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A Polling-Based Traffic-Aware MAC Protocol for Centralized Full-Duplex Wireless Networks

SONG LIU, BIAO HAN, (Member, IEEE), AND WEI PENG, (Member, IEEE)

National Laboratory for Parallel and Distributed Processing, National University of Defense Technology, Changsha 410000, China

Corresponding authors: Biao Han (nudtbill@nudt.edu.cn) and Wei Peng (wpeng@nudt.edu.cn)

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ABSTRACT Recent advances in self-interference cancellation techniques have enabled in-band full-duplex (IBFD) transmission, which can double ergodic capacity and reduce end-to-end delay. However, how to solve the channel contention problem in IBFD radios with inter-node interference and asymmetric traffic is still a challenge. This paper presents pFD-MAC, a novel polling-based traffic-aware medium access control (MAC) protocol for centralized full-duplex wireless networks. To solve the channel contention problem and fully utilize the channel resources under full-duplex mode, we first design a novel polling-based transmission mechanism and make comprehensive investigations on the effect of polling profile in full-duplex communication. By characterizing the inter-node interference into a directed non-conflict graph, we study the polling profile generation problem in which our objective is to minimize the packet transmission time. The problem is then theoretically formulated and proved to be NP-hard, which means it cannot be solved in polynomial time. Thus, we develop a heuristic traffic-aware algorithm and apply it to work with the packet transmission procedure in parallel. Full-duplex communication opportunities are highly exploited by parallelly organizing per-node upstream/downstream traffic according to the generated polling profile. Moreover, to achieve fairness without sacrificing throughput, deficit round robin algorithm has been applied with respect to the access time considering concurrent transmission time. Simulation results reveal that our proposed protocol can achieve improved performance in terms of throughput and transmission delay while maintaining fairness, compared with two state-of-the-art centralized MAC protocols.

INDEX TERMS Full duplex, MAC protocol, inter-node interference, asymmetric traffic, fairness.

I. INTRODUCTION

Traditional radios operate in half-duplex mode, in which a wireless device can not receive and transmit on the same frequency at the same time because of self-interference (SI). Most current wireless systems rely on orthogonal signaling division techniques, such as time division duplex (TDD) and frequency division duplex (FDD) [1]–[3]. Recent advances in antenna design and self-interference cancellation (SIC) techniques have enabled radios to operate in full-duplex mode on a single channel with very low residual self-interference in the physical layer, called in-band full-duplex (IBFD) transmission [4], [5]. An IBFD system can simultaneously receive and transmit packets on the same frequency band. Ideally, it can improve the spectral efficiency by duplexing ergodic capacity and reduce end-to-end delay accordingly.

Although IBFD transmission is practical at the physical layer [4], [5], issues like channel contention, collision mitigation and fairness need to be well investigated at the MAC layer. Specifically, how to resolve contention problem with inter-node interference and asymmetric traffic in order to improve the full-duplex system performance is still a challenging issue. To this end, many MAC protocols have been proposed. These protocols are either for centralized wireless networks or ad-hoc wireless networks [5]–[9]. In centralized full-duplex wireless networks, mobile terminals connect to the network through access points (APs) or base stations which act as coordinators or central controllers, in which full-duplex communications can be managed and scheduled efficiently with the aid of centralized APs.

With the introduce of IBFD radios, the channel contention problem become more complicated than that in half-duplex mode, especially when inter-node interference and asymmetric traffic are jointly considered. Here, the asymmetric traffic refers to traffic that can be used for asymmetric dual links.

First, inter-node interference would incur more collisions [10]–[12]. As illustrated in Fig.1, considering the

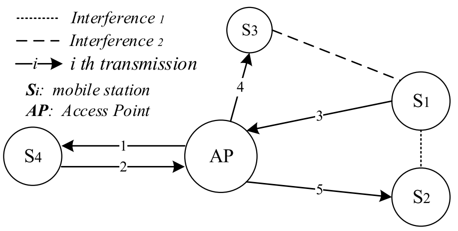

FIGURE 1. Illustrative example for exploiting full-duplex communications in a wireless network with centralized AP and multiple stations.

case that: when S_1 is uploading packets to AP ($S_1 \rightarrow AP$) and AP starts a concurrent downstream transmission to S_2 ($AP \rightarrow S_2$), interference exists between mobile stations S_1 and S_2. If the full-duplex transmission opportunity is exploited, there will be a collision at S_2 since it can overhear the signal from S_1. Nevertheless, if the interference is weak, one can choose a low data rate to transmit packet, as addressed in [8]. For example, if interference from S_1 to S_3 is weak, transmission $AP \rightarrow S_3$ is allowed as S_3 can tolerate the interference from S_1 at a low data rate. Therefore, the inter-node interference affects whether the concurrent transmission can be exploited and what data rate should be selected.

Secondly, as asymmetric traffic is quite common in wireless communications, it is potential to exploit more full-duplex communication opportunities while it has not been fully utilized in most current MAC protocols. In Fig.1, it is possible to schedule either $S_1 \rightarrow AP$ or $S_4 \rightarrow AP$ in parallel with $AP \rightarrow S_2$, $AP \rightarrow S_3$, or $AP \rightarrow S_4$. However, the channel contention issue under asymmetric traffic cannot be resolved effectively in traditional CSMA (Carrier Sense Multiple Access) based MAC protocols. The reasons are as follows: 1) If $AP \rightarrow S_2$ starts first, S_1 and S_4 will not upload packets for they sense the channel is busy. 2) Assume that there is a symmetric dual link between AP and S_4 ($AP \leftrightarrow S_4$). If $S_4 \rightarrow AP$ ends first, $S_1 \rightarrow AP$ can be scheduled. But S_1 will not upload until the symmetric dual link is over since it senses the channel is busy. 3) If $AP \rightarrow S_4$ ends first, S_1 senses the channel is idle and will start uploading, resulting in a collision at AP. Jian *et al.* [13] use a *busy tone* to avoid collisions, but may suffer from lower channel utilization ratio as the *busy tone* contains no data. Thus, how to schedule transmissions based on asymmetric traffic to fully exploit the potential of full-duplex communication remains a challenge.

In addition, the fairness among nodes in a network should be addressed [14]. Fairness issue is a classical problem in traditional wireless network, mainly caused by the CSMA mechanism. Again, this issue will be aggravated in full-duplex communication because the inter-node interference is more serious and scheduling patterns are more complex than in half-duplex mode. As shown in Fig.1, if S_1 intends to upload packet, it only needs to contend in five transmissions ($AP \rightarrow S_{2,3,4}$ and $S_{1,4} \rightarrow AP$) in half mode. And it is unfair to S_1 because it suffers more interference. However, S_1 will get less access opportunity and access time since there are less concurrent transmission opportunities for S_1 in full duplex communications [15]. For example, except for transmitting alone like in half-duplex mode, S_4 can concurrently transmit packets with $S_{1,2,3}$ while S_1 can only start a concurrent transmission with S_4. As a result, S_4 can obtain more transmission opportunities and S_1 get fewer transmission opportunities, leading to a deterioration of the fairness. More details will be discussed in Section IV.

To resolve the above issues, we propose a novel polling-based traffic-aware MAC protocol for centralized full-duplex wireless networks, named pFD-MAC. In order to solve the channel contention problem, we design a polling-based transmission scheduling mechanism incorporated with pipelined packet transmission for centralized APs. To solve the inter-node interference problem, after characterizing the inter-node interference into a directed non-conflict graph, we study the polling profile generation problem in which our objective is to minimize the packet transmission time. Specifically, the formulated problem can be transformed to the conventional traveling salesman problem (TSP) with dynamic cost, which is proved to be NP-hard. Thus, we develop a heuristic traffic-aware algorithm to solve the problem and apply it to work with the packet transmission procedure in parallel. pFD-MAC highly exploits full-duplex opportunities by effectively organizing per-node upstream/downstream traffic in parallel according to the generated polling profile. Moreover, to solve the fairness issue, pFD-MAC refines the fairness metric in full-duplex communication and adopts deficit round-robin (DRR) algorithm, which can achieve high level fairness and maintain good network performance. Through extensive simulation, we validate that our proposed pFD-MAC protocol can improve throughput by 39% and 69% and reduce the average packet delay by 48% and 33%, comparing with Janus [8] and IEEE 802.11 PCF (Point Coordination Function) [16], respectively.

