HyFDMAC: A Hybrid Access Full-Duplex MAC Protocol

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***Abstract*—In this paper, we propose a hybrid medium access control (HyFDMAC) protocol that integrates random and scheduled access for infrastructure-based wireless networks. HyFDMAC consists of multiple stages based on IEEE 802.11 distributed coordination function and enables a full duplex access point (AP) to collect the channel and interference information required for multiuser transmission. HyFDMAC guarantees fairness using the random and scheduled access mechanisms. Our simulation results show that the HyFDMAC throughput outperforms two state-of-the-art MAC protocols, namely MU-FuPlex and EnFD-OMAX, by an average gain of 18% and 11.3%, respectively, with backlogged traffic. Also, HyFDMAC throughput is 7% higher than a purely random-access protocol with a 10% reduction in the delay. Furthermore, we evaluate the performance of HyFDMAC with non-backlogged users compared with purely scheduled access and random-access protocols. The results show that HyFDMAC increases the throughput by 53% and 45% compared with scheduled and random access, respectively.**

Keywords— Full-Duplex, IBFD, MU-MIMO, WLAN.

I. Introduction

The annual growth rate of machine-to-machine connected devices is estimated to be 30% [1]. This rapid growth in the number of connected devices has led to the investigation of new techniques to increase data transmission rates and improve link efficiency. Currently, the IEEE 802.11be task group for next-generation wireless local area network (WLAN) standard [2] considers several techniques to fulfill this demand, including using wireless in-band full duplex (IBFD) and improving the current deployment of the multiuser multi-input multi-output (MuMIMO) techniques [3]. In this paper, we develop a new medium access control (MAC) technique that supports IBFD in conjunction with MuMIMO to meet the increasing need for connectivity.

The primary appeal of IBFD is the potential to double the spectral efficiency by allowing a node to send and receive data simultaneously using a single frequency band [4]. IBFD also provides a solution for hidden and exposed node problems [5] and an additional layer of security in the presence of eavesdroppers [6]. Furthermore, IBFD reduces average packet delay and improves fairness [7]. However, self-interference (SI) cancellation is a major challenge when deploying IBFD for wireless communication. Fortunately, many works have been done to address this issue in the propagation, analog, and digital domains to enable IBFD [8]. Another critical challenge for IBFD is the need for an effective medium access control (MAC) protocol. The benefits of IBFD diminish without a MAC that manages the active transmissions to avoid collisions and mitigate interference [9]. Currently, there is no wireless communication standard that includes IBFD. Nevertheless, there are many proposed IBFD medium access solutions for WLAN and cellular networks [10]–[15].

MuMIMO increases the spatial diversity by allowing multiple users to send or receive data simultaneously. However, MuMIMO requires sophisticated techniques that enable the AP to distinguish the data of each user from received signals and enables users to decode their data from the received signal [16]. These requirements can be accommodated by using an appropriate beamforming combiner at the receiver or transmit beamforming precoder. However, the design of those combiners and precoders requires the acquisition of all participating users' updated Channel State Information (CSI). The CSI acquisition can be obtained explicitly at the AP by asking the users for their CSI or implicitly by estimating the CSI from the received packets and using channel reciprocity. Consequently, a MAC protocol is needed to operate a MuMIMO network, as proposed in [17] and [18]. In WLAN, the IEEE 802.11ac introduced only downlink MuMIMO for four streams in sub-6 GHz bands. The current IEEE 802.11ax standard includes uplink and downlink MuMIMO. The next generation WLAN aims to support 16 uplink and downlink streams.

There are several proposed MAC protocols that combine IBFD and MuMIMO using different methods [10]–[14]. For instance, the authors of [10] proposed a spatial grouping strategy for multiuser IBFD. In this protocol, users are divided into multiple groups such that the uplink users in one group do not interfere with the downlink users in another group to mitigate the inter-user interference during the multiuser data transmission by avoiding selecting a downlink user from a group that has an uplink user. A protocol that uses a full duplex trigger frame to establish a multiuser IBFD connection by using multiple resource units (RU) is proposed in [11]. A pairing algorithm that maximizes the multiuser full duplex throughput by using multiple RUs is proposed in [12]. The previous two works only consider one full duplex pair (one uplink and one downlink user) per RU to limit the effect of inter-user interference. However, using multiple RUs reduces the accessed bandwidth for transmitting data. For asymmetric uplink-downlink data transmission, the authors of [13] proposed a MAC that establishes a second uplink or downlink connection during the idle time of the asymmetric link, which means only one full duplex pair transmits at any given time. Finally, the authors of [14] proposed a multiuser MAC protocol for an asymmetric IBFD configuration. However, this protocol introduces a massive overhead from the time allocated to the control frames, which affects the overall throughput significantly.

