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# Asym-FDMAC: In-band full-duplex medium access control protocol for asymmetric traffic in wireless LAN

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**Abstract**

Recent advancements in antenna design and signal processing have made it feasible to transmit and receive simultaneously by using the same carrier frequency, which is defined as in-band full-duplex (IBFD) wireless communications. Along with physical layer advancements, efficient medium access control (MAC) design is required to derive optimal benefit from this latest technology. In this paper, an IBFD MAC protocol named Asym-FDMAC, is proposed for infrastructure based WLAN to support asymmetric lengths of traffic for uplink and downlink. This MAC protocol enables multiple users to transmit data to the access point (AP) during the transmission of a single downlink frame from the AP. In Asym-FDMAC, the AP always initiates the transmission. Therefore, there is no contention period and thus, there is no collision among the user terminals and the AP for channel access. A mathematical analysis of Asym-FDMAC is presented together with an evaluation of its performance, which involved a comparison with traditional IBFD and half-duplex (HD) communications. On average, the highest throughput gain achieved by Asym-FDMAC was approximately 54% and 94% compared with traditional IBFD and HD communications respectively, although the lowest average throughput gain was observed as about 50% and 89%, respectively.

**Keywords** Full duplex · MAC protocol · FD-MAC · Asymmetric traffic

## 1 Introduction

In-band full-duplex (IBFD) wireless communication has emerged as one of the latest techniques to meet the challenges of posed by the upcoming demand in future wireless communications. Wireless communications deployed in the traditional manner cannot transmit and receive by using the same carrier frequency at the same time. However, the use of IBFD wireless communications makes it possible to transmit and receive simultaneously by using the same carrier frequency. The two most important challenges associated with implementing IBFD are: firstly, the minimization of self-interference and secondly, the mitigation of inter-user interference. To achieve the advantages from IBFD wireless communication successfully, we need to design suitable medium access control (MAC) protocol. On the other hand, asymmetric traffic for uplink and downlink is very common in wireless communications. As asymmetric traffic is very typical in our practical wireless LAN (WLAN), it should be considered for the MAC design of IBFD wireless communications.

This paper proposes a novel FD-MAC protocol, which is named Asym-FDMAC that supports asymmetric length of traffic for uplink and downlink. The main feature of Asym-FDMAC is that it enables multiple users to transmit their uplink data to the AP while the AP is transmitting the downlink data to a single user. This MAC is designed for a WLAN and its basic structure of the WLAN is shown in Fig. 1. The WLAN consists of an IBFD-capable access point (FD-AP) and some IBFD clients (FDC). However, this Asym-FDMAC can be utilized for a WLAN that consists of both FDC and traditional half-duplex (HD)

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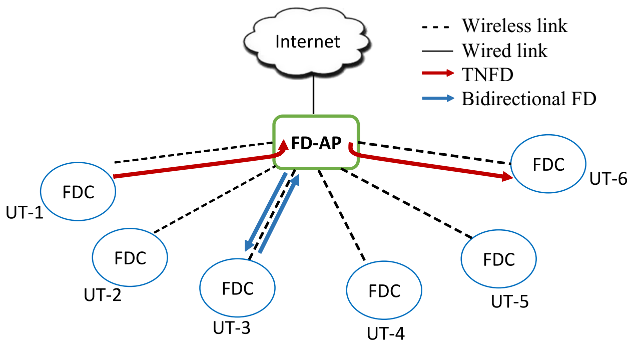



**Fig. 1** Structure of a wireless LAN

clients (HDC). According to this MAC, the AP always initiates the data transmission and selects user terminals (UTs) to send their data to the AP, and thus there is no backoff mechanism or contention period for channel access. The basic concept of this Asym-FDMAC was proposed in [1]. This paper extends the idea more clearly with additional performance analysis. This paper provides new algorithms for the queue management and for the UT selection. In addition, the research in the current paper extends and generalizes the mathematical analysis for any number of uplink frame length to downlink frame length (UFL/DFL) ratio. Apart from the previous performance analysis in [1], Asym-FDMAC in this paper is more extensively evaluated by comparing its performance with various aspects of traditional IBFD.

FD communications are categorized in this paper in two ways, i.e. bi-directional FD (BFD) and three node FD (TNFD) communications. During BFD communications, the AP and one user terminal (UT) transmit data to each other simultaneously; whereas in TNFD, one UT transmits data to the AP, while the AP transmits data to another UT simultaneously (Fig. 1). For example, as shown in Fig. 1, UT-1 is transmitting data to the AP and the AP is transmitting data to UT-6 simultaneously, which is a TNFD communication. In case of TNFD, the data being transmitted are different, unlike relay FD. The main contributions of Asym-FDMAC are summarized as below:

- This MAC supports asymmetric as well as symmetric traffic for uplink and downlink.
- If one user terminal (UT) finishes its transmission earlier, another UT can transmit data to the AP, by which multiple UTs can transmit their data in the same data transmission cycle.
- Asym-FDMAC can suppress the inter-user interference successfully.
- The AP always initiates the transmission. Hence, there neither is any contention period nor is there collision for channel access.
- This MAC can be utilized for a WLAN consisting of an FD-AP and some UTs. The flexibility of this protocol is that all UTs can either be FD capable or traditional HD capable devices; even a combination of these two types is possible.
- The performance analysis of the proposed MAC is performed by mathematical analysis and MATLAB simulation.

The remainder of this paper is arranged as follows: Sect. 2 provides the related researches in this area, Sect. 3 provides a brief description of the problem statement regarding FD-MAC, Sect. 4 describes the proposed MAC design, Sect. 5 presents the mathematical analysis, and Sect. 6 contains the result and discussion.

## 2 Related works

A substantial amount of research works have been conducted to minimize the self-interference to enable successful IBFD communications. In [13], a balanced/unbalanced (balun) cancellation technique is used for self-interference cancellation. Along with balun, a digital cancellation technique is used, which achieves 110-dB cancellation. Two antennas are used to conduct that research. In contrast, single antenna is used to support IBFD WiFi radio in [2]. A passive circuit is used here to minimize the self-interference as a first step, after which digital cancellation is used as a second step. A balanced cancellation technique for front-end RF is proposed in [23]. In addition, other research works have been conducted in the physical layer for the advancement of IBFD wireless communications [6, 9, 20]. Several research efforts are currently underway to achieve the highest correctness in IBFD wireless communications for both analog and digital cancellation techniques [14, 17]. Hence, expectations are that the researchers will succeed in suppressing the self-interference almost perfectly in the near future. On the other hand, to attain the full leverage of IBFD technology in wireless communications, medium access control (MAC) protocols play a vital role.

On the other hand, a number of MAC protocols have been proposed for efficient IBFD communications in recent years. However, these protocols are not sufficiently capable of addressing all the challenges in this arena. Some MAC designs are proposed for ad-hoc networks or distribute networks and some other protocols are proposed for wireless local area networks (WLANs). A full-duplex (FD) MAC design is proposed for a WiFi networks, in which both HD and FD clients are available [8]. However, in that research, the IBFD communications are limited to a situation in which the AP and an FD client only have packets for each other. This MAC design considers the same length of frame size for downlink and uplink. A cross-layer protocol design for both single-channel and multi-channel networks is proposed for distributed FD networks in [15]. That paper also considers the same frame size for downlink and uplink. In PocMAC, a power-controlled FD-MAC is proposed, where symmetric traffic lengths are used for uplink and downlink [7]. A MAC protocol is proposed for wireless ad-hoc networks, which supports multi-hop communications [21].

Asymmetric length of traffic is considered in this proposed MAC, as this type of traffic is very common in the existing WLANs. The uplink and downlink traffic statistics are discussed in [18]. It is mentioned in that paper that the ratio of the uplink frame length (UFL) to the downlink frame length (DFL) is 1:5, although the ratio depends on the applications. The packet arrival ratio for uplink and downlink is observed as about 1:1. However, the DFL is much higher than the UFL and the downlink transmission is not always paired with the corresponding UT for the uplink transmission. Therefore, more uplink packet requests from different users are received in the uplink queue of the AP, while the AP transmits a single downlink packet. In another paper, the authors observe that the UFL/DFL ratio is about 1:3 [24]. This ratio is observed to be 1:3.47 in another similar study [5]. Some technical reports also confirm this traffic asymmetry in wireless communications. For example, NOKIA reports that traffic asymmetry is downlink dominated during normal day time hours by 1/10 [19]. Moreover, the UFL/DFL ratio is reported to have increased from 1/2 to 1/10 in Sweden during the course of 2.5 years only (from 2012 to 2014) [12]. This ratio is observed as being approximately 1/6 in China and Japan. Based on these traffic statistics and trends, the UFL/DFL ratio is expected to be in the range of 1/7–8 for the period up to 2024 [12].

