Provisioning QoS in Wi-Fi Systems with Asymmetric Full-duplex Communications

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***Abstract*—The traffic volume carried by wireless local area networks (WLANs) continues to increase at a rapid pace. Full-duplex communications is a key solution for satisfying the growing traffic demand, enhancing spectrum efficiency, and reducing latency for WLAN users. In this paper, we consider the application of asymmetric full-duplex (AFD) communications in WLANs, exemplified by a Wi-Fi system. Our system model relies on a full-duplex-enabled Wi-Fi access point to simultaneously transmit uplink and downlink to a pair of half-duplex Wi-Fi stations. Providing QoS guarantees in WLANs with AFD communications capabilities is challenging due to inter-node as well as residual self-interference. The heterogeneity of the QoS requirements between paired uplink and downlink stations further complicates the problem. To tackle these challenges, we introduce a framework called AFD-QoS, which incorporates AFD communications in WLANs and supports QoS. AFD-QoS consists of three components: AFD-enabled uplink/downlink station-pair selection algorithm, AFD-enabled block-acknowledgment session initiation/termination protocol, and joint transmission rate/AFD communication mode adaptation scheme. Our adaptation scheme relies on intelligent and cognitive approaches to improve Wi-Fi networks awareness about channel dynamics as well as inter-node and self-interference. We introduce new intelligent MAC-layer procedures for supporting QoS services in AFD communications, and cast light on many challenges and their solutions. Our simulation results indicate that AFD-QoS outperforms classical half-duplex frameworks and achieves up to 90% of the optimal AFD performance.**

***Index Terms*—Asymmetric full-duplex, Wi-Fi, EDCA, block acknowledgment, TXOP sharing, joint transmission rate and communication-mode control, POMDP.**

I. Introduction

A. Background and Motivation

Mobile data traffic is expected to increase by sevenfolds between 2016 and 2021 [2]. In 2016, about half of the mobile traffic volume was offloaded onto WLAN connections over unlicensed bands [3]. To cope with this high demand, future WLANs require a substantial change in their design. In-band full-duplex (FD) communications, in which two radios communicate simultaneously at the same time and on the same frequency channel, are considered a promising solution. Historically, FD communications was deemed challenging due to the existence of strong self-interference from the transmit (Tx) chain onto the receive (Rx) chain of the same radio. The infeasibility of FD communications was challenged by several studies (see [4] for a survey), which successfully demonstrated the possibility of FD communications using self-interference suppression (SIS) techniques. *Symmetric* FD communications require the two ends of a wireless link to be SIS-capable. Although implementing SIS techniques in Wi-Fi access points (APs) and relatively large communication devices (e.g., laptops, TVs, large tablets, etc.) is foreseeable, it is currently impractical to do that in small form-factor devices (e.g., smart phones). Hence, in this paper we consider FD-enabled APs but half-duplex (HD) Wi-Fi stations (STAs). Under this setting, an AP can operate in an *asymmetric full-duplex (AFD)* fashion, whereby it can transmit downlink (DL) frames to a STA while simultaneously receiving uplink (UL) frames on the same channel from another STA, as shown in Figure 1.

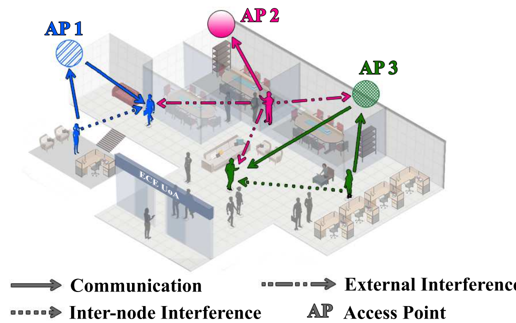

Fig. 1: Example of asymmetric full-duplex communications in a WLAN. APs are full-duplex-enabled whereas STAs are half-duplex.

