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Full Duplex Radio Communications in High Efficiency WLANs: Study and Comparison of the Main MAC Protocols

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Abstract. The incoming IEEE 802.11ax standard designed for HEW (High Efficiency WLANs : Wireless Local Area Networks) networks aims at improving spectral efficiency and area throughput in real world densely deployed Wi-Fi (Wireless-Fidelity) environments. To meet these needs, several innovative techniques and methods have been incorporated at both Physical (PHY) and Medium Access Control (MAC) layer of the IEEE 802.11ax standard. Among these new amendments, we focus on Full Duplex (FD) radio communications, which double the throughput of the Half Duplex (HD) radio without any effort. In this paper, our main goal is studying and comparing the two main MAC protocols existing for enabling the innovative Full Duplex radio communications in the future standard IEEE 802.11ax, namely: OFDMA Two-symbol Coordination MAC (O2-MAC) and In-Frame-Querying. These protocols allow to solve the same problem, which is maximizing the radio capacity of full duplex transmissions. The simulation results obtained show for the first time that, the In-Frame-Querying protocol is efficient in case where the down-link (DL) and up-link (UL) data streams have variable lengths. In contrary, when the lengths of down-link and up-link data streams are the same, the O2-MAC protocol is the best. The performance metrics considered in the analysis are throughput and overhead.

Keywords: High Efficiency WLANs · IEEE 802.11ax Standard · Full Duplex Radio Communications · Medium Access Protocols · Study and Comparison.

1 Introduction

Recently, IEEE 802.11 has started a task group to investigate and deliver next generation Wireless Local Area Network (WLAN) technologies for the scenarios of dense networks with a large number of stations (STAs) and access points (AP). Due to the significant network capacity increase achieved by 802.11ax, the term High Efficiency WLANs (HEW) is also used in reference to this new amendment. The IEEE approved 802.11ax (HEW) in March, 2014 [1], which will replace both IEEE 802.11n-2009 and IEEE 802.11ac-2013 [2]. The scope of 802.11ax amendment is to define standardized modifications to both Physical (PHY) and Medium Access Control (MAC) layers. These modifications enable at least one mode of operation capable of supporting at least four times improvement in the average throughput per station in a dense deployment scenario [1].

For this, several modifications have been proposed at both PHY and MAC layers [3], including: Orthogonal Frequency Division Multiple Access (OFDMA), dynamic channel bonding, Down-Link/Up-Link Multi-User Multiple-Input Multiple - Output (DL/UL MU MIMO), multi-user aggregation, spatial reuse, Transmit Power Control (TPC), Basic Service Sets (BSS) color, higher order cording rate 1024 Quadrature Amplitude Modulation (1024 QAM), Full Duplex (FD) radio communications, etc. Among these new amendments, we focus on Full Duplex technology, which double the throughput of the Half Duplex (HD) radio without any effort [4]. Full-duplex radio technology with single antenna based on Self-Interference Cancellation (SIC) technology has been recently introduced [5] at the PHY layer of the IEEE 802.11ax. This means that, it is possible to simultaneously transmit and receive data on the same channel, which was assumed to be impossible in the previous version of the IEEE 802.11 standard [6].

The efficiency of Full Duplex radio communications in IEEE 802.11ax WLANs is highly dependent on channel access protocol used at MAC layer. The best protocol is the one that can efficiently exploit the Full Duplex radio resources available at PHY layer, by maximizing system throughput and minimizing protocol overheads. This is why; the main goal of this paper is implementing, simulating and comparing the main MAC protocols proposed in the available literature for enabling Full Duplex radio communications. Indeed, this paper is an extension of the work in [7]. In particular, we conduct an in-depth comparative study by running intensive simulations of two main MAC protocols: (*i*) OFDMA Two-symbol Coordination MAC (O2-MAC) based on the assumption that the length of down-link (DL) and up-link (UL) data streams are the same, and (*ii*) In-Frame-Querying which considers that the down-link data stream is many times larger than the up-link data stream. Although the basic functioning of these protocols is different, they have the same goal, which is maximizing the efficient use of Full Duplex radio communications. The obtained numerical results demonstrate the benefits and drawbacks of each MAC protocol in terms of throughput and overhead. We clearly note that In-Frame-Querying protocol is efficient in case where the down-link (DL) and up-link (UL) data streams have variable lengths. However, the O2-MAC protocol is the best, when the lengths of down-link and up-link data streams are the same.

The rest of this paper is organized as follows: Section 2 is divided into two sub-sections, we describe the main innovative features of the IEEE 802.11ax standard in Subsection 2.1, and we review the Full Duplex radio communications in Subsection 2.2. In Section 3, we provide a state of the art of existing MAC protocols enabling Full Duplex radio communications. In Sections 4 and 5, we respectively describe and compare in detail the operation rules of the most important Full Duplex MAC protocols, namely: O2-MAC and In-Frame-Querying. We end our paper with a conclusion in Section 6.

2 Overview of the New IEEE 802.11ax Standard

This second section is divided into two subsections. In subsection 2.1, we describe the main innovative features of the IEEE 802.11ax standard. In subsection 2.2, the Full Duplex radio communications at IEEE 802.11ax MAC layer level are detailed.

2.1 Main Innovative Features of the IEEE 802.11ax

In this subsection, we give an overview of the important features proposed for the IEEE 802.11ax amendment. The Table 1 summarizes these improvements, which are described as follows:

- **1024 Quadrature Amplitude Modulation (QAM):** 802.11a/g introduced 64 QAM, and 802.11ac 256 QAM. In 802.11ax, the highest order modulation is extended to 1024 QAM, where each symbol encodes a larger number of data bits when using such a dense constellation. It allows encoding 10 bits per OFDM symbol. Together with forward error correction codes which have code rates of 1/2, 2/3, 3/4 and 5/6, these modulations generate a palette of data rates with a maximum of 9.6 Gbps [8].
- **Dynamic Channel Bonding:** to adapt to the instantaneous channel occupancy, IEEE 802.11ax-2019 may consider extending the dynamic bandwidth channel access (DBCA) scheme introduced in the IEEE 802.11ac-2013 amendment. Using DBCA, only the available channel width is used at each transmission, which allows WLANs to adapt to the instantaneous spectrum occupancy. This mechanism helps fill most spectrum gaps and share them fairly among neighboring WLANs [2].