A few research studies have been conducted to address the asymmetric traffic in designing MAC protocols for IBFD wireless communications. A cross-layer model is proposed to accommodate asymmetric traffic for IBFD wireless networks in [16]. However, the paper does not describe any MAC protocol in detail. Another MAC protocol named as A-Duplex was proposed for WLANs and the authors considered both symmetric and asymmetric traffic for uplink and downlink [22]. However, the FD communication is performed only, when the clients send request to send (RTS) first. If the AP sends the RTS first, a half-duplex (HD) communication takes place. In A-Duplex, during asymmetric traffic in IBFD, the transmitter sends a busy tone, if it finishes its transmission earlier than its counterpart. Another paper also describes an FD-MAC that uses a busy tone to support the asymmetric traffic [10]. Other researchers also consider the traffic asymmetry in FD-MAC, but without using the busy tone [4]. In that case, the transmitter only waits for the transmission of its counterpart to finish, if it finishes its transmission earlier.

The MAC protocol in this paper is proposed to support this traffic asymmetry. Although some MAC protocols are proposed to support traffic asymmetry, which is discussed earlier; but the supports are insufficient. Those protocols use a busy tone or wait technique to support traffic asymmetry. However, for the duration of the busy tone or waiting period, only one-way transmission (i.e., HD communication) is allowed to take place. Depending on the applications, the period of this busy tone or waiting period may be shorter or longer. If we are able to use this time (the busy tone or wait period) for any other data transmission, it may be possible to increase the throughput by using IBFD wireless communications. This is the main motivation of this research work in this paper.

## 3 Problem statement of IBFD communications in WLAN

### 3.1 Inter-user interference

The hidden terminal and exposed terminal problem is an important matter in WLANs. However, the severity of this problem is reduced, when the network is designed as an AP based WLAN and the communication is maintained by using the RTS and clear to send (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 in wireless LANs, inter-user interference is a crucial problem. This problem is depicted in Fig. 2. Here, suppose user terminal-1 (UT-1) sends data to the AP, after which the AP takes the decision to send data to UT-2 while receiving data from UT-1. However, if UT-1 and UT-2 are close to each other, the data frame from UT-1 is likely to interfere at UT-2 with the

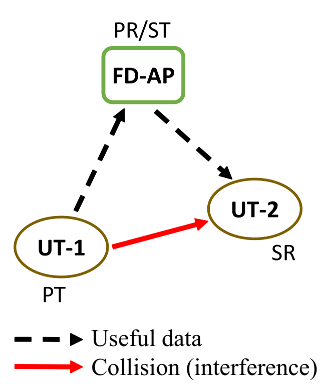



**Fig. 2** Inter-user interference in IBFD wirelss LAN

data frame being sent by the AP; this phenomenon is regarded as the inter-user interference problem. Here, UT-1 and the AP are considered as the primary transmitter (PT) and primary receiver (PR) respectively. However, UT-2 and the AP are considered as the secondary receiver (SR) and secondary transmitter (ST), respectively. Thus, the AP has the role of both PR as well as ST. Clearly, the performance of IBFD cannot be optimized without taking appropriate steps to minimize the inter-user interference.

### 3.2 Busy-tone during FD transmission

A busy tone is not required in symmetric FD transmissions, where the uplink and downlink frame sizes are the same. However, in most of the cases, the traffic volume is asymmetric for uplink and downlink, as mentioned in Sect. 2. Hence, in case of asymmetric traffic, some researchers proposed the busy tone in FD-MAC as in shown Fig. 3(a), where the UT sends a busy tone if it finishes its transmission earlier than its counterpart [10, 22] or waits for the transmission of its counterpart to finish [4]. However, the problem is that no uplink data transmission can take place during the time of the busy tone or while waiting. Therefore, it becomes HD communication in terms of data communication in that case. Hence, if other UTs could transmit their uplink data for the duration of this busy tone or while waiting, the overall throughput would be higher as in Fig. 3(b). This concept is utilized in this research for the proposed Asym-FDMAC.

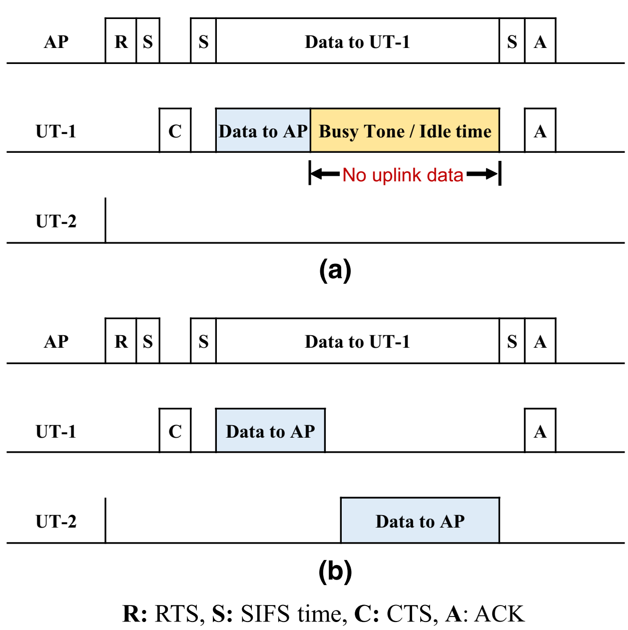



**Fig. 3** **a** Busy-tone in traditional IBFD communication and **b** efficient use of busy tone time

## 4 Proposed FD-MAC protocol

### 4.1 Description of Asym-FDMAC

The AP always initiates the transmission in Asym-FDMAC. Hence, there is no contention period or backoff time for channel access. According to the IEEE 802.11 standard, a number of management frames are exchanged between the AP and UTs at the time when the UTs or devices join the WLAN [11]. For example, after exchanging the probe request and response, the AP grants access to the device, if the device can satisfy the authentication and association procedure. The AP assigns an association ID for each UT to which it grants the channel to access. This association ID is a numerical number and is regarded as the slot number (SN), which is used in this MAC design. The maximum SN is broadcasted by the AP by using the beacon frame.

The AP transmits RTS, if it has data to send to a UT. The AP sends RTS to the UT, based on first in first out (FIFO) queuing system, if it has packets for multiple UTs. Suppose the AP has data to send to UT-1 as shown in Fig. 4. Therefore, the AP sends an RTS to UT-1 and UT-1 sends a CTS to the AP. After that, packet-length declaration and interference prevention (PDIP) is transmitted by each UT according to the assigned SN. The PDIP is a new control frame of two bytes. Each UT transmits PDIP to the AP to inform its UFL according to the time sequences (Figs. 4, 6). This control frame is used in Asym-FDMAC to combat the inter-user interference, which is described in Sect. 4.2. The inter-user interference mainly occurs when the AP has downlink data to a UT and another one or more UTs have uplink data to the AP in the same transmission cycle (Fig. 4). In this case, after exchanging the RTS and CTS, all UTs send their UFL to the AP by using PDIP, which is also used to minimize the inter-user interference.