Traditional HD Wi-Fi systems support QoS using two mechanisms: The enhanced distributed channel access (EDCA) scheme and block-acknowledgment (BA) [5]. EDCA is an extension of the well-known distributed coordination function (DCF) scheme. It is designed to support four access categories (ACs) with different channel access parameters: Voice (AC_VO), video (AC_VI), best effort traffic (AC_BE), and

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background (AC_BK). Contending stations can reserve the channel for a transmit opportunity (TXOP) period, whose duration depends on the specific AC. During a TXOP, the AP/STA transmits multiple packets [6]. The BA, on the other hand, aims at improving latency and reducing control overhead by allowing STAs to acknowledge multiple received frames using a single acknowledgement (ACK) frame. Enabling BA requires initiating what is known as *BA session*.

Provisioning QoS and extending the EDCA and BA mechanisms to AFD Wi-Fi communications is challenging due to the following reasons. First, it is not clear how prospective UL and DL stations can be paired. Various factors affect this pairing, including inter-node interference and QoS requirements. Note that different ACs have different QoS requirements and TXOP durations. Therefore, the difference between stations' AC type and traffic loads should be considered when selecting the paired stations. Second, IEEE 802.11 standards do not discuss how BA session establishment and tearing down can be performed in AFD settings. Therefore, a new AFD-enabled BA protocol is needed to initiate and tear down BA sessions. Third, during AFD-enabled TXOP, UL and DL channels could experience different fading and channel impairments that might make AFD communication unsuccessful. In this case, operating the AP in HD fashion may be more beneficial than using the AFD mode. Specifically, under excessive external interference (dense deployment) and/or strong self-interference (due to limited SIS capabilities), it is more beneficial for the AP to operate in the HD mode [7] (i.e., UL or DL but not both). Therefore, a channel/interference-cognitive scheme is needed to jointly adapt the communication mode (i.e., AFD-mode, UL-only, and DL-only) and transmission rates for UL/DL frames. Addressing these challenges using adaptable and cognitive AFD-based WLAN designs is crucial for boosting the performance of future AFD-based WLANs.

To address the above challenges, in this paper, we introduce AFD-QoS, a unified cognitive and adaptable framework that incorporates AFD communications in Wi-Fi systems and supports applications QoS. The goal of AFD-QoS is to maximize the sum-throughput for UL and DL links for Wi-Fi traffics once these links get mapped to the supported ACs of the EDCA channel access scheme. To achieve this goal, AFD-QoS relies on three cognitive components: AFD-enabled STA pair selection algorithm, AFD-enabled BA session initiation and termination protocol, and a transmission rate/communication mode adaptation scheme. These components could be added as cognitive features in future FD-enabled APs, and they can be configured to work interactively or separately based on operational requirements. The first component includes an algorithm that helps an AP decide the possible UL and DL station AFD-pairs, which can be part of an AFD-enabled BA session and share an AFD-enabled TXOP period. This algorithm takes into account external interference from nearby networks, inter-node interference between the paired stations as well as the differences in their ACs and traffic loads. It also ensures that all stations are treated fairly. The second component helps AP accommodate an AFD-enabled BA session initiation and termination by using low overhead multi-way handshaking procedures. The third component allows the AP to become cognitive about interference and channel dynamics, and adapt its transmission rates and communication modes with the paired UL and DL stations during the TXOP using a framework based on partially observable Markov decision process (POMDP). This component, referred to as AFD communication mode and rate adaptation (AFRA) scheme, allows AP to operate in four communication modes: AFD, i.e., simultaneous uplink and downlink, uplink-only, downlink only, and backoff mode. AP operates in UL-only and DL-only modes when the self-interference and inter-node interference limit the capabilities of AFD communications. Extensive simulations reveal that our adaptation framework achieves up to 90% of the optimal performance and outperforms other classical approaches.

B. Related Works

Incorporating cognition in the design of FD-enabled wireless networks has been studied extensively in the literature (see [4] & [8] and references therein). Early works on MAC design for FD WLANs include [9]–[12]. In [9], the authors considered bidirectional (symmetric) FD operation and proposed MAC enhancements to remedy the hidden-node problem and ensure fairness between Wi-Fi STAs. Authors in [10] considered both symmetric and asymmetric FD modes, and proposed exploiting SIS to eliminate the hidden-node problem. FD-MAC [11] let nodes that do not interfere to join FD transmissions, while [12] relaxed this to a tolerable level of inter-node interference. A series of subsequent works focused on improving FD/AFD WLANs by proposing different approaches to enhance the previously mentioned protocols, including Janus [13], RCTC [14], A-Duplex [15], and power control MAC (PoCMAC) [16].

