization problem

$$\min_{P_{T_i}^{Tx}, P_{R_i}^{Tx}} (\frac{L_{T_i}}{r_{T_i}})$$
$$s.t. \begin{cases} r_{T_i} = f(SINR_{R_i'}) \\ P_{min}^{Tx} < P_{T_i}^{Tx} < P_{max}^{Tx} \\ P_{min}^{Tx} < P_{R_i}^{Tx} < P_{max}^{Tx} \end{cases}. \tag{16}$$

Since R_i and T_i transmit the same frame, R_i' can deal with T_i's signal as multi-path interference, which can be ignored in wireless OFDM system [16]. But in the first case, T_i's transmission can cause inter-beam interference (IBI) to R_i', which cannot be ignored, because T_i and R_i transmit different frames. Furthermore, from the equation (9) and (12), the transmit power has an crucial impacts on the IBI and the residual SI, which further affects the received SINR. Thus, adjusting the transmit power can effectively improve the link throughput. Considering that the transmit powers in practical communication systems are discrete, such as the integers in the range $[-12, 19]$dBm [17]. Therefore, the optimization problems can be reformulated as integer programming problems, which can be easily solved. To support the mentioned three types of FD transmissions and maximize the link throughput with power control, we propose a new MAC protocol for mmWave FD networks in next section.

III. DIRECTIONAL FULL-DUPLEX MAC PROTOCOL

Based on IEEE 802.11ad/ay, we propose a directional FD MAC (DFDMAC) protocol for mmWave networks. DFDMAC is capable of supporting the mentioned two-node and three-node directional FD transmissions via improved RTS/CTS handshaking and busy-tone scheme. Furthermore, we also provide a solution based on power control to enhance link throughput via adjusting channel rates.

A. Frame Structure

Since IEEE 802.11ad/ay supports only HD directional transmissions using RTS/CTS handshaking, we redesign the structure of RTS and CTS frames to support two-node and three-node directional FD transmission, as shown in Fig. 2. Next, we introduce the new frame structures in details as follows.

RTS:	Frame Control	Duration/ ID	Receiver Address	Transmitter Address	Duplex Mode	Work Mode	MCS Mode	FCS
Bytes	2	2	6	6	1 bits	2 bits	4 bits	4

CTS:	Frame Control	Duration/ ID	Receiver Address	Duplex Mode	Work Mode	MCS Mode	FCS
Bytes	2	2	6	1 bits	2 bits	4 bits	4

Fig. 2. Frame structures for RTS and CTS.

The RTS frame: In the DFDMAC protocol, the RTS frame is a request signal from a transmitter to a receiver. To support the mentioned directional FD transmissions, we add three new fields, i.e., duplex mode, work mode, and MCS mode. The duplex mode field contains 1 bit and indicates if the transmitter supports FD, where 0 represents HD and 1 represents FD. The work mode field contains 2 bits, indicating the following three cases:

- $Work\ Mode = 00$: It means that the RTS frame is sent by a primary transmitter without indicating the transmission mode, which is determined by the primary receiver;
- $Work\ Mode = 01$: It means that the RTS frame is sent by a primary transmitter and used to inform a receiver of three-node FD relay transmission;
- $Work\ Mode = 10$: It means that the RTS frame is sent by a secondary transmitter and used to inform a receiver to work in HD receiving mode.

The MCS mode field contains 4 bits and indicates the physical transmission rate for DATA frame.

The CTS frame: In the DFDMAC protocol, the CTS frame is a response signal from a receiver to a transmitter. For CTS frame, we also add the three new fields. The duplex mode field contains 1 bit and indicates if the transmitter supports FD. The MCS mode field contains 4 bits and indicates the physical transmission rate for DATA frame. The work mode field contains 2 bits, indicating the following four cases:

- $Work\ Mode = 00$: It means that the node transmitting the CTS frame will work in HD mode to receive DATA;
- $Work\ Mode = 01$: It means that the node transmitting the CTS frame will work in two-node FD mode to transmit and receive DATA simultaneously;
- $Work\ Mode = 10$: It means that the node transmitting the CTS frame will work in three-node FD mode to transmit DATA to another node while receiving;
- $Work\ Mode = 11$: It means that the node transmitting the CTS frame will work in FD relaying mode to amplify and forward the received signal.

