Full Duplex Medium Access Control Design for Heterogeneous WLAN

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***Abstract*—Full duplex (FD) wireless communication has an enormous prospect in near future. To leverage the FD benefit successfully, efficient medium access control (MAC) protocols are very crucial along with physical layer performance. Although a number of FD-MAC protocols were proposed earlier, most of them are not for wireless local area networks (WLANs). On the other hand, as still there are a lot of half duplex (HD) capable devices in existing WLANs, the integration of FD clients and HD clients in the same WLAN is an urgent need. This type of WLAN can be named as heterogeneous WLAN (Het-WLAN). In this paper, we proposed a FD-MAC for the Het-WLAN, where all possible cases of FD transmission are considered. Our proposed FD-MAC protocol suppresses inter-user interference. The simulation result shows that a significant throughput gain (about 50%) can be achieved by using our proposed FD-MAC as compared to traditional HD communications. Moreover, this MAC is compared with another existing FD-MAC design and our proposed MAC shows a better performance (average throughput gain is 11%) with comparing to that existing one. In addition, the probability analysis suggests that the probability of FD transmissions increases as the number of total clients increases, when the WLAN is not in saturation condition.**

***Index Terms*—Full Duplex, MAC protocol, Het-WLAN, FD-MAC.**

I. Introduction

In general, traditional radio transceivers cannot transmit and receive at the same time by using the same band of frequency because of the self-interference (cross-talk) at the receiver end. However, recent technological development in antenna design and radio frequency (RF) interference cancellation techniques reduce the self-interference up to 110 dB [1]. Some other papers also proposed this kind of full duplex (FD) radio technology [2]–[5]. But, to attain the full leverage of FD technology in wireless local area networks (WLANs), medium access control (MAC) protocols play a vital role.

On the other hand, as different kinds of half duplex nodes (HDNs) still exist in our existing WLANs, it is impractical to replace all HDNs with new full duplex nodes (FDNs). So, it is crucial to incorporate some FDNs with existing HDNs in such a way that they can operate simultaneously in the same WLAN. This kind of WLAN is named here as heterogeneous WLAN (Het-WLAN) which includes HDNs, FDNs and an AP. Moreover, HDNs have some advantages over FDNs; such as the FDN will be more costly and it will require more consumption of power. Hence, some people may use the HD devices intentionally.

The basic structure of a Het-WLAN is shown in Fig. 1. Here, a Full Duplex Access Point (FD-AP), some HDNs and some FDNs are used. So, a suitable MAC design is required for this purpose, as the existing MAC protocols do not support the Het-WLAN. All FD transmissions in this design can be classified in two broad categories, such as bidirectional full duplex (BFD) transmission and relay full duplex (RFD) transmission. As in Fig.1, BFD communication is performed between AP and any FDN, when they transmit and receive data simultaneously at the same time; however, during R-FD transmissions, AP transmits data to any one node and receives data from another node simultaneously. Here, the data that is receiving and transmitting by AP are different to each other. In addition, HD transmission is also possible.

A few number of MAC designs have been published earlier for the full duplex data transmission in WLANs. But, those are not able to describe all of the possible cases of FD transmissions. In addition, many of them were proposed for the distributed wireless networks or ad-hoc networks, where all the client-nodes were considered as FDNs [5]–[9]. Full duplex multi-channel MAC (FD-MMAC) was proposed to eliminate the controlling signal to mitigate multi-channel hidden terminal problems [6]. In FD-MMAC, full-duplex capability was not fully utilized for user data communication.

So, in terms of user data transmission, it is actually a half-duplex (HD) communication. Another FD-MAC was proposed in [7] for distributed networks, where all the nodes are FD nodes. The inter-user interference is not considered here. As

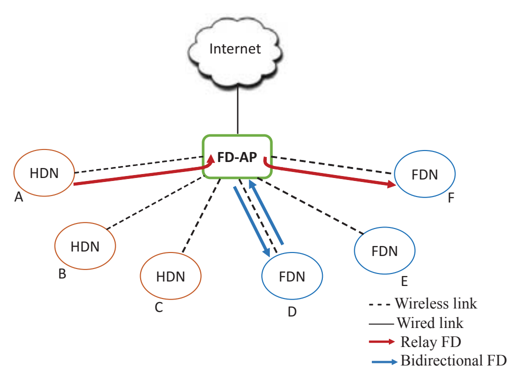

Fig. 1. Structure of a Het-WLAN

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a result, FD communication will be affected by inter-user interference. An infrastructure based FD-MAC was proposed in [8], where a buffer is used in the access point (AP). Their simulation shows that increasing buffer-depth has no effect for the full-duplex communication. But the simulation has been done only for five mobile client nodes. All the nodes are full-duplex capable here.

