Probabilistic Medium Access Control for Full-Duplex Networks with Half-Duplex Clients

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Abstract

The feasibility of practical in-band full-duplex radios has recently been demonstrated experimentally. One way to leverage full-duplex in a network setting is to enable *three-node full-duplex*, where a full-duplex access point (AP) transmits data to one node yet simultaneously receives data from another node. Such three-node full-duplex communication however introduces *inter-client interference*, directly impacting the full-duplex gain. It hence may not always be beneficial to enable three-node full-duplex transmissions. In this paper, we present a distributed full-duplex medium access control (MAC) protocol that allows an AP to adaptively switch between full-duplex and half-duplex modes. We formulate a model that determines the probabilities of full-duplex and half-duplex access so as to maximize the expected network throughput. A MAC protocol is further proposed to enable the AP and clients to contend for either full-duplex or half-duplex transmissions based on their assigned probabilities in a distributed way. Our evaluation shows that, by combining the advantages of centralized probabilistic scheduling and distributed random access, our design improves the overall throughput by 2.70× and 1.53×, on average, as compared to half-duplex 802.11 and greedy downlink-uplink client pairing.

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I. INTRODUCTION

Recent works [1]–[5] have demonstrated the feasibility of in-band full-duplex transmission using system level design and experiments. Based on current experimental evidence, it appears that the first potential adoption of full-duplex radios could be at AP serving primarily half-duplex mobile (thin) clients. Thus, to fully exploit the capability of a full-duplex AP, it is potentially beneficial for a network to leverage three-node full-duplex [6], where downlink and uplink transmissions can be to and from two different half-duplex clients. The three-node full-duplex scenario however introduces the new challenge of *inter-client interference* (ICI), which is caused by the transmission of an uplink client to the reception at a downlink client. The presence of ICI implies that the doubling in spectral efficiency due to full-duplex transmission may not be feasible, and client pairing – the choice of downlink and uplink clients – has a significant impact on the resulting network throughput.

Some methods have recently been proposed to select simultaneous downlink-uplink clients for three-node full-duplex. The first method avoids ICI by picking nodes that are completely hidden from each other [7]. This is however not only unfair, but also underutilizes the full-duplex opportunities since pairing partially interfering clients can possibly improve the network throughput. The second method, e.g., [8] [9], allows clients to randomly contend for uplink access, while selecting the downlink client producing the maximal throughput according to the ICI introduced by the winning uplink client. This method however can only pair a proper downlink client for a given uplink client, which could not fully extract the full-duplex gains by jointly paring the downlink and uplink clients. The third method is weighted random pairing [10], where the downlink and uplink clients are randomly chosen based on the reactively measured historical success probabilities. Such an approach however only implicitly considers the effect of ICI, and hence might perform even worse than half-duplex, especially in the cases of medium to high ICI. The last method optimizes client pairing by explicitly scheduling all the transmission sequences with consideration of ICI and traffic demands reported from all pairs of clients [11]. However, such centralized scheduling requires large signaling overhead, fails to adapt to network dynamics, and, in general, has not gained traction in IEEE 802.11 standardization.

In this paper, we present a *distributed* MAC protocol that determines the best client pairings *probabilistically* and utilizes the full-duplex mode only when it achieves a higher network throughput. In particular, we adopt a probabilistic access mechanism, which assigns to each

full-duplex pairing and each half-duplex transmission an *access probability* so as to maximize the expected network throughput while maintaining fairness. The high-level intuition of our probability assignment is to allow nodes to best adapt between the half-duplex mode and the full-duplex mode based on inter-client interference among clients. The assigned access probabilities can then be used as guidelines for both the AP and clients to perform CSMA/CA-based contention and opportunistically pair full-duplex transmissions in a distributed way. Thus, our design retains the desirable properties of 802.11's random access, while adaptively exploiting the full-duplex opportunities.

A practical challenge needs to be solved is that the assigned access probability should be no higher than the traffic demand of a client. Otherwise, if we allocate more transmission opportunities than the demand to a client, the spectrum resources will be wasted, leading to lower channel utilization and throughput degradation. Therefore, we should assign access probability with careful consideration of heterogeneous traffic demands of clients. To address this concern, we propose an *epoch-based* MAC protocol, which updates access probabilities for every epoch according to the short-term average traffic arrival rate of each client. Within each epoch, the clients and the AP then adopt *prioritized* contention to share transmission opportunities based on the updated access probability. By combining the benefits of both centralized probabilistic scheduling and distributed random access, nodes efficiently exploit the full-duplex opportunities to best serve their traffic demands and maximize the overall network throughput.

We conduct extensive simulations to evaluate the performance of the proposed probabilistic-based MAC protocol. The simulation results show that our design achieves 2.70× and 1.53× throughput gains over 802.11's half-duplex contention and greedy client pairing, respectively. The more-than-double gains over half-duplex 802.11 come from both the ability to utilize full-duplex opportunities and to reduce the number of collisions and overhead in our prioritized contention process.

The rest of this paper is organized as follows. Section II summarizes recent works on full-duplex designs. We define our probabilistic MAC protocol in Section III. The proposed access assignment scheme is given in Section IV, and the probabilistic-based contention protocol is presented in Section V. We evaluate the performance of our design in Section VI, and, finally, conclude this work in Section VII.

II. Related Work

Recent works [1]–[5], [12], [13] have designed and implemented full-duplex radios that cancel self-interference using different techniques, including beamforming, RF chain cancellation, digital domain cancellation and circulators. With the exciting results of these full-duplex radio implementations, several later studies then either theoretically analyze the full-duplex gains or design the MAC protocols for full-duplex communications. The works can be classified into two categories.

Bidirectional full-duplex: Several papers have studied the gain of enabling bidirectional full-duplex links, where both the transmitter and receiver are equipped with full-duplex radios. Theoretical works model how hardware linearity [14] and power allocation [15] affect the achievable throughput of bidirectional full-duplex. In [16], the authors propose a distributed MAC protocol [16] to enable bidirectional full-duplex in 802.11 networks, and analyze its bandwidth and energy efficiency. The gains of using multiple antennas to enable half-duplex multiplexing or full-duplex are characterized in [17]. An adaptation scheme is then proposed in [18] to make the best choice between MIMO and bidirectional full-duplex transmissions.

Three-node full-duplex: More recently, the three-node full-duplex scenario has also been considered where two half-duplex clients communicate simultaneously with a full-duplex AP. FD-MAC [7] modifies 802.11's CSMA/CA so that hidden nodes can be selected to form three-node full-duplex, whereas [19] allows any node introducing limited ICI to join full-duplex transmissions. Both the above approaches however favor only part of the clients. Later works [10] [11] then further take fairness into consideration. ContraFlow [10] uses historical transmission success probability of each pair of clients to implicitly infer the degree of their ICI. The client pairings are then determined by exploiting the tradeoff between fairness and success probability. Estimation based on statistics however is not accurate enough because an error might be caused by many factors other than ICI, e.g., improper bit-rate selection. PoCMAC [9] lets the AP and the uplink client control their transmit power. It solves an optimization problem of finding the transmit power of the AP and the uplink client so as to maximize the minimum SINR of the uplink and downlink transmissions. Moreover, it gives a downlink client more chances to access the medium if it experiences lower ICI or has a strong receiving power from the AP. However, as the number of clients increases, the average throughput degrades due to the increasing collision probability. In contrast, the average throughput of our design increases as the number of clients

increases because we efficiently assign full-duplex opportunities, while adopting probabilistic-based contention to avoid collisions. A-Duplex [8] uses the capture effect to establish full-duplex transmissions. That is, it aligns two packets from the AP and the uplink client at the downlink client properly such that the downlink client can recover its intended packet in the presence of the interfering uplink client. It then proposes a user selection mechanism to only pair clients if a downlink client receives a much higher signal strength from the AP than that from the uplink client. Both works [9] [8] still enable clients to contend for uplink randomly, while only selecting downlink clients to improve the throughput gain. In contract, our design jointly considers both uplink and downlink to seek for more full-duplex gains and maximize the average total throughput.

Janus [11] collects the numbers of buffered packets and ICI from all the clients, and schedules batch half-duplex/full-duplex transmissions in a time-division manner to minimize the completion time of the buffered packets. Centralized scheduling however not only requires an expensive overhead, but can also fails to adapt to network dynamics. Our proposed protocol differs from the above MAC design in that it assigns full-duplex/half-duplex transmission probabilities based on ICI among clients, but leverages probabilistic-based contention to realize thees assigned access probabilities in a *distributed* manner. In addition, different from our prior work [20] which only considers backlogged traffic, this work considers a more general scenario where clients might have various traffic demands and, hence, the access probability should be adjusted accordingly.

III. Problem Definition

In this section, we first define the access probability assignment problem for a three-node full-duplex network. We will describe the formal model and our proposed probability assignment algorithm in Section IV, and then design a distributed random access control protocol that realizes the assigned access probabilities in Section V.