- **Orthogonal Frequency Division Multiple Access (OFDMA):** it is a technique that has been used in other systems, like cellular LTE. OFDMA adds a new degree of flexibility to the use of spectrum resources by dividing the channel width into multiple narrow channels. Then these narrow channels can be used to transmit to multiple users in parallel. TGax has quadrupled the duration OFDM symbols used for the physical payload up to 12.8 μs. Indeed, based on the channel conditions, an 802.11ax device can separate OFDM symbols by the Guard Intervals (GI) selected among the values 0.8 μs, 1.6 μs and 3.2 μs [2].
- **Down-Link and Up-Link Multi-User MIMO (DL and UL MU MIMO):** the downlink version extends an existing 802.11ac feature where an access point transmits frames to different client devices. However, uplink multiuser MIMO is a new addition to 802.11ax, the AP should coordinate the simultaneous transmissions of multiple clients, by using the adoption of the space diversity technique [3].
- **Spatial reuse:** when contending for a transmit opportunity, a device is allowed to transmit over the top of a distant transmission, which would previously have forced it to wait. This increases network capacity by allowing more simultaneous transmissions in a given geographic area, such as Basic Service Sets (BSS) color, Transmit Power Control (TPC) [8].
- **Full Duplex:** Full Duplex (FD) radio technology enables simultaneous transmission and reception, which may double the throughput of Half Duplex (HD) radio in one to one communication. This is possible through the adoption of Self-Interference Cancellation (SIC) at the physical (PHY) layer [2].

Table 1. Main Features of IEEE 802.11ax standard.

Spectrum	Between 1 and 6 GHZ
Bandwidth	20 to 160 MHZ
Modulation	BPSK to 1024 QAM
FFT size	256 to 2048
OFDM symbol duration	12.8 μs
OFDM Guard Interval	0.8; 1.6 or 3.2 μs
Subcarrier spacing	78.125 KHZ
Number of spatial streams	1 to 8
Maximal Data Rate	9.6 Gbps
MIMO	SU and DL-UL-MU
Spatial reuse	BSS color, TPC
Power management	TWT

2.2 Full Duplex Radio Communications

Full Duplex technology has attracted attention as a viable solution to increase the spectral efficiency [9]. Full Duplex operation enables wireless terminals to transmit and receive simultaneously over the same frequency band. Then, the channel capacity can be theoretically doubled [4]. However, Full Duplex operation yields self-interference (SI) which is generated from its own transmitted signal and interferes with desired received signal. Note that since the SI is much larger than the desired signal power, residual SI significantly degrades signal to interference and noise ratio (SINR). Therefore, self-interference-cancellation (SIC) is obviously a key technology for Full Duplex [10] at the PHY layer of the IEEE 802.11ax standard. While using Full Duplex radio two desired transmission cases exist [11], namely:

- **Bidirectional Full Duplex (BFD) transmission:** in which AP (Access Point) and STA (station) can simultaneously transmit or receive to or from each other, as shown in Figure 1.a.
- **Unidirectional Full Duplex (UFD) transmission:** in which AP can simultaneously transmit to STA while receiving from another STA, as shown in Figure 1.b.

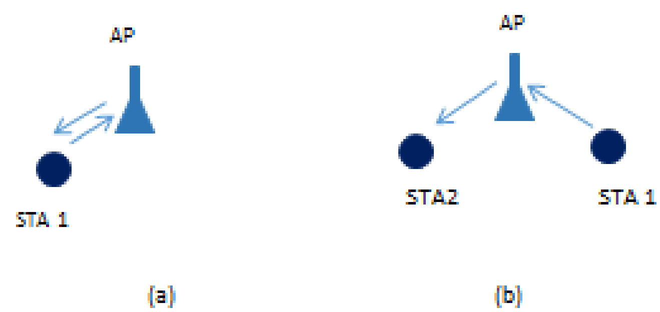

Fig. 1. Full Duplex transmission: (a) Bidirectional, (b) Unidirectional.

3 A State of the Art

In this section, we provide a state of the art of the existing solutions enabling Full Duplex radio communications in IEEE 802.11ax standard designed for HEW networks.

Qu et al. in 2015 [12] have proposed a Full Duplex MAC protocol named *Fuplex*, it assumes that only AP has Full Duplex capability. Therefore, each node follows channel access mechanism in 802.11 DCF to ensure compatibility with legacy WLANs. The protocol consists of two transmission procedures:

the first transmission is primary transmission procedure, and the latter is secondary transmission procedure. Primary transmission procedure consists of primary access, primary data transmission, and primary ACK (acknowledgment) transmission while secondary transmission procedure consists of secondary access, secondary data transmission, and secondary ACK transmission. When an AP transmits a data frame to a station, the other stations which do not affect the transmission of legacy link by using interference measurement mechanism, start a secondary backoff procedure, and the winner station acquires the channel of using full duplex.

Kim et al. in 2016 [11] have proposed an efficient MAC protocol for OFDM based full duplex radio. So, the protocol proposed tries to utilize UL without control packet exchange and without collision, by using one OFDM subcarrier. For this, it allows to find stations with uplink traffic in the hidden relation with the station for downlink traffic, and provides transmission opportunities to balance the amount of traffic in the both direction. After one UL transmission from bidirectional station B-STA, hidden node detection is finished, each station decides its state itself. When station transmits a packet to an AP, the latter transmits busy signal by using one OFDM subcarrier. Then B-STA and hidden station transmit packet if busy tone is idle after waiting RIFS and SIFS respectively plus Timeslot*(random backoff).

To overcome the problem of imbalances between downlink and uplink traffics in full duplex enabled WLANs, *Ahn et al.* in 2016 [13] have proposed a MAC protocol called hidden chain. The protocol consists of two schemes; the first scheme enables an uplink ACK to be transmitted simultaneously with the next downlink, if the ACK uplink station and data downlink station have a hidden terminal relationship, and this may reduce the waste of uplink space. In the second scheme; the AP sends a query to provide an uplink data transmission opportunity to another station after the current uplink transmission as long as the remaining downlink period is available. A station receiving a query must be the downlink STA or hidden from the downlink STA.

