Full Duplex Medium Access Control Protocol for Asymmetric Traffic

Md. Abdul Alim and Takashi Watanabe
Graduate School of Information Science and Technology
Osaka University, Osaka, Japan
Email: {abdul.alim, watanabe}@ist.osaka-u.ac.jp

***Abstract*—Recent advancements in antenna design and signal processing have made it feasible to transmit and receive at the same time by using same carrier frequency, which is called in-band full-duplex (IBFD) wireless communications. Along with physical layer advancements, efficient medium access control (MAC) design is required to achieve optimum benefit from this latest technology. In this paper, a full-duplex MAC (FD-MAC) is proposed for a WLAN to support asymmetric length of traffic for uplink and downlink, which is named as Asym-MAC. The main feature of this MAC is that multiple users can transmit data to the access point (AP) during the transmission of a single downlink frame from AP. Moreover, there is no contention period and hence, there is no collision among the user terminals and AP for channel access. In Asym-MAC, AP always initiates the transmission. The performance of Asym-MAC is compared with the traditional half-duplex MAC (HD-MAC) and another proposed FD-MAC. Asym-MAC outperforms traditional HD-MAC by about 100% throughput gain. Moreover, this MAC shows higher throughput gain as compared to another existing FD-MAC and the throughput gain is about 67%. The results suggest that a significant throughput gain can be achieved by using this MAC, which can be used for future FD WLANs.**

***Index Terms*—Full Duplex, MAC protocol, FD-MAC, asymmetric traffic.**

I. Introduction

In-band full-duplex (IBFD) wireless communication has been attracted by many researchers, as it is one of the latest techniques to meet the upcoming demand in wireless communications. The traditional deployed wireless networks are not able to transmit and receive on the same frequency at the same time. However, by using IBFD wireless communication, it is possible to transmit and receive simultaneously by using the same frequency at the same time. There are two most important challenges to implement IBFD. First one is minimization of self-interference and second one is mitigation of inter-user interference.

A substantial number of research works have been conducted to minimize the self-interference. In [1], balanced/unbalanced (balun) cancellation technique is used for self-interference cancellationin. Along with this, digital cancellation technique is also used here, by which 110 dB cancellation is achieved. That research was conducted by using two antennas. In [2], single antenna is used to support IBFD WiFi radio. Here, a passive circuit is used to minimize the self-interference as a first step. After that, digital cancellation is used as a second step. A balanced cancellation technique for RF front-end is proposed in [3]. In addition, some other research works have been conducted in the physical layer for the advancement of IBFD wireless communication [4]–[6]. However, to attain the full leverage of full-duplex (FD) technology in wireless communications, medium access control (MAC) protocols play a vital role.

Although some MAC protocols are proposed in recent years, these are not sufficient to cover all issues for the IBFD wireless communications. Some MAC designs are proposed for adhoc networks or distribute networks and some other designs are proposed for wireless local area networks (WLANs). A full-duplex MAC (FD-MAC) design is proposed for a WiFi networks, where both half-duplex (HD) and FD clients are available [7]. However, that paper limits their IBFD communication for the situation, when the AP and a FD client have packets for each other. That research considered the same length for downlink and uplink data frames. A cross-layer protocol design is proposed for distributed FD networks in [8]. The paper proposed their design for single channel as well as multi-channel networks. The authors of the paper also considered the same packet size for uplink and downlink.

On the other hand, supporting asymmetric traffic for downlink and uplink for IBFD wireless communication is a crucial issue. As asymmetric traffic is very usual in our practical life, it should be considered for the MAC design of IBFD wireless communication. In [9], the research was conducted for uplink and downlink traffic statistics. It is mentioned in [9] that the ratio of uplink frame length (UFL) to downlink frame length (DFL) is 1:5, although the ratio depends on applications. However, the packet arrival ratio is almost 1:1. From another research, authors observed that the the ratio of UFL to DFL (UFL/DFL) is about 1:3 [10]. This ratio is observed as 1:3.47 in another similar kind of research [11]. As there are different kind of applications nowadays, we have set that ratio as 1:3 to design our FD-MAC.