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The main contributions of this paper are as follows:

- We propose a hybrid MAC for a full duplex AP that incorporates random and scheduled access for uplink transmissions and simultaneously allows concurrent downlink transmissions to multiple users. HyFDMAC obtains the benefits of random access by allowing users to contend for the transmission as soon as they have data to send, which reduces the packet delay. In addition, it allows the AP to schedule uplink transmission, which improves spectrum utilization and ensures fairness. Also, HyFDMAC increases the successful uplink access probability, increasing the network's overall throughput. The HyFDMAC design is compatible with full duplex and half duplex legacy users.
- HyFDMAC throughput outperforms two state-of-the-art protocols. In particular, HyFDMAC average throughputs are 18% and 11.3% higher compared with MU-FuPlex [11] and EnFD-OMAX [15]. Also, we compare the HyFDMAC performance against two baselines that represent two extreme cases. The first baseline uses scheduled access (*i.e.,* TDMA), and the second baseline is a random-access MAC. The simulation results show that HyFDMAC outperforms the random access in all metrics (throughput, average packet delay, and fairness) and maintains a comparable performance level to the optimal case with fully backlogged traffic. Also, we show that HyFDMAC deployment for non-backlogged traffic increases throughput by 53% and 45% compared with TDMA and random access, respectively.

The rest of the paper is organized as follows. In Section II, we present the system model. Then, we describe HyFDMAC in Section III. In Section IV, we show the results of the proposed MAC. Finally, we conclude the paper in Section V.

Notations: We use boldface capital and small letters to express matrices and vectors, respectively. We use X^T and X^H to denote the transpose and the Hermitian form of a matrix X, respectively.

II. System Model

We consider an infrastructure-based WLAN system that consists of a full duplex AP that is equipped with N antennas and M single-antenna users that are associated with the AP. The AP can send data to N downlink users while simultaneously receiving data from N uplink users. We denote the actual number of uplink and downlink users as J and K, respectively, such that J and K are less than or equal to N, as shown in Fig. 1. To enable the downlink multiuser transmission, the AP uses a beamforming precoder ($\mathbf{F}_D \in \mathbb{C}^{N\times K}$) to mitigate the effect of the downlink channels ($\mathbf{h}_k \in \mathbb{C}^{N\times 1}$) [19]. Also, the downlink users receive the concurrent uplink transmission from other uplink users since the AP operates in the full duplex mode, which is denoted as inter-user interference. The resulting received signal, y_k, at user k is given by:

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

Here, ($\mathbf{x}_D \in \mathbb{C}^{K\times 1}$) 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. From (1), the SINR of downlink user k is given by:

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

where σ_k^2 is the downlink noise power. For multiuser reception, the AP uses a beamforming combiner ($\mathbf{W}_u \in \mathbb{C}^{J\times N}$) that enables the AP to distinguish the signal of each uplink user and decode its data. As a result, the received signals, y_{AP}, at the AP are given by:

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

Here, $\mathbf{h}_j \in \mathbb{C}^{N\times 1}$ is the channel vector 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 between the antennas of the AP; $\mathbf{n}_u \in \mathbb{C}^{N\times 1}$ is the AWGN with zero mean and covariance as a unity matrix. The SINR for the uplink user j at the AP is given by:

$$SINR_j = \frac{\left|\boldsymbol{w}_{Uj} \sum_{j=1}^{J} \boldsymbol{h}_j x_j\right|^2}{\left|\boldsymbol{w}_{Uj} \boldsymbol{G}_D \boldsymbol{F}_D \boldsymbol{x}_D\right|^2 + \sigma_u^2}, \quad (4)$$

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

We use the channel $h=\partial\,\vartheta$, where ∂ is the large-scale fading 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 [20]. Also, we use the beamforming technique based on the minimum mean square estimate (MMSE) and the path loss model in [19] to find the beamforming precoder and combiner. Then, we use the IEEE 802.11ax rate adaptation technique based on the signal to interference and noise ratio (SINR) and the received signal strength indicator (RSSI) for each user after the beamforming (see Table 20-20 in [21]).

