Throughput-Fairness Tradeoff MAC for Multiuser IBFD (TFMAC)

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***Abstract*— In this paper, we investigate the user selection techniques for an in-band full-duplex access point that simultaneously transmits and receives data from multiple users for the next-generation wireless local area network. Then, we propose a throughput-fairness tradeoff selection algorithm to enable the AP to maximize the throughput with a maintainable fairness level. In addition, we propose a throughput-fairness medium access control (TFMAC) based on the 802.11 standards to accommodate the requirements of the proposed selection algorithm and support legacy nodes. Our simulation results show that TFMAC improves the throughput compared to multiple state-of-the-art benchmarks while maintaining the desired fairness levels. Also, we study the interplay between the throughput, the uplink fairness, and the downlink fairness for the operation of TFMAC. Finally, we discuss the complexity of the proposed scheme.**

Keywords*— *IBFD, MU-MIMO, MAC, WLAN.

I. Introduction

Increasing demand for higher data rates from new applications has led to research for advanced techniques to improve the performance of wireless networks. In-band full-duplex (IBFD) is a promising technology that improves the spectral efficiency by enabling a node to send and receive data simultaneously using the same frequency [1]. However, self-interference presents a significant challenge for implementing IBFD. Fortunately, several works have been done recently to cancel the self-interference in the propagation, analog, and digital domains [2], making IBFD feasible. Nevertheless, the self-interference cancellation methods are hard to implement and still not feasible in some cases for small form factor devices. Therefore, the research community focused on implementing IBFD only at an access point (AP) as an initial starting point for the new technology in the presence of half-duplex users. Recently, the IEEE 802.11be task group considered including IBFD in the standard of the next-generation wireless local area networks (WLANs) [3]. Another leading technique is multiuser multi-input multi-output (MU-MIMO) which significantly improves the throughput. Also, MU-MIMO enhances the spatial diversity by simultaneously serving multiple users through multiple streams. However, implementing MU-MIMO requires a sophisticated medium access control (MAC) that allows the AP to collect the necessary channel state information (CSI) of the users for multiuser beamforming [4]. Recently, IEEE 802.11ax standardized both uplink and downlink MU-MIM O for the first time in the WLAN [5].

By combining IBFD and MU-MIMO, the AP is able to serve multiple uplink and downlink users simultaneously, leading to a significant increase in the throughput. However, leveraging this combination requires a MAC that mitigates interference due to IBFD, captures the CSI requirements for MU-MIMO beamforming, and provides an appropriate user selection scheme to ensure fairness. There are a few proposed MAC protocols that are designed for MU-MIMO IBFD [6]–[9]. The work in [6] proposed using the idle time in IBFD transmission for constructing a secondary transmission from another user. The authors of [7] proposed using a trigger frame to check the feasibility of IBFD and multiuser transmission after selecting the users. The authors of [8] proposed a multi-stage MAC protocol for IBFD and MU-MIMO by utilizing the carrier sense multiple access with collision avoidance (CSMA/CA) procedure. In [9], the authors proposed using multiple resource units to find the optimal pairs of uplink and downlink users. However, the previous works consider that either the users are predetermined or use a single metric for selecting the users, such as ensuring fairness or maximizing the throughput. For example, the authors of [8] proposed a fairness-based selection algorithm, while the authors of [9] proposed a bipartite graph pairing method to increase the throughput. In this work, we propose a MAC protocol for an IBFD AP that simultaneously serves multiple users. Also, we propose a joint uplink and downlink selection algorithm that maximizes the throughput by trading off some of the fairness only if the fairness levels are maintained above a pre-defined threshold. The main contributions of this paper are as follows.

- We characterize the tradeoff between the throughput and the achievable fairness in an IBFD AP that supports multiuser transmissions. Also, we propose a selection algorithm, TF-FD, that maximizes the throughput with uplink and downlink fairness constraints for an IBFD AP. TF-FD is essentially a joint (uplink and downlink) selection scheme that maximizes the throughput subject to satisfying a constraint on the user-defined fairness threshold (quantified by Jain's fairness index [10]). By adjusting this fairness threshold, the proposed scheme allows a graceful tradeoff in the achieved fairness to improve the throughput in the uplink and the downlink directions among the various users. Furthermore, TF-FD is agnostic to the actual cancellation level and can adapt to the AP's self-interference cancellation capability.
- Also, we propose a medium access control (TFMAC) that offers the required frame structure to obtain the necessary channel state information (CSI), mitigate the inter-user interference that downlink users encounter during active uplink transmission, and enable the use of TF-FD. TFMAC is based on the 802.11 standards and supports legacy nodes.
- The throughput of TFMAC outperforms MuFuPlex [7], ENFD-OMAX [9], and FDMuMAC [8] by an average of 23%, 16%, and 8.5%, respectively, reaching to 39.25%, 37.65%, and 12.2% for a ten-user system. Also, we show that TFMAC can achieve the maximum achievable rate