A few research papers have mentioned this asymmetric traffic for IBFD wireless communication. In [12], a cross-layer model is proposed to accommodate asymmetric traffic for IBFD wireless networks. But, the paper did not describe any detail MAC design. A medium access MAC protocol is proposed for WLANs in [13], which is named as A-Duplex. This paper considers both symmetric and asymmetric traffic for uplink and downlink. However, the FD communication is performed only, when the clients send request to send (RTS) first. If AP send RTS first, a half-duplex (HD) communication takes place. In A-Duplex, during asymmetric traffic in IBFD, the transmitter sends busy tone, if it finishes its transmission earlier than that of its counterpart. Some other papers also used busy tone in case of asymmetric traffic for IBFD wireless networks [14].

As IBFD is a new technology for the next generation WLANs, we should also need to include new MAC to achieve the optimum performance of this technology. In this paper, we propose a full-duplex MAC design for IBFD WLANs. We discussed earlier that a few number of papers described the asymmetric traffic for the IBFD MAC protocols. So, we are motivated to do our research in this area. On the other hand, some papers that described asymmetric traffic, they used busy tone. So, during this busy tone, it is actually HD communication in terms of data transmission. Depending on the applications, this busy tone period may be shorter or longer. So, if we are able use this time (busy tone period), we can achieve the full performance of IBFD wireless networks.

This paper proposes a full-duplex MAC protocol that supports asymmetric traffic. Here, the MAC design is proposed for a WLAN that consists of a FD access point (FD-AP) and some FD clients (FDC). The basic structure of the WLAN is shown in Fig. 1. In this MAC, AP always starts the transmission. According to this MAC, AP selects the uplink user terminals (UTs) to send their data to AP, which is like the point coordination function (PCF) in IEEE 802.11 standard. The main feature of this MAC is that more than one users can transmit their data to AP while AP transmits data to another user. We have named this FD-MAC as Asym-MAC. To the best of our knowledge, this is a novel MAC design in this area of IBFD wireless communications. Here, FD communication is categorized in two ways, i.e. one is bi-directional FD (BFD) and another is relay FD (RFD). During BFD, AP and one user terminal (UT) transmit data to each other at the same time; whereas in RFD, one UT transmits data to AP, while AP transmits data to another UT (Fig. 1). These two data are different in this research.

The rest of this paper is arranged as follows: section-II gives a brief description of problem statement regarding FD-MAC, section-III describes the proposed MAC design, section-IV gives a mathematical analysis and section-V illustrates the result and performance analysis.

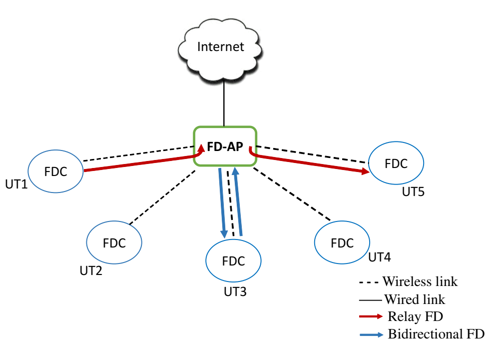

Fig. 1. Structure of a wireless LAN.

II. Problem Statement in IBFD WLAN

Hidden terminal and exposed terminal problem is an important issue in WLANs. However, the severity of this problem becomes lower, when the network is designed as a AP based WLAN and the communication is maintained by using RTS/CTS mechanism. The reason is that all UTs in a WLAN update their network allocation vectors (NAV) by using the control frames that are transmitted by the AP and UTs.

On the other hand, in case of IBFD wireless LANs, the inter-user interference is a crucial issue. Fig. 2 depicts the inter-user interference problem. Here, suppose user terminal-1 (UT1) sends data to the AP and then AP takes decision to send data to UT2 while receiving data from UT1. But, if UT1 and UT2 are close to each other, the data frame from UT1 will interfere at UT2 with the data frame that is sent by AP; this phenomenon is regarded as inter-user interference problem. Here, UT1 and AP are considered as the primary transmitter (PT) and primary receiver (PR) respectively. However, UT2 and AP are considered as the secondary receiver (SR) and secondary transmitter (ST) respectively. So, AP is working as both PR as well as ST. The optimum performance of IBFD cannot be achieved without taking proper steps to minimize the inter-user interference.