B. A Busy-Tone-Based Scheme

In the DFDMAC protocol, we design a busy-tone (BT) mechanism to avoid deafness and hidden-node problems in mmWave FD networks. The BT mechanism has the following features:

- The BT signal is a out-of-band sine-wave signal, so it cannot interfere with the reception of RTS, CTS, DATA, ACK frames;
- The duration of BT signal is very short, smaller than one slot.
- Each node has two BT signal, i.e., Start BT and End BT, to indicate the beginning and ending of a transmission;
- The BT signal is transmitted omni-directionally. [2]

In the BT mechanism, each node keeps detecting the BT signal while listening to the mmWave channel omni-directionally as in IEEE 802.11ad/ay. When a node wins the channel, it transmits the start BT signals of both its own and its receiver while starting to transmitting the RTS frame. Once a node overhears its start BT signal, it immediately transmits its start BT signal again as a response. If a node overhears its intended receiver's start BT signal when executing backoff mechanism to contend the channel, the node will freeze its backoff counter and defer its transmission until receiving its receiver's end BT signal. More details about the BT mechanism are introduced in next subsection.

In mmWave networks, traditional omni-directional physical carrier-sensing fails to obtain the channel state due to directional transmission using a beam sector. This causes deafness and HN problems which degrades the network performance. However, the proposed BT mechanism can effectively overcome these problems. In particular, the proposed BT mechanism has the following advantages:

- Avoiding deafness problem. A node N_i's omni-directional BT signal can be received by the neighboring nodes when they fail to receive N_i's directional RTS

[2] IEEE 802.ay supports fast session transfer protocol which make it backward compatible with 2.4GHz or 5GHz WLAN [18]. Thus, a mmWave node can omni-directionally transmit a BT signal with some unused frequencies in unlicensed 2.4GHz or 5GHz, which can cover much large range than directional mmWave transmission with the same power.

or CTS frame, and hence unnecessarily increasing the contention window can be avoided.

- Avoiding directional HN problem. The neighboring nodes that have packets to send will stop to transmit when they cannot receive directional RTS or CTS frame but overhear BT signals from the intended nodes, and hence HN problem can be avoided.

C. Two-node Directional FD Transmission

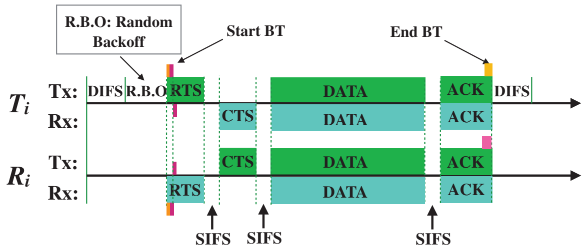


Fig. 3. Two-node directional FD transmission.

Fig. 3 shows a two-node directional FD transmission between node T_i and R_i. The initial transmitter T_i wins the channel with the random backoff mechanism, and then initiates a transmission to R_i. Specifically, T_i omni-directionally transmits its start BT signal and its receiver's start BT signal, while starting to transmit a RTS frame to R_i using a beam sector. R_i transmits its start BT once detecting it. After receiving the RTS frame in omni-directional mode, R_i waits for a SIFS time, and directionally transmits a CTS frame to T_i. If R_i has a packet for T_i and the work mode field in the received RTS frame is 00, the work mode field in the CTS frame is set to 01. After transmitting the RTS frame, T_i waits to receive the CTS frame with its receiving beam pointing to R_i. If the value of work mode in the received CTS frame is 01, R_i also has a packet for T_i. Then T_i waits for a SIFS time and then get prepared to receive the DATA frame from R_i with its receiving beam sector while directionally transmitting its DATA frame to R_i. After receiving the DATA frames, T_i and R_i wait a SIFS time and then directionally transmit ACK frames simultaneously. At the end of transmitting the ACK frames, both T_i and R_i transmit their ending BT signal omni-directionally.