compared with a hypothetical rate maximization method that sets the upper bound of the proposed MAC.

The rest of the paper is organized as follows. Section II describes the system model. Then, we introduce TF-FD and TFMAC in Section III. In Section IV, simulation results of TFMAC are provided. Finally, we conclude the paper in Section V.

Notations: We use boldface capital and small letters to express matrices and vectors. Also, we use $\mathbf{X}^T$ and $\mathbf{X}^H$ to denote the transpose and the Hermitian form of a matrix $\mathbf{X}$, respectively. Finally, we use boldface scripted letters ($\boldsymbol{\mathcal{U}}$) to represent sets.

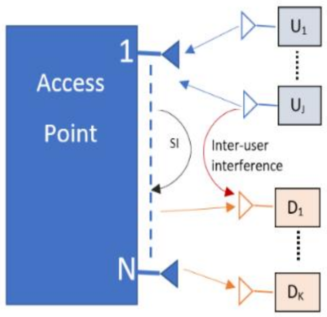

Fig. 1. System model for an IBFD AP that serves multiple users. SI represents the self-interference, U and D represent the uplink and downlink users, respectively.

II. System Model

The system consists of a full-duplex AP with N antennas that can serve up to N uplink and N downlink users simultaneously. In addition, we assume that M single-antenna users are associated with the AP. These M users are divided into J uplink and K downlink users during a multiuser transmission segment such that $K+J \leqslant 2N \leqslant M$, as shown in Fig. 1. The resulting received signal, y_k, at user k is:

$$y_k = \boldsymbol{h}_k^H \boldsymbol{F}_D \boldsymbol{x}_D + \sum_{j=1}^{J} h_{jk} x_j + n_k. \quad (1)$$

Here, $\mathbf{h}_k \in \mathbb{C}^{N\times 1}$ is the channel vector between user k and the AP; $\mathbf{F}_D \in \mathbb{C}^{N\times K}$ is the beamforming precoding matrix for K downlink users; $\mathbf{x}_D \in \mathbb{C}^{K\times 1}$ is the transmitted signal vector from the AP to K downlink users; h_{jk} is the channel between uplink user (j) and downlink user (k); x_j is the uplink signal from user (j); n_k is the additive white gaussian noise (AWGN) with zero mean and unit variance. The resulting signal to interference and noise ratio (SINR) for downlink user (k) is given by:

$$\mathrm{SINR}_{\mathrm{Dk}} = \frac{|\boldsymbol{h}_k^H \boldsymbol{F}_D \boldsymbol{x}_D|^2}{\sum_{j=1}^{J} \left|h_{jk} x_j\right|^2 + \sigma_k^2}, \quad (2)$$

where σ_k^2 is the downlink noise power. On the other hand, the received signals at the AP, $\mathbf{y}_{AP}$, are:

$$\boldsymbol{y}_{AP} = \boldsymbol{W}_U \left(\sum_{j=1}^{J} \boldsymbol{h}_j x_j + \boldsymbol{G}_D \boldsymbol{F}_D \boldsymbol{x}_D + \boldsymbol{n}_u \right). \quad (3)$$

Here, $\mathbf{W}_U \in \mathbb{C}^{J\times N}$ is the beamforming combiner matrix; $\mathbf{h}_j \in \mathbb{C}^{N\times 1}$ is the channel matrix for uplink user (j); x_j is the transmitted signal of user (j); $\mathbf{G}_D \in \mathbb{C}^{N\times N}$ represents the self-interference channel; $\boldsymbol{n}_u \in \mathbb{C}^{N\times 1}$ is the AWGN. The resulting SINR for the uplink user (j) at the AP is given by:

$$SINR_{Uj} = \frac{\left|\boldsymbol{w}_{Uj} \boldsymbol{h}_j x_j\right|^2}{\left|\boldsymbol{w}_{Uj} \boldsymbol{G}_D \boldsymbol{F}_D \boldsymbol{x}_D\right|^2 + \sigma_u^2}. \quad (4)$$

Here, $\mathbf{w}_{Uj} \in \mathbb{C}^{1\times N}$ is the beamforming vector for user (j) such that its elements are equal to the j^{th} row in $\mathbf{W}_u$, and σ_u^2 is the uplink noise power.