The main contributions can be summarized as follows:

- We explore the channel contention problem with inter-node interference and asymmetric traffic for centralized full-duplex wireless networks. To the best of our knowledge, pFD-MAC is the first full-duplex MAC protocol that highly utilizes the parallelism between transmission scheduling and packet transmission bridged by our proposed polling-based mechanism.
- We first design a novel polling-based transmission scheduling mechanism to solve the channel contention problem, and make comprehensive investigations on the effect of polling profile in full-duplex communication.
- We study the polling profile generation problem by characterizing inter-node interference into a directed non-conflict graph, which is then theoretically formulated and proved to be NP-hard. We develop a heuristic algorithm to solve the problem and apply it to work with the packet transmission procedure efficiently.
- We first consider the concurrency transmission in fairness metrics to encourage full-duplex opportunities, thereby maintaining a high-level fairness while achieving good network performance.

The rest of the paper is organized as follows. Section II introduces the system model and problem description. Section III describes our proposed pFD-MAC protocol. The polling profile generation problem is studied and a heuristic algorithm is proposed in Section IV. Experiment results are presented in Section V and the paper is concluded finally in Section VI.

II. SYSTEM MODEL AND PROBLEM DESCRIPTION

A. SYSTEM MODEL

1) NETWORK AND TRANSMISSION MODEL

In this paper, we consider an AP-based wireless network in which the AP is deployed at the center and stations are randomly distributed in a fixed area. Both AP and mobile stations in the network are equipped with omni-directional antennas and are capable of IBFD transmissions. Considering that a full-duplex link can achieve around 1.84 capacity gain compared with a half-duplex link [10], we assume perfect self-interference cancellation technique is achieved at PHY-layer. And this paper focuses on the network-level capacity.

To exploit full-duplex communication opportunities, there are two transmission modes in a full-duplex wireless network: *symmetric transmission* and *asymmetric transmission*. For instance, as shown in Fig.1, when AP and S_4 transmit packets to each other simultaneously ($S_4 \leftrightarrow AP$), we call this transmission mode *symmetric transmission*. When AP transmits a packet to S_3 and receives from another station S_1 ($S_1 \rightarrow AP \rightarrow S_3$), we call this transmission mode *asymmetric transmission*. In this paper, we consider both symmetric and asymmetric transmissions.

2) PROPAGATION AND INTERFERENCE MODEL

The propagation model is assumed with deterministic power attenuation and Rayleigh fading is used in this paper. Assume that P_t is the transmit power and the distance from a transmitter to a receiver is d, then the received signal strength P_r is:

$$P_r = \kappa P_t h d^{-n} \tag{1}$$

where κ is the propagation constant and h is the channel coefficient, and both of them are assumed with the fixed value. n is the path loss exponent, and we set $n = 4$ for Rayleigh fading in this paper.

Multi-rate transmission is supported and a mobile station can adjust its transmission rate to adapt the communication environment. That is, if the interference is strong, it will select a lower data rate. Otherwise, a higher data rate will be selected. In this paper, we define different interference levels according to the SIR (Signal-to-Interference Ratio) values. And different transmission rates can be selected according to the constructed SIR map. The details of SIR map will be introduced in Section IV.

B. PROBLEM DESCRIPTION

Traditional CSMA-based MAC protocols [16]–[19] have been widely deployed in wireless LANs (WLAN), and many efforts have been done to extend them for full-duplex wireless networks [5], [8], [11]–[13], [20]–[23]. However, CSMA will reduce the chance of full-duplex transmission and the capacity gain [24], [25]. PCF is another half-duplex MAC technique in IEEE 802.11 WLAN standards, which exploits polling mechanism to provide real-time communication service. However, it can not be applied to full-duplex communications directly as issues like inter-node interference and asymmetric traffic are not considered. As illustrated in Fig.2(a), consider the transmission procedure for Fig.1, S_1 and S_3 cannot initiate concurrent transmission as there is inter-node interference between them. Actually, if a low data rate is selected, concurrent transmission can be scheduled for S_1 and S_3. But PCF did not utilize this full-duplex transmission opportunity. Kim *et al.* [8] provides a centralized MAC protocol called Janus, in which information is collected at first and a communication plan is then calculated and packets are transmitted according to the plan, as shown in Fig.2(b). By this way, network throughput can be improved. However, this approach introduced heavy delays as an explicit stage is required to collect information and schedule the transmissions. Therefore, it needs to schedule more packets to reduce per-packet overhead, but this will bring more delay. Here, an important but challenging question is raised: *Can high network throughput and low delay be achieved in IBFD systems at the same time?*

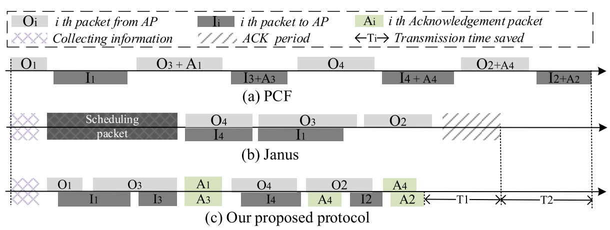

FIGURE 2. Transmission procedure of IEEE 802.11 PCF, Janus, and our proposed pFD-MAC.

In order to achieve this goal, three problems need to be addressed: 1) A novel packet transmission mechanism should be developed which is independent of scheduling process and can maximize the channel utilization, because traditional transmission mechanisms like CSMA/CA or PCF are not suitable for IBFD systems. 2) The centralized AP should be aware of the inter-node interference and traffic information, which need to be collected before the packet transmission procedure. 3) The packet scheduling process should work with the packet transmission procedure in a parallel manner, so that the overhead of scheduling can be eliminated.

In this paper, we consider a polling-based transmission scheme, which is similar to the process of PCF, but optimized for IBFD transmission. Specifically, according to a generated polling profile, an AP can receive packets from a mobile station and transmit packets to another mobile station simultaneously. Thus, it works in a pipeline-like way to accelerate the transmission process. Secondly, unlike Janus in which the traffic information is collected by sending *probe* packets, we attach the traffic information with data packets to be uploaded to APs. Considering that the uplink channel and downlink channel are entangled in full-duplex transmissions, stations in the network cannot distinguish the interference signal from their neighbors. Besides, since stations do not move very frequently in most cases, the interference information will not change for a certain period of time, such as 100*ms*. Thus, interference information can be collected periodically. Thirdly, since the AP transmits packets according to the polling profile, we can schedule packet transmissions by acting on the polling profile. In this way, the scheduling process and the packet transmission procedure can be decoupled and operated in parallel. The key idea of our proposed protocol is shown in Fig.2(c).

III. THE PROPOSED PFD-MAC PROTOCOL

In our proposed pFD-MAC protocol, contention period (CP) and contention-free period (CFP) alternate, as shown in Fig.3. In CP, network management is carried out. In CFP, packets will be transmitted in a pipelined way. The AP polls stations in the network according to a polling profile. The traffic information will be uploaded to AP during packet transmission and the polling profile will be updated by polling-based scheduling process. The scheduling process and packet transmission process work in parallel.

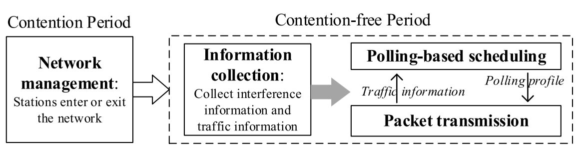

FIGURE 3. The workflow of pFD-MAC.

A. INFORMATION COLLECTION

In order to solve the inter-node interference problem and maximize the network throughput, the centralized AP needs to collect some necessary information from the network. The information includes inter-node interference information and traffic information.

1) INTER-NODE INTERFERENCE INFORMATION

pFD-MAC uses SIR to quantify the level of inter-node interference like in [8] and [20]. To calculate the SIR value, we need signal strength from the AP and the interference strength from its neighbors. The AP collects inter-node interference information as shown in Fig.4. It first starts broadcasting a *Probe* packet, in which the reply sequence for each station is specified similar with [8]. All stations keep listening and sense the signal strength from the AP. When stations receive this *Probe* packet, they will return the *CF-A* packet one by one. At this time, when a station is uploading the *CF-A* packet, its neighbors can sense the interference level from this station, so they can calculate the SIR value for this station. Here, we use the Received Signal Strength Indicator (RSSI) in the MAC layer to represent the signal/interference strength. Then the SIR value c_{ij} at station j with interference from station i can be calculated by:

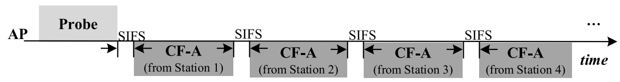

FIGURE 4. Information collection procedure in the contention-free period.

$$c_{ij} = P_r^{ap}(i)/P_r^i(j) \tag{2}$$

where $P_r^{ap}(i)$ is the signal strength at station i from the AP and $P_r^i(j)$ is the interference signal strength at station i from station j. Note that, if the interference strength of station i is weak enough, station j may fail to detect the signal so that there is no SIR record about i at station j. The AP will regard that there is no interference from uploading station i while downloading packets to station j. These SIR records will be included in the *CF-A* packet and uploaded to the AP, as shown in Fig.5(c).