D. Three-node Directional FD Transmission

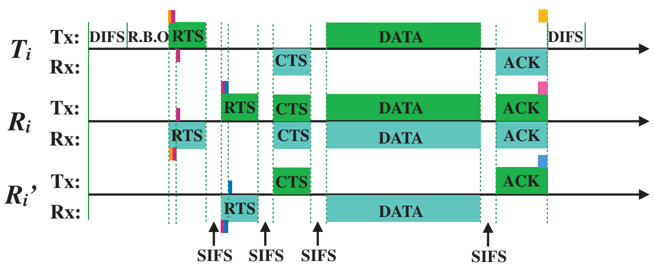


Fig. 4. Three-node directional FD transmission.

Fig. 4 shows a three-node directional FD transmission. Specifically, the primary transmitter T_i wins the channel and transmits a RTS frame to R_i, meanwhile omni-directionally transmitting its start BT signal and its receiver's start BT signal. R_i transmits its start BT once detecting it. After receiving the primary RTS frame, if R_i has a packet for another node R_i' and T_i's transmission does not interfere with the reception of R_i', it waits a SIFS time and directionally transmits its RTS frame with the work mode set to 10 to the secondary receiver R_i'. Meanwhile R_i also transmits its start BT signal and its receiver's start BT signal. R_i' transmits its start BT signal once detecting it. After receiving the secondary RTS frame, R_i' waits a SIFS time and directionally transmits a CTS frame to R_i. At the same time, R_i also directionally transmits its CTS frame to T_i. After directionally receiving the CTS frames, T_i and R_i directionally transmit their DATA frames to R_i and R_i', respectively. After receiving the DATA frames, R_i and R_i' simultaneously transmit ACK frames to T_i and R_i, respectively. At the end of transmitting ACK frames, the three nodes transmit their end BT signals omni-directionally.

E. Directional FD Relay Transmission

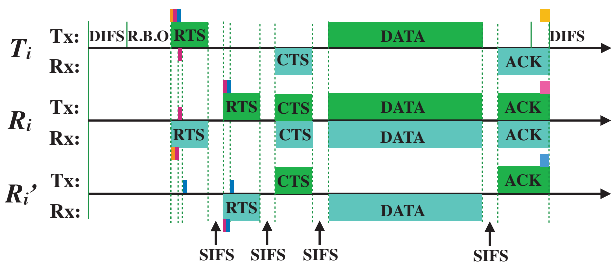


Fig. 5. Directional FD relay transmission.

Fig. 5 shows a three-node directional FD relay transmission. Specifically, T_i wins the channel and transmits a RTS frame to R_i, meanwhile omni-directionally transmitting its start BT signal, its relay's (R_i's) start BT signal and the final receiver's (R_i''s) start BT signal. R_i and R_i' transmit their start BTs once detecting it. After receiving the primary RTS frame, R_i waits a SIFS time and directionally transmits its RTS frame with the work mode set to 10 to the secondary receiver R_i', meanwhile transmitting its start BT signal and its receiver's start BT signal. R_i' transmits its start BT signal once detecting it. After receiving the secondary RTS frame, R_i' waits a SIFS time and directionally transmits a CTS frame to R_i. At the same time, R_i also directionally transmits its CTS frame to T_i. After directionally receiving the CTS frames and waiting a SIFS time, T_i starts to transmit its DATA frame to R_i, which immediately amplifies and forwards the received signal to R_i' directionally. After receiving the DATA frames, R_i' transmits ACK frame to R_i, which immediately amplifies and forwards the received ACK frame to R_i' directionally. At the end of transmitting an ACK frames, the three nodes transmit their end BT signals omni-directionally.

IV. SIMULATION RESULTS

In this section, we carry out simulations with a discrete event simulator developed on MATLAB to evaluate the network performance of our proposed DFDMAC protocol. The default system parameters are listed in Table I.