A. Three-Node Full-Duplex Networks

We consider a three-node full-duplex network, where only the AP has full-duplex capability, i.e., being able to transmit and receive simultaneously in the same band, while all the clients are only equipped with a half-duplex radio. For ease of representation, we give each node an index. We denote the index of the AP by 0, and the index set of clients is $\mathcal{C} = \{1, 2, \ldots, C\}$. The AP can operate in either the full-duplex or half-duplex mode. In the full-duplex mode, the

AP transmits a downlink stream to client i, while receiving an uplink stream from another client j at the same time. Let $P_{0,i}$ and $P_{j,0}$ be the powers used for transmission from the AP to client i and from client j to the AP, respectively. Then, the SINR at downlink client i is given by

$$\text{SINR}_d^{(i,j)} = \frac{P_{0,i}|h_{0,i}|^2}{\sigma_i^2 + \text{ICI}^{(i,j)}} = \frac{P_{0,i}|h_{0,i}|^2}{\sigma_i^2 + P_{j,0}|h_{j,i}|^2}, \tag{1}$$

where the superscript (i,j) represents the full-duplex pairing between downlink client i and uplink client j, $h_{j,i}$ is the channel coefficient from client j to client i, and σ_i^2 is the noise variance at downlink client i. Here, $\text{ICI}^{(i,j)}$ represents the inter-client interference caused by client j at downlink client i, and can be measured by $P_{j,0}|h_{j,i}|^2$. Similarly, the SINR of uplink client j is given by

$$\text{SINR}_u^{(i,j)} = \frac{P_{j,0}|h_{j,0}|^2}{\sigma_0^2 + \text{I}_{\text{self}}} = \frac{P_{j,0}|h_{j,0}|^2}{\sigma_0^2 + P_{0,i}|h_{0,0}|^2}, \tag{2}$$

where $h_{0,0}$ is the self-interfering channel after suppression and the self-interference I_{self} can be expressed as $P_{0,i}|h_{0,0}|^2$. Similarly, we let $(i,0)$ and $(0,j)$ denote the half-duplex downlink transmission to client i and half-duplex uplink transmission from client j, respectively. The SINR can be expressed similarly as in Eqs. (1) and (2) by setting $P_{0,0} = 0$.

A noïve solution to involving two clients in a full-duplex transmission is to match each downlink client with the uplink client that produces the maximal data rate. This simple method however could favor only certain clients for uplink transmission. In addition, two clients can only be paired together in the full-duplex mode if they both have traffic (one uplink and one downlink) simultaneously. We hence need to further consider the traffic demand of each client as pairing full-duplex transmissions. However, it is not only computationally expensive but also impractical to schedule transmissions on a per-packet basis. To avoid this complexity, we alternatively pair clients according to their *average traffic demands*. Specifically, the AP monitors the average uplink/downlink traffic arrival rate of each client for a historical period of time. Let $\lambda_d^{(i)}$ and $\lambda_u^{(i)}$ denote the downlink and uplink traffic arrival rate, respectively, of client i. We then use this statistical information to allocate either full-duplex or half-duplex transmission opportunities to clients. Since different clients might have various traffic demands, we assign a proper access probability to each pair of clients, i.e., a full-duplex pair of clients, (i,j), or a uplink/downlink half-duplex client, $(0,i)$/$(i,0)$, with consideration of their traffic demands and SINR.

B. Candidate Pairs of Clients

In a three-node full-duplex network, some node pairs might have strong inter-client interference such that the downlink client cannot reliably recover its packets. To avoid this undesirable situation, we first filter proper candidate node pairs before probability assignment. For a pair of clients (i, j), given the downlink and uplink transmission power $P_{0,i}$ and $P_{j,0}$, respective, we can derive the SINR of both clients based on Eqs. (1) and (2), and use the SNR-based rate adaptation algorithm [21] to select the optimal bit-rate γ, i.e., modulation and coding scheme, from a set of available bit-rates $\mathcal{R}$. Then, the effective throughput at downlink client i and uplink client j can be computed as

$$r_d^{(i,j)} = \max_{\gamma \in \mathcal{R}} \gamma \cdot \text{PDR}(\gamma, \text{SINR}_d^{(i,j)}) \tag{3}$$

and

$$r_u^{(i,j)} = \max_{\gamma \in \mathcal{R}} \gamma \cdot \text{PDR}(\gamma, \text{SINR}_u^{(i,j)}), \tag{4}$$

respectively.[1] Here, the packet delivery ratio $\text{PDR}(\gamma, \text{SINR})$ is a function of bit-rate $\gamma \in \mathcal{R}$ and the SINR at the corresponding receiver. We also define $r^{(i,j)} \triangleq r_d^{(i,j)} + r_u^{(i,j)}$ as the total throughput under the full-duplex pairing of downlink client i and uplink client j. Then, in the half-duplex mode, we have $r^{(i,0)} = r_d^{(i,0)}$ and $r^{(0,j)} = r_u^{(0,j)}$.

In the full-duplex mode, we are interested in pairing clients i and j that yield non-negligible throughput (larger than ϵ) in both the uplink and downlink, i.e., the set of index pairs

$$\mathcal{P}_{\text{full}} \triangleq \{(i, j) : i, j \in \mathcal{C},\ i \neq j, r_d^{(i,j)}, r_u^{(i,j)} > \epsilon\}; \tag{5}$$

and, in the half-duplex mode, we are interested in the set of index pairs

$$\mathcal{P}_{\text{half}} \triangleq \{(i, j) : i = 0 \text{ or } j = 0, r^{(i,j)} > \epsilon\}. \tag{6}$$

Then, all candidate pairs are collected as a set

$$\mathcal{P} \triangleq \mathcal{P}_{\text{full}} \cup \mathcal{P}_{\text{half}}. \tag{7}$$

We allow the AP to adaptively switch between full-duplex and half-duplex by allocating a proper proportion of spectrum resources to each candidate pair in $\mathcal{P}$. In particular, our goal is to assign

[1] We use r to represent the effective throughput with consideration of loss and errors, while using γ to represent an available bit-rate, i.e., modulation and coding scheme.

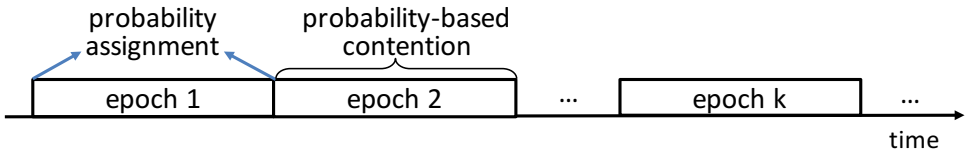


Fig. 1: Epoch-based access probability assignment

each candidate pair $(i, j) \in \mathcal{P}$, including full-duplex pairs and *virtual* half-duplex pair, a probability $p^{(i,j)}$ to access the medium. The objective of this access probability assignment problem is to maximize the *expected* sum rate of the whole network, while maintaining fairness among clients. The formal problem formulation and the proposed probability assignment algorithm will be given in the next section.

IV. Access Probability Assignment

In this section, we first describe the framework of our epoch-based access control, and then formally define our system model and the proposed solution.

A. Epoch-based Access Probability Assignment

An intuitive way to enable three-node full-duplex transmissions is to select a pair of clients, one with a downlink packet and the other with a uplink packet at the same time. Such deterministic *per-packet client pairing*, however, requires a coordinator, e.g., the AP, to exactly know the real-time traffic demands of each client, and can hardly be realized in practice. To avoid this centralized per-packet scheduling, we alternatively adopt an *epoch-based assignment* framework that pairs clients in a probabilistic way according to their historical average traffic demands, while still allowing clients to contend for medium access in a distributed way, i.e., without any coordination.

In particular, our system partitions the time slots into several time intervals, called *epochs*, each of which has a duration T, as shown in Fig. 1. The AP passively measures the average downlink/uplink traffic demand of each client in each epoch. In the beginning of an epoch e_t, the AP uses the average traffic demands measured from the previous epoch e_{t-1} to find the proper access probability $p^{(i,j)}$ for each candidate client pair (i, j) in the current epoch. The AP then notifies all the clients of their assigned probability $p^{(i,j)}$ so that the clients can perform a probabilistic-based contention in a distributed way according to their assigned probability (see Section V).