We use the channel $h=\partial\,\vartheta$, where ∂ is the path loss between two nodes, and ϑ is a complex independent and identically distributed (i.i.d.) random variable with zero mean and unit variance [11]. Furthermore, we use the minimum mean square error (MMSE) based beamforming technique in [11] to enable the multiuser full-duplex transmission. Finally, we use the IEEE 802.11ax rate adaptation procedure that is based on the effective SINR after beamforming and the received signal strength indicator (RSSI) to determine the users' rates [12].

III. Throughput Fairness Full-Duplex Mac (TFMAC) and Selection Algorithm

The presented system model requires a MAC protocol that enables joint uplink and downlink user selection and channel-based rate adaptation. However, the degree of freedom of the multiuser IBFD is limited by the number of antennas [13]. Further, the AP can only select uplink users that successfully send a request to send (RTS) frame, limiting the choices of uplink users'. In addition, non-selected users may suffer from transmission starvation, leading to dropping the packets or out-of-date transmission. Also, the MAC protocol's design must assist the AP in collecting all the necessary data for the multiuser beamforming. Hence, in this section, we introduce a selection algorithm (TF-FD) that maximizes the throughput and ensures fairness for the aforementioned system. Also, we present a MAC (TFMAC) that enables the AP to use TF-FD, mitigate the inter-user interference, and acquire the channel for the full-duplex beamforming. TFMAC is based on the IEEE 802.11 standards and is compatible with legacy nodes.

A. TF-FD Selection Algorithm

TF-FD is a user-selection algorithm that maximizes the throughput if and only if the fairness levels (uplink and downlink fairness) are above or equal to a pre-defined fairness threshold (α_{th}). TF-FD jointly considers uplink and downlink fairness in selecting the users. Therefore, if the fairness levels are lower than the fairness threshold, the AP selects the users to assure fairness. In this case, the throughput is not maximized, but the fairness is ensured to be higher than or equal to the fairness threshold. The network administrator sets fairness threshold to ensure a certain quality of service and avoid transmission starvation from non-selected users, which may lead to dropped packets or out-of-date transmissions.

We use Jain's fairness index to quantify the fairness level, which ranges between zero and one [10]. Hence, the uplink temporal fairness (α_u) is given by:

$$\alpha_u = \frac{\left(\sum_{m=1}^{M} T_u(m)\right)^2}{M \sum_{m=1}^{M} \left(T_u(m)\right)^2}, \quad (5)$$

where $T_u(m)$ is the amount of time (measured in milliseconds) that user (m) uses for uplink transmission. Similarly, we find the downlink fairness (α_d) by substituting $T_u(m)$ with ($T_d(m)$), which represents the time user (m) used downlink transmission.