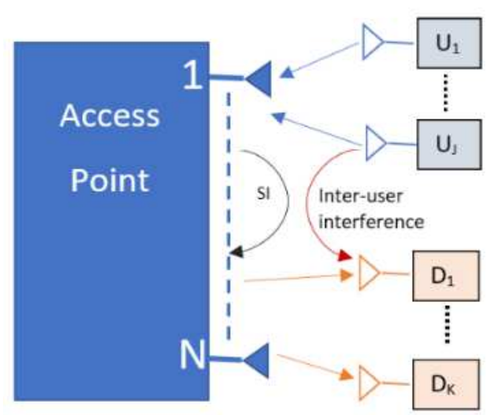

Fig. 1. Full-duplex MU-MIMO system model. SI is self-interference, U and D represent, respectively, the uplink and downlink users.

Frame Control 2 Bytes	Duration 2 Bytes	FCS 4 Bytes

(a)

Frame Control 2 Bytes	Duration 2 Bytes	AP Address 6 bytes	Transmitter address 6 bytes	FCS 4 Bytes

(b)

Frame Control 2 Bytes	Duration 2 Bytes	AP Address 6 Bytes	Stations addresses (J+R+Q)*6 Bytes	FCS 4 Bytes

(c)

Frame Control 2 Bytes	Duration 2 Bytes	AP Address 6 Bytes	Encountered Interference 2 Bytes	FCS 4 Bytes

(d)

Frame Control 2 Bytes	Duration 2 Bytes	AP Address 6 bytes	Transmitter address 6 bytes	FCS 4 Bytes

(e)

Frame Control 2 Bytes	Duration 2 Bytes	Transmitter Address 6 Bytes	FCS 4 Bytes

(f)

Fig. 2. Control frames components: (a) Beacon frame, (b) RTS frame, (c) G-CTS frame, (d) ATS frame, (e) CTS frame, (f) ACK frame.

III. CONTENTION-SCHEDULED ACCESS MAC

The HyFDMAC process consists of six stages. These stages are similar to the four-way handshake mechanism (*i.e.,* RTS-CTS-DATA-ACK) in the basic 802.11 Distributed Coordination Function (DCF). In the first stage, the AP sends a beacon frame to all users, signaling the start of the contention for uplink transmission and informing the users about the duration of the next stage. In the second stage, users with uplink data compete to send a request to send (RTS) frame to the AP to earn an uplink connection. This competition starts by assigning a contention window (CW) for each user that increases with unsuccessful RTS frame transmission. Then, the users select a random backoff timer between zero and 2^{CW} and wait for the expiration of this timer. After the expiration of this timer, users start sensing the transmission medium. If the medium is idle (*i.e.,* no active transmission), the users send an RTS frame. Otherwise, the users wait and keep sensing the medium until it becomes idle. A collision may occur if two users send an RTS simultaneously. However, if a user sends a successful RTS frame, the AP estimates the user's CSI from the received RTS frame, which is used later by the AP. The network administrator defines the length of this stage, which is included in the transmitted AP beacon frame. As the length of this stage increases, more users can win the uplink contention. However, the lengthening of the stage might decrease overall throughput.

In the third stage, the AP selects uplink and downlink users for data transmission. In this stage, the AP has two sets of potential uplink users. The first set consists of the contention winners *(i.e.,* random access users), where the members of this set are the users who successfully send an RTS frame during the contention stage. The second set consists of the other users with uplink data to send but could not send an RTS during the contention stage (*i.e.,* scheduled access users). Hence, the AP first selects the uplink contention winners for uplink transmission. Then, the AP selects additional uplink users if it can support more users for uplink transmission, meaning the contention winners are less than the number of antennas (N) at the AP. Nevertheless, if the received RTS frames are higher than the N, the AP selects only N users and ignores other contention winners' RTS frames. Then, the AP selects N users for downlink transmission. To ensure fairness, the AP selects the users by using a deficit round-robin [22] such that the AP defines and initializes uplink and downlink deficit counters for each user that joins the network. These deficits track the user's uplink and downlink transmission such that a non-selection of this user results in an increase in the deficit, and vice versa. Hence, in this stage, the selected uplink users by scheduled access are the users with the highest uplink deficits. Also, the users with the lowest uplink deficits receive less priority in selection during the contention process. . In addition, the users selected for downlink transmission are the users with the highest downlink deficits. After selecting the users, the AP sends a group clear to send (G-CTS) frame for the selected users. Non-selected uplink users who sent an RTS raise their CW and wait for the next contention stage to compete for uplink transmission.

In the fourth stage, the scheduled access users reply to the G-CTS by sending an accept to send (ATS) frame to the AP. Then, the chosen downlink users send a clear to send (CTS) frame containing the interference levels that the downlink users encounter from the selected uplink users, which is used for the downlink beamforming [23]. By the end of the fourth stage, the AP will have the uplink CSIs from the sent RTS and ATS frames by the selected uplink users. In addition, the AP will acquire the downlink CSIs from the received CTS frames.