In theory, the access probability of a pair $p^{(i,j)}$ should be defined as the probability that the pair occupies a unit of the time slot. However, note that the CSMA/CA mechanism of the standard 802.11 allows clients to share spectrum resources via frame-based transmissions and guarantee packet fairness. That is, once a client wins a transmission opportunity, it can send one data frame, no matter how many bits are in the frame and what bit-rate is chosen. In other words, each client has an equal probability to send its frames, but the data frames from different clients might occupy different channel time. To maintain the design philosophy of 802.11, i.e., packet fairness, we define the access probability of a candidate pair as the proportion of transmission opportunities allocated to it. Specifically, the access probability of a pair $p^{(i,j)}$ can be expressed by

$$p^{(i,j)} = n^{(i,j)} / \sum_{(i,j)\in\mathcal{P}} n^{(i,j)}, \tag{8}$$

where $n^{(i,j)}$ is the number of transmission opportunities obtained by pair (i,j) in an epoch. We can see from the equation that assigning access probability is equivalent to allocating each pair a proper number of transmission opportunities in an epoch. Therefore, our probability assignment model aims at solving the variables $n^{(i,j)}$ for all pairs $(i,j) \in \mathcal{P}$ and then finding the corresponding probability $p^{(i,j)}$ accordingly.

B. System Model and Algorithm

Note that we have transformed the access probability assignment problem into the problem of determining the number of transmission opportunities in each epoch. The allocation problem

can be formulated as follows:

$$\mathbf{P}_{\text{assign}}: \quad \max \sum_{(i,j)\in\mathcal{P}} \frac{n^{(i,j)} l^{(i,j)}}{T} \tag{9a}$$

$$\text{subject to} \quad \sum_{j\in\{j:(i,j)\in\mathcal{P}\}} n^{(i,j)} \geq \eta_d^{(i)}, \forall i\in\mathcal{N} \tag{9b}$$

$$\sum_{i\in\{i:(i,j)\in\mathcal{P}\}} n^{(i,j)} \geq \eta_u^{(j)}, \forall j\in\mathcal{N} \tag{9c}$$

$$\sum_{j\in\{j:(i,j)\in\mathcal{P}\}} n^{(i,j)} \leq \lambda_d^{(i)} T, \forall i\in\mathcal{N} \tag{9d}$$

$$\sum_{i\in\{i:(i,j)\in\mathcal{P}\}} n^{(i,j)} \leq \lambda_u^{(j)} T, \forall j\in\mathcal{N} \tag{9e}$$

$$\sum_{(i,j)\in\mathcal{P}} n^{(i,j)} t^{(i,j)} \leq T \tag{9f}$$

$$\text{variables:} \quad n^{(i,j)}\in\mathbb{R}_{\geq 0}, \forall (i,j)\in\mathcal{P}, \tag{9g}$$

where $l^{(i,j)}$ represents the average total frame length of pair (i,j), i.e., $l_d^{(i)} + l_u^{(j)}$ (bits), and $t^{(i,j)}$ represents the average channel time occupied by each transmission of pair (i,j), which can be estimated by

$$t^{(i,j)} = \max\left(\frac{l_d^{(i)}}{r_d^{(i,j)}}, \frac{l_u^{(j)}}{r_u^{(i,j)}}\right).$$

In our implementation, we use the average length of downlink/uplink data frames as an estimate of $l_d^{(i)}$ and $l_u^{(j)}$, respectively.

Eqs. (9b) and (9c) represent the fairness constraints. These constraints allow each client to obtain downlink and uplink access opportunities no less than the minimum number of guaranteed transmission opportunities $\eta_d^{(i)}$ and $\eta_u^{(j)}$, respectively. We will discuss how to properly configure the parameters of those minimum shares later. Eqs. (9d) and (9e) ensure that all the scheduled traffic load does not exceed the arrived traffic demands at the beginning of an epoch since we adopt epoch-based assignment. Eq. (9f) ensures that the total allocated transmission time should not exceed the epoch time T. Finally, the objective is to maximize the expected total throughput of the whole network in this epoch-based access control as shown in Eq. (9a).

Note that the assignment problem $\mathbf{P}_{\text{assign}}$ is a linear programming (LP) problem, which can be easily solved by the existing optimization solvers. Once we solve the number of allocated access opportunities $n^{(i,j)}$, we can then estimate the access probability of each pair, $p^{(i,j)}$, based

Algorithm 1: Fairness Access Assignment

Input: $\lambda_d^{(i)}$, $\lambda_u^{(i)}$, $\forall i \in \mathcal{N}$, $\bar{t}$, T

$d_d^{(i)} \leftarrow \lambda_d^{(i)} T, d_u^{(i)} \leftarrow \lambda_u^{(i)} T, \forall i \in \mathcal{N}$

// set of expected downlink and uplink traffic demands

$\mathcal{D} = \{d_d^{(i)} : d_d^{(i)} > 0, i \in \mathcal{N}\} \cup \{d_u^{(i)} : d_u^{(i)} > 0, i \in \mathcal{N}\}$

// number of minimum shared transmission opportunities

$\eta_d^{(i)} \leftarrow 0, \eta_u^{(i)} \leftarrow 0, \forall i \in \mathcal{N}$

while $\mathcal{D} \neq \phi$ **do**

  $\eta_{left} \leftarrow \left(T - \sum_{i \in \mathcal{N}} (\eta_u^{(i)} + \eta_d^{(i)}) \bar{t}\right) / \left(\bar{t} |\mathcal{D}|\right)$

  $\eta_{min} \leftarrow \min(\min_{d \in \mathcal{D}} d, \eta_{left})$

  // terminate if the channel time of an epoch has be fully utilized

  if $\eta_{min} = 0$ **then**

    break

  // allocate η_{min} to all the clients with demands

  for $i \in \mathcal{N}$ **do**

    if $d_d^{(i)} \geq \eta_{min}$ **then**

      $\eta_d^{(i)} \leftarrow \eta_d^{(i)} + \eta_{min}$

      $d_d^{(i)} \leftarrow d_d^{(i)} - \eta_{min}$

      if $d_d^{(i)} = 0$ **then** $D \leftarrow \mathcal{D} \backslash \{d_d^{(i)}\}$

    if $d_u^{(i)} \geq \eta_{min}$ **then**

      $\eta_u^{(i)} \leftarrow \eta_u^{(i)} + \eta_{min}$

      $d_u^{(i)} \leftarrow d_u^{(i)} - \eta_{min}$

      if $d_u^{(i)} = 0$ **then** $D \leftarrow \mathcal{D} \backslash \{d_u^{(i)}\}$

return $\eta_d^{(i)}, \eta_u^{(i)}$

on Eq. (8). The AP solves this probability assignment problem at the beginning of every epoch, and notifies the clients of the updated access probabilities $p^{(i,j)}$ in the beacon frame. Solving the probability assignment problem requires the AP to know some information, e.g., the bit-rates $r_d^{(i,j)}$ and $r_u^{(i,j)}$. We will describe in Section V-C how the AP obtains these information with an acceptable signaling overhead.

Algorithm 2: Access Probability Assignment

1 Solve Algorithm 1 to find the minimum shares $\eta_d^{(i)}$ and $\eta_u^{(i)}$

2 Obtain the access opportunity $n^{(i,j)}$ by solving the assignment problem $\mathbf{P}_{\text{assign}}$

3 Transform $n^{(i,j)}$ to access probability $p^{(i,j)}$ based on Eq. (8)

4 Announce $p^{(i,j)}$ to clients

Minimum fair share: The minimum allocated transmission opportunities, $\eta_d^{(i)}$ and $\eta_u^{(j)}$, can be flexibly configured by the system operator to realize their fairness policy. In our implementation, we define that the fairness is achieved when each client is guaranteed to obtain at least the same access opportunities provided by traditional half-duplex CSMA/CA. Specifically, $\eta_d^{(i)}$ and $\eta_u^{(j)}$, respectively, are set to the access opportunities for downlink client i and uplink client j in a fair half-duplex protocol. The AP adopts the max-min fairness to calculate $\eta_d^{(i)}$ and $\eta_u^{(j)}$, as shown in Algorithm 1. Since these threshold values are computed without considering channel variation, here, we assume that the AP and the clients use the lowest bit-rate. Then, $\bar{t}$ represents the average half-duplex transmission time of all the clients, i.e., the average frame length divided by the lowest rate. The basic idea of the Algorithm 1 is that all the clients equally share the access opportunities in an epoch unless the fair share exceeds one's traffic demand. In particular, let $\mathcal{D}$ denote the set of unserved traffic demands. We allocate the transmission opportunities to the demands in $\mathcal{D}$ equally until all the demands are served, i.e., $\mathcal{D} = \phi$, or an epoch terminates, i.e., $\sum_{i\in\mathcal{N}}(\eta_d^{(i)} + \eta_u^{(i)})\bar{t} \geq T$. After obtaining the minimum shares, we can solve the probability assignment problem using our algorithm summarized in Algorithm 2.

Feasibility: Note that, with our defined minimum share parameters $\eta_d^{(i)}$ and $\eta_u^{(j)}$, the assignment problem $\mathbf{P}_{\text{assign}}$ in Eq. 9 is always feasible because the half-duplex transmission assigned by Algorithm 1 meets all the constraints in $\mathbf{P}_{\text{assign}}$ and must be one of the feasible solutions of $\mathbf{P}_{\text{assign}}$.