A-duplex proposed a FD-MAC for a WLAN that consists of a full duplex AP and HD clients [10]. In this case, all of the clients are HD clients only, FD clients are not considered here. Moreover, all nodes including AP need to calculate and update the SIR map continuously, which will increase the computational load as well as increase the complexity. Here, the transmission always needs to be initiated by clients to establish dual link (FD communications). An AP based MAC protocol was proposed in [11]. But, all of the clients are full duplex capable here, so the protocol cannot be used in Het-WLANs. Another FD-MAC design has been proposed for a WiFi networks, where both HD and FD clients are available [12]. However, this paper limited their FD communication for the situation, when a mobile node and AP have packets for each other. A power controlled based MAC (PocMAC) has been proposed recently for FD WiFi networks [13]. This MAC was proposed to mitigate the inter-user interference during FD transmission. However, they considered FD-AP and HD clients only, but did not considered any FD clients. Some other research works have been published on FD communication on different issues, such as relay transmission or power control based FD [14]–[16]. So, those publications did not consider the MAC design.

In this paper, a FD-MAC is proposed for the Het-WLAN. So, the main motivation of this research is to accommodate FDN clients and HDN clients in the same WLAN. In this proposed Het-WLAN, the AP is full duplex capable and there are some FDNs as well as HDNs. All possible cases of FD transmissions are considered in this MAC protocol. To the best of our knowledge, this is the novel research that describes the FD-MAC for this kind of Het-WLAN that describes all possible transmissions. The main motivation for this research includes the following key points:

- Although a number of FD-MAC protocols are proposed, most of them were proposed for ad-hoc networks or distributed networks.
- We would like to incorporate FDNs with the existing WLAN that has HDNs.
- No FD-MAC were proposed earlier for Het-WLANs, where all possible cases of FD transmissions were discussed.

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 brief description for combating inter-user interference, section-V illustrates mathematical analysis and section-VI describes the result and performance analysis.

II. Problem Statement

The hidden terminal and exposed terminal problems are not so significant, when the network is considered as an AP based WLAN and the communication is performed using RTS and CTS handshake mechanism. The reason is that all clients in a WLAN can update their network allocation vector (NAV) by using the control frames that are transmitted by the AP.

However, in case of FD-WLAN, the inter-user interference is a vital issue. Fig. 2 depicts the inter-user interference problem. Here, suppose node A (HDN) sends RTS to AP (FD-AP) first and then AP takes decision to send data to D (FDN) while receiving data from A. If node A and D are close to each other, the packets from node A will interfere at node D with the packets that is sent by AP, which creates inter-user interference problem. Here, node A and AP are regarded as the primary transmitter (PT) and primary receiver (PR) respectively. However, node D 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. Without taking proper steps to mitigate this inter-user interference, the FD communication cannot be performed perfectly.

III. Proposed FD-MAC Protocol for Het-WLAN

A. Possible FD Transmission in Het-WLAN

In this proposed Het-WLAN, there are a FD-AP, some FD clients and some HD clients (Fig.1). So, all possible cases of full duplex transmissions are summarized as the following three cases:

- **Case-1**: A HDN starts the transmission
  - i). HDN1 $\rightarrow$ AP and AP $\rightarrow$ HDN2
  - ii). HDN1 $\rightarrow$ AP and AP $\rightarrow$ FDN1
- **Case-2**: AP starts the transmission
  - i). AP $\rightarrow$ HDN1 and HDN2 $\rightarrow$ AP
  - ii). AP $\rightarrow$ HDN1 and FDN1 $\rightarrow$ AP
  - iii). AP $\rightleftharpoons$ FDN (Bidirectional)
  - iv). AP $\rightarrow$ FDN1 and FDN2 $\rightarrow$ AP
  - v). AP $\rightarrow$ FDN1 and HDN1 $\rightarrow$ AP
- **Case-3**: A FDN starts the transmission
  - i). FDN $\rightleftharpoons$ AP (Bidirectional)
  - ii). FDN1 $\rightarrow$ AP and AP $\rightarrow$ FDN2
  - iii). FDN1 $\rightarrow$ AP and AP $\rightarrow$ HDN1

Here, the FD transmission is categorized in three cases. For example, case-1 is applicable when a HDN initiates a

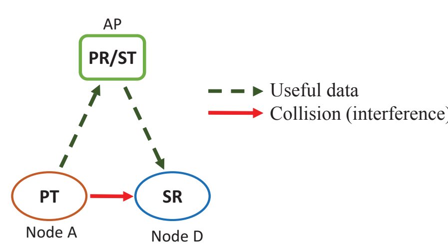

Fig. 2. Inter user interference in FD-WLAN

transmission by sending request to send (RTS). So, two kind of FD transmissions are possible in this case-1. Firstly, a HDN sends data to AP and AP sends data to another HDN (case-1(i)). Secondly, a HDN sends data to AP and AP sends data to a FDN (case-1(ii)). Similarly, in case-2, the AP initiates the transmission and there are five possible FD transmissions in this case. On the other hand, a FDN initiates the transmission in case-3 and three possible FD transmissions can take place in this case. So, case-2(iii) and case-3(i) are BFD communications in this MAC design and all other cases are regarded as RFD communication. Although HD transmission may also occur.