III. Proposed FD-MAC Protocol

A. Description of Asym-MAC

Asym-MAC is designed to support asymmetric traffic for downlink and uplink. Here, AP always initiates the transmission. Hence, there is no contention period or backoff time. In this FD-MAC, there is an initial phase, where AP broadcasts the IP address of the UT and corresponding slot number (SN). So, every UT has a specific slot number. This SN will be used later in this MAC in data transmission phase. This SN broadcasting is performed once only. However, if any new UT joins in or leaves the WLAN, AP broadcasts the new slot numbers. For the simplicity, only data transmission phase is shown in the figures (Fig. 3 and Fig. 4).

After broadcasting the SN, AP transmits the RTS, if it has data to send. Suppose, AP has data to send UT-1 as in Fig. 3. So, AP sends RTS to UT-1 and UT-1 also sends CTS (clear to send) to AP. Then, times slots for notification (TSN) will start after SIFS time. In this TSN, every UT will send its data

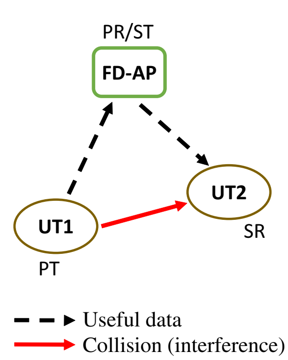

Fig. 2. Inter user interference in IBFD wirelss LAN.

length (duration) during its slot number that is broadcasted by AP earlier. If any UT has no data to send, it sends all zero in its TSN. After getting all requests from UTs, AP broadcasts notification for clients (NFC).

In NFC, AP declares the UTs and corresponding data length. AP can select any number of UTs as the uplink transmitter. AP selects the UT randomly and then compare the UT's frame length with the downlink frame length (DFL). If the duration is much less than DFL, AP selects another UT and checks the total traffic length with DFL. This process is continued until the DFL matches with the total uplink frame length (UFL). In this MAC, it is defined that total UFL may be higher than DFL. But there is a limit. The limit is as follows:

$$UFL\ (\text{Total}) \leq (\text{DFL} + 200\ \text{bytes})$$

One UT cannot be selected in two consecutive data transmission phase. acknowledgments (ACKs) are sent sequentially. All the formats of control frames for this MAC are shown in Fig. 5.

Now, we are giving an example of this FD-MAC for a clear understanding. First, suppose AP has data to send UT-1. So after exchanging RTS/CTS between AP and UT-1, TSN starts as in Fig.3. Suppose, all UTs have data to send and all of them send their corresponding UFL to AP. Now, AP selects two UTs as uplink transmitters according to the condition that is described earlier. So, AP puts the address of UT-3 and UT-2 as RA-1 and RA-2 respectively in NFC as in Fig. 5. AP also include the corresponding data length in this NFC. After broadcasting NFC, the data transmission starts as in Fig.3. ACKs are transmitted after finishing the transmission as well. As two UTs send data to AP, AP sends two ACKs. However, UT-1 also send one ACK, as it has received data from AP only. If all UTs have no data to send AP, they will send all zero during their corresponding TSN. In that case, AP just mention the receiver address (to whom AP will send data) again in NFC and it becomes HD communication. This process is continued, if AP has data to send any UT.

On the other hand, if AP has no data to send any UT, AP waits for a predefined time that is called wait before transmit (WBT). As in Fig. 4, if AP has no data to send, it sends a dummy RTS (DRTS) after WBT. Then after SIFS time, TSN starts. The rest of the part is similar to the previous description. However, this is a HD communication, as AP has no downlink data (Fig. 4).

B. Minimization of inter-user interference

As the inter-user interference occurs during IBFD wireless communication, this kind of problem is not evident in any HD communication that is described earlier (Fig. 4). To combat this interference during IBFD (Fig. 3), this MAC proposes a technique. When AP sends RTS, it is heard by every UT. However, when the corresponding UT sends CTS, it is not heard by every UT. So, a UT can send its UFL during TSN, only if it cannot hear the CTS that is sent earlier by another UT. As a result of this, the uplink data and downlink data will not interfere each other.