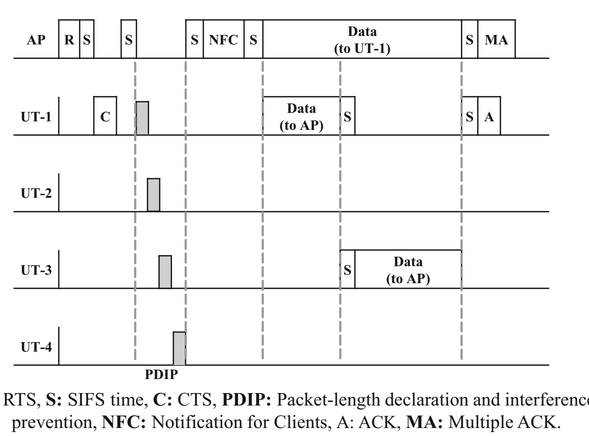



**Fig. 4** Time sequence for Asym-FDMAC (AP has data to send)

Therefore, this control frame is named as packet-length declaration and interference prevention, i.e. PDIP. However, this interference does not occur when the AP has downlink data only or the UTs have uplink data to the AP only (Fig. 6). In this case, the PDIP is sent to inform the uplink packet length only, whereupon the AP selects the UTs and inform the UTS by sending NFC (notification for clients). All the control frames that are used in Asym-FDMAC are shown in Fig. 5. The duration of each time slot (TS) is 2.6 μs in which the PDIP are sent. As the CRC and frame control are not included in PDIP, the PDIP is very short and some PDIP may have error during the transmission from the UT to the AP in real radio environment. However, after exchanging the RTS and CTS, for a successful IBFD communication, at least one successful PDIP transmission is required. Therefore, all transmissions of PDIP do not need to be error free transmissions; only a few successful transmissions of PDIP are enough for the IBFD transmission. Therefore, the PDIP is considered as a control frame of short time duration to reduce the overhead. Each UT sends the PDIP during its allocated SN after satisfying the secondary data transmission condition (SDTC). The SDTC is defined as follows:

*the UT can hear the RTS, but cannot hear the corresponding CTS.*

In this MAC protocol, all UTs can hear the RTS. However, this condition is important for another reason. In the real wireless environment, there are different kind of noises. Therefore, sometimes the RTS cannot be received correctly by all the UTs. Hence, this SDTC is required for real environment implementation. This SDTC is not applicable to the UT, to which the AP transmits the RTS. The UT sends its uplink frame duration by using PDIP to the AP, if it satisfies the SDTC. However, if it has data but cannot satisfy the SDTC, the UT sends '00000001' in PDIP. This is transmitted to the AP to inform that the UT has data, but it cannot send data to prevent the inter-user

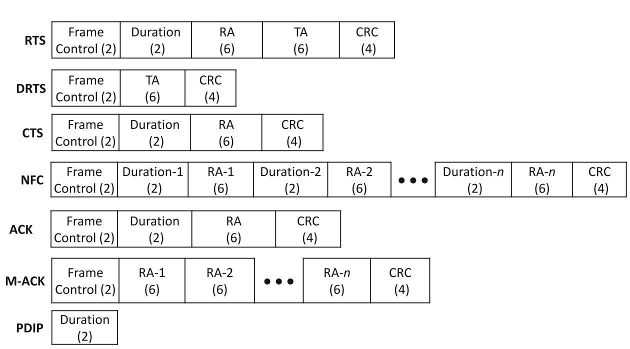



**Fig. 5** Format of control frames (in octet)

interference. On the other hand, if the UT has no data to send, it sends only zeros in its PDIP. After receiving the PDIPs from all of the UTs, the AP selects the UTs that will transmit uplink data in this transmission cycle. After the slection of UTs, the AP broadcasts NFC to inform the selected UTs as shown in Fig. 4.

The AP maintains two queues for this proposed MAC. One queue ($Q_1$) is for the UTs that have uplink packets to the AP and another queue ($Q_2$) is for the UTs, to which the AP has downlink packets to send. The AP maintains the queues to store the MAC address and corresponding frame length of the UT. The AP maintains the $Q_2$ according to the FIFO queueing system, based on downlink frame requests, but the $Q_1$ is maintained by the AP according to the Algorithm-1. $Q_1$ is the queue that store the UFL of the UT that has uplink data or packet to the AP. For this purpose, $Q_1$ stores the UFL and corresponding address of the UT. The $Q_1$ is maintained according to the FIFO queueing system.

In each transmission cycle, the AP rearranges the order of the queue after getting all PDIPs from all UTs. The UT to which the AP sends the RTS has the first priority in the $Q_1$, as it becomes bi-directional IBFD communication without inter-user interference. All other uplink requests are served as FIFO system. This is performed by the first "FOR loop" in Algorithm 1. After that, if any UT sends UFL request in both current cycle and earlier cycle, the AP updates the UFL duration of the corresponding UT (if the UFL duration is changed in current cycle), while keeping the same position in the queue. However, if any UT sends the UFL in the current cycle only, its information is appended in the queue, which is the last priority. This procedure is performed by using the last "FOR loop" in Algorithm 1.

The AP selects the UTs for NFC according to the Algorithm 2. The AP use this algorithm for each data transmission cycle, after receiving PDIPs from all the UTs. The AP collects the UFL of the first UT of $Q_1$ and compares the UFL with the DFL. If the UFL of the UT is less than the DFL, the AP selects the UT for NFC. Therefore, the AP assigns the duration of the UFL and MAC address of the corresponding UT in NFC. After that, the AP selects another UT from the queue to perform the same procedure until $Total\_UFL > DFL$. If $Total\_UFL > DFL$, the AP permits lower UFL for the last UT to transmit, so that the transmission time of the total uplink frame becomes the same as the downlink frame in each cycle. However, if the UFL is larger than the DFL for the first UT during the selection procedure, the AP selects only one UT for that cycle, but permits the UT to transmit the data of the same duration of DFL. After selecting the UTs for the NFC, $Q_1$ is updated for the next cycle. This procedure of UT selection is depicted in Algorithm 2.

**Algorithm 1** : $Q_1$ management by the AP

**Inputs:**

$DFL$ : Downlink frame length for the current cycle from ($Q_2$).

$UFL$ : Uplink frame length ($Q_1$).

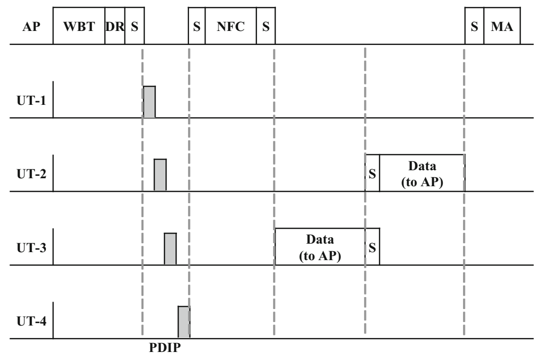
$Request\_PDIP$ : The array of all PDIP information sent by all UTs.

**Output:**

$Q_1$: Queue of the UTs that have uplink packets to send the AP.

**Start** $Q_1$ Management
$n$ = length of $Request\_PDIP$
**for** $i = 1$ to $n$ **do**
  **if** MAC address of $Request\_PDIP[i]$ == MAC address of the UT that sends CTS && $UFL$ of $Request\_PDIP[i] > 1$ **then**
    $Q_1[1] \leftarrow$ insert the MAC address and UFL of $Request\_PDIP[i]$
    $Q_1 \leftarrow$ rearrange the order of the queue
  **end if**
**end for**
**for** $i = 1$ to $n$ **do**
  **if** $UFL$ of $Request\_PDIP[i] > 1$ && MAC address of $Request\_PDIP[i] \Rightarrow$ Match with any MAC address of $Q_1[i]$ **then**
    $Q_1[i] \leftarrow$ Update the corresponding UFL
  **else**
    At the end of $Q_1 \leftarrow$ add the MAC address and UFL of $Request\_PDIP[i]$
  **end if**
**end for**
**End** $Q_1$ Management

After broadcasting the NFC by the AP, the data transmission takes place as shown in Fig. 4. The UTs are selected to transmit their uplink data while the AP transmits the downlink data. The acknowledgements (ACKs) are transmitted after finishing the data transmission. The AP transmits multiple ACK (M-ACK) to the UTs that transmit data to the AP. As shown in Fig. 5, M-ACK contains all the MAC addresses of the UTs that transmit the uplink data to the AP. However, only one ACK is transmitted to the AP by the UT that receives the downlink data.




**WBT:** Wait Before Transmit, **DR:** Dummy RTS, **S:** SIFS time, **C:** CTS, **PDIP:** Packet-length declaration and interference prevention, **NFC:** Notification for Clients, **MA:** Multiple ACK.

**Fig. 6** Time sequence for Asym-FDMAC (AP has no data to send)

However, if none of the UTs have any data to send the AP, the UTs send PDIPs that only contain zeros. In that case, the AP simply mentions the receiver's address in the NFC to which the AP sends data, whereupon it becomes HD communication, as there is no uplink data.