B. Description of the proposed FD-MAC

The working principle of this FD-MAC is based on Distributed coordination function (DCF) of IEEE 802.11. This protocol uses CSMA/CA and back-off mechanism to initiate a transmission as well as to avoid collisions. For the simplicity, the DCF interframe space (DIFS) time and back-off time is not shown in the figures. However, the short interframe space (SIFS) is shown. The SIFS time is shown by ‘S’ in all of the figures. The description of this MAC is given below according to the cases as mentioned earlier.

1) Case-1. A HDN Starts Transmission: Case-1 takes place, when a HDN wins in the back-off mechanism and sends RTS to AP. After the SIFS time, AP will send clear to send (CTS), if AP has no data to send other nodes. After that, the data transmission takes place and it is a HD transmission.

However, according to Fig. 3, after receiving RTS from a HDN (here the HDN is node A) AP may have data to send any other node that may be a HDN (case-1(i)) or a FDN (case-1(ii)). Suppose, in this case, AP wants to send data to B. The node tags are shown in Fig. 1. For this purpose, AP will mention the address of B in second receiver address (SRA) of its reply in new-CTS (NCTS). The NCTS is introduced in this MAC. The newly introduced control frame formats along with NCTS are shown in Fig. 5. From that NCTS, both A and B will be informed about their data exchange information. Node A updates its NAV after getting the NCTS. When B gets the NCTS from AP, it replies with another CTS to AP based on the secondary data transmission condition(SDTC)-1 : “if B (SR) can hear only NCTS, but not the RTS from A”. If SDTC-1 is fulfilled, B sends CTS to AP. Then data transmission takes place as in Fig. 3. Lastly, the acknowledgement (ACK) will be sent simultaneously. However, if AP does not get the CTS, it will receive data from A after finishing the SIFS and CTS time that are allocated for B. Other nodes update their NAV time according to the time that is defined by control frames.

2) Case-2. AP Starts Transmission:

- Case-2 (i) and Case-2 (ii)

In this case, after the back-off procedure, AP sends RTS to a HDN (here A) and A sends CTS to AP (Fig. 4). If another node (HDN/FDN) wants to send data to AP now, it needs to satisfy the SDTC-2: “After receiving RTS, it (ST) can not hear the CTS from A”. So, after hearing RTS from AP, all other nodes (HDN and/or FDN) who wants to send data to AP waits

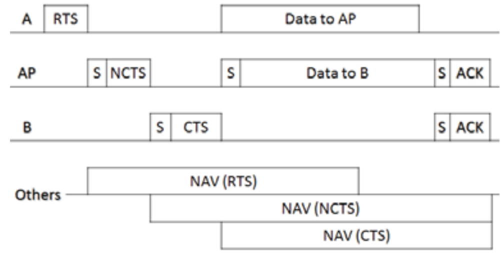

Fig. 3. HDN Starts Transmission: Case-1

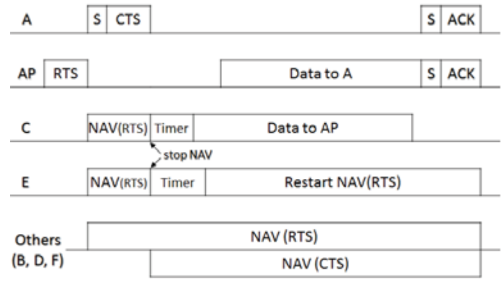

Fig. 4. AP Starts Transmission: Case-2(i) and Case-2(ii)

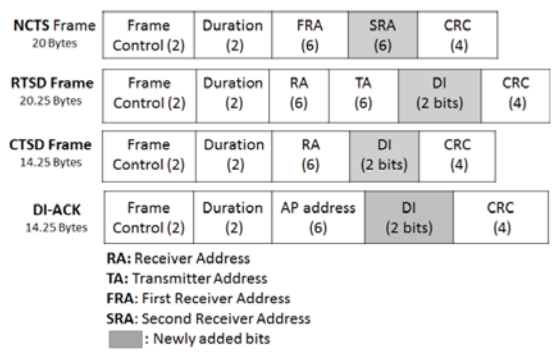

Fig. 5. Control Frame Format

for the time (SIFS+CTS). During this time, the nodes that have data to send AP and can not hear the A’s CTS will stop their NAV and start their self-timer. The timer sets a random time within a maximum limit. After that, the timer will decrease their value and the node whose timer will stop first will send data to AP. Before sending data to AP, the node will sense AP whether it is busy or not. So, other nodes (who started self-timer) will stop their timer sequentially and resume their NAV as in Fig. 4.

Suppose in this case, node C and node E want to send data to AP and satisfy the SDTC-2. Hence, C and E stop their NAVs and start their self-timers (Fig. 4). If the timer of C stops first, it will sense the channel. After finding the channel idle, C starts to send data to AP. Just after receiving data from C, AP sends data to A. When E’s timer stops, it finds that the channel is busy. So, E will resume its NAV. If AP does not receive data from any node within the predefined maximum time, it will send data to A after finishing that time limit.