IV. Mathematical Analysis

A. Probability Calculation

It is assumed that the packet arrival rate follows the Poisson arrival rate and service time is deterministic. Total Packet arrival rate at AP from internet as downlink packets is defined as:

$$\lambda_D = (\lambda_{\text{D1}} + \lambda_{\text{D2}} + \cdots\cdots \lambda_{\text{Dn}}) \tag{1}$$

$$\Rightarrow \lambda_D = \sum_{i=1}^{n} \lambda_{\text{D}i} \tag{2}$$

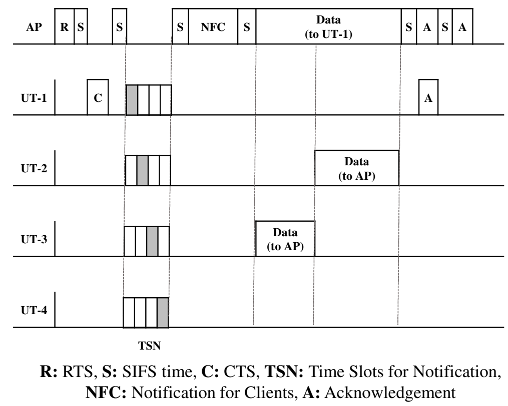

Fig. 3. Time sequence of proposed FD-MAC (AP has data to send).

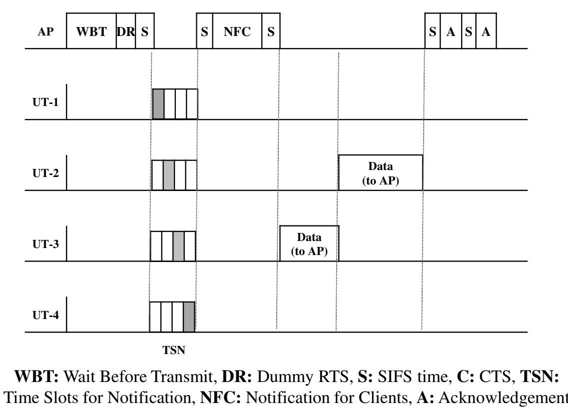

Fig. 4. Time sequence of proposed FD-MAC (AP has no data to send).

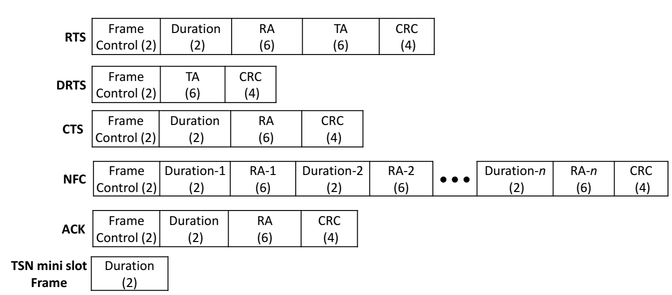

Fig. 5. Format of control frames (in octet).

where, n is the total number of UTs. λ_{D1} is the downlink packet arrival rate from AP to UT-1, λ_{D2} is the downlink packet arrival rate to UT-2 and so on.

Total Packet arrival rate at AP from the nodes as uplink packets:

$$\lambda_U = (\lambda_{\mathrm{U1}} + \lambda_{\mathrm{U2}} + \cdots\cdots \lambda_{\mathrm{Un}}) \tag{3}$$

$$\Rightarrow \lambda_U = \sum_{i=1}^{n} \lambda_{\mathrm{U}i} \tag{4}$$

where, λ_{U1} is the uplink packet that is generated by UT-1 to AP, λ_{U2} is the uplink packet that is generated by UT-2 and so on.

So, total packet arrival rate at AP for uplink and downlink:

$$\lambda_{\mathrm{Total}} = \lambda_{\mathrm{D}} + \lambda_{\mathrm{U}} \tag{5}$$

Suppose, one packet arrives at AP as a downlink packet for a UT. If there is no uplink packet request before the data transmission, the conditional probability of the half-duplex communication (P_{HD}) is:

$$P_{\mathrm{HD}} = e^{-\lambda_{\mathrm{U}} T_w} \tag{6}$$

where, T_w is the average waiting time of a uplink packet before transmission. Average waiting time (T_w) is derived in the following subsection B.