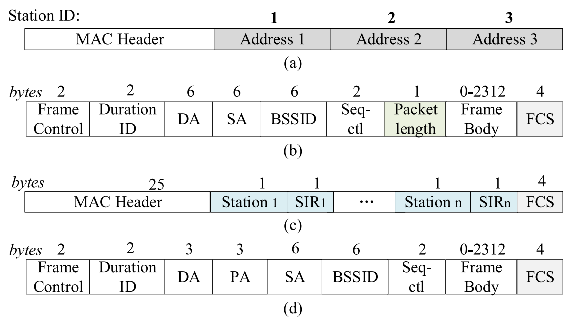

FIGURE 5. Key frame structures used in pFD-MAC.

Here, we use a frame to upload the interference information to AP, as shown in Fig.5(c). The station ID is broadcasted by the AP in the contention period. We use one byte to represent the SIR value, as Tang *et al.* have done in [20]. The first bit is used to indicate the sign of SIR and the last 7 bits give an absolute SIR value. Thus, the SIR value ranges from $-64dB$ to $64dB$, which is enough for a practical wireless system. Besides, someone may say that why don't you use the AID (association ID) in IEEE 802.11 standard to represent a station. I think it's also a solution to label a station. However, AID shares with the *Duration* field in the frame as it's useless in PCF while this field is useful in pFD-MAC.

2) TRAFFIC INFORMATION

Generally, packets to be transferred will be stored in the sending buffer. Therefore, we can read the traffic information to be transmitted from the sending buffer. Information to be downloaded can be read from the AP directly. Packets to be uploaded in the next polling round need to be collected in the packet transmission procedure. And this information will be attached with the uploading packet. Since the traffic information is sent from mobile stations to AP, we make a slight change to the *Data* frame in the IEEE 802.11 standard. And this kind of frame is only used in the packet from stations

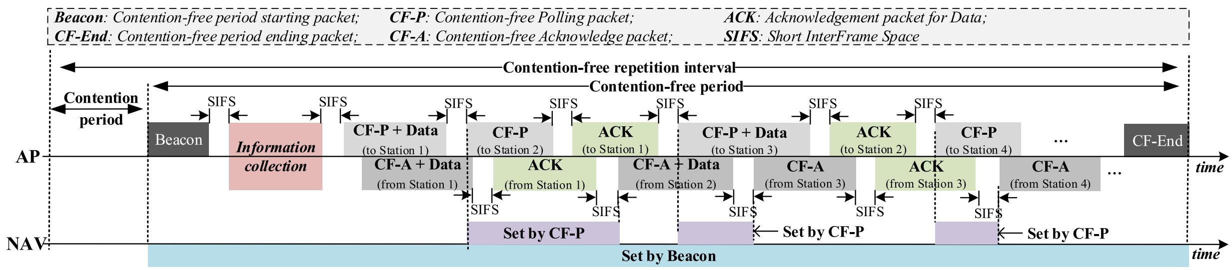

FIGURE 6. The schematic diagram of packet transmission procedure in our proposed pFD-MAC.

to AP. As shown in Fig.5(b), one byte is added in the MAC header, representing the packet length to be uploaded in the next polling round. Since a byte can only represent a range of 0-255, this value is not exactly the packet length. For example, if the value of the byte is 200, it indicates the packet length is $200 * 4 = 800$ bytes. For the AP, it needs to parse this traffic information in its protocol stack and it needs one byte to reserve the traffic information in its memory. However, the additional cost for the AP to reserve the traffic information is negligible relative to the entire protocol stack.

B. POLLING-BASED SCHEDULING

The polling-based scheduling process is responsible for generating a polling profile used in packet transmission procedure. Unlike some contention resolution schemes like CSMA/CA, the media accessing order is determined in advance by the polling profile in pFD-MAC. Thus, the scheduling process is the key to solve problems introduced by inter-node interference and asymmetric traffic. In addition, other optimizing objectives can be considered when generating the polling profile, such as fairness and quality-of-service (QoS), etc. The details of the polling-based scheduling procedure will be described in Section IV.

C. PACKET TRANSMISSION

In an AP-based network, traffic can be upstream traffic and downstream traffic. Upstream traffic is the traffic from stations to the AP and the downstream traffic is the traffic in the reverse direction. Fig.6 shows the transmission procedure of pFD-MAC, in which packets above the time axis belong to downstream traffic and packets below the time axis are upstream traffic.

1) OPERATIONS IN CONTENTION PERIOD

The CSMA mechanism is mainly used to fulfill network management in our protocol. For example, if there are mobile stations that enter or exit the network, the AP will broadcast a packet to number the stations registered in the AP as shown in Fig.5(a). When mobile stations in the network receive this packet, they will number stations according to the order they appear in the packet, i.e., Address 1 indicates station number is 1 and so on. Actually, data transmission can also be carried out in CP. Especially, when there is only a few data to be transmitted or only a few stations in the network, CSMA mechanism may be a better way since the idle stations will not be polled. And we can also develop a hybrid scheme in which data transmission switching in CP and CFP according to the traffic in future work. In this way, the CFP can be thought as a period to provide real-time service. In this paper, we mainly focus on the design of CFP.

2) OPERATIONS IN CONTENTION-FREE PERIOD

The CFP starts with a frame called *Beacon* and ends with a frame called *CF-End*. The duration time of CFP, denoted by T_{CFP}, is specified in frame *Beacon* and stations cannot upload packets until they are polled by AP during this time. The AP polls each station according to the polling profile. When all nodes in the polling profile have been visited, we say an *access round* is over and the polling profile will be updated. Once the network enters into CFP, the AP will collect the interference information and the traffic information for the first *access round*. And with these information, we can determine the polling profile and the packet transmission procedure can be started.

3) POLLING PROCEDURE

First, the AP starts a transmission using a polling packet, denoted by *CF-P*. If it has data to the station, the packet will be *CF-P + Data*. The frame structure for CF-P is shown in Fig.5(d), in which *PA* denotes the polling address and *DA* is the destination address (the address for *Data* part). Here, we use the 3 *bytes* (PA/DA address) to represent the 1 *bytes* station ID to reuse the frame structure in IEEE 802.11 standard, and we set the *subtype* in *FrameControl* to 0100. The address is a station ID numbered by Fig.5(a). Stations in the network keep listening and check whether current polling node is itself. If it is, the station will return a contention-free acknowledge packet, denoted by *CF-A*, after a duration time indicated in the *CF-P* packet. And if this station has data to be uploaded, the packet will be *CF-A + Data*. Otherwise, if a station is not the current polling node, it keeps listening.

Then, when the upload packet arrives at the AP, the AP can obtain the duration time of the packet by parsing the packet header, denoted by T_{CF-A} and the AP can start polling the next node even if current polling node's receiving process is not over. Moreover, if downloading packet is a *CF-P* + *Data* packet, the polled station should return an acknowledgment (ACK) after packet *CF-A* is transmitted. If the upload packet has a *Data* frame to be confirmed, the AP will also return an ACK when the receiving process of current polling node is over. In addition, if the next polling node conflicts with the current one, we cannot poll the next node until the receiving process of current polling node is over. Note that, there is two kinds of ACK packets, ACK from the AP to stations and ACK from stations to the AP. The ACK packet from AP to stations can be easily controlled at AP. But for the ACK packet from stations to AP, we expect stations return an ACK as soon as the transmission of *CF-A* packet is over. If there is no ACK at expected time, AP will consider that the data packet to the station has failed and retransmit in the next access round.

4) CALCULATION OF T_γ

The duration time in the *CF-P* packet, denoted by T_γ, means uplink channel reservation time instead of the duration time of the packet *CF-P* itself. The uplink channel should be reserved for T_γ time to avoid a collision, and the next polling node should be notified of the reservation time. For example, when the AP polls S_2, it should tell S_2 the duration time of uplink channel used by S_1. Therefore, AP cannot poll the next node until it obtains the duration time of the current uploading packet.

Let T_R be the time consumed from the beginning of the current uploading packet and V_t be the current data rate. And the packet length of ACK is denoted by L_{ACK}. Packets from different stations should be separated with the time of Short Interframe Space (T_{SIFS}). If there is no data packet to be confirmed at the station, T_γ can be calculated as:

$$T_\gamma = T_{CF-A} - T_R + T_{SIFS} \tag{3}$$

If there is data packet to be confirmed at the station:

$$T_\gamma = T_{CF-A} - T_R + 2T_{SIFS} + L_{ACK}/V_t \tag{4}$$

IV. POLLING PROFILE GENERATION

Since pFD-MAC transmits packets according to a polling profile, all the scheduling strategies should be reflected in the polling profile. In turn, we can optimize the polling profile to achieve our scheduling purposes, such as channel utilization maximization, fairness, and so on.