- Case-2 (iii)

If AP wants to send data to a FDN (suppose, E), AP will send RTS with duplexing indicator (RTSD) . The duplexing indicator (DI) is a two bit value that is appended to the normal RTS or CTS for the FD transmission in this MAC. The description of DI value is given in Table-I. The DI value of 00 is not used here, it can be used in future for the extension of this proposal.

AP always sends RTSD to a FDN with 11, if AP wants to send data to a FDN. Now, if E also wants to send data to AP, it will send CTSD with the DI value of 11. Other nodes who can not hear CTSD will not start their timer, as all nodes hear RTSD with the DI value of 11. Then the BFD transmission takes place and the ACK is sent simultaneously from both end as the data transmission is completed.

- Case-2 (iv) and Case-2 (v)

Suppose AP has sent RTSD to a FDN (E) with the DI value of 11, but E has no data to send AP. In this case, E will send CTSD with the DI value of 01, which means that E can receive only. So, AP sends acknowledgement with DI value (DI-ACK). Here, the DI value is 01 also, as AP wants to receive data from others. The format of DI-ACK is shown in Fig. 5. By this DI-ACK, other nodes (except E) will be informed that AP can receive only and E will only update the time duration of the transmission. Now, the nodes who want to send data to AP need to satisfy the condition SDTC-3: "after hearing RTSD from AP, the node (ST) can hear DI-ACK, but not the CTSD from E".

So, the nodes that satisfy SDTC-3 and want to send data to AP will stop their NAV and start their timer. The illustration is given in Fig. 6. Suppose, here B and C has data to send and satisfy the SDTC-3. So according to the figure, they starts their self-timer after stopping NAV. Suppose, the timer of B expires first; then, it will send data after sensing the channel as idle. Just after receiving data from B, AP starts transmission to E as like case-2 (i) and (ii). On the other hand, C will stop timer and resume its NAV. All other nodes (A, D, F) will update their NAV by the DI-ACK.

3) Case-3. A FDN Starts Transmission:

- Case-3 (i)

In this case, a FDN initiates the transmission by sending RTS to the AP. Then, if AP has also data to send for that FDN, it will reply by CTSD with the DI value of 11. After that, the BFD transmission takes place. If AP doesnt have data to send any other node, it will reply by CTS only and the HD transmission takes place.

- Case-3 (ii) and Case-3 (iii)

However, suppose a FDN sends RTS to AP and AP has data to send another node that may be another FDN or a HDN.

TABLE I
DESCRIPTION OF DUPLEXING INDICATOR

Value of DI	Meaning of DI
00	Not Used
01	Sender can receive only
10	Sender can transmit only
11	Sender can receive and transmit

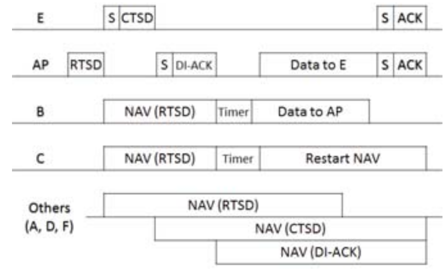

Fig. 6. AP Starts Transmission: Case-2(iv) and Case-2(v)

In this situation, AP will reply by NCTS as the Case-1. The description of this procedure is same as case-1 according to the following way:

Case-3(ii) is analogous to case-1(i) and
Case-3(iii) is analogous to case-1(ii).

IV. COMBATING INTER-USER INTERFERENCE

Our proposed MAC for Het-WLAN suppresses the inter-user interference by using three kinds of secondary data transmission condition (SDTC). These are as follows:

- SDTC-1 : "If a SR cannot hear RTS from PT, but can hear corresponding NCTS from AP".
- SDTC-2 : "If a ST can hear RTS from AP, but cannot hear corresponding CTS from PR".
- SDTC-3 : "If a ST can hear RTSD from AP and cannot hear corresponding CTSD from PR, but can hear DI-ACK".

Here, SDTC-1 is applied for RFD communication in case-1, case-3(ii) and case-3(iii). For example, the SR replies with CTS to AP, only if the SR satisfies the SDTC-1. Otherwise, HD communication takes place in these cases. On the other hand, SDTC-2 is applied for case-2(i) and case-2(ii). In this situation, if a ST wants to send data to AP, the ST requires to satisfy SDTC-2, i.e. if a ST has data to send AP and satisfy SDTC-2, it stops its NAV and starts self-timer and corresponding procedures take place for the RFD, which is described in earlier section.

Similarly, SDTC-3 is used for case-2(iv) and case-2(v). A ST can take steps to send data to AP, only if the ST satisfies the SDTC-3. This mechanism in this FD-MAC prevents the inter-user interference during the full duplex communication. If the conditions are not maintained by secondary receivers and transmitters, inter-user interference will take place; RFD communication fails for data collusion.

V. MATHEMATICAL ANALYSIS

In this section, we have derived the probability equations for different transmissions. The probability equations for different type of communication (such as BFD, RFD and HD) are derived by using packets arrival rate (PAR) at AP and packets generating rate (PGR) by the clients or nodes. The description of different symbols for the equations are given in Table II. Here, all packet arrivals are assumed to follow Poisson process.