On the other hand, if the AP has no downlink data to any UT, it waits for a predefined time known as wait before transmit (WBT). As shown in Fig. 6, if the AP has no data to send, it sends a dummy RTS (DR) after spending the time of WBT. The PDIPs are transmitted by the UTs after the SIFS time. The remaining part of the procedure is similar to the previous description. However, in this case it is HD communication, as the AP has no downlink data to send (Fig. 6).

Now, we provide an example of this Asym-FDMAC for a clear understanding. First, suppose the AP has data to send to UT-1 as shown in Fig. 4. Then, after exchanging RTS/CTS by the AP and UT-1, all UTs transmit their PDIPs as shown in the figure. Suppose, all UTs have data to send and all of them send their corresponding UFL to the AP by sending PDIPs. The AP manages the $Q_1$ after receiving all PDIPs according to the Algorithm 1, whereupon the AP selects two UTs as uplink transmitters according to the Algorithm 2.

**Algorithm 2** : UT selection for NFC

**Inputs:**
$DFL$ : Downlink frame length for the current cycle.
$Q_1$ : Queue of the UTs that have uplink packets to send the AP.
**Output:**
$UT\_NFC$ : Selected UTs for NFC.

**Start** UT selection for the current cycle
$Total\_UFL = 0$
$UT\_NFC = \Phi$
$n \leftarrow$ Length of $Q_1$
**for** $i = 1$ to $n$ **do**
  $x \leftarrow$ assign the UFL of the UT from $Q_1[i]$
  **if** $Total\_UFL + x \leq DFL$ **then**
    $UT\_NFC \leftarrow$ insert MAC address and UFL of the UT from $Q_1[i]$
    $Total\_UFL = Total\_UFL + x$
  **else**
    $y \leftarrow (DFL - Total\_UFL)$
    **if** $y > 0$ **then**
      $UT\_NFC \leftarrow$ insert MAC address of the UT from $Q_1[i]$
      $UT\_NFC \leftarrow$ insert "$y$" as the duration of $UFL$ of the corresponding UT
    **end if**
    **break for**
  **end if**
**end for**
$Q_1 \leftarrow$ Update the queue for the next cycle
**End** UT Selection for the current cycle

Therefore, the AP writes the MAC addresses of UT-1 and UT-3 as RA-1 and RA-2 respectively in the NFC as shown in Fig. 5. The AP also include the corresponding data length in this NFC. After broadcasting the NFC, the data transmission starts as in Fig. 4. M-ACK and ACK are transmitted after the data transmission finishes. As two UTs send data to the AP, the M-ACK contains the addresses of those two UTs. However, UT-1 only sends one ACK, as it has only received data from the AP.

The control frames like RTS, CTS and ACK are compatible to the IEEE 802.11 standard. However, some new control frames (such as DR, NFC, M-ACK and PDIP) are introduced in this proposed Asym-FDMAC, which are described in Fig. 5. Therefore, necessary software upgrade is required for these new control frames as well as for this MAC protocol.

### 4.2 Minimization of inter-user interference

The inter-user interference is one of the major problems for IBFD wireless communications. Asym-FDMAC proposes a technique to combat this interference during IBFD. When the AP sends an RTS, it is received by every UT in the WLAN. However, when the corresponding UT sends a CTS, it is not received by every UT, since some UTs are hidden to the UT that sends the CTS. This combating technique is depicted in Fig. 7. As shown in that figure, suppose the AP sends RTS to UT-1 and this RTS is received by all UTs in the network. Then, UT-1 sends CTS to the AP and this CTS is received by the AP and the UTs that are within the transmission range of UT-1. Therefore, only UT-2 and the AP can receive the CTS in this case as shown in Fig. 7. However, UT-3 and UT-4 cannot receive the CTS, as they are the hidden terminals to UT-1. However, they can receive the RTS from the AP. Therefore, these two UTs can satisfy the SDTC that is described in Sect. 4.1 and thus they can send their PDIPs (with actual UFL) during their time slot. As a result of this, UT-3 and UT-4 will be allowed to transmit their uplink data, while the AP transmits the downlink data to UT-1. As these two UTs are the hidden terminals to UT-1, no inter-user interference will occur for this IBFD communication and thus Asym-FDMAC combats inter-user interference.

## 5 Mathematical analysis

### 5.1 Probability calculation

It is assumed that the packet arrival rate (PAR) follows the Poisson arrival process and the service time is almost fixed or deterministic. Therefore, the system follows the

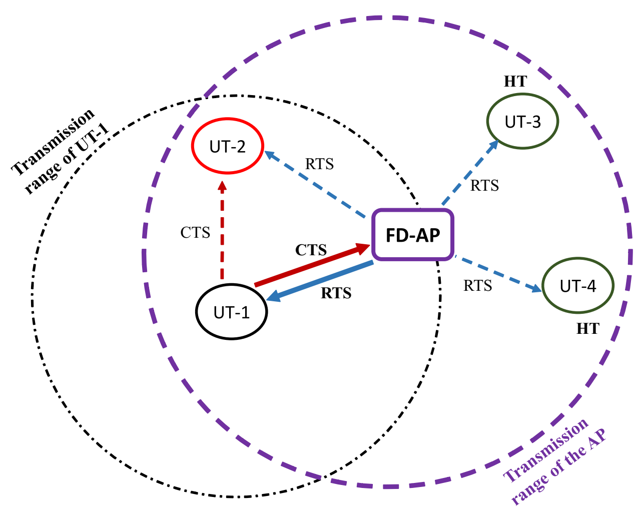



**Fig. 7** Combating inter-user interference

characteristics of an M/D/1 queueing system. The downlink traffic length is higher than that of the uplink traffic and it is assumed in this MAC protocol that the average downlink traffic length is fixed. As total uplink traffic length is matched with the downlink traffic length in this Asym-FDMAC, the service time is almost the same. Therefore, the system is assumed to be approximately M/D/1 system. The total packet arrival rate at the AP from the Internet in the form of downlink packets is defined as:

$$\lambda_{D_T} = (\lambda_{D1} + \lambda_{D2} + \cdots\cdots \lambda_{Dn}) \\ \Rightarrow \lambda_{D_T} = \sum_{i=1}^{n} \lambda_{Di} \tag{1}$$

where $n$ is the total number of UTs, $\lambda_{D1}$ is the downlink packet arrival rate at the AP for UT-1, $\lambda_{D2}$ is the downlink packet arrival rate at the AP for UT-2, and so on. If the packet arrival rate at the AP for each UT is the same, (1) can be written as

$$\lambda_{D_T} = n\lambda_D \tag{2}$$

where $\lambda_D$ is the downlink packet arrival rate at the AP for each UT. Similarly, the total packet generating rate (PGR) by the UTs as uplink packets to the AP is:

$$\lambda_{U_T} = (\lambda_{U1} + \lambda_{U2} + \cdots\cdots \lambda_{Un}) \\ \Rightarrow \lambda_{U_T} = \sum_{i=1}^{n} \lambda_{Ui} \tag{3}$$

where $\lambda_{U1}$ is the uplink packet generated by UT-1 to the AP, $\lambda_{U2}$ is the uplink packet generated by UT-2, and so on. If the PGR by each UT is the same, (3) can be written as,

$$\lambda_{U_T} = n\lambda_U \tag{4}$$

where $\lambda_U$ is the PGR by each UT. Therefore, the total packet arrival rate at the AP for both the uplink and downlink becomes:

$$\lambda_{Total} = \lambda_{D_T} + \lambda_{U_T} \tag{5}$$

Suppose, one packet arrives at the AP as a downlink packet for a UT. Therefore, the RTS and other control frames are transmitted before data transmission takes place. If there is no uplink packet request before the data transmission, it becomes half-duplex (HD) communication. The conditional probability of the HD communication ($P_{HD}$) is:

$$P_{HD} = e^{-\lambda_{U_T} T_{w_{hd}}} \tag{6}$$

where $T_{w_{hd}}$ is the average waiting time of a uplink packet before transmission, when it becomes HD communication after sending the RTS by the AP. The average waiting time is derived in the following Sect. 5.2.