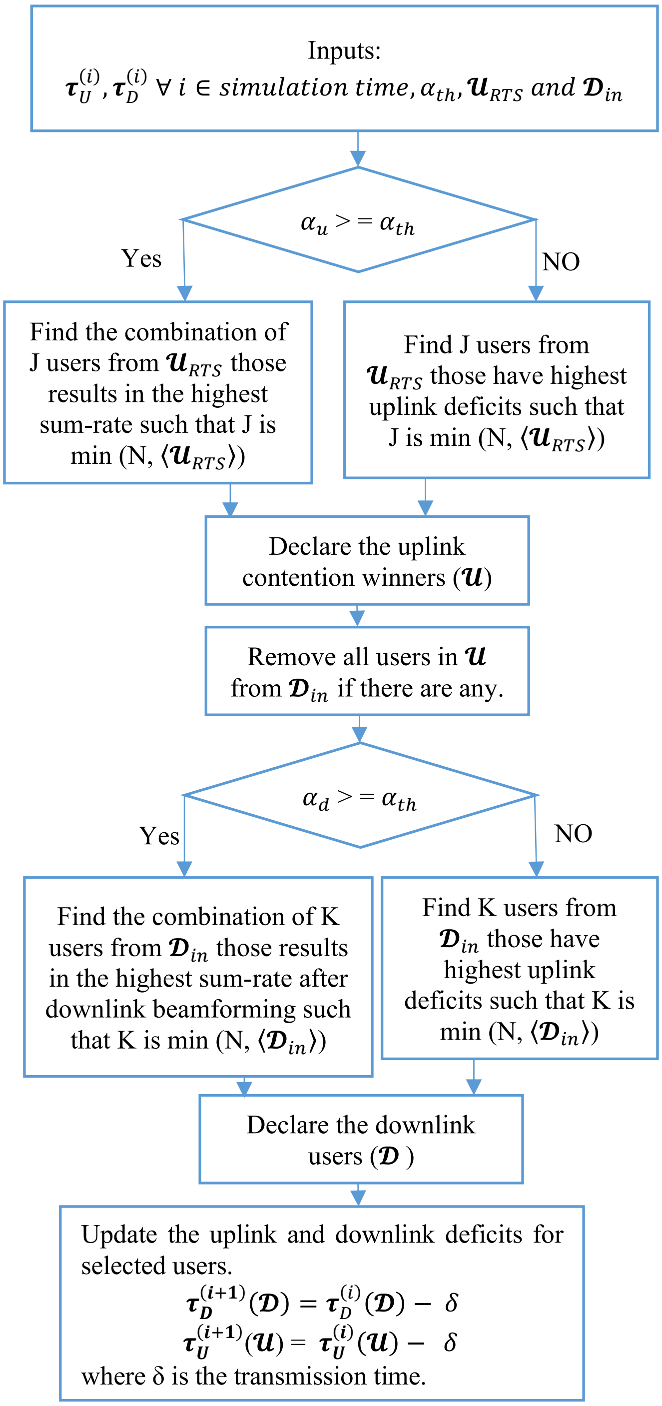

Fig. 2. Flowchart for TF-FD selection algorithm.

To implement TF-FD, we define for each user uplink deficit ($\tau_u(m)$) and downlink deficit ($\tau_d(m)$) counters that are initialized for all the users as soon as they join the network. These deficits count the number of missed transmission opportunities, *i.e.,* when the user was not selected for transmission. In other words, one deficit unit means that the user missed one transmission period. Also, we define the following sets. The first set is the potential uplink users ($\mathcal{U}_{RTS}$) that represent users who successfully send an RTS frames. The second set consists of the potential downlink users ($\mathcal{D}_{in}$) defined by the AP, as discussed later. The final two sets are the selected uplink users ($\mathcal{U}$) and downlink users ($\mathcal{D}$), representing the TF-FD output.

The algorithm, as shown in Fig. 2, starts by computing the uplink fairness index using (5) with the assumption that the uplink and downlink deficits are initialized to zero for all new users (*i.e.,* $\tau_u(m) = \tau_d(m) = 0$ for any new user). Then, if the uplink fairness index is higher than α_{th}, the AP chooses the N uplink users that maximize the throughput from the $\mathcal{U}_{RTS}$ by computing the achievable rate after beamforming to each combination of N uplink users. Otherwise, the AP selects the uplink users based on a deficit round-robin algorithm [14], which means the AP selects N users from $\mathcal{U}_{RTS}$ with the highest deficit to improve current uplink fairness levels. After selecting the uplink users, the algorithm computes the downlink fairness index α_d. Then, the AP defines the set of potential downlink users ($\mathcal{D}_{in}$) according to the current downlink fairness level. If the downlink fairness is less than the fairness threshold, the AP selects N users with the highest downlink deficit to improve the downlink fairness. Otherwise, the AP considers K_{POLL} users with the highest downlink deficits as $\mathcal{D}_{in}$, such that K_{POLL} is higher than N. Then, the AP starts searching for a combination of N users that maximizes the downlink throughput by computing the achievable rate after beamforming to each combination of N users from the K_{POLL} users. Consequently, the AP selects the N users from $\mathcal{D}_{in}$ that maximize the downlink throughput as downlink users. Finally, the AP updates the uplink and the downlink deficits for selected users. TF-FD final outputs are the uplink users ($\mathcal{U}$), the downlink users ($\mathcal{D}$), and the updated uplink and downlink deficits.