The fifth stage is the data transmission stage. In this stage, the AP sends data to the downlink users with the appropriate transmission rate for each user after beamforming. Similarly, each uplink user starts transmitting to the AP with the proper transmission rate after beamforming. In HyFDMAC, the length of this stage is significantly higher than other stages, which increases transmission efficiency.

In the final stage, the AP sends an acknowledgment (ACK) frame to the uplink users. Similarly, the downlink users send an ACK to the AP for received downlink data. By the end of this stage, the uplink stations reduce their CW size to the CWmin. Fig. 2 shows the components of the used control frames in HyFDMAC.

It is worth noting that HyFDMAC allows the AP to operate in half duplex mode under certain conditions by removing either the second or fourth stage for uplink or downlink-only transmission. Also, HyFDMAC accommodates full duplex users by considering them for concurrent uplink and downlink selection.

An example of the HyFDMAC frame structure is shown in Fig. 3 for a full duplex AP with three antennas, i.e., it can concurrently support three uplink and downlink users. In this example, users 1 and 4 win the uplink contention after successfully sending an RTS frame to the AP. Then, the AP

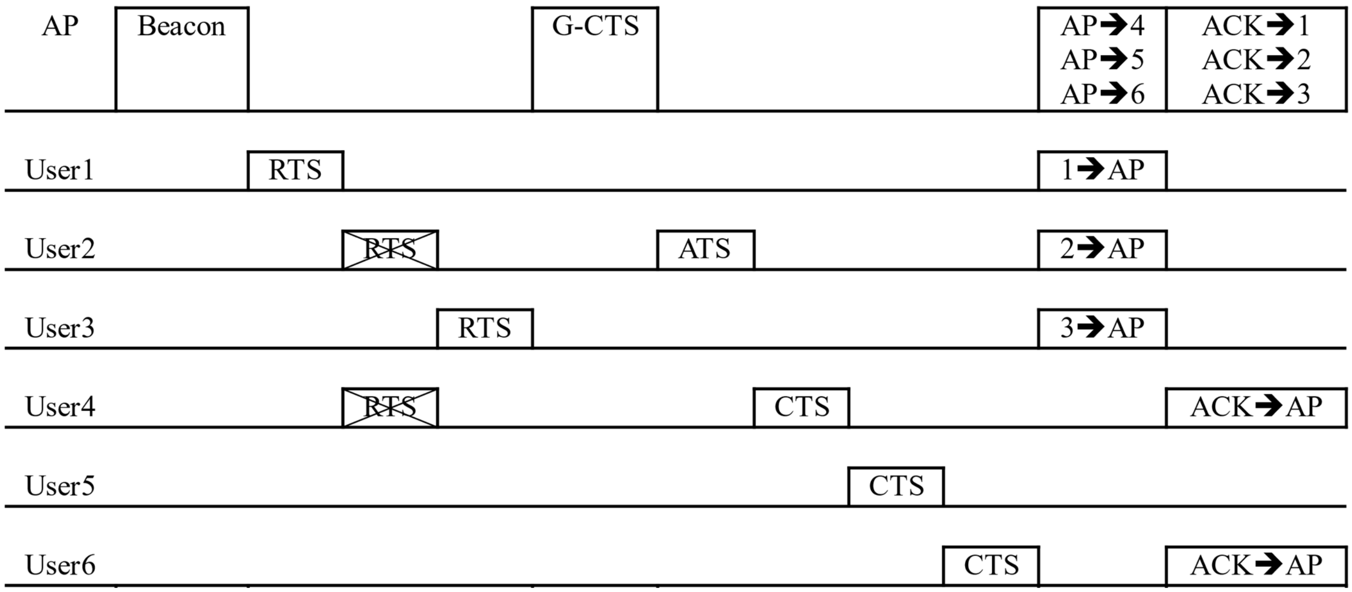

Fig. 3. Example of HyFDMAC protocol timeline. In this example, the AP has three antennas and can support 3 full duplex transmission. The AP announces users 1 and 3 as uplink contention winners and selected user 2 as a scheduled access user. Also, the AP selects users 4, 5 and 6 for downlink transmission.

chooses user 2 as a scheduled access user to fill the vacant uplink stream. Also, the AP selects users 4, 5, and 6 for the multiuser downlink stream. After selecting the users, the AP sends a G-CTS to those selected users. Next, the scheduled access user (*i.e.,* user 2) sends an ATS frame. Then, the downlink users send CTS frames containing the interference levels they encountered from the RTS and ATS frames transmission by the uplink users. After that, the AP and uplink users start transmitting their data using the appropriate transmission rate. Finally, the AP sends a block ACK frame to uplink users while receiving ACK frames from the downlink users.