As described before in Sect. 4.1, the nonzero UFL is transmitted by the UTs that cannot hear the CTS. However, a nonzero UFL can be transmitted by the UT that transmits a CTS, if it has data to send. Suppose, the AP sends an RTS to UT-1 and it sends a CTS to the AP. Hence, the UTs that cannot hear the CTS and have data to send the AP transmit nonzero UFL and this number of UTs depends on the number of hidden terminals (HT) in the network, as described in Sect. 4.2. If $\beta$ is the average percentage of HT in the network, the number of UTs that cannot hear the corresponding CTS is $m = \lfloor \beta \times n \rfloor$. Therefore, the conditional probability of the FD communication ($P_{FD1}$), where exactly one UT sends a nonzero UFL to the AP is:

$$P_{FD_1} = \left(e^{-(m+1)\lambda_U T_{w_{fd}}}\right)\left((m+1)\lambda_U T_{w_{fd}}\right) \tag{7}$$

where $1 \le m < n$ and $T_{w_{fd}}$ is the average waiting time of a uplink packet before transmission, when it becomes FD communication after sending an RTS by the AP. The term $m + 1$ includes the UT that sends the CTS and the UTs that cannot hear the CTS.

Similarly, the probability of exactly two UTs sending nonzero UFL to the AP is:

$$P_{FD_2} = \left(\left(e^{-\lambda T_{w_{fd}}}\right) \times \frac{\left(\lambda T_{w_{fd}}\right)^2}{2!}\right) \tag{8}$$

where $\lambda = (m + 1)\lambda_U$.

Therefore, we can generalize the probability equation for the FD communication, where exactly $k$ UTs send nonzero UPL to the AP, after sending an RTS. This probability equation can be generalized as:

$$P_{FD_k} = \left(\left(e^{-\lambda T_{w_{fd}}}\right) \times \frac{\left(\lambda T_{w_{fd}}\right)^k}{k!}\right) \tag{9}$$

where $1 \le k \le m + 1$.

Now, suppose the UFL/DFL ratio is 1:$x$. Therefore, at least $\lceil x \rceil$ UTs are required to send nonzero UFL to the AP to enable the AP to select UTs in such a way that the total UFL becomes almost the same as the DFL. Hence, to maximize the throughput by using Asym-FDMAC for a UFL/DFL ratio of 1:$x$, at least $k = \lceil x \rceil$ number of nonzero UFL requests need to be transmitted to the AP. However, if the number of UTs that send the PDIP with nonzero UFL is more than $x$, the AP selects only $\lceil x \rceil$ number of UTs to transmit the uplink data. Therefore, the probability of FD communications, in which at least $\lceil x \rceil$ number of UTs send nonzero UFL is written as:

$$P_{FD_{k \ge \lceil x \rceil}} = \sum_{i=\lceil x \rceil}^{m+1} \left(e^{-\lambda T_{w_{fd}}}\right) \times \frac{\left(\lambda T_{w_{fd}}\right)^i}{i!} \tag{10}$$

where $1 \le \lceil x \rceil \le m + 1$.

### 5.2 Average waiting time calculation

It is possible to calculate the utilization factor by using the corresponding arrival rate and service time. The utilization factor ($\rho$) for this MAC protocol can be defined as:

$$\rho = \frac{\text{Service time}}{\text{Average packet interarrival time}} \tag{11}$$

Therefore, the uplink utilization factor is defined as:

$$\rho_u = \frac{T_s}{1/\lambda_{U_T}} = \frac{1/\mu}{1/\lambda_{U_T}} = \frac{\lambda_{U_T}}{\mu} \tag{12}$$

where $T_s$ is the service time and $\mu$ is defined as the average service rate that is the inverse of $T_s$. Here, both the service time for downlink and uplink are the same for this MAC design, which is referred to as the time required to complete one cycle. The value of $T_s$ depends on both HD and FD transmission. After sending RTS by the AP, if HD communication takes place, $T_s$ for HD is given by ($T_{s_{hd}}$):

$$T_{s_{hd}} = T_{RTS} + T_{CTS} + nT_{PDIP} + T_{NFC-HD} + T_{DPL} + T_{ACK} + 5T_{SIFS} \tag{13}$$

The symbols in the equations are explained in Table 1. However, if the FD communication takes place, $T_s$ for FD is given by ($T_{s_{fd}}$):

$$T_{s_{fd}} = T_{RTS} + T_{CTS} + nT_{PDIP} + T_{NFC-FD} + T_{DPL} + T_{M-ACK} + 5T_{SIFS} \tag{14}$$

The main differences between (13) and (14) are the time required for NFC and ACK. The M-ACK is transmitted by the AP, when more than one UTs transmit uplink data during FD communications. If there is no nonzero UFL request, the AP only includes the address of the UT designated to receive the downlink data in the NFC. Therefore, for HD communications the NFC contains only the address of one UT, but for FD communications the NFC contains additional addresses and the time duration of the UFL.

Replacing the value of $T_s$ in (12) by $T_{s_{hd}}$ and $T_{s_{fd}}$ from (13) and (14) respectively, the uplink utilization factor for HD ($\rho_{u_{hd}}$) and FD ($\rho_{u_{Fd}}$) are achieved respectively. Therefore, we obtain,

$$\rho_{u_{hd}} = \frac{T_{s_{hd}}}{1/\lambda_{U_T}} = \frac{1/\mu_{hd}}{1/\lambda_{U_T}} = \frac{\lambda_{U_T}}{\mu_{hd}} \tag{15}$$

$$\rho_{u_{fd}} = \frac{T_{s_{fd}}}{1/\lambda_{U_T}} = \frac{1/\mu_{fd}}{1/\lambda_{U_T}} = \frac{\lambda_{U_T}}{\mu_{fd}} \tag{16}$$

According to the well-known Pollaczek–Khinchine (P–K) formula for an M/D/1 system, the average waiting time of an uplink packet before transmission is derived as:

$$T_{w_{hd}} = \frac{\rho_{u_{hd}}}{2\mu_{hd}(1-\rho_{u_{hd}})} \tag{17}$$

$$T_{w_{fd}} = \frac{\rho_{u_{fd}}}{2\mu_{fd}(1-\rho_{u_{fd}})} \tag{18}$$

### 5.3 Throughput calculation

It is assumed that the average values of DFL and UFL are $l_d$ and $l_u$ respectively. If HD transmission occurs after sending the RTS, the throughput is defined as:

**Table 1** Declaration of variables

| Variables | Explanation | Variables | Explanation |
|---|---|---|---|
| $k$ | Number of UTs that send nonzero UPL to the AP | $\beta$ | Average percentage of hidden terminal in the network |
| $n$ | Total number of UTs | $m$ | Average number of HTs in the WLAN |
| $\lambda_D$ | Average downlink packet arrival rate at the AP for each UT (packets/s) | $\lambda_U$ | Average PGR by each UT (packets/s) |
| $\lambda$ | $(m+1)\lambda_U$ | $P_{HD}$ | Conditional probability of HD communications after sending RTS |
| $P_{FD_k}$ | Conditional probability of FD communications after sending RTS, where $k$ UTs send nonzero UPL | $T_{ACK}$ | Time for ACK |
| $T_{CTS}$ | Time for CTS | $T_{DPL}$ | Time for downlink packet length |
| $T_{M-ACK}$ | Time for M-ACK | $T_{NFC-HD}$ | Time for NFC in HD communication |
| $T_{NFC-FD}$ | Time for NFC in IBFD communication | $T_{s_{hd}}$ | Service time for HD communication |
| $T_{s_{fd}}$ | Service time for IBFD communication | $\mu_{hd}$ | Average service rate for HD communication |
| $\mu_{fd}$ | Average service rate for IBFD communication | $T_{PDIP}$ | Time for PDIP |
| $T_{RTS}$ | Time for RTS | $T_{SIFS}$ | Time for SIFS |
| $T_{w_{fd}}$ | Average waiting time of a uplink packet before transmission, when it becomes FD communication after sending RTS by the AP | $T_{w_{hd}}$ | Average waiting time of a uplink packet before transmission, when it becomes HD communication after sending RTS by the AP |

$$Th_{\text{hd}} = \frac{l_{\text{d}}}{T_{\text{data}_{\text{hd}}}} \tag{19}$$

The probability of obtaining this throughput is $P_{\text{HD}}$, which is given in (6). Thus, multiplying $P_{\text{HD}}$ with (19), we obtain the expected value of $Th_{\text{hd}}$. We categorize the FD communication according to the number of transmitters that want to send data to the AP. If there is only one UT that wants to send data to the AP, the throughput is defined as:

$$Th_{\text{fd1}} = \frac{l_{\text{d}} + l_{\text{u}}}{T_{\text{data}_{\text{fd}}}} \tag{20}$$