Fig.7 shows the scheduling procedure of pFD-MAC. Firstly, an *SIR map* is constructed using the interference information, which is collected at the beginning of CFP. And a *non-conflict graph* is then generated based on the SIR map and deficit round robin (DRR) policy [26]. The problem to calculate a polling profile with the minimum transmission time in a given non-conflict graph is transformed into an optimization problem, which is proved to be NP-hard. For the scheduling process to work with the packet transmission in a parallel way, we need the scheduling algorithm to be very fast. Therefore, a heuristic traffic-aware algorithm has been

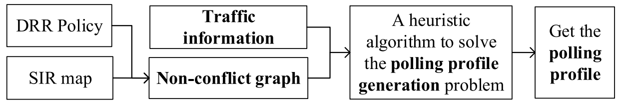

FIGURE 7. Full-duplex polling-based scheduling procedure.

developed in pFD-MAC protocol. Finally, a polling profile is generated for AP to poll and transmit data packet.

A. FAIRNESS SCHEDULING

In order to solve the fairness issue and improve throughput, two basic questions should be considered: 1) what is the metric of fairness? 2) what mechanisms can be used to achieve fairness based on the metric?

First, the fairness in MAC protocol can be understood and defined in many ways, among which the channel access time is widely used for as the fairness metric. However, the channel access time in full-duplex mode is different with that in half-duplex mode. In half-duplex mode, the wireless channel is shared by each station and a station will exclusively obtain the channel. In full-duplex mode, the wireless channel is still shared by each station but two stations can share the channel to transmit packets at the same time.

However, recently studies [11], [15] have not considered the characteristics of the channel access time in full-duplex communication, but simply thought the packet transmission time as the channel access time, result in discouraging full-duplex opportunities and reducing the throughput improvement. For example, there are two transmissions in the network, $S_4 \rightarrow AP \rightarrow S_3$ and $S_1 \rightarrow AP \rightarrow S_2$, as shown in Fig.1. If the packets length are the same, $S_4 \rightarrow AP \rightarrow S_3$ only consumes half transmission time of $S_1 \rightarrow AP \rightarrow S_2$. But recent studies think that they have consumed the same channel access time. Therefore, the half-duplex transmission, such as $S_1 \rightarrow AP \rightarrow S_2$, will in fact obtain more channel access time than full-duplex transmissions.

In this paper, we distinguish the concurrent transmission and exclusive transmission in calculating the channel access time, which we think is more reasonable in full-duplex communications. Let α be the proportion of exclusive transmission time and L_j can be D_j or U_j, the channel access time consumed by station j can be calculated as:

$$t_c(j) = \frac{L_j}{V_t} \cdot \alpha + \frac{L_j}{V_t} \cdot \frac{1}{2} \cdot (1-\alpha) = \frac{L_j}{2V_t}(1+\alpha) \tag{5}$$

Second, DRR is a widely scheduling algorithm with low complexity and it can be realized in a centralized or distributed way. Singh et al. [11] try to alleviate fairness problem by penalizing the access opportunity based on the access history in a distributed way, resulting in lower throughput. Kim *et al.* [8] implemented DRR in their protocol in a centralized manner but introduces unnecessary overhead. In our protocol, pFD-MAC provides the same access opportunities for each station. However, some stations may always have longer packet length than others, resulting in the unfairness with respect to access time. Thus, we will use DRR to solve the fairness issue in our protocol. More specifically, the fairness scheduling process handling N stations is configured with one quantum $T_{base}(j)$ for each station, and this pre-allocated access time is called *deficit*. At round n, the station j can access the wireless channel at most $T_j(n)$:

$$T_j(n) = T_{base}(j) + T_j(n-1) \cdot I_j(n-1) \tag{6}$$

where $T_{base}(j)$ is a constant value for each round, $T_j(n-1)$ is the remaining time in the last round. $I_j(n-1) = 1$ if the queue of station j is not empty and $T_j(n-1) > 0$, otherwise $I_j(n-1) = 0$.

Since the medium access order is determined by the transmission scheduling process, an accurate access time $t_c(j)$ for station j can be obtained after a packet is scheduled. After getting this transmission time by feedback from the scheduling process, we can update the deficit of station j for round n as:

$$T_j(n) = T_j(n) - t_c(j) \tag{7}$$

To encourage full-duplex communications, we will schedule the packet if $T_j(n) > L_j/2V_t$ instead of $T_j(n) > L_j/V_t$. Thus, the remaining time of last round for station j can be negative. And if $T_j(n) < L_j/2V_t$, the node will not be included in the next polling access round.

B. NON-CONFLICT GRAPH CONSTRUCTION

1) SIR MAP

As described in section III, the SIR value is calculated by Eqs.2 at each station. Then, these SIR records will be uploaded to the AP at the beginning of CFP. After the information collection stage is over, an SIR map, which has been also used in [8] and [20], is updated at the AP, denoted by M_{SIR}. The two-dimension matrix is formally defined as follows:

$$\mathbf{M_{SIR}} = \begin{pmatrix} c_{11} & c_{12} & \cdots \\ c_{21} & c_{22} & \cdots \\ \vdots & \vdots & \ddots \end{pmatrix} \tag{8}$$

Where each element $c_{ij}(i \neq j)$ represents the SIR value at node j with interference from node i. For example, the SIR map for Fig.1 can be expressed as:

$$\mathbf{M_1} = \begin{pmatrix} 30 & 10.9 & 20.6 & 23.1 \\ 10.9 & 30 & 21.7 & 20.6 \\ 15.8 & 21.1 & 30 & 20.3 \\ 22.4 & 22.4 & 20 & 30 \end{pmatrix}$$

Here, we set $c_{ii} = 30$ since this paper assumes that the PHY-layer can achieve perfect SIC and it means each node can start a symmetric transmission with the AP.

Theoretical Analysis: Here, we would like to analyze the SIR value theoretically and discuss the factors that influence the SIR value. Let P_t^{sta} be the transmit power of station i $(1 \leq i \leq N)$ and P_t^{ap} be the transmit power of the AP. Then, the theoretical value of SIR c'_{ij} can be calculated as:

$$\begin{aligned} c'_{ij} &= 10log_{10}(P_r^{ap}(j)/P_r^i(j)) = 10log_{10}(\frac{\kappa P_t^{ap} h d_{0j}^{-n}}{\kappa P_t^{sta} h d_{ij}^{-n}}) \\ &= 10log_{10}(\frac{P_t^{ap}}{P_t^{sta}}) + 10log_{10}(\frac{d_{ij}}{d_{0j}})^n \\ &= \delta + 10 \cdot n \cdot log(d_{ij}/d_{0j}) \end{aligned} \tag{9}$$

where $P_r^{ap}(j)$ means the received signal strength from the AP to station j and $P_r^i(j)$ means the received interference signal strength from station i to station j. d_{0j} is the distance from the AP to station j and d_{ij} is the distance from station i to station j. We use δ to represent the transmit power difference between the AP and stations.

From Eqs.9 we can see that the SIR value is determined by the transmit power difference δ, path loss exponent n and the distribution of two stations in a network. Generally, n is a fixed value in the specific wireless environment. And the distribution of stations may change all the time and could not be controlled. Thus, if we intend to increase the SIR value, we can increase the transmit power difference δ.

2) NON-CONFLICT GRAPH

Since an AP polls each mobile station sequentially in our protocol, it should be guaranteed that any adjacent nodes in the polling profile do not conflict with each other. That is, the AP visits each node in the network exactly once in a polling round, and the SIR value between two adjacent nodes must be greater than a threshold value τ, which guarantees that packets can be transmitted with low packet error rate (PER) at a specific data rate. Otherwise, a collision will occur at the receiving node. To prove the hardness of profile generation problem, we create a *non-conflict graph* from the SIR map. Note that, the *non-conflict graph* is a directed graph and SIR map is a two-dimension matrix, they are different.