TABLE I SIMULATION PARAMETERS

Parameter	Value
Physical header	20 µs
Slot time	9 µs
Short Interframe Space (SIFS)	16 µs
Distributed Interframe Space (DIFS)	34 µs
Transmission opportunity (TXOP)	5 mSec
Contention Stage Duration	96 µSec

IV. SIMULATION RESULTS

We run extensive simulations using MATLAB to evaluate the performance of HyFDMAC. The AP is placed in the center of a 100m x100m area, and the users are distributed at random around it. Unless otherwise stated, we assume that all users are fully backlogged (have data to send all of the time). The outcomes are the average of ten experimental trials. In addition, we fix the number of antennas on the AP to four. We set the downlink transmission power at the AP to 27 dBm and the uplink transmission power to 20 dBm. We assume the AP can cancel 83 dB of self-interference. Table I shows the remainder of the simulation parameters.

To compare the proposed MAC protocol performance, we consider the following state-of-the-art benchmarks:

- MU-FuPLEX [11]: This protocol utilizes the orthogonal frequency division multiple access (OFDMA) to establish multiple full duplex transmissions in each RU. Also, MU-FuPLEX uses a trigger frame that the AP sends for users to start a full duplex transmission. Then, the AP sets uplink and downlink pairs for each RU. Finally, the AP and downlink users send an ACK frame to the transmitters.
- EnFD-OMAX [15]: This protocol uses multiple RUs, so one pair of uplink-downlink users sends their data on each RU. In this protocol, users start contending for the uplink link using a mechanism similar to the DCF, by sending an RTS frame on one of the available RU after receiving a beacon frame from the AP. Then, the AP sends a group CTS to uplink contention winners and selected downlink users. After that, each downlink user sends a CTS frame on a specified RU by the AP. 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, exchanging the data and ACK frames.

In addition, we define two baselines to compare the performance of HyFDMAC. These baselines follow a MAC frame structure similar to HyFDMAC as follows.

- Scheduled Access (*i.e.,* TDMA): The AP selects the uplink users without the contention stage, significantly reducing overhead. Here, the AP collects the required beamforming information using the C/RTS method in HyFDMAC. This method represents the upper bound of the proposed MAC protocol with backlogged users.
- Random Access: We adopted FD-MUMAC [14] as a baseline for random access. FD-MUMAC is a contention-only MAC protocol. In this protocol, the uplink users start contending for

uplink transmission after receiving a beacon frame from the AO. Then, the AP selects uplink from users who send a successful RTS frame and selects downlink users based on a fairness mechanism. Next, the AP and uplink users start sending data. Finally, the downlink users and the AP send an ACK frame for the received data.

Fig. 4 shows a demonstration of the HyFDMAC selection mechanism compared with random and scheduled access mechanisms.

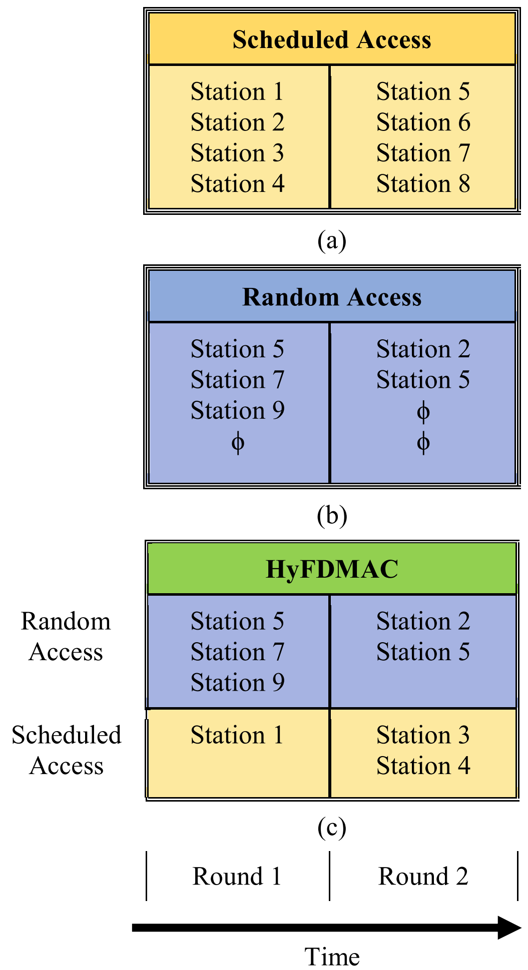

Fig. 4. Example of scheduling the transmission for four users using:(a) Scheduled Access, (b) Random Access, and (c) HyFDMAC.