V. Probabilistic-based Full-Duplex MAC

We next propose a probabilistic-based MAC protocol to realize the access probabilities $p^{(i,j)}$ solved in Algorithm 2. The protocol addresses practical issues including probabilistic access, bit-rate selection, power control and information exchange to update probabilities.

A. Probabilistic-based Contention

To allow the clients to achieve the assigned access probabilities in a distributed way, our protocol keeps the contention nature of 802.11, and hence does not require the AP to coordinate the full-duplex clients for every packet. The AP determines to switch to half-duplex or full-duplex based on the assigned probability $p^{(i,j)}$. When the AP enters the full-duplex mode, it adopts the so-called *Down-Up* full-duplex[2], where the AP first initiates its downlink stream, before it allows the remaining clients to contend for uplink transmission based on their assigned probabilities accordingly. To precede uplink contention with downlink transmission, we let multiple APs leverage *frequency-domain contention* [22], [23] to contend for downlink transmission first[3], as shown in Fig. 2. When the channel becomes idle, each full-duplex AP broadcasts a tone immediately after DIFS on a randomly-selected sub-channel (formed by a few OFDM subcarriers), and, at the same time, listens to the tones sent by neighboring APs. The one that picks the smallest sub-channel, e.g., AP1 in Fig. 2, wins the channel for downlink transmission. The winning AP then randomly selects a downlink client i with the probability

$$p_d^{(i)} = \sum_{j \in \{j:(i,j)\in\mathcal{P}\}} p^{(i,j)}, \forall i \in \{0\} \cup \mathcal{N}. \tag{10}$$

If the index of the selected client i is not '0', the AP sends the PLCP and MAC header to downlink client i after frequency-domain contention; otherwise, if $i = 0$, the AP keeps idle and the channel time is reserved for half-duplex uplink transmission. The remaining clients can overhear the header of the downlink frame, and detect its identity. Note that, idle channel implies that the downlink client is '0'. After sending the headers, the AP pauses its downlink transmissions for the remaining clients to use traditional CSMA/CA to contend for uplink transmission. However, instead of using 802.11's exponential backoff, the clients now contend for the uplink transmission opportunity using *probability-based backoff*. Specifically, each client j sets its contention window to the inverse of the following conditional access probability subject to the maximum window constraint, i.e.,

$$CW_u^{(i,j)} = \min(\lceil 1/p_u^{(i,j)} \rceil, CW_{max}), \tag{11}$$

[2]We focus on *Down-Up* full-duplex in this work because it is easier to realize power control and bit-rate selection in practice. However, our model actually can generally be applied for *Up-Down* full-duplex, if those practical issues can be addressed.

[3]To be able to coexist with legacy 802.11 nodes, the APs can further contend for channel access using traditional CSMA/CA before frequency-domain contention.

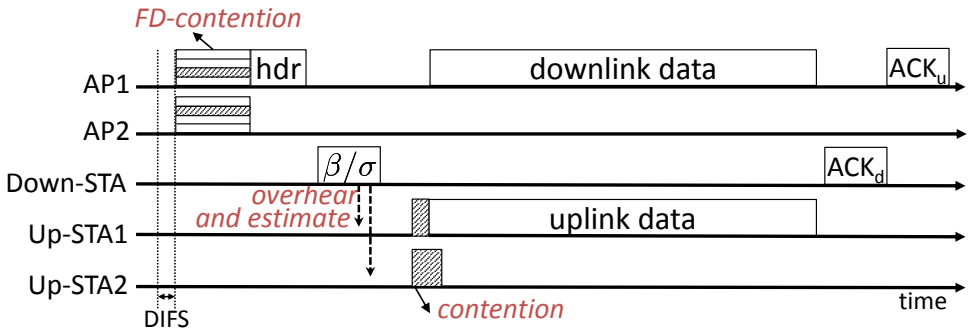


Fig. 2: MAC protocol with interference-limited power control for down-up full-duplex networks

where

$$p_u^{(i,j)} = P(j \text{ wins uplink}|\text{AP sends to } i) = p^{(i,j)}/p_d^{(i)} \tag{12}$$

is the winning probability of client j, given the selected downlink client i. By doing this, a client with a higher access probability has a smaller contention window, and can obtain an access opportunity matching its assigned probability. When the uplink client starts its data frame, the AP then continues its downlink transmission immediately, as shown in Fig. 2.

Note that we should reserve some channel time for half-duplex downlink transmission when $p^{(i,0)} > 0$. If the clients always contend for uplink transmission, the AP does not have any chance to enable its downlink half-duplex transmission. To cope with this issue, we let the AP perform uplink contention for the *virtual* uplink client '0', which means no uplink transmission. To do so, the AP computes $CW_u^{(i,0)}$, randomly picks a backoff timer $w_u^{(i,0)}$ from $[1, CW_u^{(i,0)}]$, and then announces the value of $w_u^{(i,0)}$ in the downlink packet header. Each client j gives up the uplink access opportunity if its backoff timer $w_u^{(i,j)}$, randomly picked from $[1, CW_u^{(i,j)}]$, is larger than $w_u^{(i,0)}$.

B. Power Control and Bit-Rate Selection

Since our design adopts *Down-Up* full-duplex, we should ensure that the uplink client will not affect the decodability of the existing downlink transmission. We address this problem by explicit power control and bit-rate selection. When the AP (or a client) enters the half-duplex mode, it simply uses the maximum transmission power P to send downlink (or uplink) traffic and picks the bit-rate based on its original SNR. Without loss of generality, we assume that the AP and each client i can passively learn its channel and estimate its original SNR from beacons or ACKs. On the other hand, when the AP enters the full-duplex mode, it still uses full power to

transmit the downlink streams. However, to ensure that the bit-rate used by the downlink stream can be decoded properly, the uplink client j is instructed to control its transmission power and thereby the ICI. To simplify power control, for any downlink client i, the AP picks the highest possible downlink bit-rate $\gamma_d^{(i)}$ that can tolerate a fixed ICI δ (dB), i.e.,

$$\gamma_d^{(i,j)} = \arg\max_{\gamma \in \mathcal{R}} \gamma \cdot \text{PDR}(\gamma, \text{SNR}_d^{(i)} - \delta), \tag{13}$$

where $\text{SNR}_d^{(i)} = P|h_{0,i}|^2/\sigma_i^2$ is the original SNR of downlink client i in the absence of interfering uplink transmission. By doing so, any uplink only needs to make sure that the residual ICI, after power control, should be no larger than δ (dB). Specifically, after uplink client j joins, the selected downlink bit-rate $\gamma_d^{(i)}$ can only be decoded properly if

$$\text{SINR}_d^{(i,j)} \geq \text{SNR}_d^{(i)} - \delta, \tag{14}$$

which can be rewritten as

$$10\log_{10}(\tfrac{P|h_{0,i}|^2}{\sigma_i^2}) - 10\log_{10}(\tfrac{P|h_{0,i}|^2}{\sigma_i^2 + \text{ICI}^{(i,j)}}) \leq \delta \tag{15}$$

$$\Rightarrow \qquad \tfrac{\text{ICI}^{(i,j)}}{\sigma_i^2} = \tfrac{P_{j,0}^{(i,j)}|h_{j,i}|^2}{\sigma_i^2} \leq 10^{\delta/10} - 1, \tag{16}$$

where $P_{j,0}^{(i,j)}$ is the transmission power of uplink client j when i is the concurrent downlink client. To ensure downlink client i is not harmed, client j, who wins the uplink transmission, should adjust its transmission power $P_{j,0}^{(i,j)}$ to satisfy the above constraint.

The nice part of such *interference-limited power control* is that the AP can select the best downlink bit-rate $\gamma_d^{(i)}$ based on the original downlink SNR without needing to know who will later win the uplink contention. However, since the channel might change quickly, the challenge now is how to accurately estimate $|h_{j,i}|^2/\sigma_i^2$ at the uplink client. The estimation error could increase ICI and consequently harm the decodability of the downlink stream. We hence enable per-packet inter-client channel estimation, and ask the downlink client to announce its β/σ_i before uplink contention, as shown in Fig. 2. The scalar β is applied to bound the amplitude of the announced signal within the hardware linearity range. Each contending uplink client j overhears $y_j = h_{i,j}\beta/\sigma_i$ and can approximate $|h_{j,i}|^2/\sigma_i^2$ by $(y_j/\beta)^2 = |h_{i,j}|^2/\sigma_i^2$. The client who wins the contention can use Eq. (16) to determine its power $P_{j,0}^{(i,j)}$ based on the estimated $|h_{j,i}|^2/\sigma_i^2$. After power control, the uplink client then selects its best bit-rate $\gamma_u^{(i,j)}$ based on the SINR, i.e., $P_{j,0}^{(i,j)}|h_{j,0}|^2/(\sigma_0^2 + \text{I}_{\text{self}})$, as follows:

$$\gamma_u^{(i,j)} = \arg\max_{\gamma \in \mathcal{R}} \gamma \cdot \text{PDR}(\gamma, P_{j,0}^{(i,j)}|h_{j,0}|^2/(\sigma_0^2 + \text{I}_{\text{self}})). \tag{17}$$