B. *TFMAC*

To implement TF-FD, the AP must acquire the appropriate uplink and downlink channels and the interference level that a downlink user would encounter from the potential uplink users. This information enables the AP to compute the rates after beamforming for uplink and downlink users. Then, the AP can select a combination of uplink and downlink users to maximize the throughput or ensure fairness based on the outcomes of TF-FD. In this section, we present the TFMAC that enables the AP to fulfill the aforementioned requirements.

TFMAC has six stages, as shown in Fig. 3. In the first stage, the AP sends a beacon frame to all M users that notifies them about the beginning and the length of the contention stage. Then, users start contending for the uplink channel by sending an RTS after the expiration of a randomly selected backoff counter during the second stage. In this stage, a transmission collision may occur if two users have the same backoff counter and send an RTS frame simultaneously. Aside from that, the AP receives the transmitted RTS frame and acquires the user's channel that the AP uses in the beamforming combiner. By the end of the contention stage, the AP receives multiple RTS frames where the number of the received RTS frames may exceed N, which is the highest number of users that the AP can serve for uplink transmission. Therefore, the AP selects J (up to N) uplink users from those who successfully send an RTS to the AP using TF-FD. Then, the AP sends a C/RTS frame that serves as a clear-to-send (CTS) frame to the J uplink users in TFMAC's fourth stage. Also, this C/RTS frame serves as an RTS to the K_{POLL} potential downlink users, which determines the duration of this stage. The number of polled users (*i.e.,* K_{POLL}) plays a critical role in TFMAC. High K_{POLL} increases the search space for downlink users, which maximizes the downlink

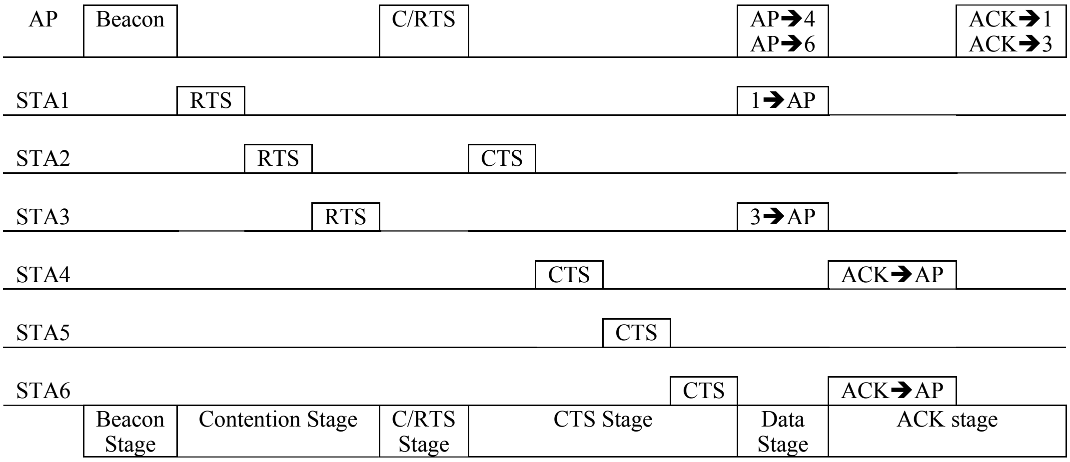

Fig. 3. TFMAC's frame structure. Here, the AP selects users 1 and 3 as uplink users and considers users 2,4,5 and 6 as downlink users by sending a C/RTS frame to these users. Then, the AP finalizes the downlink users selection by using TF-FD, which results in selecting users 4 and 6 in this example.

throughput with a cost of an increased protocol overhead due to increasing the length of this stage and vice versa. In Section IV.C, we empirically study the effect of K_{POLL} to determine its optimal value under different scenarios. In the next stage, these K_{POLL} users sequentially send CTS frames to the AP, which enables the AP to acquire the channels of the downlink users. Also, these downlink users report in their CTS frames the interference levels they encounter from the selected J uplink users to mitigate the effect of inter-user interference in the downlink beamforming. Then, the AP chooses K (up to N) users for downlink transmission according to the output of TF-FD. After that, The AP sends data to the downlink users while receiving data from the uplink users. Finally, the AP and the users exchange the acknowledgment (ACK) frames for the received data upon successful data transmission. Fig. 3 shows an example of a TFMAC frame structure for a two-antenna AP and six users that are associated with the AP.