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TABLE II
DECLARATION OF VARIABLES

Variables	Explanation
m	Number of HDNs
n	Number of FDNs
λ_{AP}	Packet arrival rate at AP to all clients (packets/s)
λ_{APH}	Packet arrival rate at AP for each HDN (packets/s)
λ_{APF}	Packet arrival rate at AP for each FDN (packets/s)
λ_{H}	Packet generating rate by each HDN for AP (packets/s)
λ_{F}	Packet generating rate by each FDN for AP (packets/s)
P_{BFD}	Probability of bidirectional FD communicaiton
P_{RFD}	Probability of relay FD communication
P_{HD}	Probability of HD communication
T_{RTS}	Time for RTS
T_{CTS}	Time for CTS
T_{RTSD}	Time for RTSD
T_{CTSD}	Time for CTSD
T_{SIFS}	Time for SIFS
T_{avg}	Average waiting time

Packet arrival rate at AP from the internet to all clients is:

$$\lambda_{AP} = m\lambda_{\mathrm{APH}} + n\lambda_{\mathrm{APF}} \tag{1}$$

Total packet arrival rate at AP from internet and from clients is:

$$\lambda_{\mathrm{Total}} = \lambda_{\mathrm{AP}} + m\lambda_{\mathrm{H}} + n\lambda_{\mathrm{F}} \tag{2}$$

So, if one packet arrives at AP from internet, the conditional probability of that packet arrival at AP for a FDN is $\frac{n\lambda_{\mathrm{APF}}}{\lambda_{\mathrm{Total}}}$ and conditional probability of that packet arrival for a HDN is $\frac{m\lambda_{\mathrm{APH}}}{\lambda_{\mathrm{Total}}}$. Similarly, if a packet arrives at AP from a node, the conditional probability of that packet arrival from a FDN can be defined as $\frac{n\lambda_{\mathrm{F}}}{\lambda_{\mathrm{Total}}}$ and conditional probability of that packet arrival from a HDN is $\frac{m\lambda_{\mathrm{H}}}{\lambda_{\mathrm{Total}}}$. During any data transmission, the packets still arrive at nodes; but the nodes differ to start the transmission as the channel is busy. We consider the utilization factor (ρ) to find out the average waiting time (T_{avg}).

So, T_{avg} = $\rho *$ average data transmission time

The probability of the bidirectional communication (P_{BFD}) is:

$$\begin{aligned} P_{BFD} = &\frac{n\lambda_{\mathrm{APF}}}{\lambda_{\mathrm{Total}}}\left(1-e^{-\lambda_{\mathrm{F}}T_1}\right) \\ &+\frac{n\lambda_{\mathrm{F}}}{\lambda_{\mathrm{Total}}}\left(1-e^{-\lambda_{\mathrm{AP}}T_2}\right)\left(\frac{\lambda_{\mathrm{APF}}}{\lambda_{\mathrm{AP}}}\right) \end{aligned} \tag{3}$$

where, T_1= $T_{\mathrm{RTSD}} + T_{\mathrm{SIFS}} + T_{avg}$ and T_2= $T_{\mathrm{RTS}} + T_{\mathrm{SIFS}} + T_{avg}$.

The probability of the relay FD communication (P_{RFD}) is:

$$\begin{aligned} P_{\mathrm{RFD}} = &\frac{m\lambda_{\mathrm{H}}}{\lambda_{\mathrm{Total}}}\left(1-e^{-\{(m-1)\lambda_{\mathrm{APH}}+n\lambda_{\mathrm{APF}}\}T_2}\right) \\ &+\frac{m\lambda_{\mathrm{APH}}}{\lambda_{\mathrm{Total}}}\left(1-e^{-\{(m-1)\lambda_{\mathrm{H}}+n\lambda_{\mathrm{F}}\}T_3}\right) \\ &+\frac{n\lambda_{\mathrm{APF}}}{\lambda_{\mathrm{Total}}}\left(e^{-\lambda_{\mathrm{F}}T_1}\right)\left(1-e^{-\{m\lambda_{\mathrm{H}}+(n-1)\lambda_{\mathrm{F}}\}T_4}\right) \\ &+\frac{n\lambda_{\mathrm{F}}}{\lambda_{\mathrm{Total}}}\left(1-e^{-\lambda_{\mathrm{AP}}T_2}\right)\left(\frac{(n-1)\lambda_{\mathrm{APF}}+m\lambda_{\mathrm{APH}}}{\lambda_{\mathrm{AP}}}\right) \end{aligned} \tag{4}$$

where, T_3= $T_{\mathrm{RTS}} + T_{\mathrm{SIFS}} + T_{\mathrm{CTS}} + T_{avg}$ and T_4= $T_{\mathrm{RTSD}} + 2T_{\mathrm{SIFS}} + T_{\mathrm{CTSD}} + T_{\mathrm{DI-ACK}} + T_{avg}$.