The probability of this $Th_{\text{fd1}}$ occurring is defined in (7). Similarly, we can derive $Th_{\text{fd2}}$, where two UTs aim to send data to the AP and for which the corresponding probability can be found in (8). If the UFL/DFL ratio is 1:$x$, at least $\lceil x \rceil$ number of UTs are required to send data to the AP to enable it to select the UTs in such a way that the total UFL and DFL become almost the same. Therefore, the throughput in this case is achieved as follows:

$$Th_{\text{fd}_{k \geq \lceil x \rceil}} \cong \frac{l_{\text{d}} + \lceil x \rceil l_{\text{u}}}{T_{\text{data}_{\text{fd}}}} \tag{21}$$

Here, $Th_{\text{fd}_{k \geq \lceil x \rceil}}$ is the throughput, when the number of UTs that want to send uplink data is greater than or equal to $\lceil x \rceil$. However, if this number is less than $\lceil x \rceil$, we obtain the throughput by using the following equation:

$$Th_{\text{fd}_{k < \lceil x \rceil}} \cong \frac{l_{\text{d}} + k l_{\text{u}}}{T_{data}} \tag{22}$$

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

$$E[Th] = \sum_{x:p(x)>0} x p(x) \tag{23}$$

Here, $p(x)$ is the probability mass function (PMF) of $Th$. By using the values of PMF from (6) to (10), we obtain the mean value of $Th$.

$$E[Th] = (Th_{\text{hd}} \times P_{\text{HD}}) + (Th_{\text{fd1}} \times P_{\text{FD1}}) + (Th_{\text{fd2}} \times P_{\text{FD2}}) \cdots\cdots + (Th_{\text{fd}_k} \times P_{\text{FD}_k}) \tag{24}$$

Asym-FDMAC needs to satisfy two conditions for IBFD communications. Firstly, the AP should have packets to send any UT and secondly, at least one UT should have packets to send to the AP at the same time. However, if more than one UT has packets to send, the throughput becomes higher.

It is possible to derive the equation to determine the throughput under the saturation condition. The saturation condition is defined as the situation in which all the UTs and the AP always have packets for transmission, i.e., the transmission queues of each of the UTs and the AP are always nonempty [3, 22]. Under this condition, the AP and all UTs have data to send. Therefore, the communication is always IBFD communication in saturation condition. For this reason, the value of $P_{\text{HD}}$ becomes zero in (24). However, the values of the other probabilities depends on the total number of UTs. Thus, under the saturation condition, the probabilities have the following values:

- $P_{\text{HD}} = 0$; for $n \geq 1$, and
- $P_{\text{FD1}} = 1$; for $n = 1$.
- $P_{\text{FD2}} = 1$; for $n = 2$.
- $P_{\text{FD}_{k<\lceil x \rceil}} = 1$; for $n = k$.
- $P_{\text{FD}_{k \geq \lceil x \rceil}} = 1$; for $n \geq \lceil x \rceil$.

By using these values in (24), we can calculate the mean throughput in the saturation condition.

## 6 Results and discussion

The performance of Asym-FDMAC is described in the following two subsections.

### 6.1 Performance result based on mathematical analysis

This analyses is performed based on the mathematical equations which is described in Sect. 5. Here, both the average uplink and downlink packet arrival rates at the AP are set to 42 packets/s for each UT. The parameters for mathematical analyses as well as for the simulation (Sect. 6.2) are provided in Table 2. The result of this evaluation is shown in Fig. 8, which shows the performance for an average HT ratio of 45%, 30% and 15% in Fig. 8(a)–(c), respectively. The HT is considered in terms of one UT in the netwrok, i.e. if a UT is considered to transmit data, there are some UTs that cannot receive the data as they are hidden to that corresponding UT. For each UT, a number of hidden UTs are found in a wireless network. Therefore, an average number of HT can be obtained and thus we can calculate a percentage of the average HT, which is regarded as the average HT ratio in this paper. In the simulation, the average HT ratio is assumed to be the respective number, such as 45%, 30% and 15% in Figs. 8 and 9. On the other hand, the AP can receive data from all UTs in the network and vice versa. The UFL/DFL ratio is assumed to be 1/3 for this analysis, where the downlink frame length is 2000 bytes.

In this simulation, four different cases are considered, if the AP has a downlink packet:

- There is no uplink packet.
- Exactly one UT sends uplink data.

**Table 2** Simulation parameter

| Parameter | Value |
|---|---|
| DFL (payload for downlink) | 2000 bytes |
| TS duration for PDIP | 2.6 µs |
| Data rate | 54 Mbps |
| Control frame (RTS, CTS, etc.) rate | 12 Mbps |
| WBT time | 25 µs |
| DIFS time | 28 µs |
| SIFS time | 10 µs |
| Minimum backoff window size ($CW_{min}$) for traditional IBFD | 32 µs |
| PLCP preamble duration | 16 µs |
| PLCP header duration | 4 µs |

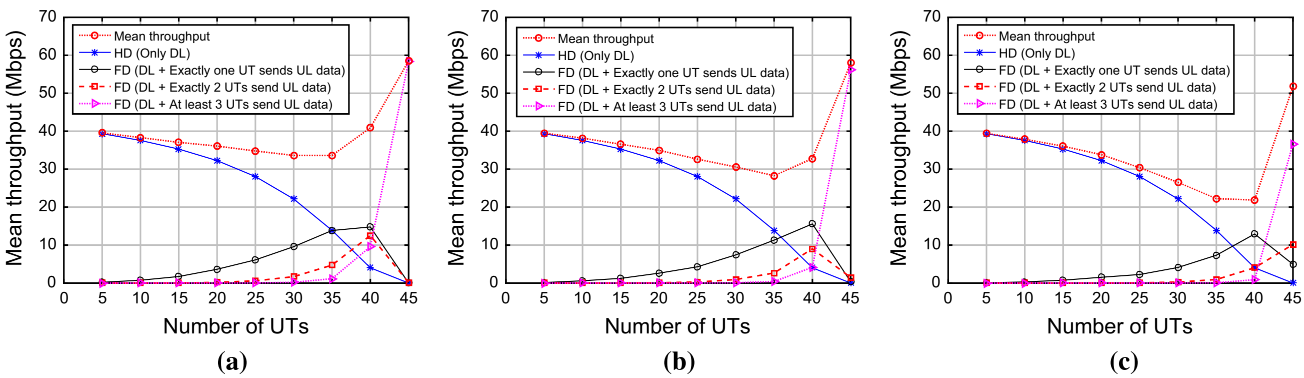



**Fig. 8** Mean throughput under different situations, after sending RTS by the AP. **a** Average HT ratio is 45%. **b** Average HT ratio is 30%. **c** Average HT ratio is 15%

- Exactly two UTs send uplink data.
- At least three UTs send uplink data.

As shown in Fig. 8(a), the mean throughput decreases gradually as the number of UT increases from 5 to 35, where the average HT ratio is 45%. The main reason lies in the fact that the decreasing rate of throughput for HD is higher than the total increasing rate of other cases of FD transmissions. However, the mean throughput increases rapidly from 33 to 54 Mbps as the number of UTs increases from 35 to 45. As the average PAR is fixed, the probability of FD communication (where at least 3 UTs send uplink data) is very low up to 30 UTs. As the UFL/DFL ratio is 1/3, at least three UTs are required to send nonzero UFL to achieve the highest throughput. However this probability increases very rapidly as the number of UTs increases from 30 to 45 and thus the mean throughput increases sharply. The figure shows that the throughput for HD communication follows a decreasing trend towards zero as the number of UTs increases. Because, the probability of HD communication decreases as the number of UTs increases while the PGR remains fixed. Contrary to this, the throughput for FD communications with exactly one or two uplink frame increases gradually up to a certain level and then decreases sharply towards zero as the network size increases. Because, since the network size increases, the probability that at least three or more UTs will send uplink data to the AP.