TABLE I. SIMULATION PARAMETERS

Parameter	Value
Physical header	20 µs
Slot time	9 µs
Short Inter-Frame Space (SIFS)	16 µs
Distributed Interframe Space (DIFS)	34 µs
Frame Size	1500 Bytes
TXOP	0.005 s
Contentions Stage Length	360 µs
Number of streams (N)	4

IV. SIMULATION RESULTS

We conduct extensive simulations using MATLAB to evaluate the performance of the proposed MAC protocol. We assume the AP is placed in the center of an area of 100m x 100m to ensure the signal is distributed equally within this area. We consider a system with 10, 20, 30, and 40 half-duplex users associated with the AP. The results represent the average of ten trials with different random placements of the users in each trial. We set the maximum transmission power to 27 dBm and 20 dBm for downlink and uplink transmission, respectively. We assume that all users are fully backlogged (*i.e.,* users have data to send at all times). Also, we consider that the full-duplex AP can cancel 83 dB from its self-interference [11]. The rest of the simulation parameters are shown in Table I.

A. Throughput Comparison

In this section, we compare the results of TFMAC with the following state-of-the-art MAC protocols:

- MuFuPlex [7]: In this protocol, the AP sends a full duplex trigger frame for users. Then, the AP defines uplink and downlink pairs to each RU. Finally, the AP sends a bulk ACK frame to uplink users while the downlink uses to send an ACK frame to the AP for the received data.
- FDMuMAC [8]: A contention only MAC protocol with a full duplex AP that supports multiple users. In this protocol, the AP sends a beacon for all users to start contending for uplink transmission. Then, the AP announces the uplink contention winners and selected downlink users based on a fairness mechanism. After that, the AP and uplink users start sending data. Finally, the downlink users and the AP send an ACK frame for the received data.
- ENFD-OMAX [9]: In this protocol, users start contending for uplink link by sending an RTS frame on one of the available RUs after receiving a beacon frame from the AP. Then, the AP sends a group CTS to the winners and selected downlink users. After that, each downlink user sends a CTS frame on a specified RU. The received control frames enable the AP to search for optimal uplink-downlink pairs on each RU using a bipartite graph method. Finally, the data transmission phase occurs where the data and ACK frames are exchanged.

In this comparison, we set the fairness threshold for TFMAC to 0.8, which means that the uplink and downlink Jain's fairness index must be higher than or equal to 0.8. In addition, we set K_{POLL} to eight, which means that the AP selects N users from eight users as downlink users. The results in Fig. 4 show that TFMAC achieves an average gain of 23%, 16%, and 8.5% compared with MuFuPlex, ENFD-OMAX, and FDMuMAC, respectively. For a ten-user system, TFMAC achieves significant gain improvement by 39.25% and 37.65% compared with MuFuPlex and ENFD-OMAX, respectively, since TFMAC's chances of completely utilizing the four streams increase with the relaxation of the fairness restrictions compared with other protocols. In addition, the gain of TFMAC is 12.2% compared with FDMuMAC with ten users since ensuring fairness with TFMAC is easier with few users. Nevertheless, TFMAC outperforms the MuFuPlex, ENFD-OMAX, and FDMuMAC with forty users by a gain of 13.75%, 6.2%, and 6.7% since TFMAC maximizes the uplink and downlink throughput as long as the overall Jain's fairness index is higher than the fairness threshold.

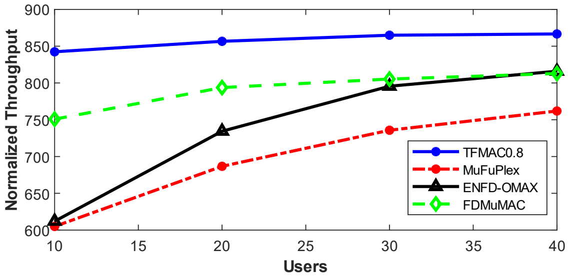

Fig. 4. Throughput comparison between TFMAC, MuFuPlex [7], ENFD-OMAX [9], and FDMuMAC [8], where 0.8 indicates the fairness threshold for TFMAC is 0.8, and the normalization is to the throughput of TFMAC for forty users.