A full duplex MAC protocol named interference aware FD-MAC (IAFM) is proposed by *Luo et al.* in 2016 [14] for the next generation WLANs on the assumption that only AP has FD capability. IAFM protocol supports three modes: scheduling mode for normal full duplex transmission, the AP selects a station for the full duplex link and announces the AID of this station in new design FD-RTS or FD-CTS. Interference collection mode, for interference collection usage, the station in the BSS reports their interference state information in OFDMA manner to reduce the overhead. None FD mode for the legacy transmission, the node including AP and station obey DCF protocol.

In-band full-duplex (IBFD) wireless transmission is widely supported for Next Generation WLANs. Half-Duplex (HD) and Full-Duplex (FD) stations are usually coexistence in IBFD WLANs. However, the simultaneously transmitting and receiving in a station not only causes extra interfering signal in the system but also leads to carrier-sensing mechanism fail to avoid hidden terminal problem. Hence, the collision problems, Inter-Station Interference Problem (ISIP), may happen and are conducted. As a result, *Chen et al.* in 2018 [15] have proposed an Interference Free Full Duplex with power control (IFFD) MAC protocol for IBFD WLANs to avoid collisions. IFFD can not only prevent Inter-Station Interference Problem (ISIP) but also can increase network performance.

Kim et al. in 2018 [16] have proposed an opportunistic MAC protocol for Full Duplex communications in WLANs, in order to solve the problem of channel under-utilization that occur in the Full Duplex environment, due to the difference of uplink and downlink transmission time. So, secondary backoff process that is performed to access the channel which is the under-utilized parts, stations competes in the interval of [0, FCW]. Each station sets up a FCW size according to the RTS and CTS frame information, such as the buffer status, data rate, and signal-to-interference plus noise ratio (SINR).

Lee et al. in 2015 [17] revealed a significant phenomenon of asymmetry of uplink (UL) and downlink (DL) traffic in FD enabled WLAN for next generation. The authors have developed In-Frame-Querying method to instantly find the candidate stations which are able to support the full duplex capability with AP. During DL communication between AP and a station in BSS, if this station has DL data to send, in the DL heavy case, at the end of the UL transmission, station opportunity window starts. In order to designate the winner station, the candidate stations which know hidden relationship send their 12 bit station ID to AP. If AP receives decodable 12 bit station ID, then AP announces the winner frame should immediately start its UL transmission. If AP cannot decode the signal due to collision, then the candidate stations follow the binary exponential backoff behavior.

Lee et al. in 2017 [18] have proposed a novel MAC protocol for full-duplex OFDMA wireless networks, called OFDMA Two symbol Coordination MAC (O2-MAC), which extends the concurrent transmission opportunities as much as possible and resolves contention with minimum overhead. In particular, their MAC protocol is targeted at densely populated access point based WLAN, which operates as follows: each subcarrier possesses a number, and subcarrier 0 is reserved for the AP. At association phase, a station is randomly assigned to one of the available subcarriers. When a station (including AP) has data to send, it must wait for a DIFS period, after, it must send a signal in its subcarrier in the first symbol OFDM. The AP determines the role of each station and accordingly signals to subsequent subcarriers in the second symbol OFDM. For full duplex communication, the AP selects the bidirectional full duplex first if available, otherwise, it attempts to select unidirectional full duplex, if AP fails, and half duplex is conducted.

Among the existing solutions, we are interested in the following section to analyze and compare two main Full Duplex MAC protocols: In-Frame-Querying and O2-MAC. Although these two protocols are based on different assumptions, they have the same goal, which is enhancing and maximizing the efficient use of Full Duplex radio communications.

4 Main Existing Full Duplex MAC Protocols

In this section, we describe the operation functioning of In-Frame-Querying and O2-MAC Full Duplex MAC protocols. For each protocol, an example illustrating its operation steps is given. These steps are then modeled by a state machine.

4.1 In-Frame-Querying Protocol

In-Frame-Querying protocol [17] allows avoiding the hidden terminals problem between stations (STAs), by designating candidate stations to use opportunity window. This latter is defined as the empty channel time caused by the unbalance of the length between DL and UL frames. The hidden terminals problem is explained as follows: if a STA can decode AP's DL frame without interference to current transmission UL, then it is hidden. On the contrary, if a STA cannot decode AP's DL frame, then it is not hidden, it is exposed. The hidden and exposed terminals problem is illustrated in Figure 2. In this figure, we call STA2 hidden to STA1, then STA2 grabs the opportunity window and cannot hear STA1's signal because of the hidden terminal relations. However, STA3 exposed to STA1 and cannot use opportunity window, it cannot decode DL frame because of interference caused by STA1's UL frame. Even with Full Duplex radio, STA3 cannot receive two frames simultaneously.

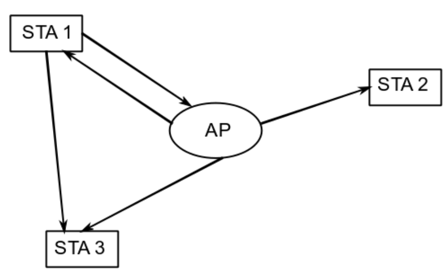

Fig. 2. Hidden and exposed terminals in full duplex transmissions.

The operation functioning of In-Frame-Querying is as follows:

- Before Full Duplex transmission, AP does not inform the station to start full duplex, but it imposes one station. Then, we have two cases: if station has data to send then real bidirectional full duplex is established. Otherwise, imaginary bidirectional full duplex is produced and in this case the station in question is enforced to send a dummy frame to find hidden terminals.
- First, AP sends Query Start frame on the query subcarrier immediately when the STA opportunity window happens. Query Start frame means that AP is receiving STA IDs for selection.
- Candidate stations which know the hidden terminals send their 12-bit STA ID immediately. If the AP receives decodable 12-bit STA ID in any query slot, then the AP announces the winner STA ID immediately by Announce Winner frame. The STA ID signal received after the Announce Winner frame is ignored by AP. The Winner STA listened to announce Winner frame should immediately start its UL transmission.
- If AP cannot decode the signal in given query slot due to collision, AP simply does not transmit anything on query subcarrier. Then, the candidate stations know that their transmission of STA ID had collided and follow the binary exponential backoff behavior.