Definition 1 (NON-CONFLICT GRAPH): A non-conflict graph is a directed graph, denoted by $G_{nc} = (V_{nc}, E_{nc})$, where V_{nc} is the collection of mobile stations in the network. $E_{nc} = \{e_{ij}\}$, where e_{ij} indicates whether there is interference from node i to node j at a certain transmission rate. $e_{ij} = 1$ if signals from AP to node i will not collide with signals from node i to node j, or else $e_{ij} = 0$. e_{ij} can be determined by:

$$e_{ij} = \begin{cases} 1 & \text{if } c_{ij} > \tau \\ 0 & \text{otherwise} \end{cases} \tag{10}$$

In a non-conflict graph, the edge between two nodes exists if there is no collision between them. Two nodes without collision can be adjacent to each other in the polling profile. For example, the non-conflict graph in Fig.1 can be calculated as following. Assume that $\tau = 16.2dB$, the minimal data rate will be $12Mbps$ according to Table 1. Let $G_1 = (V_1, E_1)$, in which $V_1 = \{s_1, s_2, s_3, s_4\}$. For that $c_{1,3} = 20.6 > \tau$ and $c_{3,1} = 15.8 < \tau$ in M_1, $nc_{1,3} = 1$ and $nc_{3,1} = 0$, that is, $< s_1, s_3 > \in E_1$ and $< s_3, s_1 > \notin E_1$. Accordingly, we can get $E_1 = \{< s_1, s_4 >, < s_2, s_4 >, < s_3, s_4 >, < \mathbf{s_1}, \mathbf{s_3} >, < s_2, s_3 >, < s_4, s_3 >, < s_3, s_2 >, < s_4, s_2 >, < s_4, s_1 >\}$.

TABLE 1. Transmission rates with respect to SIR values.

SIR (dB)	10	12.3	13.4	16.2	18.3	19.6
Rate (Mbps)	3	6	8	12	14	18

And $< s_1, s_3 >$ means AP can start polling s_3 even if the receiving process of s_1 has not completed.

C. POLLING PROFILE GENERATION PROBLEM

In pFD-MAC protocol, a polling profile is generated to ensure the wireless channel is accessed in a contention-free way. A scheduling approach is required to get a polling profile with the objective to minimize the packet transmission time. However, there are some constraints to determine the polling profile. As mentioned in the previous section: 1) if the downloading transmission of current node ends first, the AP can poll the next node even if the receiving process of current polling node is not completed. 2) However, it is forbidden that the node behind the next node is polled. 3) Besides, an appropriate downloading data rate should be selected to guarantee a low packet error rate (PER) when the packets are transmitted concurrently.

In order to specify the polling profile generation process explicitly, some metrics are introduced here. The difference in completion time between concurrent transmission and separate transmission of two adjacent stations *i* and *j* is represented by ΔT_{ij}, which can be calculated as:

$$\Delta T_{ij} = T_{ij}^{sep} - T_{ij}^{con} \tag{11}$$

where T_{ij}^{sep} means the separate transmission time between station i and j and T_{ij}^{con} means the concurrent transmission time between station i and station j. T_{ij}^{sep} and T_{ij}^{con} are intermediate variables and their values could be calculated by in the scheduling process. Besides, ΔT_{ij} can be positive or negative. If $\Delta T_{ij} > 0$, it means concurrent transmission is preferred; otherwise, separate transmission should be better.

To obtain a polling profile with the minimal packet transmission time, the Polling Profile Generation (PPG) problem is defined. Next, this problem is proved to be NP-hard. Note that, scheduling packets to maximize overall throughput in IBFD system is proved to be NP-complete in Kim *et al.* [8]. But its transmission mechanism is different with ours.

Definition 2 (Polling Profile Generation (PPG) Problem): In an AP-based full-duplex wireless network, a non-conflict graph, denoted by $G_{nc} = (V_{nc}, E_{nc})$, is used to represent the interference among mobile stations in the network. And a complete graph, denoted by $G = (V_{nc}, E)$, is constructed to represent the network, where $E = \{(i, j) : i, j \in V_{nc}$ and $i \neq j\}$. Let the cost function from station i to station j be $c(i, j)$:

$$c(i,j) = \begin{cases} -\Delta T_{ij} & \text{if } i,j \in E_{nc} \\ 0 & \text{if } i,j \notin E_{nc} \end{cases} \tag{12}$$

The Polling Profile Generation (PPG) problem is to find a path visiting every node in non-conflict graph with a minimal cost function c.

Lemma 1: The PPG problem is NP-hard.

Proof: The NP-hard proof of PPG problem is derived from Traveling Salesman Problem (TSP) [27], which has been shown to be NP-hard. Let us denote TSP as P_1. Then, we show that a special case of PPG problem to minimize the completion time of transmission procedure of a polling round is equivalent to P_1. In fact, when ΔT_{ij} is a fixed value, PPG problem is equivalent to P_1. Therefore, we only need to find a special case in which ΔT_{ij} is fixed.

Assume there are $N(> 3)$ stations in the network with only one transmission rate V_t. And there is only upstream traffic in the network so that the packet length of upstream traffic L_u is much longer than the packet length of downstream traffic (polling packet) L_d ($L_u \gg L_d$). If there is no conflict, ΔT_{ij} is a fixed value, as shown in Fig.8.

$$\Delta T_{ij} = (L_{ACK} + L_{Header})/V_t + T_{SIFS} \tag{13}$$

Hence, the PPG problem is NP-hard. ■

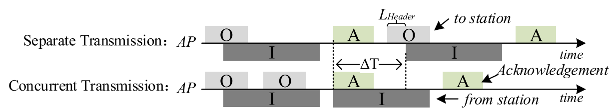

FIGURE 8. The special case with only upstream traffic.

As the PPG problem is NP-hard, we need to develop a fast algorithm to get an appropriate polling profile. Especially, our scheduling mechanism works with the transmission mechanism in parallel. Thus, we hope our scheduling algorithm works in a pipeline way as well. The details of our scheduling algorithm will be discussed in the next section.

D. PROPOSED TRAFFIC-AWARE SCHEDULING ALGORITHM

pFD-MAC generates the polling profile according to the traffic information and interference information. There are three cases need to be considered: 1) the SIR value between two stations is too small to concurrently schedule them. Hence, these two stations should be scheduled separately in which only the symmetric transmission opportunity can be used. 2) the SIR value is small, but we can still choose a data rate to start a concurrent transmission. 3) the SIR value is big enough, so the concurrent transmission time is shorter than scheduling them alone.

Since the goal of our scheduling algorithm is to obtain a polling profile with the minimum transmission time, we arrange the nodes registered in the AP step by step with the minimum transmission time for each node. Here, a heuristic traffic-aware scheduling algorithm is presented in Algorithm 1, in which $\theta_u(i)$ is the uplink channel time and $\theta_d(i)$ is the downlink channel time after polling station i. At each step, a station is selected and a proper transmission

Algorithm 1 The Traffic-Aware Scheduling Algorithm

$S_\mu \leftarrow$ all stations need to be scheduled
while S_μ not NULL **do**
  if $\theta_u(i) > \theta_d(i)$ **then**
    calculate ΔT_{ij} for each s_j in S_μ
    if $max\{\Delta T_{ij}\} > 0$ **then**
      send s_i with $max\{\Delta T_{ij}\}$
    else
      $\theta_d(i) = \theta_u(i)$
    end if
  else
    randomly select and remove s_j from S_μ
    calculate ΔT_i for each s_i in S_μ with s_j
    if $max\{\Delta T_{ij}\} > 0$ **then**
      send s_j and s_i with $max\{\Delta T_{ij}\}$ concurrently
    else
      send s_j alone
    end if
  end if
end while

rate is set as well. To generate the polling profile, the following situations will be considered:

1) **The uplink channel is longer than the downlink.** In this situation, the AP can poll the next node while receiving packet of current polling node. We have an opportunity to start a concurrent transmission. Assume that current polling node is node i. Then, ΔT_{ij} for all unscheduled node j will be calculated. If none of them is positive, it means separate transmission is preferred and the downlink channel will be set the same as the uplink channel. Otherwise, pick up the unscheduled node with the maximal ΔT_{ij} and start a concurrent transmission at the appropriate data rate.

2) **The uplink channel is shorter than or equal to the downlink.** An unscheduled node, called s_i, will be selected randomly (stations with upstream packet are preferred) and transmits a packet at this time. However, it cannot be determined to transmit node s_i separately or concurrently with other nodes. Thus, node s_i will try to transmit with another node s_j in the unscheduled node list concurrently, and a group of ΔT_{ij} will be calculated. If none of them is positive, node s_i will be sent alone. Otherwise, choose one with the maximal ΔT_{ij} and send them concurrently at the appropriate data rate.

Complexity analysis: In the scheduling algorithm, we need to try to match current polling node with at most n nodes to find the best next polling node in each step, in which n represents the number of stations in the network. When we get the next polling node, the AP can start polling the next node without having to wait until all the polling orders have been calculated. Thus, we can say that the *time complexity* of our algorithm is $O(n)$. During the calculation at each step, we mainly need $a * n$ bytes to store the polling profile, $b * n$ bytes to store the variable vector $\{\Delta T_{ij}\}$ and c bytes to store the other things, where a, b, c are constants. Thus, the *space complexity* of our algorithm is also $O(n)$.