C. Information Exchange

Solving the model $\mathbf{P}_{\text{assign}}$ in Eq. (9) requires the AP to know some information such as the bit-rates, $r_u^{(i,j)}$ and $r_u^{(i,j)}$, and traffic arrival rates, $\lambda_u^{(i)}$ and $\lambda_d^{(i)}$. A simple way to estimate the bit-rates is to collect the SINR information from clients and estimate the bit-rates based on Eqs. (13,17). However, to reduce the overhead of information feedback, we alternatively let the AP estimate the downlink throughput $r_d^{(i,j)}$ based on $(\text{SNR}_d^{(i)} - \delta)$ because the ICI has been limited to at most δ via uplink power control. We then approximate $r_u^{(i,j)}$ by its best bit-rate $\gamma_u^{(i,j)}$, which can be offline measured by client j as mentioned in Sec. V-B. Each client j only needs to piggyback in any uplink packet the index of the selected bit-rate $\gamma_u^{(i,j)}$ for all $i \in \mathcal{N}$, which requires only $\log_2 |\mathcal{R}|(|\mathcal{C}|-1)$ bits. Hence, the signaling overhead can be reduced significantly, as compared to reporting the information about SINR or the transmit power. We will check in Sec. VI how this approximation affects the performance. On the other hand, the average traffic arrival rates, $\lambda_u^{(i)}$ and $\lambda_d^{(i)}$, are offline measured at the AP and clients. Each client j also periodically piggybacks in any uplink packet the measured average arrival rate of its uplink traffic $\lambda_u^{(j)}$ to the AP.

VI. Performance Evaluation

We conduct extensive simulations to evaluate the performance of our probabilistic-based protocol. A full-duplex AP and several half-duplex clients are uniformly randomly distributed in an $100m \times 100m$ area. Each node has a maximum transmission power 15dBm and noise power -95dBm, respectively. According to [3], we assume that each full-duplex AP can cancel up to 110 dB of self-interference. We use i.i.d. complex Gaussian channel with zero mean and unit variance and the log-distance path loss model with the path loss exponent of 3. The ICI threshold δ is set to 5 dB. The set of available bit-rates is $\{6, 9, 12, 18, 24, 36, 48, 54\}$ Mb/s, which are supported in 802.11a, and the packet delivery ratio (PDR) of different SNRs and bit-rates is measured using WARP platforms [24] over a 2.4GHz band. The best bit-rate of each packet transmission is picked based on the SNR and the measured PDR function. We use the Bernoulli process with the time interval of 0.5 milliseconds as our traffic arrival model. Unless otherwise stated, we by default let each client have backlogged (nearly unlimited) traffic demands, which can be approximated by setting the traffic arrival rate to 2,000 frames/sec. We will also evaluate the performance for limited traffic loads, and the detailed configurations will be specified later. Each packet contains 1,500 bytes. Each simulation consists of 1,000 epochs, each of which lasts

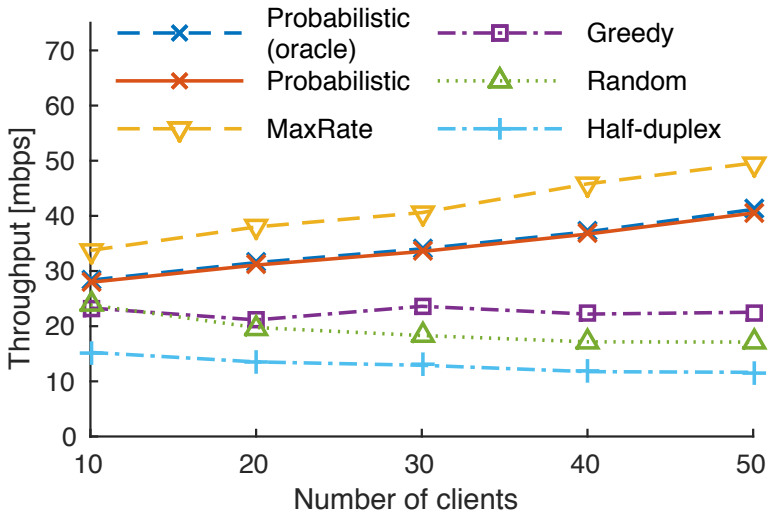


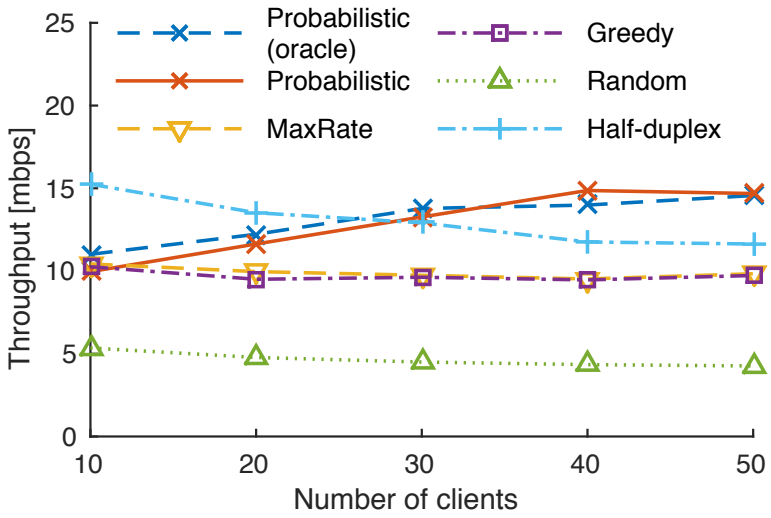
Fig. 3: Total throughput

for 100 milliseconds. We repeat each simulation for 5 random topologies, and report the average throughput.

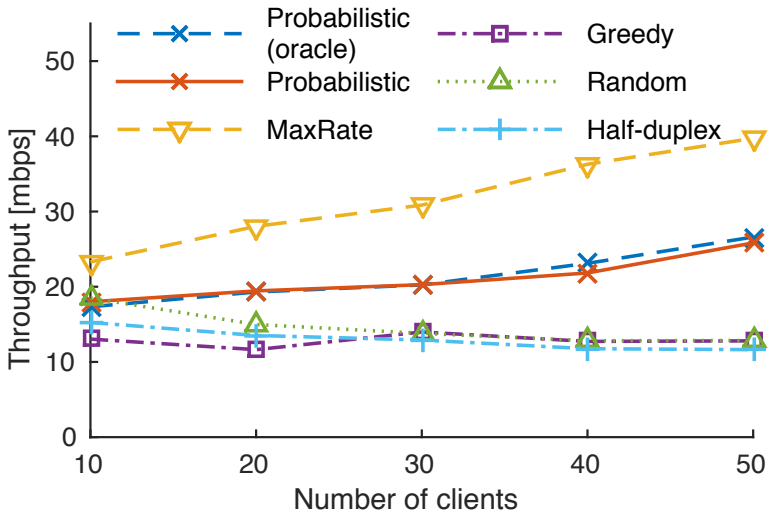
We compare our design with the following baseline schemes.

- *Oracle:* It is our design, except that the AP knows the exact information of the achievable throughput $r^{(i,j)}$, instead of the ones approximated by the best bit-rate, as mentioned in Section V-C.
- *MaxRate:* The AP randomly selects a downlink client, and lets the client that achieves the maximal uplink bit-rate join the full-duplex transmission without contention. This scheme also applies our power control, and is used as an upper bound for comparison.
- *Greedy:* The AP schedules deterministic pairing; that is, each client is only paired with one other client. Specifically, it greedily picks the pair (i^*, j^*) from $\mathcal{C}_{\text{full}}$ that produces the maximal throughput. All the other pairs (i^*, j) and (i, j^*), for all $i, j \in \mathcal{N}$, are then removed from $\mathcal{C}_{\text{full}}$. The clients that cannot be paired then switch to the half-duplex mode. For each selected full-duplex pair, the downlink client is in charge of performing contention.
- *Random:* The AP randomly selects a downlink client, and the other clients use 802.11's CSMA/CA to contend for uplink transmission without considering ICI.
- *Half-duplex:* The traditional 802.11 MAC allows only half-duplex transmissions.

In Greedy, Random and Half-duplex, nodes use full power to transmit, and select the proper bit-rate based on the SINR.



(a) Downlink throughput



(b) Uplink throughput

Fig. 4: Downlink/Uplink Throughput

A. *Throughput Performance*

Fig. 3 plots the average total throughput (i.e., the sum of downlink and uplink throughput) of the comparison schemes when the number of clients varies from 10 to 50. The results show that MaxRate, as expected, outperforms all the other schemes because it favors some particular clients that are hidden to others. We will however show later that some clients could starve in MaxRate and cannot send any uplink traffic. Greedy cannot efficiently utilize the full-duplex opportunities because it runs in iterations, without taking the overall throughput into account.