In the following, we provide in Figure 3 an example of In-Frame Querying protocol illustrating its operation steps:

We assume that the AP has A-MPDU of different sizes to send to station 1, and stations 1, 2, 3, 4, 5, 6, 7, 8 have MSDUs of different sizes to send to the AP. We assume the following sizes of data to be exchanged in the considered network: AP ->STA1(20000 bytes), STA1 ->AP(8000 bytes), STA2 ->AP(9000 bytes), STA3 ->AP(5000 bytes), STA4 ->AP(11000 bytes), STA5 ->AP(600 bytes), STA6 ->AP(8500 bytes), STA7 ->AP(10000 bytes), STA8 ->AP(9000 bytes).

For Full Duplex communication, the AP sends DL frame to station 1 and the latter sends UL frame to AP. During Full duplex transmission between AP and station1; the other stations listen to the DL frame, if they can decode the DL frame of AP without interference to current transmission UL (STA1 ->AP); thus, they are hidden. We assume stations 2, 4, 5, 6 are hidden stations, however stations 3, 7, 8 are exposed stations.

The AP knows the length of both frames. So, at the end of UL transmission, the STA1 opportunity window starts. AP sends Query start frame on the query subcarrier; candidate stations which know the hidden terminal relation, i.e., stations 2, 4, 5, 6 send their 12 bit STA ID immediately in one symbol OFDM. Candidate stations know that their transmission had collided and follow the binary exponential backoff behavior. The candidate STAs choose one random integer from the interval of [0, 2^{k-1}-1] where k is the number of transmission attempt. This backoff counter is the number of slot for which a candidate STA needs to wait.

When k=2, stations 2 and 4 choose integer 0 from the interval of [0, 1] and stations 5, 6 choose integer1. Candidates stations detected collision, they must increase k; k=3, stations 4, 5 choose integer1 from the interval [0, 3] and stations

2, 6 choose respectively 2 and 3. As soon as AP receives decodable 12 bits STA ID, i.e., ID = 2 which is station2, then AP announces the winner station ID immediately by announce winner frame and station2 sends the UL frame.

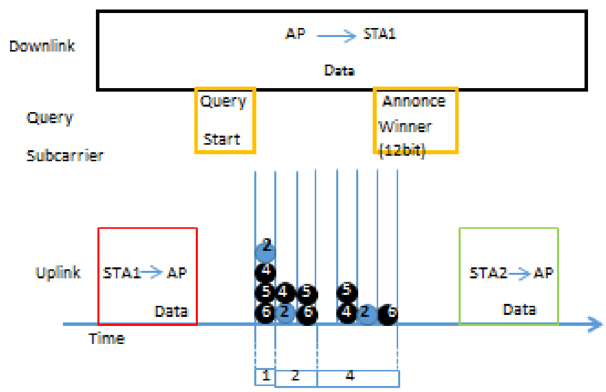

Fig. 3. Example of In-Frame-Querying protocol [17].

In Figure 4 and 5, we respectively describe In-frame Querying by means of the state machine how AP and stations operate.

4.2 O2-MAC Protocol

O2-MAC protocol [18] proposed in order to maximize the spectral capacity of Full Duplex (FD) transmissions, by significantly reducing the overhead during the communications. Unfortunately, the O2-MAC protocol is based on a strong assumption, which is not real in High Efficiency WLANs (HEW). This hypothesis considers that the downlink (DL) and uplink (UL) data flows have the same lengths.

The O2-MAC functioning is described as follows:

– Each station in the BSS (Basic Set Service) is randomly assigned to one of the available sub-carriers during the association phase of the latter.
– When a given station (including the AP) has data to send, it should wait for a DIFS (Distributed Inter-Frame Space) duration.
– After the current transmission and subsequently issue a signal in its subcarrier as OFDMA. The AP determines the role for each station in the second symbol OFDM.
– For full-duplex communication, the AP selects the bidirectional full duplex BFD first, if available. Otherwise, it attempts to select the unidirectional full duplex UFD. If the AP fails, one-way transmission is half duplex HD.