The probability of the HD communication (P_{HD}) is:

$$\begin{aligned} P_{\mathrm{HD}} = &\frac{m\lambda_{\mathrm{H}}}{\lambda_{\mathrm{Total}}}\left(e^{-\{(m-1)\lambda_{\mathrm{APH}}+n\lambda_{\mathrm{APF}}\}T_2}\right) \\ &+\frac{m\lambda_{\mathrm{APH}}}{\lambda_{\mathrm{Total}}}\left(e^{-\{(m-1)\lambda_{\mathrm{H}}+n\lambda_{\mathrm{F}}\}T_3}\right) \\ &+\frac{n\lambda_{\mathrm{APF}}}{\lambda_{\mathrm{Total}}}\left(e^{-\lambda_{\mathrm{F}}T_1}\right)\left(e^{-\{m\lambda_{\mathrm{H}}+(n-1)\lambda_{\mathrm{F}}\}T_4}\right) \\ &+\frac{n\lambda_{\mathrm{F}}}{\lambda_{\mathrm{Total}}}\left(e^{-\lambda_{\mathrm{AP}}T_2}\right) \end{aligned} \tag{5}$$

From these equations, we can estimate the probability of FD and HD transmissions and thus can do the performance analysis for this proposal.

VI. RESULT AND PERFORMANCE ANALYSIS

The simulation has been performed in MATLAB to analyze the performance of this FD-MAC. The performance analysis of our FD-MAC has been described in two sub-sections, such as probability analysis and throughput analysis.

A. Probability Analysis

The comparison of the probability of BFD, RFD and HD transmission in this FD-MAC with respect to downlink packet arrival rate is shown in Fig. 7 and Fig. 8. In both cases, the packet generating rates (PGR) by HDNs and FDNs are 20 and 30 packets/s respectively and the number of both HDNs and FDNs are 10 (fixed). The PGR of FDNs is higher than that of HDNs, as FDNs can handle more data than HDNs. The packet arrival rate (PAR) at AP for HDNs is 20 packets/s in Fig. 7.

The simulation result shows that the probability of HD communication decreases significantly with the increase of PAR at AP for each FDN (Fig. 7). However, P_{RFD} increases significantly as the PAR for FDN increases. Because, the probability of converting a HD communication to a RFD communication increases, when PAR increases for each FDN. Moreover, P_{BFD} also increases, but not as P_{RFD}. As a result of this, total probability of FD communication (P_{RFD} + P_{BFD}) increases significantly. However in Fig. 8, the PAR at AP for FDNs is fixed (20 packets/s) and that for HDNs is variable. It shows that the probability of BFD increases with

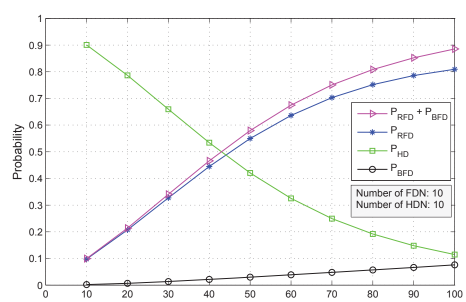

Fig. 7. Probability vs. packet arrival rate at AP for FDNs

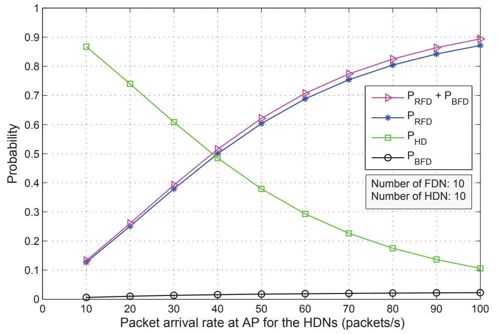

Fig. 8. Probability vs. packet arrival rate at AP for HDNs

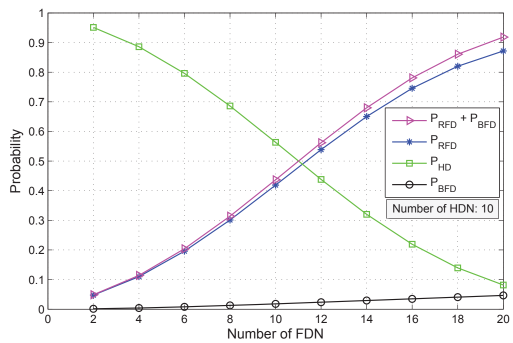

Fig. 9. Probability vs. FDN number

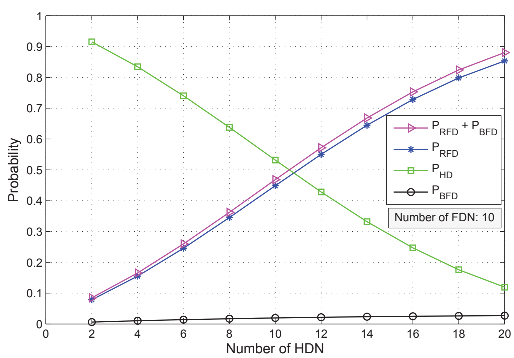

Fig. 10. Probability vs. HDN number

the increase of PAR at AP for HDNs, but not so significant as in Fig. 7. Although the probability of RFD increases rapidly as the PAR for HDNs increases. So, the total probability of FD is found 90%, when the PAR for each HDN is 100 packets/s. The utilization factor is 97.2% in this case. On the other hand, almost same probability of FD (P_{RFD} + P_{BFD}) is observed as the PAR for each FDN is 100 packets/s (Fig. 7), where the utilization factor is observed as 91.7%.