Almost similar trends are found in Fig. 8(b, c). As shown in Fig. 8, the lowest value of the mean throughput decreases as the average HT ratio decreases. For example, the lowest mean throughput is 33 Mbps, 28 Mbps and 22 Mbps for an average HT ratio of 45%, 30% and 15% respectively. Similarly, the highest peak of the mean throughput decreases as the HT ratio is reduced. The reason is that if the HT ratio decreases, the number of UTs that send uplink data decreases and the probability of FD communications decreases, as the PAR and PGR are fixed, and thus the mean throughput also decreases. As the average PGR is fixed, the maximum uplink utilization ratio is about 98% for all the cases, i.e. the utilization factor is 98%, when the total number of UTs is 45. Since the throughput of HD only in the figure is decreases to zero as the number of UTs increases to 45, this performance analysis suggests that the proposed MAC can achieve higher throughput in high traffic load; because the utilization factor is 98% in this case.

### 6.2 Performance result in saturation condition

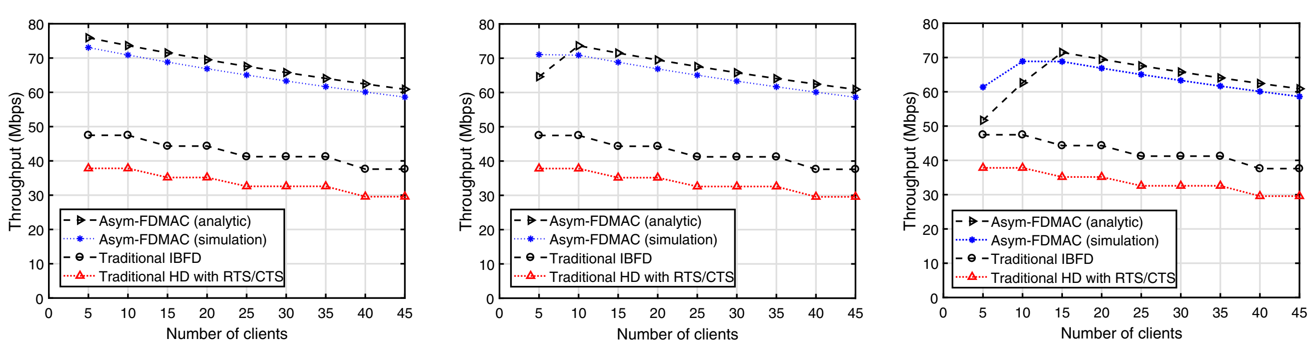
The performance of Asym-FDMAC under the saturation condition is evaluated by conducting an extensive MATLAB simulation. Asym-FDMAC is compared with traditional IBFD and HD communications performed with RTS/CTS. Traditional IBFD is explained in Fig. 3(a).

The simulation results are shown for different HT ratios with a fixed UFL/DFL ratio of 1/3 in Fig. 9. As shown in Fig. 9(a), the maximum simulation throughput for Asym-FDMAC is about 73 Mbps for 5 UTs under saturation conditions, where the average HT ratio is 45%. The throughput decreases gradually to 58 Mbps, as the number of UTs increases to 45. Because, the number of TS increases for transmitting PDIP, as the number of UTs increases and thus the throughput decreases. On the other hand, as traditional IBFD and HD use the distributed coordination function (DCF) to access the channel, the number of collisions increases as the number of UTs increases and thus the throughput decreases. Asym-FDMAC outperforms traditional IBFD and HD by 59% and 100% throughput gain respectively for 5 UTs in terms of the maximal throughput (Fig. 9a). However, in case of minimal throughput for 45 UTs, the gains are achieved as 55% and 98% in comparison with traditional IBFD and HD respectively, and the average throughput gain achieved by Asym-FDMAC is 54% and 94% respectively.

It is noticeable from Fig. 9 that the maximal throughput decreases for Asym-FDMAC as the average HT ratio decreases. For example, the maximal simulation throughputs are 73 Mbps for 5 UTs (Fig. 9a), 71 Mbps for 5 UTs (Fig. 9b) and 69 Mbps for 10 UTs (Fig. 9c) for different average HT ratios, i.e., 45%, 30% and 15% respectively. This can be understood by considering that, if the average number of HT decreases, the number of UTs available to satisfy the SDTC is insufficient. In this simulation, as the UFL/DFL ratio is 1/3, at least two hidden UTs are required after the CTS transmission to achieve the maximal throughput. Therefore, two hidden UTs and the UT that sends CTS (a total of three UTs) can send uplink data to the AP. For this reason, in case of 15% HT ratio, it is not possible to get the sufficient number of UTs that can satisfy the SDTC and thus the throughput is lower in case of five UTs (Fig. 9c). The lowest average throughput gain is observed as about 50% and 89% for the average HT ratio of 15% compared with traditional IBFD and HD respectively (Fig. 9c).

The performance analysis also shows that there is little difference between the simulation and analytic result of Asym-FDMAC as shown in the Fig. 9. The main reason lies in the fact that the SIFS time between the transmissions of different UTs is not considered in (21) and (22). Therefore, the analytic throughput is slightly higher than simulation throughput for the cases in which the minimum number of hidden UTs (this number is two in this simulation) are available to achieve the maximal throughput. On the other hand, the average number of UTs ($m$) in (7)–(10) is calculated by rounding down the product of the average HT ratio and total number of UTs. Therefore, the analytic result requires more UTs than the simulation environment to achieve the maximal throughput and thus the analytic value falls behind the simulation throughput for lower average HT ratios and for lower number of total UTs as shown in Fig. 9(b) (for 5–10 UTs) and Fig. 9(c) (for 5–15 UTs). However, this is not observed in Fig. 9(a), as the average HT ratio is 45%. Hence, the minimum number of hidden UTs is obtained for five UTs as well as for a higher number of UTs.

The result of another evaluation of the throughput performance is depicted in Fig. 10 in terms of the UFL/DFL ratio for 20 UTs under saturation condition, where the downlink frame size is fixed at 2000 bytes. The figure shows that Asym-FDMAC outperforms traditional IBFD by about 52% throughput gain for the UFL/DFL ratio of 1/3, which is the maximal gain in this analysis. The throughput gain decreases as the UFL/DFL ratio decreases. This happens for two reasons. Firstly, the number of UTs available for transmitting uplink data increases to match




(a) (b) (c)

**Fig. 9** Throughput comparison under saturation conditions (the UFL/DFL ratio is 1/3). **a** Average HT ratio is 45%. **b** Average HT ratio is 30%. **c** Average HT ratio is 15%

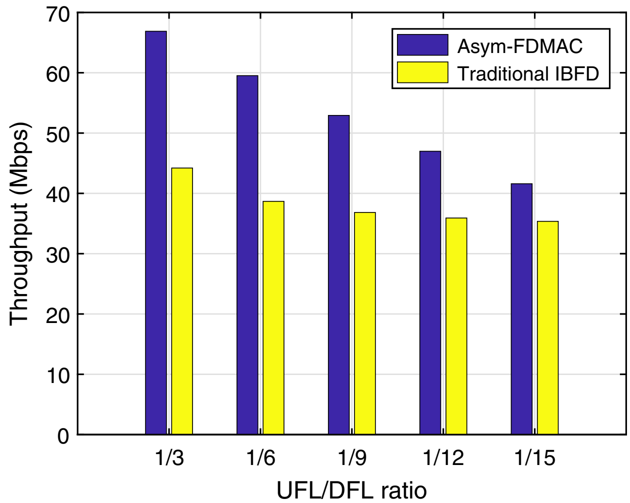



**Fig. 10** Throughput comparison with respect to UFL/DFL ratio (for 20 UTs)

the downlink data transmission, as the UFL/DFL ratio decreases and thus the number of SIFS time increases in-between the transmission of uplink data by different UTs. Therefore, the total uplink data decreases. Secondly, as the number of uplink data transmitting UTs increases, the total transmission time increases, because the AP needs to include their addresses in both NFC and M-ACK. Therefore, the total amount of transmitted data decreases for the first reason and the total transmission time increases for the second reason, which leads to a lower throughput as the UFL/DFL ratio decreases. However, in case of traditional IBFD, the total transmission time remains the same for all the UFL/DFL ratios. Moreover, comparing to the total transmission time only a little amount of uplink data decreases as the UFL/DFL ratio decreases. Since the downlink frame size is fixed at 2000 bytes, the throughput of traditional IBFD remains almost stable as shown in Fig. 10.