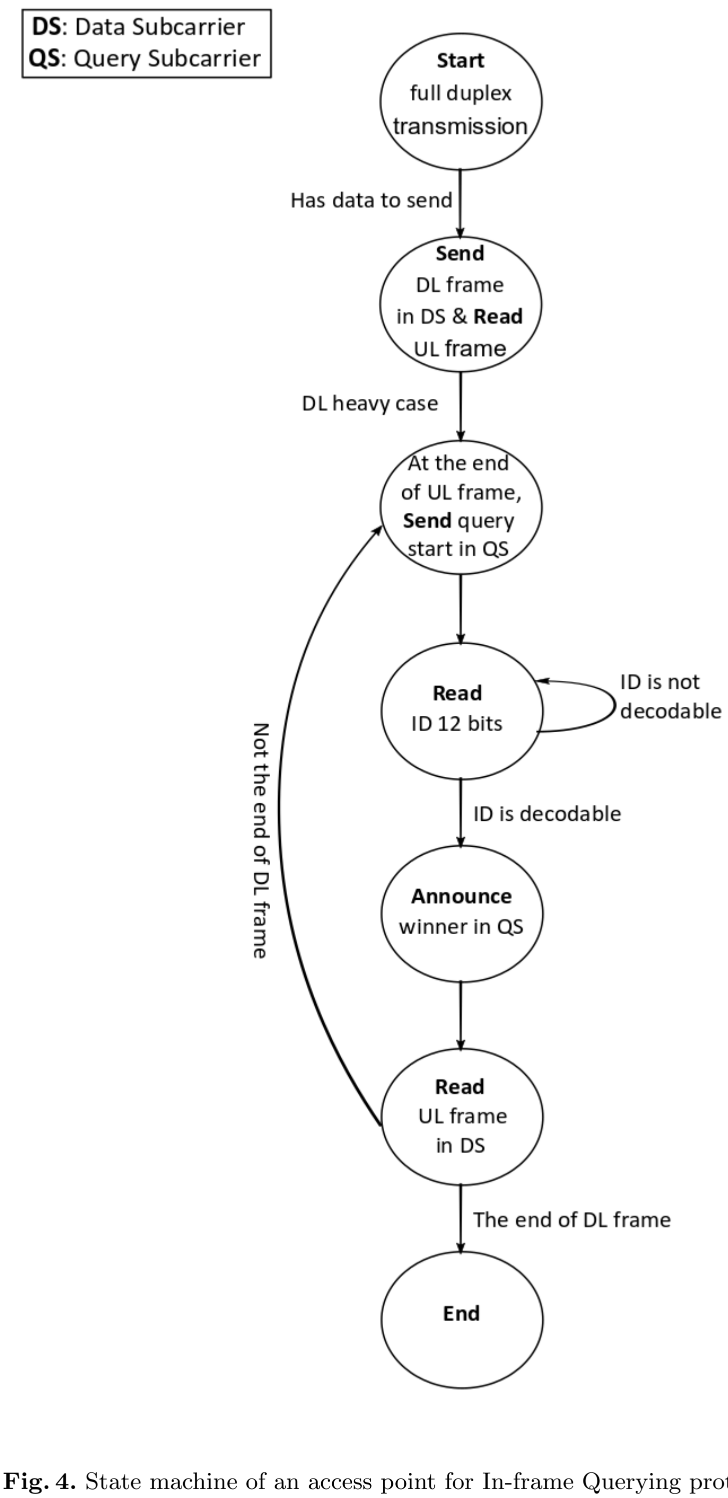

Fig. 4. State machine of an access point for In-frame Querying protocol.

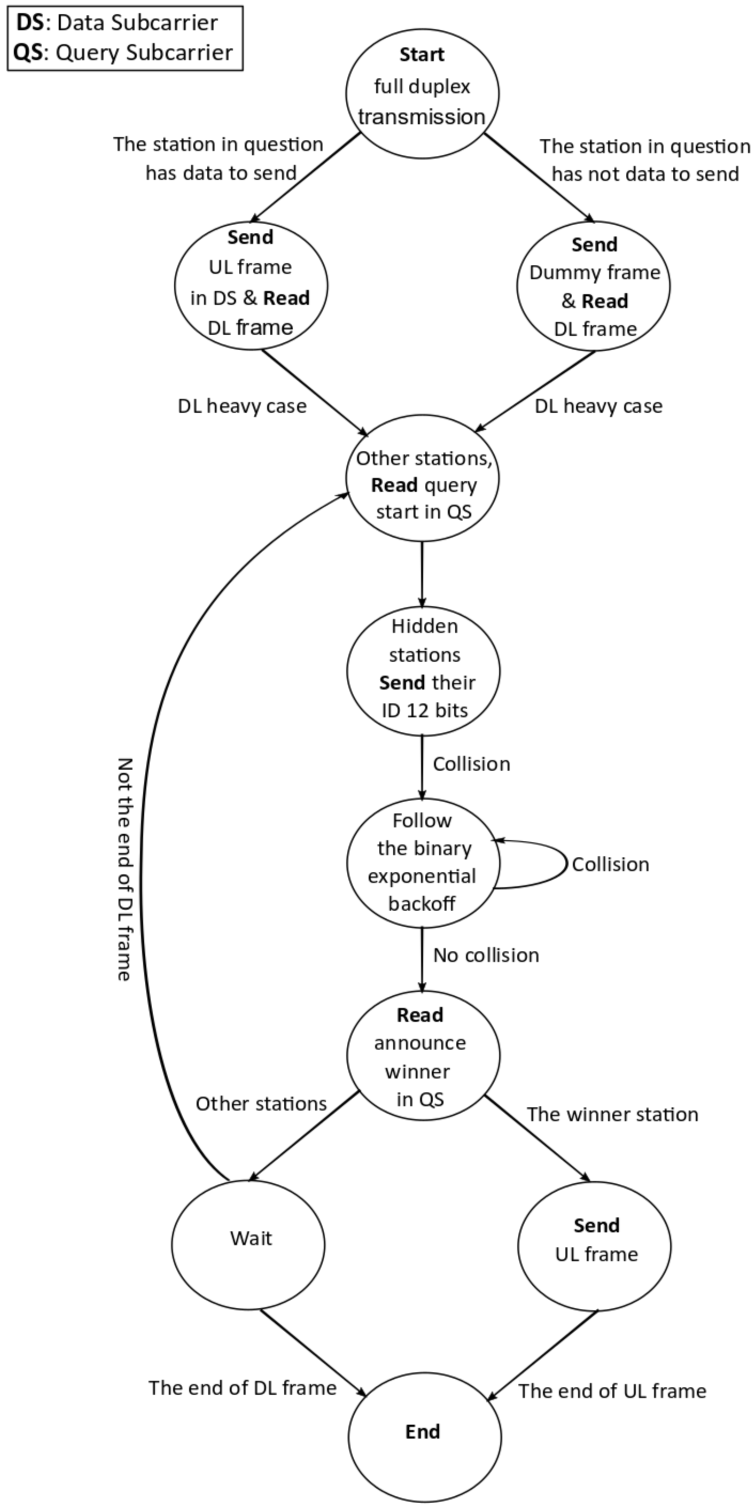

Fig. 5. State machine of a station for In-frame Querying protocol.

– After the data transmission and a SIFS (Short Inter-Frame Space) duration, an acknowledgment (ACK) is transmitted in the opposite direction of the data transmission.

Note that, the case of unidirectional full duplex UFD is possible if two stations are hidden from each other. However, O2-MAC does not manage hidden stations problem and communications are wrong. Effectively, overall throughput is overestimated.

In the following, we give an example in Figure 6 for illustrating the operation steps of the O2-MAC protocol.