Another comparison with respect to the number of FDN and HDN is shown in Fig. 9 and Fig. 10 respectively. In both cases, the PGRs are same as the previous analysis and PARs at AP for FDNs and HDNs are 30 and 20 packets/s respectively. These figures show that the total probability increases rapidly with the increase of number of nodes. However, the impact of FDN number on BFD and RFD is higher than that of HDN, but not so significant. As BFD can be occurred between AP and a FDN only, the impact of FDN number on BFD is higher than HDN number. Moreover, as PGR and PAR for FDN are higher than that for HDN, the probability of RFD also increases more, if the FDN number increases.

This analyses suggest that the PAR at AP for FDNs has more impact on FD communication than PAR at AP for HDNs. On the other hand, total number of nodes (HDNs and FDNs) has also a significant impact on probability of FD transmission.

B. Throughput Analysis

An extensive simulation is carried out in MATLAB for the throughput analysis of our proposed FD-MAC in saturation condition. Saturation condition is explained as the situation, when all clients and the AP always have packets to transmit [10]. All of the simulation parameters of this FD-MAC are given in Table III. Initially, both the FDN and HDN numbers were two. Then each number is increased by one. However, the number of AP is only one. The simulation result is shown in Fig.11. The performance of our proposed MAC is compared with CSMA/CA based HD communication and another existing FD-MAC [12].

For this simulation, we have taken 10 values of throughput for each number of nodes and then calculated the average throughput. The result shows that the mean value of the average throughput for this FD-MAC is 54.79 Mbps; however, the value is 27.91 Mbps and 48.73 Mbps for traditional HD and existing FD-MAC [12] respectively. So the mean value of the average throughput of our proposed MAC is increased by 49.1% and 11% as compared to traditional HD and existing FD-MAC respectively. As in Fig. 11, it is observed that all the throughput decreases as the number of nodes increases. Because, the number of collisions increases as the number of nodes increases. On the other hand, the throughput of the proposed FD-MAC is lower, when the number of nodes is less than 6. Because, the SDTC (secondary data transmission

TABLE III
SIMULATION PARAMETER

Packet payload (data)	2000 bytes
RTS	20 bytes
CTS	14 bytes
RTSD	20.25 bytes
CTSD	14.25 bytes
ACK	14 bytes
DI-ACK	14.25 bytes
Data rate	54 Mbps
Control frame (RTS, CTS, etc.) rate	6 Mbps
DIFS time	34 μs
SIFS time	16 μs
Slot time	9 μs
Minimum backoff window size (CW_{min})	15 μs
PLCP preamble duration	16 μs
PLCP header duration	4 μs
Maximum time of self-timer	50 μs

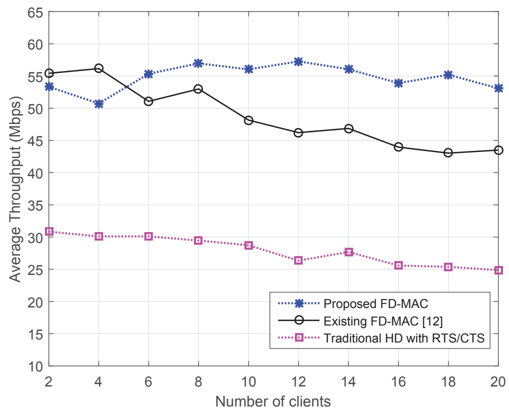

Fig. 11. Average throughput with respect to number of nodes

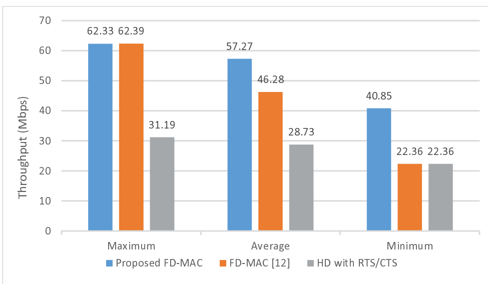

Fig. 12. Throughput comparison for 10 number of nodes

condition) cannot be always satisfied, if number of nodes is lower.

Another comparison is shown in Fig. 12, where the number of nodes is 10. Here, we compare the achievable maximum, average and minimum throughput in saturation condition. It is noticeable that the maximum achievable throughput of our proposed MAC and existing FD-MAC is almost same (about 62 Mbps), however the value is 31.19 Mbps for traditional HD. So, maximum achievable throughput gain by using our FD-MAC is 50% as compared to HD communication. This throughput gain (comparing to HD) is almost same in case of average throughput (50%) and minimum throughput (45%). On the other hand, the proposed MAC achieved average throughput increase by 19% as compared to existing FD-MAC [12]; however, if it is compared in terms of minimum achieved throughput, our proposed MAC shows 45% gain. The reason is that, in saturation condition, always there are FD communications in our proposed MAC, however in case of existing FD-MAC [12], either FD or HD communication takes place.