So, the conditional probability of the FD communication (P_{FD1}), where only one UT wants to send data to AP is:

$$P_{\mathrm{FD}_1} = \left(e^{-\lambda_{\mathrm{U}} T_w}\right)\left(\lambda_{\mathrm{U}} T_w\right) \tag{7}$$

The probability of the FD communication that at least m (where, $m \leq n$) UTs want to send data to AP, or the probability of FD communication that at least m notifications arrive at AP during the TSN is:

$$P_{\mathrm{FD}_m} = \left\{1 - \sum_{i=0}^{m-1} (e^{-\lambda_{\mathrm{U}} T_w}) \times \frac{\left(\lambda_{\mathrm{U}} T_w\right)^i}{i!}\right\} \tag{8}$$

If $m \geq 3$, it is assumed that AP can select UTs in such a way that the size of uplink and downlink traffic will be almost same. So in this case, the probability of full-duplex communication is:

$$P_{\mathrm{FD}_{m\geq 3}} = \left\{1 - \sum_{i=0}^{2} (e^{-\lambda_{\mathrm{U}} T_w}) \times \frac{\left(\lambda_{\mathrm{U}} T_w\right)^i}{i!}\right\} \tag{9}$$

B. Average Waiting Time Calculation

It is possible to calculate the utilization factor by using corresponding arrival rate. The utilization factor (ρ) for this MAC protocol can be defined as

$$\rho = \frac{\text{The average data transmission time}}{\text{The packet interarrival time}} \tag{10}$$

So, the uplink utilization factor is defined as:

$$\rho_{\mathrm{u}} = \frac{T_{data}}{1/\lambda_{\mathrm{U}}} = \frac{1/\mu}{1/\lambda_{\mathrm{U}}} = \frac{\lambda_{\mathrm{U}}}{\mu} \tag{11}$$

here, T_{data} is average data transmission time and μ is defined as service rate that is inverse of T_{data}. Here, both the data transmission time for downlink and uplink are same for this MAC design.

So, according to Pollaczek-Khinchine formula for M/D/1 system, the average waiting time of a uplink packet before transmission is derived as:

$$T_w = \frac{\rho_{\mathrm{u}}}{2\mu(1-\rho_{\mathrm{u}})} \tag{12}$$

C. Throughput Calculation

It is assumed that the average frame length for downlink is l_{d} and that for uplink is l_{u}. If only HD transmission occurs, the throughput is defined as:

$$Th_{\mathrm{hd}} = \frac{l_{\mathrm{d}}}{T_{data}} \tag{13}$$

The probability of getting this throughput is P_{HD} that is given in (6). So multiplying P_{HD} with (13), we get the expected value of Th_{hd}. We categorize the FD communication according to the number of transmitters that want to send data to AP. If there is only one UT that wants to send data to AP, the throughput is defined as:

$$Th_{\mathrm{fd1}} = \frac{l_{\mathrm{d}} + l_{\mathrm{u}}}{T_{data}} \tag{14}$$

The probability of occurring of this Th_{fd1} is defined in (7). Similarly, we can derive Th_{fd2}, where two UTs want to send data to AP and the corresponding probability can be found in (8). As we assumed earlier that if at least three UTs want to send data to AP, AP can select the UTs in such a way that the uplink and downlink data traffic will be almost same. So, the throughput in this case will be:

$$Th_{\mathrm{fd}} \cong \frac{2l_{\mathrm{d}}}{T_{data}} \tag{15}$$

here, Th_{fd} is the throughput, when the uplink users are greater than two.