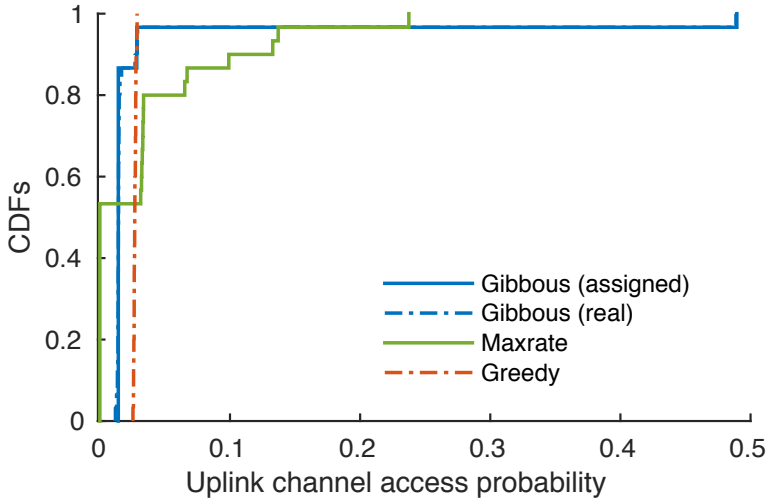


Fig. 5: CDFs of uplink transmission probability

Consider a simple four clients scenario. Say a possible pairing solution $\{(1,2),(3,4)\}$ produces the throughput 20 and 5 Mb/s, respectively, while another pairing $\{(1,3),(2,4)\}$ produces the throughput 15 and 15 Mb/s, respectively. Greedy would output the first solution, which however achieves a lower total throughput than the second one. Our probabilistic-based paring performs better than greedy pairing and random pairing, and improves the throughput by 1.53$\times$ and 2.70$\times$, on average, over Greedy and Half-duplex, respectively. The gain increases when there exist more clients because more candidate pairs are available for scheduling. The gain over half-duplex is sometimes more than doubling because *(i)* the achievable throughput of different links are inherently different, and *(ii)* more interestingly, our contention protocol prioritizes clients by assigning different pairing probabilities, and hence naturally decreases the number of collisions. The results also show that our design with approximated rate information performs similar to that using full information (i.e., oracle). This means that the quantized information does not affect efficiency of our design much, but reduces the signal overhead significantly.

To check where the gains come from, we further plot the average downlink throughput and uplink throughput in Figs. 4(a) and 4(b), respectively. Random pairing significantly reduces the downlink throughput because they might select a pair that introduces strong ICI. Greedy, MaxRate and our scheme all pair clients with consideration of ICI, and hence do not affect the downlink throughput much. The results in Fig. 4(b) also answer one's reasonable concern: Does uplink power control sacrifices the uplink throughput? We however observe that the clients achieve an even higher uplink throughput than that in Half-duplex. This is because, in our

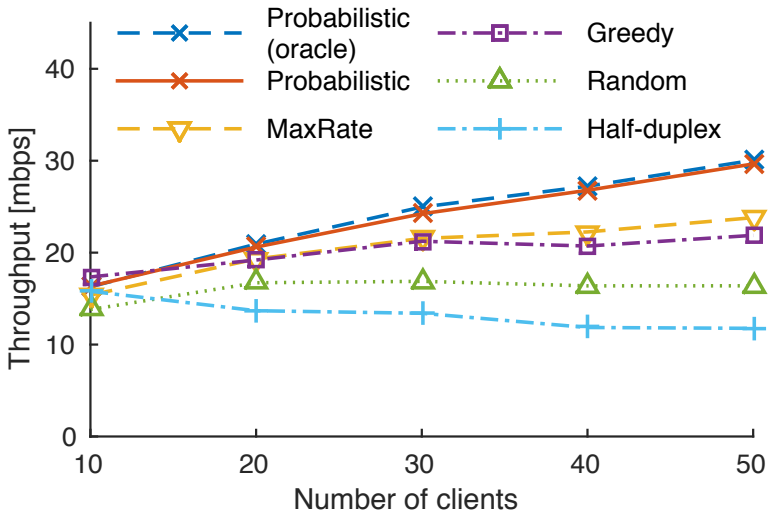


Fig. 6: Total throughput for heterogeneous traffic arrival rates

scheme, clients that introduce a smaller ICI have a higher probability to participate in full-duplex transmissions. These clients also would not need to reduce their power levels significantly. More importantly, full-duplex communications allow clients to better utilize the channel time for both downlink and uplink access, and hence increase both downlink and uplink throughput.

MaxRate produces a much higher uplink throughput because it always allocates the uplink transmission opportunities to certain clients introducing negligible ICI. To verify this point, we plot in Fig. 5 the cumulative distribution functions (CDFs) of the uplink access probability of clients, which is calculated by the number of uplink transmissions occupied by one client divided by the total number of uplink transmissions. The figure shows that, in MaxRate, 53% of clients starve and cannot send any uplink traffic. In contrast, our scheme ensures that all the clients at least obtain their minimum share for uplink transmissions.

B. Impact of Traffic Demands

We next check the impact of heterogeneous traffic demands on our probabilistic-based MAC protocol. Specifically, in this simulation, we assign each client a different traffic arrival rate, randomly picked from 0 to 80 frames per second. The choice of this demand range is based on the observation that the network is mostly saturated when each of 30 clients has a traffic demand of 16 frames per second. Hence, the maximal demand, 80 frames per second, is about 5$\times$ of the traffic arrival rate in the above saturated scenario. We also check a lower traffic arrival rate here to evaluate the performance of our design when the network is not fully saturated. Fig. 6 plots the

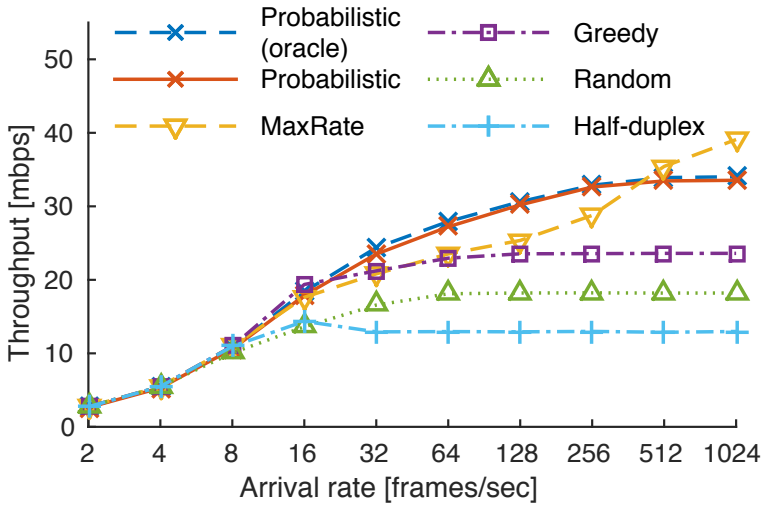


Fig. 7: Impact of traffic arrival rate

average total throughput when the number of clients varies from 10 to 50. The results show that our design again outperforms the comparison schemes even when the network is not congested. The MaxRate scheme now performs worse than our scheme because, when the uplink traffic is limited, instead of backlogged, the AP cannot always select those uplink clients introducing negligible interference, but now needs to allocate transmission opportunities to other pairs with stronger inter-client interference. By contrast, our probability-based scheme can flexibly fall back to half-duplex transmissions when no suitable full-duplex pairs can be identified. More importantly, the achievable total throughput of our probability-based access control can scale linearly with the increasing number of clients (and thereby the increasing traffic load) when the network is not fully saturated. However, the performance of the other comparison schemes converges when the number of clients increases, since those greedy algorithms might converge to a local optimum.

We further check the impact of the overall traffic load on the throughput performance. In this simulation, we fix the number of clients to 30, and assign all the clients a fixed traffic arrival rate. The traffic arrival rate of each client is configured from 2 to 1024 frames/sec in different rounds of simulations. As a result, the total traffic load increases when each client has an increasing demand. Then, the network is almost saturated when each of the 30 clients has a traffic demands of 16 frames per second. The average total throughput for various traffic arrival rates is plotted in Fig. 7. The figure shows that the throughput of half-duplex converges when the traffic demand increases to 16 frames per second because the traffic load already saturates

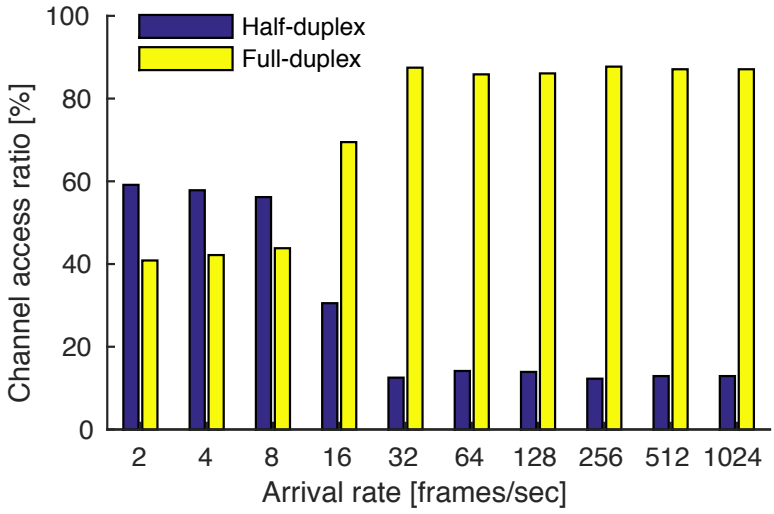


Fig. 8: Proportion of channel time occupied by full-duplex and half-duplex transmissions

the available spectrum resources. The throughput of half-duplex then degrades slightly when the traffic arrival rate exceeds 16 frames/sec due to the increasing probability of collisions. The throughput of all the other comparison schemes, however, can grow and converge later when clients have a larger demand because of the benefit of full-duplex opportunities.