We assume that the AP has data to send to stations A and C, and the stations A and B have data to send to the AP; while station C does not have data to send to the AP. In Figure 6.a, the AP and stations A and B send signals in its subcarriers, i.e., subcarrier 2 and 3, respectively. the AP reads the received signals and selects the station A as Primary Receiver (PR) and Secondary Transmitter (ST). So, it is Bidirectional Full Duplex (BFD) transmission. In Figure 6.b, the AP selects the station B as Secondary Transmitter (ST), and station C as the Primary Receiver (PR). Thus, Unidirectional Full Duplex (UFD) transmission is done with AP and stations B and C. In Figure 6.c, the AP only has data to send to the station C and selects this latter as the Primary Receiver. It is Half Duplex (HD) transmission. In Figure 6.d, illustrates the case where in station B has data to send to the AP and no other stations have data to send. AP selects station B as Primary Transmitter (PT). So, it is Half Duplex (HD) transmission. After the data transmission and Short Inter-Frame Space (SIFS), ACKnowledgment (ACK) is transmitted in the opposite direction of the data transmission.

We illustrate the operation of the O2-MAC protocol through state machine for access point and stations as shown in Figure 7 and 8, respectively.

In Table 2 provides an intuitive comparison between In-Frame-Querying and O2-MAC protocols.

Table 2. Comparison between In-Frame-Qerying and O2-MAC.

	In-Frame-Qerying	**O2-MAC**
Number of stations	4096 stations	52 stations (including AP)
Management of hidden stations	Yes	No
Using of opportunity window	Yes	No
Overhead	Variable	Fixed (8 μs)
Overall throughput	Medium	Maximum; Overestimated

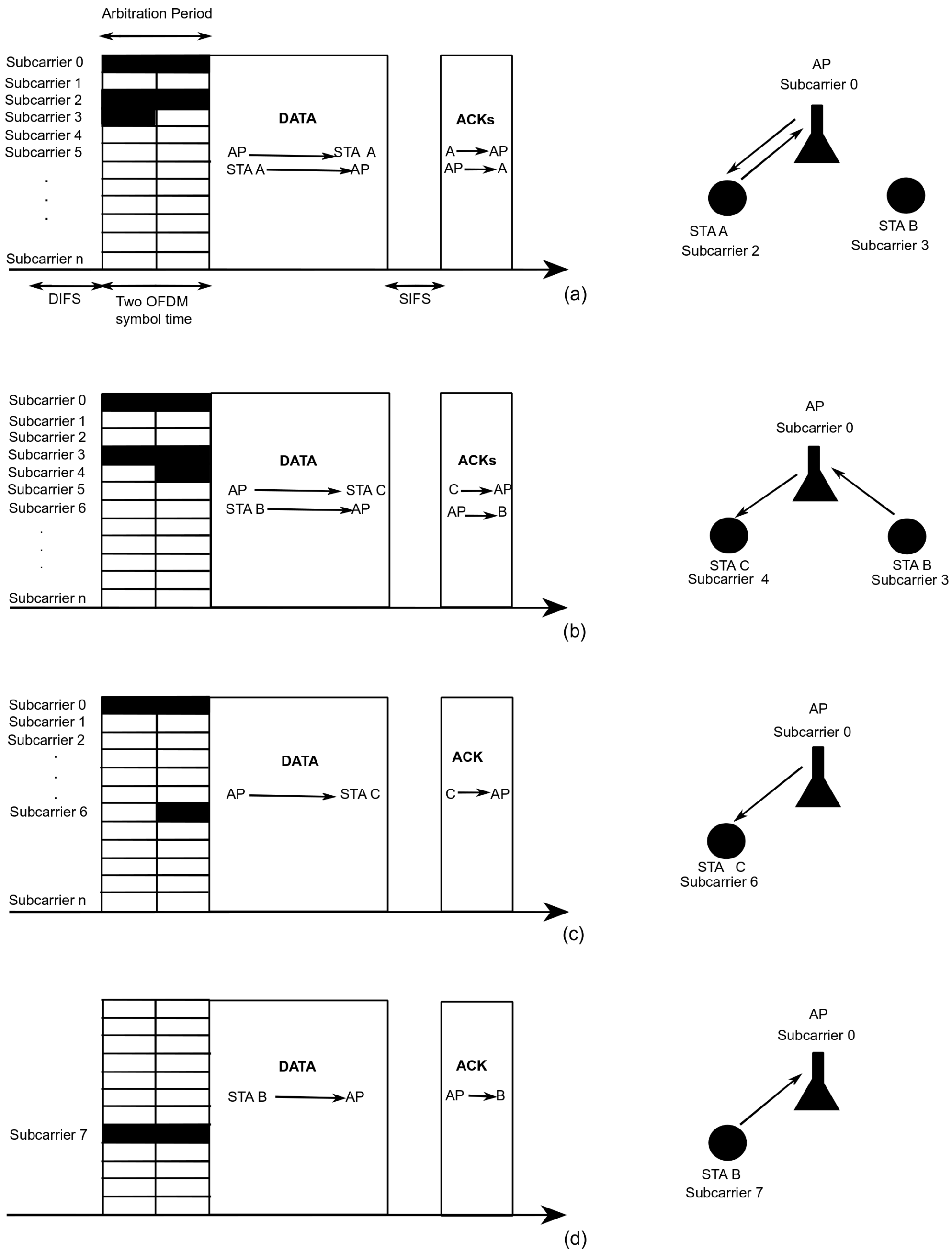

Fig. 6. Example of the operation steps of the O2-MAC protocol [18].

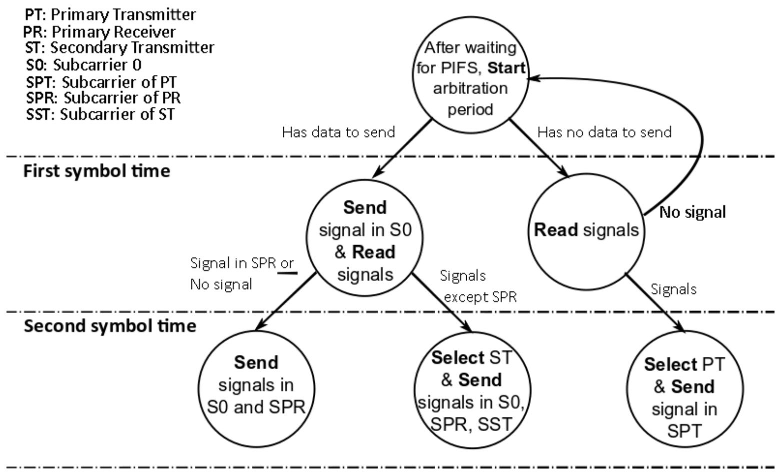

Fig. 7. State machine for arbitration of access point of O2-MAC protocol [18].