VII. Conclusion

A FD-MAC protocol is proposed in this paper for a heterogeneous WLAN, which consists of FD clients, HD clients and an AP. In our proposed FD-MAC, all possible FD transmissions in a Het-WLAN are considered. This protocol minimizes inter-user interference during FD transmission. The simulation result shows that our proposed FD-MAC increases the overall throughput significantly with comparing to that of traditional half duplex transmission. In addition, the performance of this MAC is also better than that of another existing FD-MAC. The result also suggests that the probability of FD transmission is increased significantly as the total number of clients increased, if the WLAN is not in saturation condition. This type of FD-MAC is crucial to support high speed FD-WLANs in near future.

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References

[1] D. Bharadia, E. McMilin, and S. Katti, "Full duplex radios," in *ACM SIGCOMM Computer Communication Review*, vol. 43, no. 4, 2013, pp. 375–386.
[2] E. Everett, M. Duarte, C. Dick, and A. Sabharwal, "Empowering full-duplex wireless communication by exploiting directional diversity," in *Proc. of ASILOMAR Conference on Signals, Systems and Computers*, 2011, pp. 2002–2006.
[3] M. Jain, J. I. Choi, T. Kim, D. Bharadia, S. Seth, K. Srinivasan, P. Levis, S. Katti, and P. Sinha, "Practical, real-time, full duplex wireless," in *Proc. of ACM MobiCom*, 2011, pp. 301–312.
[4] M. Duarte and A. Sabharwal, "Full-duplex wireless communications using off-the-shelf radios: Feasibility and first results," in *Proc. of ASILOMAR Conference on Signals, Systems and Computers*, 2010, pp. 1558–1562.
[5] J. I. Choi, M. Jain, K. Srinivasan, P. Levis, and S. Katti, "Achieving single channel, full duplex wireless communication," in *Proc. of ACM MobiCom*, 2010, pp. 1–12.
[6] Y. Zhang, L. Lazos, K. Chen, B. Hu, and S. Shivaramaiah, "FD-MMAC: Combating multi-channel hidden and exposed terminals using a single transceiver," in *Proc. of IEEE INFOCOM*, 2014, pp. 2742–2750.
[7] W. Cheng, X. Zhang, and H. Zhang, "RTS/FCTS mechanism based full-duplex mac protocol for wireless networks," in *Proc. of IEEE GLOBECOM Workshops*, 2013, pp. 5017–5022.
[8] A. Sahai, G. Patel, and A. Sabharwal, "Pushing the limits of full-duplex: Design and real-time implementation," *Technical Report of Rice University*, 2011.
[9] S. Goyal, P. Liu, O. Gurbuz, E. Erkip, and S. Panwar, "A distributed mac protocol for full duplex radio," in *Proc. of ASILOMAR Conference on Signals, Systems and Computers*, 2013, pp. 788–792.
[10] A. Tang and X. Wang, "A-duplex: Medium access control for efficient coexistence between full-duplex and half-duplex communications," *IEEE Trans. Wireless Commun.*, vol. 14, no. 10, pp. 5871–5885, 2015.
[11] J. Y. Kim, O. Mashayekhi, H. Qu, M. Kazandjieva, and P. Levis, "Janus: A novel mac protocol for full duplex radio," *Technical Report*, Computer Science Department, Stanford University, 2013.
[12] M. Duarte, A. Sabharwal, V. Aggarwal, R. Jana, K. Ramakrishnan, C. W. Rice, and N. Shankaranarayanan, "Design and characterization of a full-duplex multiantenna system for wifi networks," *IEEE Trans. Veh. Technol.*, vol. 63, no. 3, pp. 1160–1177, 2014.
[13] H. L. w. Choi and A. Sabharwal, "Power-controlled medium access control protocol for full-duplex wifi networks," *IEEE Trans. Wireless Communications*, vol. 14, no. 7, pp. 3601–3613, 2015.
[14] T. Riihonen, S. Werner, R. Wichman, and Z. Eduardo, "On the feasibility of full-duplex relaying in the presence of loop interference," in *Proc. of IEEE Workshop on Signal Processing Advances in Wireless Communications, (SPAWC'09)*, 2009, pp. 275–279.
[15] W. Cheng, X. Zhang, and H. Zhang, "Full/half duplex based resource allocations for statistical quality of service provisioning in wireless relay networks," in *Proc. of IEEE INFOCOM*, 2012, pp. 864–872.
[16] T. Riihonen, S. Werner, and R. Wichman, "Hybrid full-duplex/half-duplex relaying with transmit power adaptation," *IEEE Trans. Wireless Commun.*, vol. 10, no. 9, pp. 3074–3085, 2011.