TABLE I
SIMULATION PARAMETERS

Parameter	Value	Parameter	Value
Control PHY header	40bits	DIFS	13us
SC PHY header	64bits	SIFS	3us
MAC header	320bits	Slot time	5us
Packet payload	8000bytes	CW_{min}	16
Control PHY rate	27.5Mbps	CW_{max}	1024
RTS	352bits	β	-85dB
CTS	304bits	n_0	-90dBm
ACK	304bits	α	2

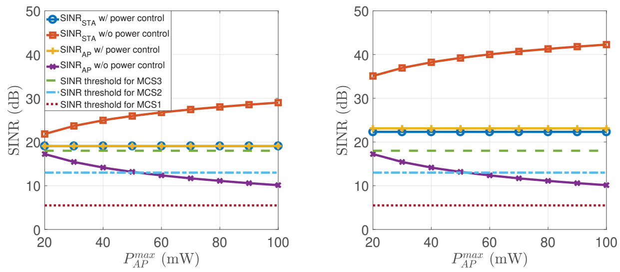
A. Power Control

We consider a three-node FD link enabling simultaneous uplink and downlink transmissions between an AP and two stations. The transmit power at a station that enables uplink to AP varies from 1mW to 20mW with the interval of 1mW. The transmit power at AP that enables downlink to another station varies from 1mW to P_{AP}^{max} ($P_{AP}^{max} \in [20, 100]$mW) with the interval of 1mW. The distance between the AP and each station is 15m. The AP and stations have 32 and 8 beam sectors, respectively. Three MCS rates and the corresponding SINR thresholds are shown in Table II. The SI cancellation level is 85dB. We consider two cases, i.e., the FD link with IBI and without IBI. When power control is not used, the transmitters always choose the maximum transmit power. Assume that uplink and downlink transmit DATA frames with identical payload size, then maximizing the total link throughput becomes maximizing the received SINRs at both the AP and the receiving station.

TABLE II
MCS AND THE CORRESPONDING SINR THRESHOLDS

MCS	MCS 1	MCS 2	MCS 3
Modulation	QPSK	QPSK	16QAM
Code rate	1/2	2/3	2/3
Data rate	952Mbps	1904Mbps	3807Mbps
SINR threshold	5.5dB	13dB	18dB

Fig. 6 shows the received SINR at the AP and the station with respect to P_{AP}^{max}. From the two figures, we can observe that the SINR at the receiving station increases and the SINR at the AP decreases as P_{AP}^{max} increase when power control is not used. This is because the AP always select the maximum transmit power to maximize the received SINR at the station, which leads to the decreasing of the SINR at the AP due to the impact of residual SI. When power control is used to maximize the received SINRs of uplink and downlink, it is observed that both uplink and downlink can choose MCS 2 in Fig. 6(a) and MCS 3 in Fig. 6(b). Without power control, the transmission time of the FD link increases when the uplink only supports lower rate than the one using power control. Therefore, adjusting transmit power is able to effectively reduce the transmission time of an FD link and increase the link throughput.



(a) With IBI (b) Without IBI

Fig. 6. The impacts of power control on SINR of simultaneous uplink and downlink transmission.

B. Network Performance

Consider a mmWave FD network with n nodes, including an AP and $n-1$ stations, which are randomly distributed in a circle area with AP as the center, and transmission range $10m$ as the radius. All the stations always have packets to send to AP, while AP randomly selects a station to transmits a packet after successfully finishing a transmission. All the nodes have 12 beam sectors covering all the directions and assume that each node already has the beam table storing the best beam sector to transmit and receive a packet from another node. MCS 2 shown in Table II is used in the simulations. In this network, we test the following three MAC protocols:

- DFDMAC: our proposed MAC protocol with the BT mechanism;
- 802.11ad w/ BT: IEEE 802.11ad protocol with the BT mechanism;
- 802.11ad w/o BT: IEEE 802.11ad protocol without the BT mechanism.

Fig. 7 shows the network throughput performance with three MAC protocols with respect to the number of nodes. From the figure, we can observe that our proposed DFDMAC can achieve the highest network throughput, 60% higher than the throughput achieved by traditional IEEE 802.11ad. Furthermore, IEEE 802.11ad with the proposed BT mechanism cannot achieve better throughput performance compared with traditional IEEE 802.11ad. It illustrates that HN problem is not serious and the channel utilization is not affected by the deafness problem in half-duplex mmWave networks.