A. Throughput

The throughput of the aforementioned baselines and HyFDMAC are shown in Fig. 5. The results show that HyFDMAC significantly outperforms the MU-FuPLEX and EnFD-OMAX by an average gain of 18% and 11.3%, respectively, reaching 36% and 33% gain improvement for a system with ten users. The main reason for these gains with HyFDMAC comes from not using RU, which would introduce additional overhead in HyFDMAC. In addition, HyFDMAC improves the utilization of the available resources by asking for more uplink users even if there are few users (*i.e.,* less than N) to win the uplink contention.

By comparing HyFDMAC to other baseline protocols, we observe that HyFDMAC outperforms Random Access by an average gain of 7% and a peak gain of 15% for a ten-user system. The advantage of HyFDMAC compared with Random Access comes from the better utilization of the available resources by the additional scheduled access feature in HyFDMAC. However, the throughput of TDMA is 1.5% higher compared with HyFDMAC due to the backlogged traffic pattern and reduced overhead from the lack of a contention stage in the TDMA scheme.

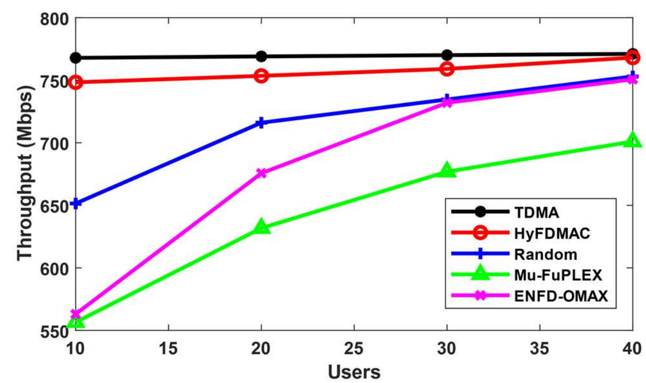

Fig. 5. Throughput of MU-FuPLEX [11], EnFD -OMAX [15], Random [14], TDMA and HyFDMAC with different number of stations.

B. Average Packet Delay

The average packet transmission delay is defined by the time a user spends from starting the contention period for uplink transmission to receiving the ACK frame for the transmitted data. Reducing the average packet transmission delay is essential for time-sensitive applications such as video calls and interactive gaming. Using HyFDMAC reduces the average packet delay by more than 10% compared with the Random scheme with a 68% peak improvement for a network with ten users, as shown in Table II. This performance improvement comes from the additional scheduled access scheme in HyFDMAC, which enables the AP to ask more users to participate in the uplink transmission. Also, the results show that the HyFDMAC average packet delay is slightly higher than the TDMA by an average increase of 1.6%. This increase comes from the contention stage overhead that is introduced in HyFDMAC.

TABLE II. THE AVERAGE PACKET DELAY OF HYFDMAC WITH RANDOM AND TDMA.

Protocol	Average packet delay per user (ms) index for different number of stations					
	10	20	30	40	100	250
Random	19	30	42	55	138	346
TDMA	13	26	39	52	130	326
HyFDMAC	13	26	40	53	132	331

C. Fairness

Uplink fairness is another metric that we consider in our simulation since the uplink user selection is determined by receiving an RTS at the AP, unlike the selection of the downlink users, which can be arranged to meet the fairness requirements by the AP. We use Jain's fairness index [24] to calculate the uplink fairness, α_u, as:

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

where T_u (m) is the user m uplink throughput.

Table III shows the fairness results of HyFDMAC, TDMA, and Random schemes. The results show, as expected, that TDMA achieves the highest level of fairness since all users are backlogged and have a similar period to transmit data. Nevertheless, HyFDMAC results show that it also approaches the fairness level of TDMA. Also, HyFDMAC fairness levels outperform the Random scheme. For instance, with 40 users, the HyFDMAC fairness index outperforms the Random scheme by 3%.