In other works, authors suggested a probabilistic selection of AFD station pairs. Authors in [17] & [18] suggested enabling hybrid operation between HD and FD/AFD communication modes through assigning probabilities for running in these modes. Other approaches were proposed to improve FD/AFD communications through a cross-layer design that combines signal cancellation techniques and MAC layer procedures to mitigate inter-node interference in AFD communications for SISO-based [19] and MIMO-based [20] FD/AFD networks. Other recent works investigated the design for FD MAC protocols with multi-channel operations associated with different goals such as maximizing network throughput [21] and/or improving network security against FD/AFD-based attacks [22]. In other works, authors suggested combining AFD communications with multi-user operation in uplink and downlink communications [23] [24]. Previous works addressed many important issues in FD/AFD MAC layer design, and presented exciting ideas and results, however, they focused on the basic DCF scheme and did not take into account the QoS features currently implemented in IEEE 802.11 standards, such as ACs, TXOPs, BA session, different ACK policies, etc. Our work aims at filling this gaps and incorporating these QoS features in the design of future AFD-based WLANs through our cognitive and adaptable AFD-QoS framework.

Adapting transmission rate in WLANs has been studied extensively in the literature (see [25] for a survey). Auto-rate fallback (ARF), Onoe, SampleRate, Minstrel, and RBAR,

AC	CWmin	CWmax	AIFSN	Max TXOP
Background (AC_BK)	15	1023	7	0
Best effort (AC_BE)	15	1023	3	0
Video (AC_VI)	7	15	2	3.008ms
Voice (AC_VO)	3	7	2	1.504ms
Legacy DCF	15	1023	2	0

TABLE I: Default EDCA parameters for each AC [5].

etc, are some examples of famous rate adaptation schemes proposed in literature. Most of these schemes adapt the rate using heuristic based approaches, and rely on either long-term statistics, packet delivery rate, random channel probing, or SINR measurements. A common feature of these schemes is their relatively long reaction time, which can range from hundreds to thousands of milliseconds. In contrast, artificial-intelligence-based and decision-theory-oriented rate adaptation approaches, such as those based on POMDP, exploit partial knowledge about the radio environment to provide relatively faster adaptation [26]–[28]. Our proposed AFRA scheme relies on POMDPs to jointly adapt the transmission rates and communication mode on an AFD-enabled AP. In [28], we addressed the problem of joint transmission rate and duplex-mode adaptation for *symmetric* FD communications, assuming both the AP and STAs are equipped with SIS capabilities while coexisting with an LTE-unlicensed (LTE-U) system. In [29], the authors investigated the adaptation of transmission rates and MIMO modes for symmetric MIMO-FD-enabled links using multi-armed bandits. In our work, we consider different network setup and problem motivations, and use different adaptation methodology than [29].

II. Overview of QoS Provisioing in Current IEEE 802.11 Standards

IEEE 802.11 DCF channel access scheme is not designed to provide QoS guarantees. EDCA was later introduced in IEEE 802.11 standards to support delay-sensitive applications. EDCA provides a contention free (CF) channel access TXOP period during which a STA can send multiple frames. As shown in Table I, Wi-Fi traffic is prioritized by assigning different TXOP limits, contention window (CW) parameters, and Arbitration Inter-frame Space numbers (AIFSNs) to different ACs [6]. AC_VO has the highest priority, while AC_VI has the longest TXOP duration. A TXOP time interval of 0 means it is limited to a single MAC service data unit (MSDU) or MAC management protocol data unit (MMPDU). STAs must perform a short frame exchange (RTS/CTS or Data/ACK) at the beginning of the TXOP to detect collisions and reduce hidden node problems.