To validate the proposed BT mechanism, which can avoid deafness and directional HN problems, we adopt Jain's fairness index defined in [19] to evaluate the fairness performance in throughput among stations. Jain's fairness index F is given by

$$F = \frac{(\sum_{i=1}^{n-1} S_i)^2}{(n-1)\sum_{i=1}^{n-1} {S_i}^2} \tag{17}$$

where S_i denotes the throughput at the ith station. Fig. 8 shows the throughput fairness with respect to the number of nodes.

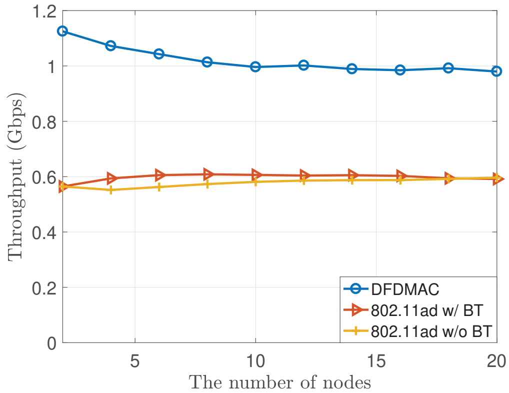


Fig. 7. Comparison of saturation throughput achieved by different MAC protocols.

It is observed that DFDMAC achieves the highest fairness index among all the three MAC in our test. Introducing the proposed BT mechanism, IEEE 802.11ad can improve the fairness index by 32.58%, compared with the traditional one. This further proves that the proposed BT mechanism can effectively improve the fairness performance via overcoming deafness and directional HN problems.

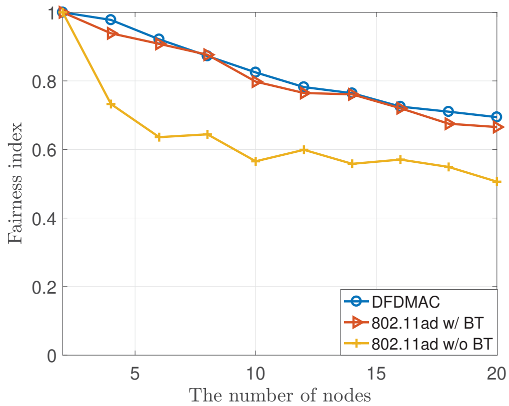


Fig. 8. Comparison of fairness index achieved by different MAC protocols.

V. Conclusion

In this paper, we propose a new MAC protocol named DFDMAC for mmWave FD networks. The DFDMAC protocol can support two-node FD transmission and two types of three-node FD transmissions. To solve the deafness and hidden-node problems in mmWave FD networks, we propose a new bust-tone mechanism to omni-directionally notify the neighboring nodes. Furthermore, we formulate optimization problems for three types of FD transmissions, to maximize the link throughput via adjusting the transmit power. The performance of DFDMAC is evaluated under various simulation configurations with regard to SINR, throughput, and fairness. In future work, we will theoretically analyze the DFDMAC protocol based on Markov chain model, and carry out more simulations to evaluate the performance of DFDMAC protocol.

References

[1] X. Wang, L. Kong, F. Kong, F. Qiu, M. Xia, S. Arnon, and G. Chen, "Millimeter wave communication: A comprehensive survey," *IEEE Communications Surveys Tutorials*, vol. 20, no. 3, pp. 1616–1653, 2018.

[2] T. S. Rappaport, Y. Xing, O. Kanhere, S. Ju, A. Madanayake, S. Mandal, A. Alkhateeb, and G. C. Trichopoulos, "Wireless communications and applications above 100 Ghz: Opportunities and challenges for 6G and beyond," *IEEE Access*, vol. 7, pp. 78 729–78 757, 2019.

[3] X. Shen, J. Gao, W. Wu, M. Li, C. Zhou, and W. Zhuang, "Holistic network virtualization and pervasive network intelligence for 6G," *IEEE Commun. Surveys Tuts.*, vol. 24, no. 1, pp. 1–30, 1st. Quart. 2022.