TABLE III. FAIRNESS OF RANDOM, TDMA, AND HYFDMAC

Protocol	Jain's Fairness index for different number of stations					
	10	20	30	40	100	250
Random	0.99	0.98	0.95	0.91	0.81	0.64
TDMA	1	1	1	1	1	1
HyFDMAC	1	1	0.98	0.95	0.84	0.68

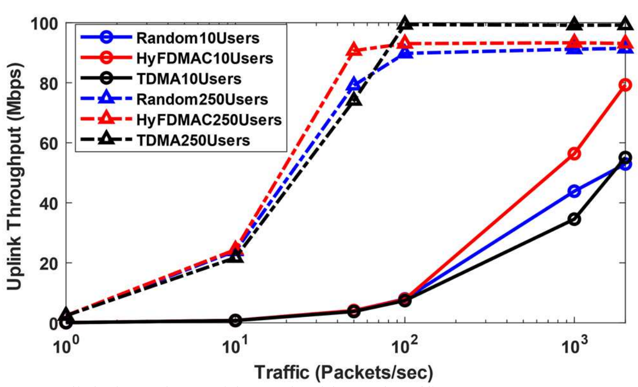

Fig. 6. Uplink throughput with non-backlogged traffic.

D. Results for Non-Backlogged traffic

We now study HyFDMAC performance with non-backlogged traffic since the AP has no control over the received RTS frames from the uplink users. Furthermore, we assume that each user has a local buffer to store incoming data frames for the uplink transmission, where the users start contending for uplink transmission as soon as they have data. Therefore, we use the uplink throughput to study HyFDMAC performance with non-backlogged traffic. Also, we consider a system with 10 and 250 users, to cover the sparse and dense networks. In addition, we compare HyFDMAC performance with Random and TDMA with different traffic rates, as shown in Fig. 6.

The results show that the HyFDMAC outperforms the TDMA and Random with different traffic rates. For instance, HyFDMAC throughput is 53% higher than TDMA for a ten-user system with a traffic rate of 2000 packets/sec. This performance gain is due to the nonutilized transmission slots by the TDMA. Furthermore, HyFDMAC throughput is 45% higher than the Random scheme because of the improved spectrum utilization by using the hybrid access mechanism.

These HyFDMAC gains are also noticeable with 250 users. However, HyFDMAC gains start shrinking with an increased traffic rate since most users will have data to send at any given time. Notably, the TDMA outperforms HyFDMAC with traffic of 100 packets per second and higher because the wasted transmission slots with the TDMA scheme were reduced significantly with 250 users.

V. CONCLUSION

In this paper, we proposed a hybrid access protocol, HyFDMAC, to serve multiple users using an in-band full duplex connection. In addition, the proposed protocol HyFDMAC offers a comprehensive procedure to collect the requirements for multiuser beamforming and ensures fairness. We showed that the HyFDMAC throughput outperforms the state-of-the-art mechanisms of MU-FuPlex and EnFD-OMAX by 18% and 11.3%, respectively. Also, we compared the performance of HyFDMAC with random and scheduled access, representing two extreme baselines. We showed that the HyFDMAC average packet delay reduces by 30%, and the fairness index improved by 3% compared with a typical random access scheme for fully backlogged users and maintained comparable performance levels with the scheduled access scheme. Furthermore, we showed that HyFDMAC increased the saturation throughput by 53% compared to scheduled access for a system with non-backlogged traffic.

For future work, we plan to find the optimal operation style for a dense network. We are considering an adaptive MAC that can change the operation mode based on the network variables such as the number of users, traffic type, and the number of cooperative APs.

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REFERENCES

[1] Cisco, "Cisco: 2020 CISO Benchmark Report," 2020. doi: 10.1016/s1361-3723(20)30026-9.

[2] D. Denteneer *et al.*, "The IEEE 802 . 11 Universe," *IEEE Communications Magazine*, vol. 48, no. January, pp. 62–70, 2010, doi: 10.1109/MCOM.2010.5394032.

[3] E. Khorov *et al.*, "Current Status and Directions of IEEE 802.11be, the Future Wi-Fi 7," *IEEE Access*, vol. 8, no. May 2019, pp. 1–1, 2020, doi: 10.1109/access.2020.2993448.

[4] A. Sabharwal *et al.*, "In-band full-duplex wireless: Challenges and opportunities," *IEEE Journal on Selected Areas in Communications*, vol. 32, no. 9, pp. 1637–1652, 2014, doi: 10.1109/JSAC.2014.2330193.

[5] S. Liu *et al.*, "Hidden-node problem in full-duplex enabled CSMA networks," *IEEE Transactions on Mobile Computing*, vol. 19, no. 2, pp. 347–361, 2020, doi: 10.1109/TMC.2019.2895034.

[6] J. Zhang *et al.*, "Physical Layer Security Based on Full-Duplex under the Impact of Channel Convergence," *International Conference on Communication Technology Proceedings, ICCT*, vol. 2021-Octob, pp. 259–262, 2021, doi: 10.1109/ICCT52962.2021.9657986.