To reduce the overhead of control messages, IEEE 802.11 standards introduced the block acknowledgement (BA) mechanism. After transmitting a sequence of data frames, the originator sends a BA request (BAR) to the recipient, which can reply right away with a BA frame (*immediate* BA) or delay the response (*delayed* BA). A new 'QoS data frame' was introduced to support these features. Compared to regular data frames, QoS data frames include additional fields such as a traffic identifier (TID), which conveys the AC and the ACK policy (i.e., normal ACK, no ACK, BA).

The BA mechanism needs to be enabled by establishing a BA session between the originator and the recipient. Figure 2

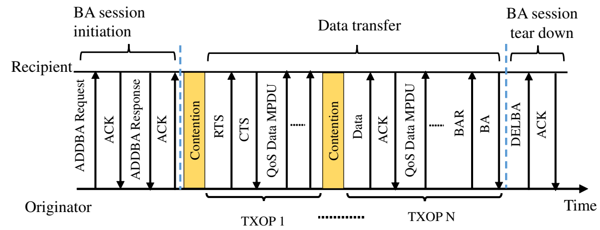


Fig. 2: BA session initiation, data transfer, and tear down in the IEEE 802.11 standards.

shows an example of a typical BA session, which consists of three phases. The first phase is the BA session initiation, where the originator and recipient exchange 'add BA' (ADDBA) request/response frames. These frames include the BA policy and the TID. Once a BA session is established, the originator can send a block of data frames to the recipient. The data transfer phase may consist of multiple TXOPs, each of which is preceded by channel contention. A sequence of data frames may be transmitted in single/multiple TXOP(s). Under the immediate BA policy, the originator may send BAR to the recipient, which replies back with the BA. The BA session can be terminated after a BA session timeout if the originator does not have more data to send and all frames have been acknowledged. BA session tear down can be done either by the originator or the recipient by exchanging a 'delete BA' (DELBA)/ACK frames.

III. Proposed AFD-QoS Framework

Our AFD-QoS framework aims at facilitating cognitive AFD communications in WLANs with goal of maximizing the sum-throughput of UL and DL links of the supported AC traffics. In contrast to previous works on AFD communications, AFD-QoS considers QoS aspects and resolves conflicts due to the heterogeneity of transported traffic. AFD-QoS consists of the following three components:

1) **AFD-enabled station-pair selection algorithm:** This algorithm decides the most suitable set of stations to be paired for AFD communication with the AP during an AFD-enabled BA session or TXOP period. This algorithm takes into account inter-node interference, external interference, the AC, and traffic loads of the paired stations.
2) **AFD-enabled BA session initiation and termination protocol:** This protocol facilitates AFD-enabled BA session through several low overhead multi-way handshaking control frames. Once the various station pairs are determined, this protocol allows AP to inform and invite AFD pairs to be part of an AFD-enabled BA session. We extend the traditional BA session initiation and termination procedures, and enable them to work in an AFD setting. To reduce the control overhead, we introduce special *dual-purpose* control messages that allow AP to send control information to the selected AFD pair stations using one control message.

3) **Joint AFD communication mode and transmission rate adaptation (AFRA) scheme:** This scheme aims at enhancing the spectrum efficiency by improving the AP cognition and adaptability during AFD-enabled TXOP periods. Once UL station or AP have successfully contended using EDCA, UL and DL station pair start exchanging frames with the AP. AFRA supports four modes of communication: *uplink-only* (UL-only) with UL station; *downlink-only* (DL-only) with DL station; simultaneous UL/DL with the UL/DL stations, which simply refer to *asymmetric FD*, i.e., AFD mode; and *Backoff* (BO) mode. The BO mode is optional and is selected when neither UL nor DL connections are successful. AP selects UL-only and DL-only when it believes that these modes are more efficient than AFD mode. Channel gains and SINR vary due to shadowing, fading, self-interference, external interference, and inter-node interference, and it is important to adapt the communication mode and associated transmission rates according to these dynamics. The AFRA scheme helps AP make efficient utilization of the TXOP period by adapting these communication modes and associated transmission rates, as explained in Section VI-B, whereby it maximizes sum-throughput of UL and DL links. AP builds beliefs about SINRs at both uplink and downlink receivers, and uses these beliefs to pick the suitable communication mode and associated transmission rates according to a predefined policy.