[4] M. Maso, C.-F. Liu, C.-H. Lee, T. Q. S. Quek, and L. S. Cardoso, "Energy-recycling full-duplex radios for next-generation networks," *IEEE Journal on Selected Areas in Communications*, vol. 33, no. 12, pp. 2948–2962, 2015.

[5] T. Chen, M. B. Dastjerdi, J. Zhou, H. Krishnaswamy, and G. Zussman, "Wideband full-duplex wireless via frequency-domain equalization: Design and experimentation," in *Proc. ACM MOBICOM*, 2019.

[6] V. Singh, S. Mondal, A. Gadre, M. Srivastava, J. Paramesh, and S. Kumar, "Millimeter-wave full duplex radios," in *Proc. ACM MOBICOM*, 2020.

[7] I. P. Roberts, J. G. Andrews, H. B. Jain, and S. Vishwanath, "Millimeter-wave full duplex radios: New challenges and techniques," *IEEE Wireless Communications*, vol. 28, no. 1, pp. 36–43, 2021.

[8] T. Dinc, A. Chakrabarti, and H. Krishnaswamy, "A 60 Ghz CMOS full-duplex transceiver and link with polarization-based antenna and rf cancellation," *IEEE Journal of Solid-State Circuits*, vol. 51, no. 5, pp. 1125–1140, 2016.

[9] W. Wu, N. Cheng, N. Zhang, P. Yang, W. Zhuang, and X. Shen, "Fast mmwave beam alignment via correlated bandit learning," *IEEE Trans. Wireless Commun.*, vol. 18, no. 12, pp. 5894–5908, Dec. 2019.

[10] S. A. Busari, K. M. S. Huq, S. Mumtaz, L. Dai, and J. Rodriguez, "Millimeter-wave massive MIMO communication for future wireless systems: A survey," *IEEE Communications Surveys Tutorials*, vol. 20, no. 2, pp. 836–869, 2018.

[11] C. Pielli, T. Ropitault, N. Golmie, and M. Zorzi, "An analytical model for cbap allocations in IEEE 802.11ad," *IEEE Trans. Communications*, vol. 69, no. 1, pp. 649–663, 2021.

[12] A. A. Abdullah, L. Cai, and F. Gebali, "DSDMAC: Dual sensing directional MAC protocol for ad hoc networks with directional antennas," *IEEE Trans. Veh. Technol.*, vol. 61, no. 3, pp. 1266–1275, 2012.

[13] Q. Chen, J. Tang, D. T. C. Wong, X. Peng, and Y. Zhang, "Directional cooperative MAC protocol design and performance analysis for IEEE 802.11ad WLANs," *IEEE Trans. Veh. Technol.*, vol. 62, no. 6, pp. 2667–2677, 2013.

[14] A. Akhtar and S. Coleri Ergen, "Directional MAC protocol for IEEE 802.11ad based wireless local area networks," *Ad Hoc Networks*, vol. 69, pp. 49–64, 2018.

[15] S. Singh, R. Mudumbai, and U. Madhow, "Interference analysis for highly directional 60-ghz mesh networks: The case for rethinking medium access control," *ton*, vol. 19, no. 5, pp. 1513–1527, 2011.

[16] B. Chen, Y. Qiao, O. Zhang, and K. Srinivasan, "Airexpress: Enabling seamless in-band wireless multi-hop transmission," in *Proc. ACM MOBICOM*, 2015, pp. 566–577.

[17] W. Choi, H. Lim, and A. Sabharwal, "Power-controlled medium access control protocol for full-duplex WiFi networks," *IEEE Trans. Wireless Commun.*, vol. 14, no. 7, pp. 3601–3613, July 2015.

[18] C. Cordeiro, D. Akhmetov, and M. Park, "IEEE 802.11ad: Introduction and performance evaluation of the first multi-Gbps WiFi technology." Association for Computing Machinery, 2010.

[19] R. K. Jain, D.-M. W. Chiu, W. R. Hawe *et al.*, "A quantitative measure of fairness and discrimination," *Eastern Research Laboratory, Digital Equipment Corporation, Hudson, MA*, 1984.