[7] K. Madushan, "Medium Access Control Design for Full Duplex Wireless Systems : Challenges and Approaches," *IEEE Communications Magazine*, vol. 53, no. 5, pp. 112–120, 2015, doi: 10.1109/MCOM.2015.7105649.

[8] C. D. Nwankwo *et al.*, "A Survey of Self-Interference Management Techniques for Single Frequency Full Duplex Systems," *IEEE Access*, vol. 3536, no. c, 2017, doi: 10.1109/ACCESS.2017.2774143.

[9] A. H. Gazestani *et al.*, "A Survey on Implementation and Applications of Full Duplex Wireless Communications," *Physical Communication*, vol. 34, pp. 121–134, 2019, doi: 10.1016/j.phycom.2019.03.006.

[10] M. Peng *et al.*, "A spatial group-based multi-user full-duplex OFDMA MAC protocol for the next-generation WLAN," *Sensors*, vol. 20, no. 14, pp. 1–19, 2020, doi: 10.3390/s20143826.

[11] Q. Qu *et al.*, "MU-FuPlex: A multiuser full-duplex MAC protocol for the next generation wireless networks," *IEEE Wireless Communications and Networking Conference, WCNC*, 2017, doi: 10.1109/WCNC.2017.7925936.

[12] H. Ahn *et al.*, "Frequency Domain Coordination MAC Protocol for Full-Duplex Wireless Networks," *IEEE Communications Letters*, vol. 23, no. 3, pp. 518–521, 2019, doi: 10.1109/LCOMM.2019.2894151.

[13] W. Kim *et al.*, "An opportunistic MAC protocol for full duplex wireless LANs," in *International Conference on Information Networking*, 2018, vol. 2018-Janua, pp. 810–812. doi: 10.1109/ICOIN.2018.8343230.

[14] Y. Alkhrijah *et al.*, "Full Duplex Multiuser MIMO MAC Protocol (FD- MUMAC)," *2020 IEEE Global Communications Conference*, pp. 1–6, 2020, doi: 10.1109/GLOBECOM42002.2020.9348214.

[15] M. Peng *et al.*, "A trigger-free multi-user full duplex user-pairing optimizing MAC protocol," *International Conference on Internet of Things as a Service, Springer*, 2019, doi: 10.1007/978-3-030-44751-9_51.

[16] R. Liao *et al.*, "MU-MIMO MAC protocols for wireless local area networks: A survey," *IEEE Communications Surveys and Tutorials*, vol. 18, no. 1, pp. 162–183, 2016, doi: 10.1109/COMST.2014.2377373.

[17] T. Kim *et al.*, "Phase-Divided MAC Protocol for Integrated Uplink," *IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY*, vol. 67, no. 4, pp. 3172–3185, 2018.

[18] R. Liao *et al.*, "Uni-MUMAC: a unified down/up-link MU-MIMO MAC protocol for IEEE 802.11ac WLANs," *Wireless Networks*, vol. 21, no. 5, pp. 1457–1472, 2015, doi: 10.1007/s11276-014-0861-4.

[19] J. Kim *et al.*, "Beamforming for Full-Duplex Multiuser MIMO Systems," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 3, pp. 2423–2432, 2017, doi: 10.1109/TVT.2016.2581213.

[20] M. W. Un *et al.*, "Joint transmit beamforming optimization and uplink/downlink user selection in a full-duplex multi-user MIMO system," *ICASSP, IEEE International Conference on Acoustics, Speech and Signal Processing - Proceedings*, pp. 3639–3643, 2017, doi: 10.1109/ICASSP.2017.7952835.

[21] L. A. N. Man *et al.*, *Part 11 : Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 3 : Enhancements for Very High Throughput in the 60 GHz Band IEEE Computer Society*, vol. 2012, no. December. 2012.

[22] M. Shreedhar and G. Varghese, "Efficient fair queuing using deficit round-robin," *IEEE/ACM Transactions on Networking*, vol. 4, no. 3, pp. 375–385, 1996, doi: 10.1109/90.502236.

[23] W. Ouyang *et al.*, "Leveraging one-hop information in massive MIMO full-duplex wireless systems," *IEEE/ACM Transactions on Networking*, vol. 25, no. 3, pp. 1528–1539, 2017, doi: 10.1109/TNET.2017.2648878.

[24] R. Jain *et al.*, "A Quantitative Measure Of Fairness And Discrimination For Resource Allocation In Shared Computer Systems." 1998. [Online]. Available: http://arxiv.org/abs/cs/9809099