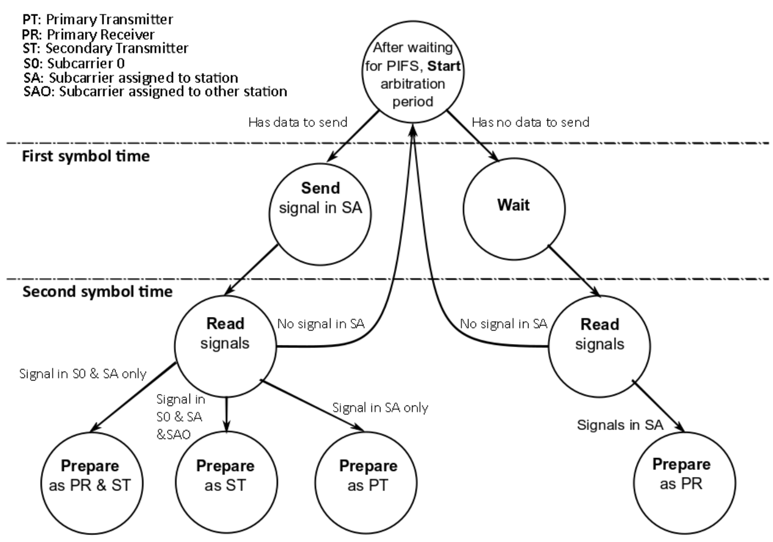

Fig. 8. State machine for arbitration of stations of O2-MAC protocol [18].

5 Simulation results and Comparison

In this section, we present the simulation results obtained with both O2-MAC and In-Frame-Querying protocols. For this purpose, we have developed an event-driven simulation program written in C++ programming language under Linux operating system. The 802.11ax PHY and MAC parameters used in simulations are presented in Table 3. The simulated environment consists of one AP and n stations associated.

Table 3. Simulation Parameters.

PHY Parameters	**Numerical Values**
Duration Symbol OFDMA	12.8 μs
Guard Interval	0.8 μs
short inter-frame space (SIFS)	16 μs
Control Packet PHY rate (CPP)	8.6 Mbps
Data Packet PHY rate (DPP)	143.4 Mbps
PHY header time	40 μs
MAC Parameters	**Numerical Values**
MAC header length	36 bytes
Management information in an A-MPDU (HDR)	47 bytes
Frame Control Sequence (FCS)	4 bytes
Delimiter in an A-MPDU length (DLT)	4 bytes
Padding in an A-MPDU length (PAD)	3 bytes
Block Ack length (BA)	40 bytes
Maximum MSDU length	11414 bytes
Maximum Number of MPDUs	64

We focus on throughput and overhead metrics and we define these performance metrics as follows:

- **Throughput (TH)**: is determined by the amount of payload bits successfully transmitted during a time unit, as given by Equation 1. In the latter E[payload] denotes the amount of payload bits successfully transmitted, $T_{simulation}$ is the simulation duration, T_{DL} is DL frame time. E[payload] and $T_{simulation}$ are respectively given by Equation 2 and 3.

$$TH = E[payload]/T_{simulation}. \tag{1}$$

$$E[payload] = DL_{payload} + UL_{payload}. \tag{2}$$

$$T_{simulation} = T_{DL}. \tag{3}$$

– **Overhead (OH)**: is expressed as the fraction of time that the transmission channel is not used to successfully transmit the payloads bits of UL frame. OH is determined by Equation 4.

$$OH = (T_{simulation} - T_{UL-payload})/T_{simulation}. \quad (4)$$

Where, $T_{UL-payload}$ is the transmission time of payload bits of UL frame. $T_{simulation}$ and $T_{UL-payload}$ are respectively given by Equation 3 and 5.

$$T_{UL-payload} = UL_{payload}/DPP. \quad (5)$$

In particular, the considered 802.11ax network uses OFDMA technology over a 20 MHz channel. So, a 20 MHz channel is divided into 256 subcarriers (SCs), where: 234 SCs are allocated as data SCs, 11 SCs are allocated as guard SCs, 8 SCs are allocated as pilot SCs, 3 SCs are used as null SCs [8]. In addition, the AP builds A-MPDUs frames (DL frame) on the basis of MSDUs frames received by stations.

In order to compare the throughput and overhead between O2-MAC and In-Frame-Querying, we have considered two cases:

1. First case, DL and UL have a variable lengths, such as DL is sufficiently longer than UL (please refer to Figure 9 and Figure 10).
2. Second case, DL and UL have the same lengths (please refer to Figure 11).

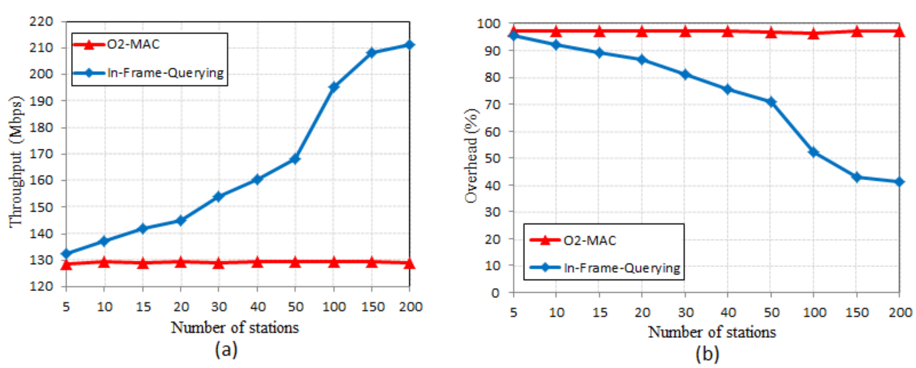

Fig. 9. Throughput, overhead versus number of stations.