To facilitate the operation of AFRA, we introduce a new timing structure and control frames to be used during an AFD-enabled TXOP period. We divide the TXOP period into time slots of equal length. The AP can switch between the four modes at slot boundaries. Each time slot is divided into two periods, *data phase* and *control phase*, as shown in Figure 3. The data phase is used to exchange UL and DL data frames, while the control phase is used to exchange control frames such as *acknowledgment* (ACK), and *negative-ACK* (NACK). The NACK frames are used for synchronization and '*keep-alive*' purposes and to keep other hidden Wi-Fi stations silent during the TXOP period. The control phase provides observations that are important for the AP to adapt its operation during the AFD-enabled TXOP period. We provide an arbitrary example for AFRA adaptation during TXOP in [1] (Section IV-B).

A. Network Model

Our network setup considers typical WLAN scenarios that could take place in office and residential environments, as shown in Figure 1. We consider an AFD-based WLAN that consists of a set $\mathcal{P}$ of n_a FD-enabled APs, where AP i serves a set X_i of HD-enabled stations. Each AP exchanges data frames with its associated STAs using the proposed modes in Figure 3, and switch between these modes according to AFRA scheme. APs and STAs are heavily loaded with traffics of different AC types, and the ultimate goal of STAs is to have Internet access for their traffics through their associating AP. Therefore, STAs exchange data packets of different AC types with the AP. These packets are encapsulated in UL and DL data frames, and the AP, in turn, sends these data packets to the ISP using a wired backhaul network. In this network setup, there are three sources of interference: Inter-node interference between UL and DL paired stations, self-interference at APs, and external interference generated by nearby APs and their associated STAs. To account for any other possible source of external interference that might be present, we let each STA update the AP about potential STAs belonging to adjacent APs and who can cause harmful interference to them. We define what we call as the *external interference set* (EIS), which informs the AP of potential external interference sources that might affect its DL transmissions. AP also announces its own EIS to account for external interference affecting its UL transmissions. APs and STAs can populate their own EISs by overhearing MAC addresses and service-set-IDs (SSIDs) of their adjacent networks.

Let access point AP-p decide the set of stations that are to be AFD pairs, we focus on modeling the performance for one of these pairs, say STA-U and STA-D. Let h_{up}, h_{pd}, and h_{ud} be the channel gains between STA-U and AP-p, AP-p and STA-D, and STA-U and STA-D, respectively. Let h_{pp} be the channel gain of the self-interference channel at the AP, modeling the medium between its transmit and receive chains. To model self-interference at AP-p, let χ_p be the SIS capability at the AP-p (perfect SIS occurs at $\chi_p = 0$). To account for external interference, let E_p and E_d be EISs of AP-p and STA-D, respectively, and h_{kp} and h_{kd} be channel gains of interference channels between STA-k and AP-p and STA-D, respectively. The UL and DL received signals depend on the communication mode $a \in \{\text{AFD}, \text{UL-only}, \text{DL-only}\}$, and they are expressed, respectively, as:

$$y_p^{(a)} = h_{up}s_u + h_{\text{pp}}\chi_{\text{p}}\, s_p \mathbf{1}_{\text{AFD}} + w_p + \sum_{k\in E_p} h_{kp}s_k,$$

$$y_d^{(a)} = h_{pd}s_p + h_{ud}s_u \mathbf{1}_{\text{AFD}} + w_d + \sum_{k\in E_d} h_{kd}s_k,$$

where s_u, s_k, and s_p are STA-U, STA-k, and AP-p transmitted signals, respectively, w_p and w_d are the additive-white-Gaussian noise (AWGN) signals at AP-p and STA-D receivers, respectively, and $\mathbf{1}_{\text{AFD}} = \{1 : a = \text{'AFD'}\}$. The SINRs for both UL (i.e., $\text{SINR}_p^{(a)}$) and DL (i.e., $\text{SINR}_d^{(a)}$) connections, respectively, are functions of the communication mode a, and are written as:

$$\text{SINR}_p^{(a)} = \frac{|h_{up}|^2 P_{\text{u}}}{\underbrace{|h_{\text{pp}}|^2 \chi_p^2 P_{\text{a}} \mathbf{1}_{\text{AFD}}}_{\text{self-interference}} + N_p + \underbrace{\sum_{k\in E_p} |h_{kp}|^2 P_{\text{k}}}_{\text{external interference}}}, \quad (1)$$

$$\text{SINR}_d^{(a)} = \frac{|h_{pd}|^2 P_{\text{a}}}{\underbrace{|h_{ud}|^2 P_{\text{u}} \mathbf{1}_{\text{AFD}}}_{\text{inter-node interference}} + N_d + \underbrace{\sum_{k\in E_d} |h_{kd}|^2 P_{\text{k}}}_{\text{external interference}}}, \quad (2)$$

where P_{u}, P_{a}, and P_{k} are STA-U, AP-p, and STA-k transmit powers, respectively. N_p and N_d are AWGN powers at AP-p and STA-D receivers, respectively. Selecting the AFD mode causes a self-interference at the AP-p and inter-node interference at STA-D. External interference may not impose

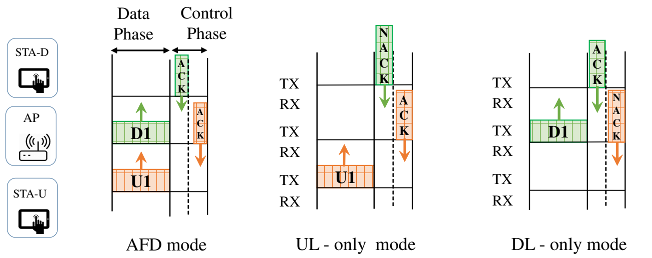


Fig. 3: Communication modes: AFD, UL-only, and DL-only. STA-U is the uplink and STA-D is the downlink (D1: Downlink frame 1; U1: Uplink frame 1).

significant impact on our framework, and this is due to the following reasons. First, in practice, Wi-Fi APs are designed to select unlicensed channels deemed to be less occupied by other Wi-Fi networks. UNII bands at 5 GHz include multiple subbands (e.g., UNII-1, UNII-2, UNII-3, and UNII-4) and many channels. Thus, adjacent Wi-Fi networks are likely to operate on different channels, which reduces the probability of having strong external interference among Wi-Fi APs. Second, Wi-Fi APs/STAs perform CSMA/CA prior to their transmission, whereby they back off once they detect transmission from other nearby Wi-Fi networks. This implies that even if two or more adjacent Wi-Fi networks happened to operate on the same unlicensed channel, they will backoff and abandon transmission until others finish their communications. The only remaining source of external interference is due to the hidden node problem. This problem can be largely alleviated by letting nodes exchange 'request-to-send' (RTS) and 'clear-to-send' (CTS) packets prior to their data exchange [30], forcing hidden nodes to back off once they hear the CTS packet. In our framework, the first time slot at each TXOP period can be designed to incorporate RTS/CTS frames so as to reduce the possibility of having hidden nodes.

IV. AFD-enabled Station-Pair Selection Algorithm

AFD-QoS framework provides an algorithm for selecting Wi-Fi downlink station to get paired with the uplink station for AFD operation. The algorithm considers the potential inter-node interference and external interference, as well as accounts for fairness and differences in AC types between AFD pairs. AFD pairs are supposed to share AFD-enabled BA session and/or TXOP period. First, the AP builds and maintains an interference graph for its associated stations and nearby STAs and APs that could cause harmful interference to AP and DL station. To enable this, each STA includes in its transmitted frame the *association identities* (AIDs) of neighboring stations it overhears as well as EISs of STAs associated to nearby APs. AP updates the interference graph frequently, where it disassociates any STA that remains silent for a certain period.