B. *Throughput-Fairness Tradeoff Results*

Here, we consider the following user selection methods to compare with the results of the proposed selection scheme:

- Random: The AP randomly selects N uplink users from the contention winners. Then, the AP randomly selects N downlink users other than the chosen uplink users.
- Opportunistic (MAX): The opportunistic scheme theoretically produces the maximum achievable throughput by the proposed MAC protocol. In this scheme, the AP selects users that maximize the throughput. Here, we hypothetically assume that the AP has full knowledge of all the channels and interference levels without additional overhead requirements.
- Fairness: The AP strictly selects uplink and downlink users based on their deficits to achieve maximum fairness, which means that the AP only selects users with the highest deficits to ensure fairness.

Fig. 5 shows the throughput and fairness results for TFMAC with different fairness thresholds and three other selection methods. For TFMAC, we set K_{POLL} to eight and varied the fairness threshold (α_{th}) between 0.1 to 0.9. Fig. 5(a) shows the normalized throughput for the aforementioned selection schemes, where we use the Random method as the reference for the results. As expected, the MAX scheme achieved the highest throughput since this scheme maximized the throughput without additional overhead, making this scheme the theoretical upper bound. Also, the figure shows that TFMAC outperforms the Random and Fairness scheme by an average gain of 12.5% and 13%, respectively. As expected, decreasing the fairness threshold from 0.9 to 0.1 leads to an increase in the throughput. This result is due to the fact that for small values of α_{th}, the measured fairness is always higher than α_{th}. Consequently, the TFMAC throughput is similar to the throughput of the MAX scheme. Further, the throughput improvement by decreasing α_{th} experiences diminishing returns after α_{th} decreases below 0.5. Next, we show in Fig. 5(b and c) the downlink and uplink fairness levels of TFMAC as well as the other schemes. The results show that TFMAC downlink fairness levels are higher than the fairness threshold. In fact, these downlink fairness levels approach the Fairness scheme levels and significantly outperform the MAX

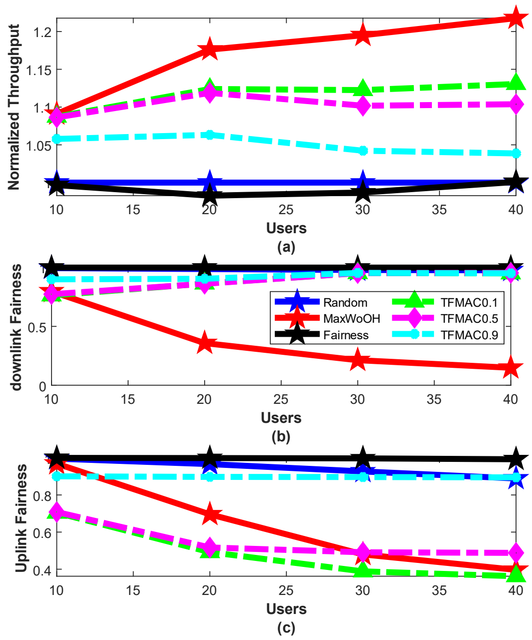

Fig. 5. Comparing TFMAC results with different selection schemes. (a) throughput, (b) downlink fairness, and (c) uplink fairness.

scheme levels with an increased number of users. On the other hand, TFMAC maintains the uplink fairness level to be higher than or equal to the fairness threshold, as shown in Fig. 5(c).

To further study TFMAC, we show in Fig. 6 the saturation throughput (x-axis) and the uplink and downlink fairness indices (y-axis) for twenty users. Also, we show the results of the MAX scheme if we consider the required overhead to implement the MAX scheme using the proposed frame structure, which we label as MaxWOH. The results show that reducing the fairness restriction by a few points to α_{th}=0.9 with TFMAC results in an improvement of 7.9% and 10% compared to the Random and Fairness schemes with the uplink and downlink fairness levels that are similar to the levels for the fairness scheme. Furthermore, TFMAC throughput gains increase with increased relaxation in the fairness threshold. For example, the TFMAC throughput with a fairness threshold of α_{th}=0.5 outperforms random and fairness schemes by 13.8% and 14%, respectively.