The results also show that the gap between our probabilistic-based protocol and other greedy schemes increases when the traffic load increases. This is because when clients have more traffic demands, an efficient user pairing algorithm can better identify those suitable pairs and extract more full-duplex gains. To verify this argument, we further plot the proportion of channel time occupied by full-duplex and half-duplex transmissions, respectively, in Fig. 8 for various traffic arrival rates. The figure shows that our probability-based protocol can flexibly switch between the half-duplex mode and the full-duplex mode according to the traffic demands. Also, when traffic demands are large sufficiently, in most of the channel time (around 90%), we can identify full-duplex pairs producing a rate higher than half-duplex transmissions, and effectively utilize the full-duplex capability of the AP. Due to the same reason, our scheme performs better than MaxRate when the clients have a lower traffic demand and, thereby, those non-interfering pairs cannot always be matched as full-duplex transmissions. The performance of MaxRate increases when the traffic load grows beyond 440 frames per second. It, however, causes the starvation problem as we have shown in Fig. 5. Overall, our design produces a much higher total throughput as compared to the others, while ensuring fair access.

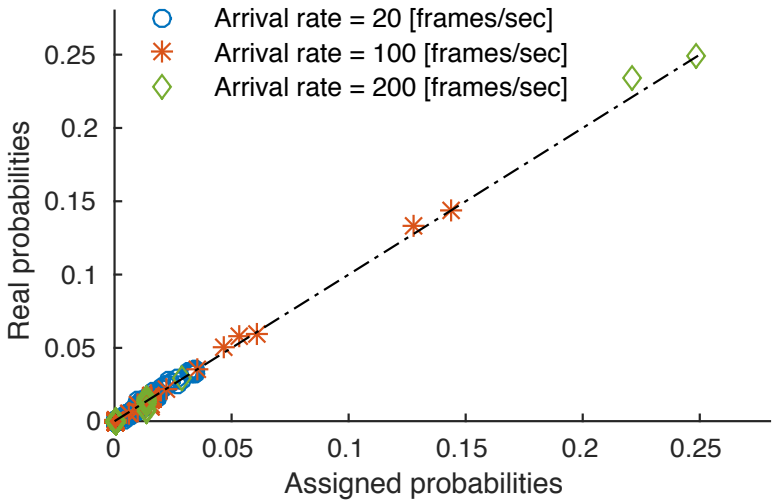


Fig. 9: Comparison between the assigned probabilities and the contention results

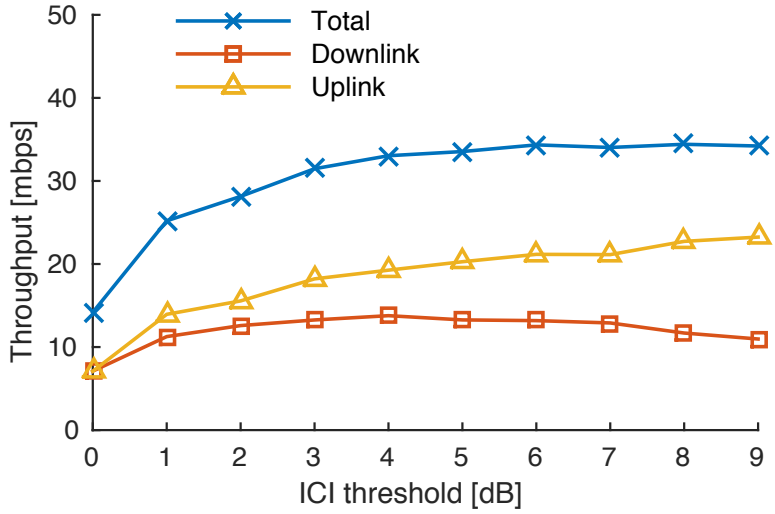


Fig. 10: Impact of the ICI threshold

C. Performance of Probabilistic-based Contention

We now check whether our probabilistic contention design can realize the theoretical assigned access probability in practice. Fig. 9 compares the real access probability measured in the simulations with the assigned probability solved from the model, when the traffic arrival rate varies from 20 to 200 frames per second. The results show that the real probabilities are fairly close to the assigned ones. It confirms that our probability-based contention can effectively prioritize clients *in a distributed way* according to the assigned probability, no matter the network is congested or not. With this distributed probabilistic-based contention, the AP does not need

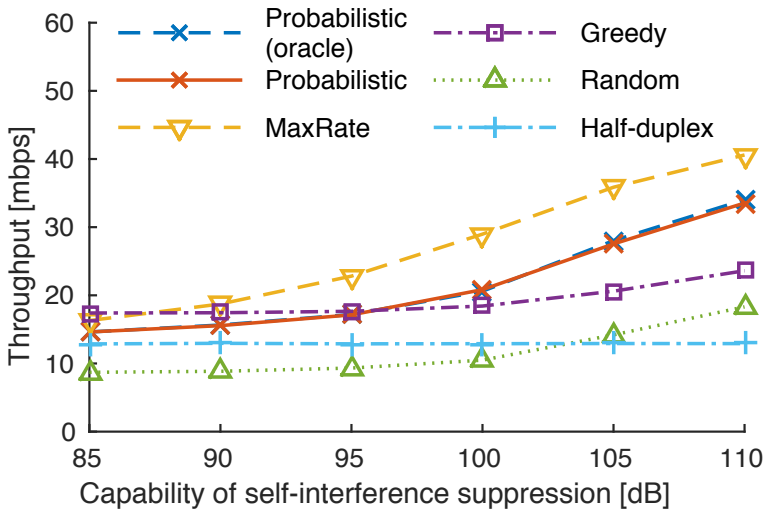
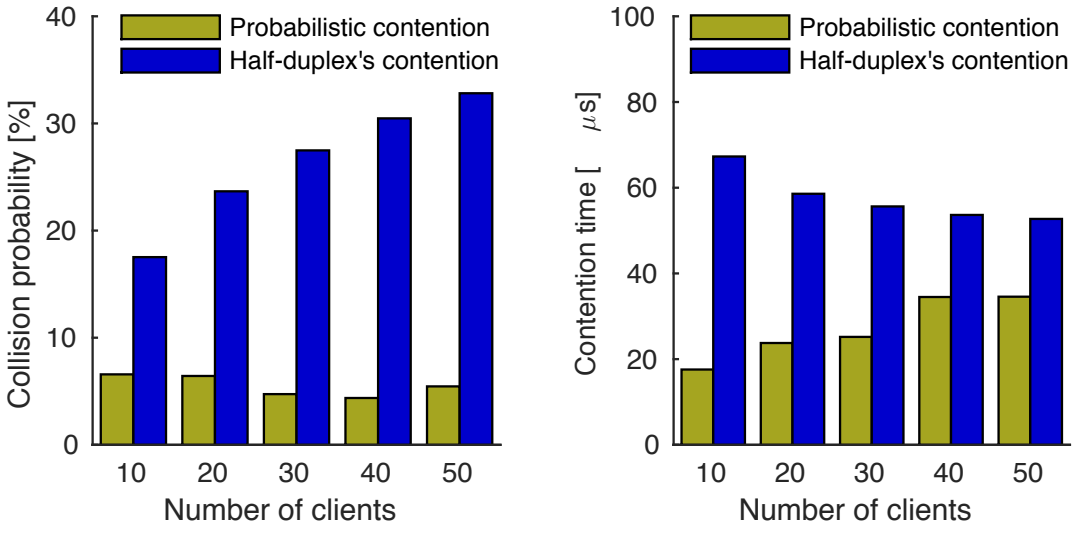


Fig. 11: Impact of self-interference suppression capability

to explicitly schedule all the transmissions in a time-division manner. Our design hence is more practical to be implemented, and maintains the advantage of distributed access in the traditional 802.11.