From the above analysis, it is obvious that the throughput (Th) has different values with different probabilities. So, the expected value of Th is given by:

$$E[Th] = \sum_{x:p(x)>0} xp(x) \tag{16}$$

here, $p(x)$ is the probability mass function (PMF) of Th. By using the values of PMF from earlier equations, we get the mean value of Th.

$$\begin{aligned} E[Th] = {} & (Th_{\mathrm{hd}} \times P_{\mathrm{HD}}) + (Th_{\mathrm{fd1}} \times P_{\mathrm{FD1}}) \\ & + (Th_{\mathrm{fd2}} \times P_{\mathrm{FD2}}) + (Th_{\mathrm{fd}} \times P_{\mathrm{FD}_{m\geq 3}}) \end{aligned} \tag{17}$$

So, for IBFD communication in this MAC, it requires to satisfy two conditions at least. Firstly, AP should have packets to send any UT and secondly, at least on UT should have packets to send AP at the same time. However, if more than two UTs have packets to send AP, the throughput becomes higher.

V. Results and Performance Analysis

The evaluation of Asym-MAC is performed by MATLAB simulation. In this simulation, both the uplink and downlink packet arrival rate is 45 packets/s. however, UFL is smaller than DFL. Here, the average ratio of UFL to DFL is 1:3 (500 bytes/1500 bytes) and the packet arrival rate ratio is considered as 1:1. We have evaluated of our FD-MAC in two ways. These are described in following two sections:

A. Performance Result Based on Mathematical Analysis

This evaluation is done based on mathematical equations that is described in the earlier section. This evaluation result is shown in Fig. 6. From the figure, it is observed that in general, the average throughput is almost constant (30 Mbps), when the number of UTs is less than 25. However, this throughput increases gradually to 41 Mbps when the number of UTs become 40. In this simulation, four different cases are considered if AP has a downlink packet, such as:

- There is no uplink packet.
- Only one UT has packets to send AP.
- Only two UTs have packets to send AP.
- More than two UTs have packets to send AP.

So, for a fixed packet arrival rate, the probability that more than two UTs have packets to send AP is much less. As a result of this, the throughput is also negligible upto the 25 number of UTs. However, as there is a high probability that no UT has packets to send data within the average waiting time, the throughput is higher for this case (blue line in Fig. 6). But, this throughput decreases gradually as the number of UTs increases and on the contrary, throughput for other cases increases gradually. The figure shows that the mean throughput increases as the number of UTs increases.

B. Performance in Saturation Condition

We have evaluated Asym-MAC in saturation condition by extensive MATLAB simulation. Saturation condition is defined as the situation, when all the UTs and the AP always have packets for transmission, i.e. the transmission queues of each UTs and the AP are always nonempty [13], [15]. The simulation result is depicted in Fig. 7.

Asym-MAC is compared with A-Duplex [13] and traditional HD wireless communications. From Fig. 7, it is observed that our proposed FD-MAC outperforms A-Duplex as well as traditional HD transmissions. The comparison is performed in terms of average throughput. Each simulation has been done ten times and got the average. The simulation parameters are shown in Table I.

It is observed that the average throughput for Asym-MAC is about 38 Mbps, which is lower than A-duplex in case of five number of nodes. The reason is inter-user interference. As there is a condition to send the UFL for the minimization of inter-user interference (described in section-III), some user cannot send the request during TSN. So, AP cannot get sufficient number of users to select as the uplink user so that the DFL and total UFL becomes almost same. However, when the number of users increases to 10 and more, the throughput becomes much higher than that of other MAC designs (Fig. 7). It should be mentioned here that there is no contention period in Asym-MAC. So, there is no collision among the users in this FD-MAC. However, as the number of users increases from 10 to 40, it is observed that the average throughput decreases gradually. The reason behind this is the TSN. During TSN, every user sends its UFL. So if the number of users increases, the number of slots in TSN increases. Hence, the overhead also increases and the throughput decreases as well.

On the other hand, A-duplex and traditional HD communications have contention period. So, these MAC protocols have the collision probability during the period of contention window. Therefore, these protocols show a decreasing trend of average throughput for the increasing number of user terminals. In this simulation, A-Duplex is considered for 2 types of UFL/DFL ratio. When the UFL/DFL ratio is 2/3, the uplink and downlink frame lengths are considered as 1000 and 1500 bytes respectively; however, this value is 500 and 1500 bytes respectively, when UFL/DFL ratio is 1/3.