In figure 9(a), we compare throughput obtained with O2-MAC and In-Frame-Querying methods according to the number of stations. As shown in figure, with the increase of number of stations, the throughput of In-Frame-Querying method increases also, this is due to an efficient use of the UL opportunity window, which means more stations can transmit UL frames during the UL opportunity window. Contrary to O2-MAC which does not use this window. Effectively, the throughput obtained is stable.

In Figure 9(b), we analyze the variation of the overhead according to the number of stations for both O2-MAC and In-Frame-Querying methods. It shows that, when the number of stations increases, overhead decreases for In-Frame-Querying. This is due to the fact that, the UL opportunity window is efficiently used. So, the time spent to transmit the useful data of UL frames is more and more important. Consequently, the overhead decreases. But, the O2-MAC protocol produces significant overhead. So, it offers the same values, because of the absence of the opportunity window whatever the down-link data flow.

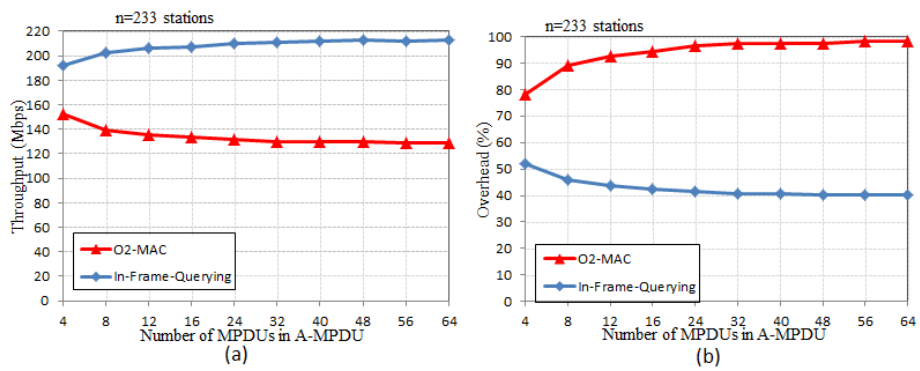

Fig. 10. Throughput, overhead versus number of MPDUs.

In Figure 10(a), we analyze the variation of throughput according to the number of MPDUs. We have fixed the number of stations n at its maximum value in the network (233 stations). We observe in this figure that, the achievable throughput increases with the increase of the number of stations in In-Frame-Querying method. This is due to the enlargement of the size of the UL opportunity window. More the number MPDUs increases, more DL size is important, more the opportunity window UL size is larger. Consequently, more UL packets can be transmitted during this opportunity. As opposed to O2-MAC protocol that does not use this opportunity window regardless of its size. So, throughput decreases.

In Figure 10(b), we have fixed the number of stations n at its maximum value in the network (233 stations), in order to compare the obtained overhead between O2-MAC and In-Frame-Querying according to the number of MPDUs. This figure indicates that, the overhead decreases with the number of MPDUs in In-Frame-Querying method, as a result of using the UL opportunity window, more the number of MPDUs increases and more DL size is important. Therefore, more UL frames can be transmitted successfully. Then, overhead decreases. However with O2-MAC, the overhead increases with increasing number of MPDUs. This is due to the fact that, the absence of the UL opportunity window.

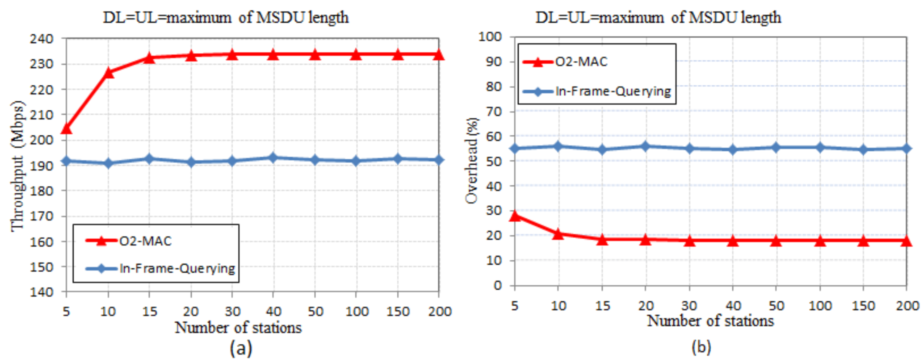

Fig. 11. Throughput, overhead versus number of stations.

In Figure 11(a), we have fixed the DL and UL lengths at its maximum MSDU length values and we have varied the number of stations. This allows us to compare the throughput obtained with both O2-MAC and In-Frame-Querying. We see that the achieved throughput increases with the increase of the number of stations for O2-MAC, when the number of stations is between 5 and 20. This implies that O2-MAC favors bidirectional first, if available. Otherwise, it attempts to select the unidirectional full duplex. Else, half duplex. Indeed, with a number of stations greater than 20 stations, we have usually the case bidirectional Full Duplex. Then, AP and STA transmit data simultaneously. Throughput reaches the maximum and it becomes stable. With In-Frame-Querying method, we obtain sensibly the same values because In-Frame Querying does not favor, but it imposes one station to transmit data.

In Figure 11(b), we analyze the overhead according to the number of stations in the network, in order to do comparison between O2-MAC and In-Frame-Querying. We remark that the increase of the number of stations allows to decrease the overhead of the O2-MAC protocol. We can justify this by the fact that O2-MAC favors bidirectional Full Duplex first, if available. Otherwise, it attempts to select the unidirectional full duplex. Else, half duplex. However, with In-Frame-Querying, we see nearly the same values, as a result of dummy frames caused in case imaginary bidirectional Full Duplex.

6 Conclusion

In this paper, we have studied and compared the two main MAC protocols existing for enabling the innovative Full Duplex technology in the incoming IEEE

802.11ax standard designed for High Efficiency WLANs networks, namely, O2-MAC and In-Frame-Querying. Both of them allow to maximize the efficient use of full duplex transmissions. Simulation results have shown that, in the case where DL and UL flows have variable lengths, such as the DL flow is sufficiently longer than the UL flow; the superiority of In-Frame-Querying by report to O2-MAC in terms of throughput and overhead. In the other case that, DL and UL flows have the same lengths; we recognize easily that O2-MAC protocol provides a significant gain in terms of both throughput and overhead metrics compared to In-Frame-Querying.

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