Fig.9 shows an example of our scheduling algorithm in Fig.1, in which O means downstream packet, I means upstream packet and A means ACK packet. There are four stations with related information to be scheduled. At first, in Step 0, we consider each node as transmitting separately, which is the worst case. In Step 1, s_1 with uploading data will be selected, but it cannot decide to be sent concurrently or separately. In step 2, s_1 will try to start a concurrent transmission with an unscheduled node. And s_2, s_3 and s_4 can transmit with it concurrently. Note that, O_2 will be longer because the upload signal of s_1 will interfere the download signal of s_2, so we choose a low data rate for O_2. Through the comparison of ΔT for each unscheduled node, s_3 will be selected and transmit at a proper transmission rate. In Step 3, s_4 is selected and try to start concurrent transmission with s_2. For $\Delta T > 0$, in Step 4, s_2 will transmit with s_4 concurrently and the scheduling is over.

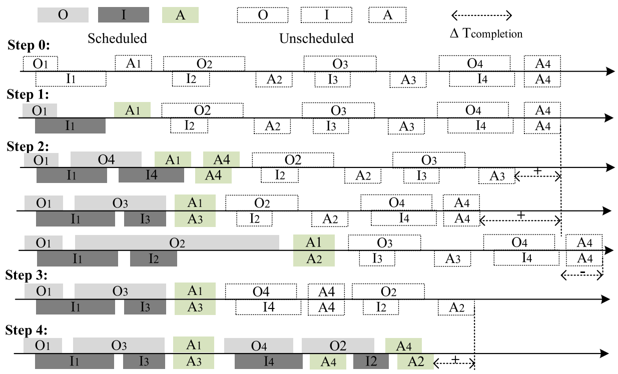

FIGURE 9. An example of the heuristic traffic-aware scheduling algorithm for network in Fig.1.

V. PERFORMANCE EVALUATION

In this section, we analyze the effects of various features of our proposed MAC protocol on network performance. Firstly, we compare the performance of pFD-MAC protocol with two state-of-the-art centralized MAC protocols, Janus and PCF, in terms of network throughput and packet delay, through extensive simulations using a network simulator developed in Python [28]. Then, we analyze the efficiency of our scheduling mechanism and compare it with Janus's scheduler under various traffic types. Thirdly, we evaluate the fairness of pFD-MAC protocol with respect to access time for each station. Moreover, we investigate the effects of asymmetric traffic and inter-node interference on our proposed MAC protocol, which can provide some valuable advice to the future design of full-duplex MAC protocol. Finally, we analyze the effects of the duration time of CFP on the network performance, from which we can see that the time of CFP is a compromise between mobility and network throughput.

A. SIMULATION SETUP

1) NETWORK AND TRAFFIC

In the simulation, random topologies are used. Stations are randomly distributed and the AP is located at the center in an area of $300m * 300m$. The default number of stations is set to 20 and we vary the number from 5 to 100 to evaluate the performance under different traffic. We use five different traffic types in the simulation. As shown in Table 3. For TR1, both upstream and downstream are 100%, which means each station in the network always has a packet to transmit/receive. TR2 has only downstream traffic while TR3 only has only upstream traffic. TR2/3 can be considered as the extreme traffic in our life, for example, most end users like to download but not upload (TR2) and most sensors prefer to upload data to the controller/AP instead of downloading data in the sensor network (TR3). TR4 is a typical asymmetric traffic, in which some stations only have upstream and the others only have downstream. In TR5, stations and AP have packets to each other with a probability of 50%. TR5 can be seen as a scenario with random traffic. Moreover, for real traffic on the Internet, it is shown that the distribution of packet size is not uniform [29]. The packet size varies from 64 bytes to 1500 bytes. Thus, in our simulation, we test our protocol with different packet lengths, in which the fraction of large packets ($>$ 1400 bytes) is 40% and the fraction of small packets ($<$ 100 bytes) is 40% while others account for 20%, just like the statistic data at Chicago exchange point [29].

2) PHY AND MAC LAYER MODEL:

Most frame structures are the same as the frame structures in 802.11 standard and only minor changes have been made as mentioned above. The parameters of the physical and MAC layers are given in Table 2. We set SIFS to $10us$ and PIFS to $20us$. The duration time of contention-free period is default set to $100ms$, which is a typical value for 802.11 PCF and the maximal value is about $400ms$. The default transmission rate is set to $18Mbps$. As mentioned in the previous section, different data rates can be selected based on different SIR values. Table 1 shows the relationship between transmission rates and SIR values, which has been measured on the hardware platform WARP [8]. In addition, the SIR value is calculated according to Eqs.9 in the simulation.

TABLE 2. Parameters for PHY and MAC layers.

Parameter	Value	Parameter	Value
CF-P	28 bytes	T_{CFP}(default)	100 ms
CF-A	29 bytes	SIFS	10 us
ACK	14 bytes	PIFS	20 us

B. SIMULATION RESULTS

In this section, the reported values for the simulation results are the average of 50 times repeated simulation with randomly generated topologies. In addition, to ensure the fairness of the evaluation and without losing the generality, we set the test time of a round to $200ms$ for Janus and pFD-MAC. For Janus, it means a round of Janus MAC packet exchanges is $200ms$. For pFD-MAC, it means the contention-free period time is $200ms$.

TABLE 3. Five different traffic types.

Traffic Type	S_1	S_2	...	S_{n-1}	S_n
TR1 Upstream	100%	100%	...	100%	100%
TR1 Downstream	100%	100%	...	100%	100%
TR2 Upstream	100%	100%	...	100%	100%
TR2 Downstream	0	0	...	0	0
TR3 Upstream	0	0	...	0	0
TR3 Downstream	100%	100%	...	100%	100%
TR4 Upstream	100%	0	...	100%	0
TR4 Downstream	0	100%	...	0	100%
TR5 Upstream	50%	50%	...	50%	50%
TR5 Downstream	50%	50%	...	50%	50%

1) THROUGHPUT AND TRANSMISSION DELAY

a: Throughput

We first verify the network throughput of pFD-MAC with respect to different number of stations under different traffic types. And we compare our proposed MAC protocol, Janus and 802.11 PCF as well. Fig.10 shows the throughput of three different protocols. For saturated traffic like TR1, pFD-MAC improves throughput by 39% and 69% over Janus and PCF respectively, when the number of stations is 40. In addition, the throughput performance of pFD-MAC increases at first and decreases as the number of stations grows while the throughput of Janus decreases almost at first when the number of stations grows. There are mainly two reasons: 1) for pFD-MAC, as the number of stations in the network increases, the full-duplex communication opportunities increase. Thus, the network throughput is improved. However, since the duration time of CFP is a fixed value in this test, the more stations in the network, the more overhead of collecting interference information at the beginning of CFP, thus increasing the overall throughput of the network; 2) for Janus, as the number of stations increases, the overhead to collect information and scheduling transmission increases. But the performance gain in the packet exchange period will not increase because it may reach the maximum value.

Under extreme traffic like TR2/3, both pFD-MAC and Janus can only slightly improve the network throughput since only a few concurrent transmission opportunities can be utilized. The throughput performance of TR3 is better than TR2 for pFD-MAC and PCF. It's easy to understand: 1) for pFD-MAC, the AP can poll the next station when a station is uploading while the AP cannot poll the next station even if the uploading process of current node is over; 2) for 802.11 PCF, the data ACK for uploading packets can be sent with the next polling packet together. For asymmetric traffic TR4 and random traffic TR5, pFD-MAC can outperform Janus as well. The pFD-MAC protocol can obtain better performance in TR5 than TR4 while there is not much difference for Janus because of the limitation of polling mechanism in pFD-MAC. As for PCF, same performance is achieved under TR4/5 since the throughput performance is almost determined by the total traffic. Moreover, pFD-MAC can obtain the best performance with saturated traffic among different traffic types because the overhead of collecting information is relatively minimal in this kind of traffic. But for Janus, the performance in random

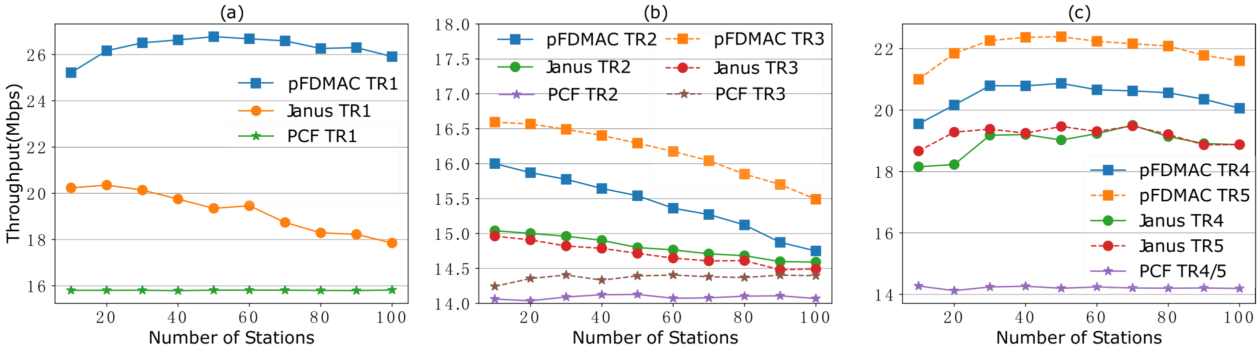

FIGURE 10. Throughput of different MAC protocols with different number of stations and different traffic types.