D. Impact of the ICI threshold

We next examine the impact of the ICI threshold δ on the performance of our probabilistic-based MAC protocol. Fig. 10 plots the average downlink throughput, uplink throughput and total throughput, when the ICI threshold δ is set from 0 to 9 dB. When ICI threshold is 0 dB, we should ensure that a downlink client cannot hear any interference from the concurrent uplink at all. It means that our probability assignment algorithm can only give hidden nodes full-duplex transmission opportunities. All the other nodes should fall back to the half-duplex mode. In this case, the full-duplex opportunities could be reduced significantly. As the threshold increases, a downlink client can tolerate an increasing amount of inter-client interference, and, hence, can allow more full-duplex transmission opportunities. This implies that clients have more opportunities to send uplink traffic, as a result achieving a higher uplink throughput and also a higher total throughput. Increasing the threshold, however, introduces a higher interference to downlink clients, and, hence, slightly degrades the downlink throughput. Overall, the total throughput is quite stable when the ICI threshold exceeds 5 dB. Therefore, considering the trade-off between performance and fairness, we choose 5 dB as our default threshold.



(a) collision probability (b) contention overhead

Fig. 12: Protocol effectiveness

E. Impact of Self-Interference Suppression Capability

We finally check the impact of self-interference suppression capability on the throughput gain. Fig. 11 shows that, in general, the full-duplex gain increases when the AP is able to suppress more self-interference. The performance gap between the comparison schemes also increases when the AP has a better suppression capability because an efficient pairing algorithm can identify suitable full-duplex pairs from more full-duplex opportunities. Even with only 85dB interference suppression, which has been verified feasible in [5], our design can produce an average throughput gain of 13% over half-duplex. With more advanced full-duplex radio designs, which can cancel up to 110 dB of self-interference [3], the average throughput gain can be 160%.

F. Protocol Efficiency

We finally examine efficiency of our protocol design. Fig. 12(a) compares the collision probability in our probabilistic-based contention to that in traditional 802.11 half-duplex contention. The results show that the proposed MAC not only delivers the full-duplex gains, but also reduces the collision probability significantly. The main reason is that our scheme leverages frequency-domain contention to reduce the contention overhead for downlink traffic, and, also, given a downlink transmission, only part of clients are allowed to contend for full-duplex uplink transmission. Not only this, unlike 802.11, which *detects* collisions and then applies exponential

random backoff, we allows clients to *avoid* collisions by adjusting its contention window based on the assigned probabilities. The clients that are assigned a higher probability can have a smaller contention window, and prevent from being collided by other clients. We also show in Fig. 12(b) that this probabilistic-based contention further decreases the required contention time, as a result improving the resulting effective throughput.

VII. Conclusion

In this paper, we introduced a probabilistic-based MAC protocol for three-node full-duplex. We adopted probabilistic client pairings to best exploit the full-duplex opportunities to deliver the overall network throughput gain. Each AP periodically assigns an access probability to each pair of downlink-uplink clients based on not only their historical ICI but also their heterogeneous traffic demands. The APs and clients then use the allocated access probabilities as hints to contend for full-duplex or half-duplex transmissions using traditional random backoff in a distributed manner. To preventing from affecting the decodability of downlink clients, each uplink client performs power control to manage inter-client interference on a per-packet basis. With the cooperation of uplink clients, the AP can hence adapt the transmission bit-rate of both the downlink and uplink packets accordingly and ensure successful decoding in both directions. We showed via simulations that, by combining probabilistic-based scheduling and random access, our design efficiently extracts the full-duplex gains and improves the overall throughput, while maintaining the distributed nature and fairness provision of 802.11.

References

[1] J. I. Choi, M. Jain, K. Srinivasan, P. Levis, and S. Katti, "Achieving Single Channel, Full Duplex Wireless Communication," in *ACM MobiCom*, 2010.

[2] M. Jain, J. I. Choi, T. Kim, D. Bharadia, S. Seth, K. Srinivasan, P. Levis, S. Katti, and P. Sinha, "Practical, Real-time, Full Duplex Wireless," in *ACM MobiCom*, 2011.

[3] D. Bharadia, E. McMilin, and S. Katti, "Full Duplex Radios," in *ACM SIGCOMM*, 2013.

[4] D. Bharadia and S. Katti, "Full Duplex MIMO Radios," in *USENIX NSDI*, 2014.

[5] M. Duarte, A. Sabharwal, V. Aggarwal, R. Jana, K. Ramakrishnan, C. Rice, and N. Shankaranarayanan, "Design and Characterization of a Full-Duplex Multiantenna System for WiFi Networks," *IEEE Transactions on Vehicular Technology*, vol. 63, no. 3, pp. 1160–1177, March 2014.

[6] J. Bai and A. Sabharwal, "Distributed Full-Duplex via Wireless Side-Channels: Bounds and Protocols," *IEEE Transactions on Wireless Communications*, vol. 12, no. 8, August 2013.

[7] A. Sahai, G. Patel, and A. Sabharwal, "Pushing the Limits of Full-Duplex: Design and Real-time Implementation," *CoRR*, vol. abs/1107.0607, 2011.

[8] A. Tang and X. Wang, "A-Duplex: Medium Access Control for Efficient Coexistence Between Full-Duplex and Half-Duplex Communications," *IEEE Transactions on Wireless Communications*, vol. 14, no. 10, Oct 2015.

[9] W. Choi, H. Lim, and A. Sabharwal, "Power-Controlled Medium Access Control Protocol for Full-Duplex WiFi Networks," *IEEE Transactions on Wireless Communications*, vol. 14, no. 7, July 2015.

[10] N. Singh, D. Gunawardena, A. Proutiere, B. Radunovic, H. Balan, and P. Key, "Efficient and Fair MAC for Wireless Networks with Self-Interference Cancellation," in *International Symposium on Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks (WiOpt)*, 2011.

[11] J. Y. Kim, O. Mashayekhi, H. Qu, M. Kazandjieva, and P. Levis, "Janus: A Novel MAC Protocol for Full Duplex Radio," University of Stanford - Computer Science Department, Tech. Rep. CSTR 2013-02, July 2013.

[12] M. Duarte and A. Sabharwal, "Full-Duplex Wireless Communications Using Off-the-Shelf Radios: Feasibility and First Results," in *Asilomar Conference on Signals, Systems and Computers (ASILOMAR)*, 2010.

[13] B. Radunovic, D. Gunawardena, P. Key, A. Proutiere, N. Singh, V. Balan, and G. Dejean, "Rethinking Indoor Wireless Mesh Design: Low Power, Low Frequency, Full-duplex," in *IEEE Workshop on Wireless Mesh Networks (WiMesh)*, 2010.

[14] B. Day, A. Margetts, D. Bliss, and P. Schniter, "Full-Duplex Bidirectional MIMO: Achievable Rates Under Limited Dynamic Range," *IEEE Transactions on Signal Processing*, vol. 60, no. 7, pp. 3702–3713, July 2012.

[15] W. Cheng, X. Zhang, and H. Zhang, "Optimal Dynamic Power Control for Full-Duplex Bidirectional-Channel Based Wireless Networks," in *IEEE INFOCOM*, 2013.

[16] S. Kim and W. Stark, "On the Performance of Full Duplex Wireless Networks," in *Conference on Information Sciences and Systems (CISS)*, 2013.

[17] S. Barghi, A. Khojastepour, K. Sundaresan, and S. Rangarajan, "Characterizing the Throughput Gain of Single Cell MIMO Wireless Systems with Full Duplex Radios," in *International Symposium on Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks (WiOpt)*, 2012.

[18] E. Aryafar, M. A. Khojastepour, K. Sundaresan, S. Rangarajan, and M. Chiang, "MIDU: Enabling MIMO Full Duplex," in *ACM MobiCom*, 2012.

[19] S. Goyal, P. Liu, O. Gurbuz, E. Erkip, and S. Panwar, "A Distributed MAC Protocol for Full Duplex Radio," in *Asilomar Conference on Signals, Systems and Computers*, 2013.

[20] S. Y. Chen, T. F. Huang, K. C. J. Lin, Y. W. P. Hong, and A. Sabharwal, "Probabilistic-Based Adaptive Full-Duplex and Half-Duplex Medium Access Control," in *IEEE GLOBECOM*, 2015.

[21] D. Halperin, W. Hu, A. Sheth, and D. Wetherall, "Predictable 802.11 Packet Delivery from Wireless Channel Measurements," in *ACM SIGCOMM*, 2010.

[22] K. Tan, J. Fang, Y. Zhang, S. Chen, L. Shi, J. Zhang, and Y. Zhang, "Fine-Grained Channel Access in Wireless LAN," in *ACM SIGCOMM*, 2010.

[23] S. Sen, R. Roy Choudhury, and S. Nelakuditi, "No Time to Countdown: Migrating Backoff to the Frequency Domain," in *ACM MobiCom*, 2011.

[24] "Wireless Open Access Research Platform (WARP)." [Online]. Available: http://warpproject.org