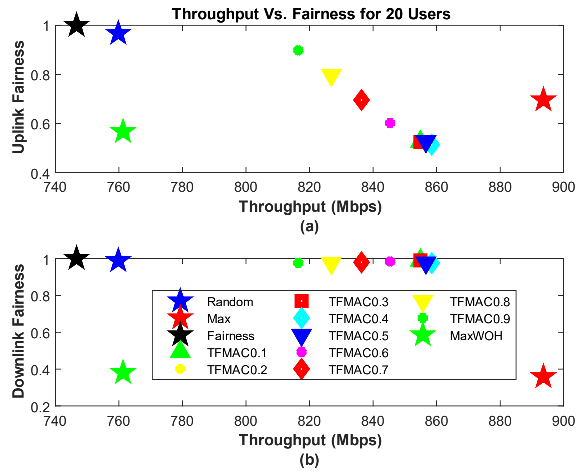

Fig. 6. Comparing twenty users' system results with different selection schemes. The x-axis shows the throughput. The y-axis in (a) shows uplink fairness and (b) shows the downlink fairness.

C. TFMAC Parameters Study

We empirically study the effect of the number of polled downlink users in TFMAC. In Section III.B, we showed that increasing the polled users (*i.e.,* K_{POLL}) for downlink transmission resulted in an undesired increase in the protocol overhead. On the other hand, the search space for downlink users that achieve higher throughput increases with increasing polled users. To find the optimal value of K_{POLL}, we use the case for ten and forty users to cover a low and high number of users with a fixed fairness threshold while varying the value of polled users such that K_{POLL} varies from 4 to 8. Fig. 7 shows that increasing K_{POLL} from four to five significantly improves the downlink throughput since the AP is able to search for a combination of downlink users, which results in higher downlink throughput. This increase, however, slightly reduces the uplink throughput, but the sum throughput is still higher than when K_{POLL} equals four. Also, the results show that increasing K_{POLL} to eight results in a degradation in the throughput due to the additional overhead from K_{POLL}. In conclusion, we believe the size of K_{POLL} should be slightly above the number of antennas (N) to ensure that there are enough polled users and to avoid extreme overhead addition that reduces the throughput.

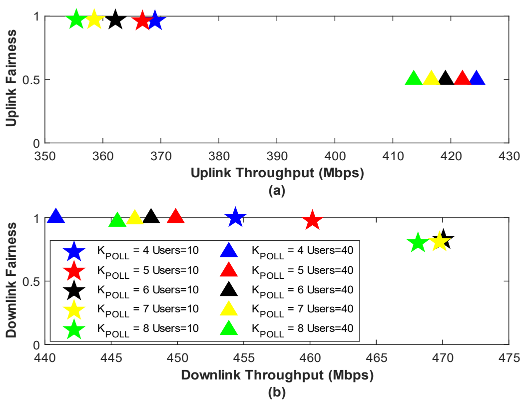

Fig. 7. Comparing a TFMAC with 10 and 40 users results with different K_{POLL}. (a) uplink throughput vs. uplink fairness and in (b) downlink throughput vs. downlink fairness.

D. Complexity Analysis

The complexity of TFMAC is dominated by finding the combination of uplink and downlink users that produce the highest rate during the data transmission time. For uplink users, the AP selects N uplink users after sorting their transmission rate. This user selection has a worst-case complexity of $O(J^2)$. However, the growth of J is upper bounded by the length of the contention stage for uplink users, which makes only a few users win the contention (*i.e.,* the size of J is small). On the other hand, finding the combination of downlink users has a worst-case scenario complexity of $O(K_{POLL}$ choose N). Here, the value of K_{POLL} dominates the complexity of TFMAC since N is fixed by the number of antennas, so increasing K_{POLL} will result in a massive increase in complexity. However, in the previous sub-section, we show that TFMAC does not need an enormous increase in K_{POLL} to achieve its purpose. In fact, the TFMAC maximum throughput is achieved in most cases by a K_{POLL} higher than N by only one. This limits the proposed method's complexity and makes it feasible to implement without any complexity concerns.

V. Conclusions

In this paper, we characterized the throughput-fairness tradeoff for an IBFD AP that supports MU-MIMO and proposed TFMAC, a MAC protocol that achieves this tradeoff. We showed that TFMAC throughput outperformed existing state-of-the-art schemes and approached the throughput of an optimal scheme with ideal downlink fairness and a controlled reduction in the uplink fairness. Then, we empirically studied TFMAC under different conditions to find the optimal operation points. Finally, we studied the complexity of TF-FD and showed that it is feasible to implement without intensive computational resources. In future work, we plan to study user-selection methods for a multi-AP system. In addition, we will study the effect of the AP's self-interference cancellation capability on TFMAC.

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