Comparing to A-Duplex (UFL/DFL: 2/3), the average throughput gain is achieved by using Asym-Mac is about 35%; however, this gain is observed as about 67% when UFL/DFL is 1/3. On the other hand, Asym-MAC outperforms

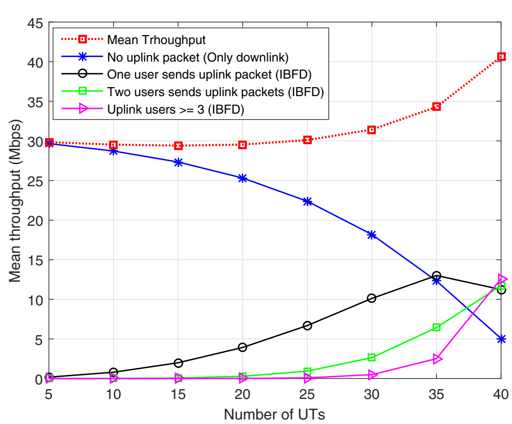

Fig. 6. Mean throughput in different situations.

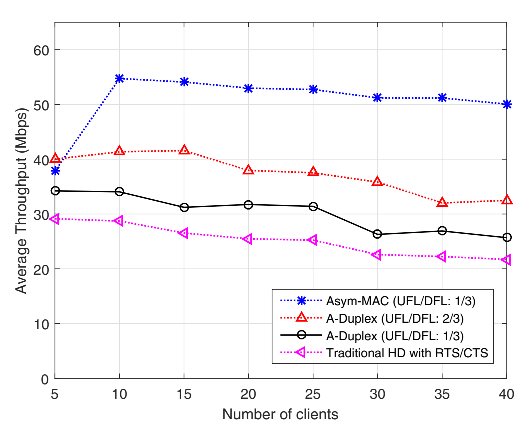

Fig. 7. Throughput comparison in saturation condition.

TABLE I
SIMULATION PARAMETER

Parameter	Value
UFL/DFL (2/3)	1000/1500 (bytes)
UFL/DFL (1/3)	500/1500 (bytes)
RTS	20 bytes
CTS	14 bytes
DRTS	12 bytes
TSN mini slot frame	2 bytes
NFC	$(6 + n * 8)$ bytes; where, n is the selected number of UTs
ACK	14 bytes
Data rate	54 Mbps
Control frame (RTS, CTS, etc.) rate	12 Mbps
WBT	30 μs
DIFS time	34 μs
SIFS time	16 μs
Minimum backoff window size (CW_{min})	15 μs
PLCP preamble duration	16 μs
PLCP header duration	4 μs

traditional HD communications (with RTS/CTS) by about 100% increase of average throughput. For this comparison, the mean of the average throughput is considered. Another comparison is shown in Fig. 8. The figure compares the achievable maximum, average and minimum throughput for 15 number of UTs in saturation condition, where the UFL/DFL is 1/3 in case of A-duplex. It also depicts almost same results as discussed earlier.

VI. CONCLUSION

In this paper, we proposed a full-duplex MAC protocol that supports asymmetric traffic for uplink and downlink. As asymmetric traffic is very usual in WLANs, we need to include this feature in future FD wireless communications. This Asym-MAC supports multiple uplink user terminals during a single downlink transmission. Hence, the busy time (used in other FD-MAC) can be used for transmitting or receiving data. This MAC protocol is not compatible with IEEE standard. As IBFD is a new technology and existing IEEE standard does not support IBFD communication, we need new MAC protocols to achieve the full advantage of this latest technology. The simulation results show that the proposed FD-MAC outperforms traditional HD as well as another existing FD-MAC. More evaluations will be performed as well as detail algorithms will be discussed in future research.

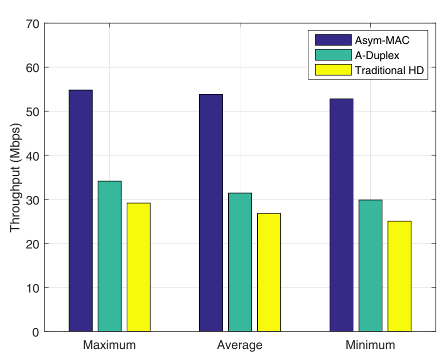

Fig. 8. Throughput comparison for 15 number of UTs.

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