A comparison in terms of overhead generated under saturation condition is shown in Fig. 11. This comparison is depicted in two different ways. For example, Fig. 11(a, b) compare Asym-FDMAC with traditional IBFD in terms of total overhead. However, Fig. 11(c, d) compare them by considering overhead/byte, where the unit is nanosecond/byte (ns/B). In this comparison, the overhead is calculated in terms of time from the beginning to the end of the transmission cycle except for the time required for user data (payload) transmission. For example, in the time sequence of the AP as shown in Fig. 4, the overhead time includes the time starting at the point of transmitting the RTS until the ending point of M-ACK transmission, except the time of the data transmission. It is observed that the total overhead generated by of Asym-FDMAC is almost the same as that of traditional IBFD for the UFL/DFL ratio of 1/3 (Fig. 11a). However, for a UFL/DFL ratio of 1/9,

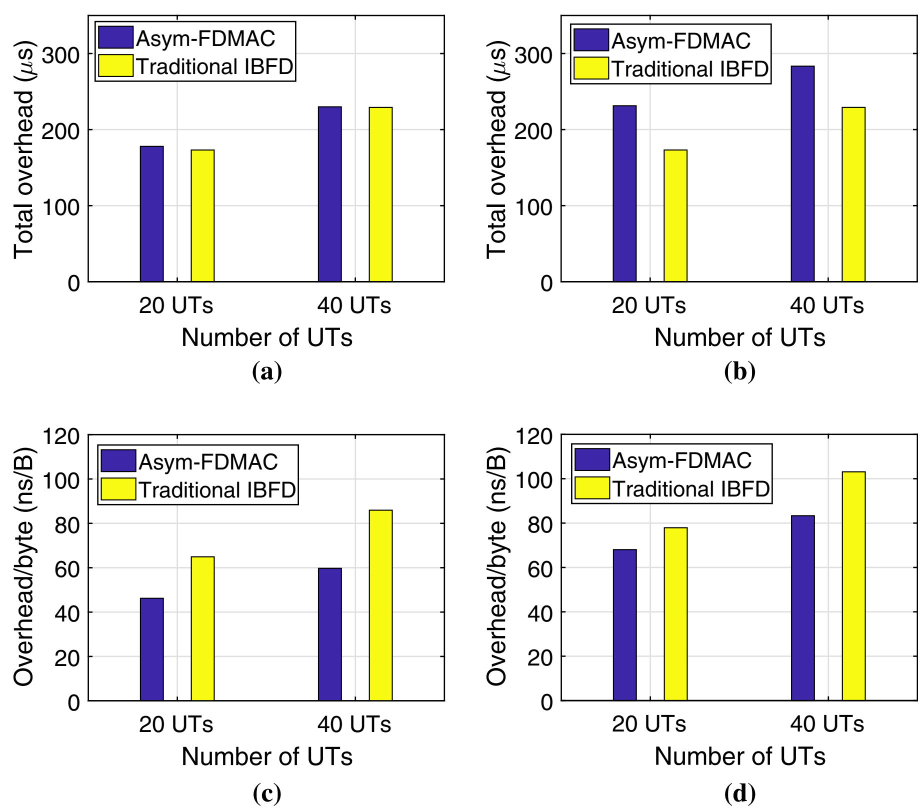



**Fig. 11** Overhead comparison: **a**, **b** show total overhead comparison and **c**, **d** show overhead/byte comparison. **a** UFL/DFL ratio is 1/3, **b** UFL/DFL ratio is 1/9, **c** UFL/DFL ratio is 1/3, **d** UFL/DFL ratio is 1/9

**Table 3** Effect of missing frames

| Name of missing control frames | Nodes that miss the control frame | Impact on that node (In terms of data communication) | Overall impact on data transmission |
|---|---|---|---|
| RTS | Corresponding receiver client | The client cannot transmit to and receive from the AP | HD transmission is possible from other clients to AP. |
| | Any other client | The client cannot send PDIP during its slot number (SN) | FD communication is possible. |
| CTS | AP | Still the AP can receive data from other clients | HD transmission is possible. |
| | Any other client | The corresponding client can send PDIP during its SN | Inter-user interference can occur. HD communication is possible. Sometimes FD communication is also possible. |
| PDIP | AP | The corresponding client cannot send data to AP | FD communication is possible. |
| | Any other client | No effect | FD communication is possible. |
| NFC | Corresponding client | The corresponding client cannot send data to AP | Corresponding client cannot send data to the AP, FD communication is possible with lower throughput. |
| | Any other client | No effect | No effect on FD communication. |
| DR | Any other client | The corresponding client cannot send PDIP | HD communication is possible. |
| ACK from a client | AP | It seems that the client does not receive data from AP | Transmission from AP to client is discarded and re-transmission is required. |
| ACK from the AP | Corresponding client | It seems that the AP does not receive data from the client | The transmission is discarded and re-transmission is required. |
| Data from a client | AP | AP will not send ACK to the corresponding client | FD is possible with other clients with lower throughput. Re-transmission is required from the client. |
| Data from the AP | Corresponding client | The client will not send ACK to AP | HD transmission is possible. Re-transmission is required from the AP. |

Asym-FDMAC generates 33% and 23% more overhead for 20 UTs and and 40 UTs respectively (Fig. 11b). On the other hand, Asym-FDMAC outperforms traditional IBFD with lower overhead/byte. Although Asym-FDMAC has higher total-overhead in most of the cases, it has a lower overhead/byte compared to traditional IBFD in all cases (Fig. 11c, d).

Overhead/byte is an important parameter for performance analysis, as it describes the overhead as well as the amount of transmitted data. Therefore, the MAC protocol with lower overhead/byte performs more effectively. Asym-FDMAC outperforms traditional IBFD with lower overhead/byte in all cases as shown in Fig. 11(c, d).

## 6.3 Effect of missing frames

Any control frames or any transmitted data can be lost and thus the corresponding frame cannot be received by a node or by the AP in real environment due to noise or interference. Table 3 describes the impact of any missing control frames as well as data on the proposed Asym-FDMAC. In case of traditional HD communication, if any RTS or CTS is missed out, the communication is discarded and the re-transmission of RTS as well as CTS is required. This re-transmission is also required, if the data or the ACK are lost. However, in case of Asym-FDMAC (as shown in the Table 3), most of the cases the data transmission can be possible; only the exception is for missing of data and ACK. Even in case of missing RTS and CTS, some times communication is possible with lower throughput. Therefore, this proposed Asym-FDMAC is theoretically more robust than the existing traditional IBFD and HD communication. For example, after sending the RTS by the AP, if the RTS is not received by the corresponding UT, HD transmission is still possible. In this case, the corresponding UT cannot send the CTS. Therefore, all the UTs that have uplink data can send the PDIP, as all UTs satisfy the SDTC in this case. Now, as the AP does not receive the CTS, it will not transmit the downlink data. However, the AP can select the UTs for the uplink data transmission and thus HD transmission is possible. On the other hand, if the RTS is not received by an individual UT, it cannot send the PDIP in this transmission cycle only, but FD communication is possible as other UTs receive RTS. However, if the RTS is totally lost (i.e. no UTs can receive the RTS correctly), the re-transmission is required.

## 7 Conclusion

This paper proposes a MAC protocol for IBFD wireless communications. This MAC protocol supports asymmetric traffic for uplink and downlink communication, which can be utilized in an infrastructure based WLAN. As asymmetric traffic is very common in WLANs, we need to include this feature in future FD wireless communications. The proposed Asym-FDMAC supports the transmission of uplink data by multiple user terminals during a single downlink transmission. Hence, the busy time or idle time (used in other FD-MAC protocols) can be used for data transmission. The simulation results showed that the proposed FD-MAC outperforms traditional IBFD and HD communications significantly.

This MAC protocol is not compatible with the IEEE standard. As IBFD is a new technology and the existing IEEE standard does not support IBFD communication, we need new MAC protocols to achieve the full advantage of this latest technology. In addition, to implement this Asym-FDMAC with the existing devices, the software up-gradation and proper scheduling are required. For example, the AP can give chance to the existing WiFi devices by switching the channel access mechanism to the contention based mechanism. This issues can be considered more deeply in the upcoming future research. The concept of hidden terminal is utilized here for combating inter-user interference. However, other techniques can be utilized in future research for this purpose, such as the capture effect.

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