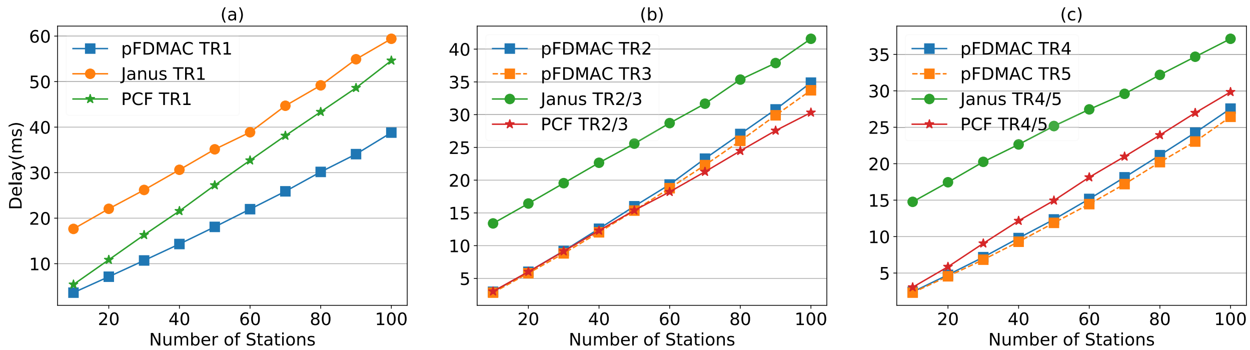

FIGURE 11. Delay of different MAC protocols with different number of stations and different traffic types.

traffic might better than saturated traffic since the overhead in scheduling preparation period might be smaller while the performance gain in exchange period is the same.

b: Delay

is another important metric to measure the network performance. One MAC protocol may have a large throughput while suffering a long delay. In the simulation, considering that the overhead of collecting information and the scheduling preparation (only Janus) is suffered by each packet, the overhead time will be counted in the total delay time. Thus, the delay time of pFD-MAC will be the overhead of collecting interference information and the average time of an access round in CFP. As for Janus, the delay time is calculated as the overhead of scheduling preparation period and ACK period pluses the average time of an access round in the packet exchange period. And we use the duration time of an access round to present the packet delay time of PCF. The overhead time of Janus is 2530us to schedule 36 packets in a round and the per-packet overhead is 69us [8]. And it is hard to be optimized because the *scheduling process* and *packet transmission procedure* of Janus work in serial mode. In the simulation, we set the average scheduling time for a packet is 25us since we think scheduling process can be accelerated by more powerful hardware. And the per-packet overhead is about 30us for Janus in the simulation.

Fig.11 shows the delay time of different protocols with different traffic types. From this figure, we can see that our proposed protocol has the shortest delay time under different traffic types while achieves the highest throughput as shown in Fig.10. And this mainly benefits from the parallelism between scheduling process and transmission process in pFD-MAC. For saturated traffic TR1, the pFD-MAC protocol can reduce the average packet delay by 48% and 33%, as compared to Janus and PCF with the number of stations is 40, respectively. With increasing the number of stations, the delay time increases for all three protocols. Among them, packet delay of PCF increases faster than the other two protocols, pFD-MAC and Janus, since the delay time largely depends on the average transmission time of an access round in this case. When it comes to unsaturated traffic like TR4/5, the delay time of PCF is approximately to pFD-MAC because the overhead time of collecting information is relatively high. Especially, for extreme traffic TR2/3, the delay time of pFD-MAC is higher than PCF when the number of stations is large since the overhead time of collecting information starts dominating the overall delay time. Moreover, there is a gap between pFD-MAC and Janus with respect to the delay time under different traffic types, which can be considered as the overhead of packet scheduling. In our proposed protocol, the scheduling process works with the packet transmission process in parallel so that the delay time is largely decreased. In other words, we can say that our protocol has better scalability than Janus.

All in all, our proposed MAC protocol can achieve good network throughput performance while maintaining low transmission delay. Moreover, as network size grows up, the performance of pFD-MAC is steady and shows good scalability.

2) EFFICIENCY OF THE PROPOSED POLLING-BASED SCHEDULING MECHANISM

To verify the efficiency of scheduling mechanism of our proposed protocol, we compare our polling-based scheduling mechanism with Janus's scheduling mechanism. In the evaluation, the overhead of information collection and transmission scheduling is ignored. In order to ensure the integrity of our protocol, the ACK has not been deleted in our protocol while the ACK period is ignored in Janus'. In addition, the duration time of a round is set to 100*ms*. As shown in Fig.12, our polling-based scheduling mechanism can largely outperform Janus' in saturated traffic TR1. The reason why our scheduler can outperform Janus's is that the optimization policy is different. The optimization policy of Janus is trying to find the optimal full-duplex connection to decrease the transmission time by matching the maximum *LF value* [8]. However, the optimization policy of our protocol is to minimize the transmission time as much as possible. For the same reason, as the number of stations increases, the performance gain of our polling-based scheduling mechanism increases as well since there will be more full-duplex transmission opportunities to start asymmetric transmission as the number of stations increases. However, the performance of Janus's scheduler will decreases since the scheduling policy of Janus is that matching the concurrent transmission with the maximum value of *LF* while our scheduling policy is to minimize the transmission time. Obviously, our scheduling mechanism is more efficient in saturated traffic.

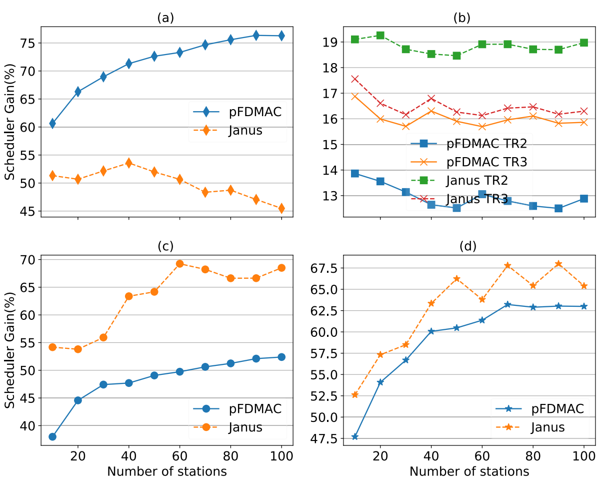

FIGURE 12. The efficiency comparison of scheduling mechanism between pFD-MAC and Janus under different traffic type, in which we ignore the overhead of information collection and scheduling.

For unsaturated traffic like TR2/3/4/5, the performance gain of our proposed scheduling mechanism is slightly worse than Janus's. There are two main reasons: 1) the polling-based mechanism limits the use of asymmetric transmission. Especially when it comes to TR2 and TR4, each upstream packet cannot be transmitted until they are polled by the AP. However, Janus can schedule the packet in a free way so the scheduler gain of Janus is large than pFD-MAC's; 2) the transmission of ACK packet is counted in our scheduling mechanism while the ACK period of Janus is not included in the simulation. For TR3, the scheduling gain should be the same between pFD-MAC and Janus, the gap between them is the overhead of the transmission time of ACK packet in pFD-MAC. Moreover, as shown in Fig.12, the performance of our scheduling mechanism is more steady than Janus since the scheduling policy in Janus largely depends on the network topology. And there is a big difference in the inter-node interference in different topologies. On the other hand, to illustrate the performance of the scheduling mechanism in pFD-MAC, we also compare the network throughput with and without the scheduling algorithm. Since the scheduling mechanism mainly utilizes the asymmetric transmission in different traffic, the performance gain of our scheduling algorithm is equivalent to the performance gain of asymmetric transmission, which is shown in Fig.13. And we will discuss it together with the effects of inter-node interference in the next subsection.

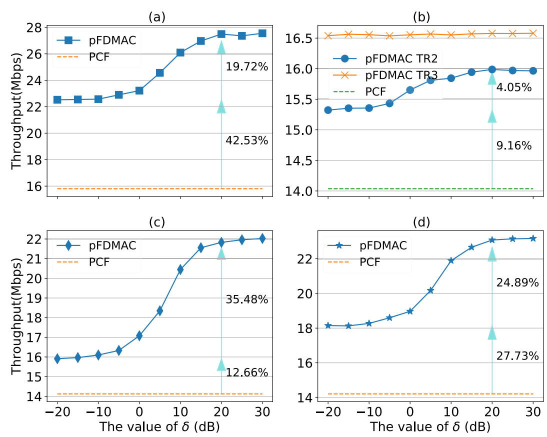

FIGURE 13. The throughput with different inter-node interference and different traffic types in which the inter-node interference is determined by the value of δ according to Eqs.9.

3) EFFECTS OF INTER-NODE INTERFERENCE AND ASYMMETRIC TRAFFIC ON NETWORK PERFORMANCE

To study the effects of inter-node interference and asymmetric traffic on network performance, we evaluate the network throughput with different power difference under different traffic types. According to Eqs.9, we can regulate the inter-node interference (SIR value) by changing the value of the power difference δ. The throughput will increase as we increase the value of δ. However, the inter-node interference only limits the asymmetric transmission between different stations, the symmetric transmission will not be influenced. Thus, the effect of inter-node interference varies with different traffic. The result is shown in Fig.13, in which we think there is no asymmetric transmission can be utilized when $\delta = -20dB$ and there are plenty opportunities to start asymmetric transmission when $\delta = 30dB$. Moreover, we can say that the performance gain by utilizing asymmetric transmission benefits from our proposed polling-based scheduling algorithm.

For TR1, the asynchronous characteristic is determined by the difference in upstream and downstream traffic in the symmetric transmission. And the throughput can be improved by 19.72% with asymmetric transmission while the throughput can be improved by 42.53% with the symmetric transmission compared with PCF. For TR2, there is only a few opportunity to utilize asymmetric transmissions so that only 4% throughput improvement is obtained, but we can still improve the network throughput by 9.16% with symmetric transmissions. For TR3, only symmetric transmission can be used and no concurrent transmission between two different stations. When it comes to the asymmetric traffic like TR4, our proposed traffic-aware scheduling algorithm can increase the network throughput by 35.48% and only 12.66% throughput improvement benefits from symmetric transmissions. With the random traffic like TR5, symmetric and asymmetric transmissions bring almost the same throughput improvement to the network.

From the perspective of system design, the symmetric transmission determines the lower bound of the network performance and the asymmetric transmission determines the upper bound of the network performance. In addition, the full-duplex station supports symmetric transmission and the half-duplex station only support asymmetric transmission in the AP-based network. Thus, if the inter-node interference is strong, we should deploy more full-duplex stations in the network; if the inter-node interference is weak, we might use more half-duplex stations in the network to exploit the asymmetric transmission in the network. Of course, the AP must support full-duplex communication to start a symmetric/asymmetric transmission.

4) FAIRNESS IN OUR PROTOCOL

This part verifies the fairness of our proposed pFDMAC protocol. As described in Section IV-A, we use the channel access time of a station as the fairness metric in the wireless system. And the fairness is measured by Jain index [30]. The deficit time T_{base} for each station is allocated according to the duration time of CFP and the number of stations in the wireless network. For example, we have 10 stations in the network and $T_{CFP} = 100ms$, then the access time for each station will be $100ms/10 = 10ms$. However, the channel access time includes the upload time and download time for a station, $10ms$ usually is not enough to transmit all packets because the AP cannot maintain concurrent transmissions all the time. Yet rigorous time allocation obtains perfect fairness, as shown in Table.4. The minor imperfect fairness in TR4/5 could be the mechanism that we allow a station slightly overuse its deficit. To get a better network performance, we can relax the deficit allocation. For example, again, we have 10 stations in the network and $T_{CFP} = 100ms$, then the access time for each station can be $1.2 * 100ms/10 = 12ms$. Thus, more packets

TABLE 4. Fairness under different traffic types.

Traffic type	TR1	TR2	TR3	TR4	TR5
I_{Jain}	1	1	1	0.99	0.99

could be transmitted and the network performance will be increased as well. However, it could introduce unfairness to some extent but it is very small. After all, we give each node the same access opportunity, and the packet length distribution for each node is the same.

5) EFFECT OF T_{CFP} ON NETWORK PERFORMANCE

As mentioned in the above section, the SIR map may only be updated at the beginning of CFP. The longer the duration time of CFP is, the smaller the overhead time of collecting the interference information. However, the real SIR map is changing all the time as stations move. Fig.14 shows the throughput with different T_{CFP} under traffic type TR6. When the number of stations in the network increases, the throughput with a small T_{CFP} decreases faster than a big one since the overhead time to collect interference information is the same. With increasing T_{CFP}, the throughput will be improved as expected. Actually, we can choose the value of T_{CFP} according to specific scenario. If the stations in a network move slow, a long CFP can be selected. And if the stations in a network move fast, a short CFP should be set.

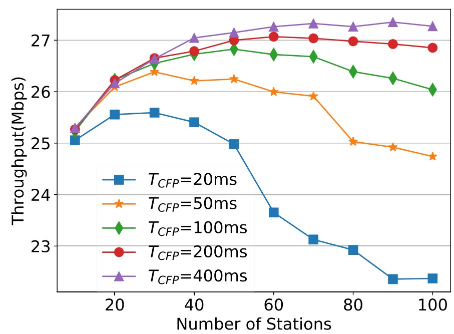

FIGURE 14. Throughput with respect to the duration time of contention-free period under different network sizes.

However, if stations move fast while the number of stations is large in the network, we should set a small value of T_{CFP}. However, if we still collect the interference information among all stations, the overhead time of collecting these interference information may be 100% of the contention-free period. At this time, we can only poll part of the overall stations registered in the AP so we only need to collect part of the inter-node interference in the network. And this is one of the future work to improve our proposed MAC protocol as well. On the other hand, we can give up collecting the inter-node interference information and only utilize the symmetric transmission which is the last choice.

VI. CONCLUSIONS AND FUTURE WORK

This paper presents a polling-based traffic-aware MAC protocol called pFD-MAC for AP-based full-duplex wireless networks. pFD-MAC uses a polling scheme to transmit packets according to a polling profile. And a heuristic traffic-aware algorithm is developed to generate the polling profile in order to fully exploit full-duplex opportunities. Extensive simulations reveal that the parallelism between scheduling mechanism and packet transmission significantly improve the network performance in term of throughput and transmission delay. More importantly, we analyze many factors influence the design of full-duplex MAC protocol which can provide valuable advice in future work. In order to make pFD-MAC practical, there are still many works to do. And we intend to evaluate our protocol on WARP platform in our future work. Besides, we also want to extend our protocol to ad-hoc wireless networks because it is now only available in an AP-based wireless network. How to mitigate pFD-MAC to use other emerging full-duplex techniques in the physical layer, such as full-duplex multi-input multi-output (MIMO) [31], remains an open problem.

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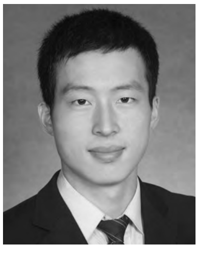

SONG LIU received the B.S. degree in electrical and computer engineering from Shanghai Jiao Tong University, Shanghai, China, in 2013, and the M.S. degree in computer science from the National University of Defense Technology, Changsha, Hunan, China, in 2015, where he is currently pursuing the Ph.D. degree. His research interests include wireless network, full-duplex communications, and optimization theory.

BIAO HAN (M'13) received the B.E. and master's degrees in computer science from the National University of Defense Technology (NUDT), China, in 2007 and 2009, respectively, and the Ph.D. degree from the University of Tsukuba, Japan, in 2013. From 2012 to 2012, he has been a Visiting Scholar with the Department of ECE, University of Florida. He is currently an Assistant Professor with NUDT. His research interests are in software-defined networking, wireless communication, and network security.

WEI PENG was born in Dayi City, Sichuan, China, in 1973. He received the M.S. and Ph.D. degrees in computer science from the National University of Defense Technology (NUDT), China, in 1997 and 2000, respectively. From 2001 to 2002, he was a Research Assistant with the School of Computer, NUDT, China, where he has been a Research Fellow since 2003. His major research interests are Internet routing, network security, and mobile wireless networks.