Let STA-U be an uplink station that gains the TXOP by contending for the channel. The AP seeks to find a downlink station that can be a part of an AFD-pair with STA-U. Algorithm 1 shows the procedure for selecting the downlink station, e.g., STA-D, where the AP utilizes the interference graph to determine stations that are not impaired by STA-U inter-node interference (i.e., inter-node interference is below a specific threshold) as well as those not affected by external interference. If no such STA is found, the AP continues with the TXOP period in a HD mode (for STA-U to AP transmission). Otherwise, it sorts stations based on their ACs as well as on how fairly they have been treated. Fairness is computed by monitoring successful transmissions in the last T_A seconds for all candidate downlink stations. The AP ranks STAs based on their achieved throughput during the T_A monitoring time. Greedy stations (i.e., stations whose throughput exceeding a certain threshold value) are excluded. Finally, the AP selects downlink STAs based on their ACs, recall first that the EDCA scheme supports several priority categories and assigns each category specific channel access parameters and TXOP period. For example, AC_VO and AC_VI have TXOP periods of 1.5 and 3.008 milliseconds, respectively. Within the candidate set of downlink STA, the AP searches a STA with the same AC as STA-U. If the AC of STA-U is AC_VO and no candidate downlink station has the same AC, the AP proceeds with an HD-based transmission. If the AC of STA-U is AC_VI and no downlink station has the same AC, AP selects any station with AC_VO and treats it as AC_VI, otherwise, it proceeds with an HD transmission. The feasibility of promoting a station with AC_VO to an AC_VI TXOP of 3.008 milliseconds duration comes from the fact that the channel has already been reserved for an AC_VI TXOP (i.e., using the AIFS and contention window parameters of AC_VI) by the uplink station.

Algorithm 1 AFD-enabled Station-Pair Selection

```
for Each AFD-enabled BA session do
    AP receives ADDBA request from uplink station STA-U
    AP sorts associated stations based on their inter-node interference with
    STA-U, and their external interference with adjacent Wi-Fi networks by
    looking into their EISs, and omit these exceeding a certain threshold
    if no downlink STA with buffered data is found in the sorted set then
        AP continues the BA session in HD mode
    else
        AP sorts stations again based on the fairness of their service and
        their AC types
        if a downlink station with the same AC as STA-U is found then
            AP selects this to be paired with STA-U
        else if the STA-U AC type is VI then
            AP selects a downlink station with AC_VO, then HD if no
            such is found
        else
            AP operates in BA session as HD
        end if
    end if
end for
```

V. AFD-enabled BA Protocols

AFD-QoS framework includes procedures for the initiation and termination of AFD-enabled BA sessions. We first present a general description of these procedures for session initiation, data transfer, and session tear down, assuming an AFD pair, i.e., STA-U and STA-D, has the same traffic load, AC, and BA policy. We later discuss the cases where AFD pair could have different traffic volumes, AC types, and BA polices. All of the protocols presented in this section rely on multi-way hand shaking messages between AP and the AFD pair, and assume

AFD pair has already been selected. To reduce the overhead of control frames, we rely on what we call *dual-purpose* control frames. AP uses these control frames to multicast STA-U and STA-D using a single transmission.

A. AFD-enabled BA Session Initiation

We extend the traditional half-duplex BA session initiation to an AFD-enabled setting. Figure 4 shows the AFD-enabled BA session initiation phase. STA-U (originator) transmits an ADDBA request frame to the AP to establish a BA session. The AP checks whether there is any buffered data for any downlink STA. If not, AP proceeds with the traditional HD BA session with STA-U. Otherwise, it selects the downlink station based on Algorithm 1, as was described in Section IV.

After selecting an STU-D for AFD operation, the AP replies with a new frame called 'ACK to uplink station - ADDBA Request to downlink station' (AU-ABQD). This frame is a dual-purpose frame and targets both STA-U and STA-D. Its first purpose is to ACK the ADDBA request of STA-U. It also includes a timeout value for sending the ADDBA Response back to STA-U. This timeout value is a function of the number of the candidate downlink stations that AP believes could be paired with STA-U. Another purpose of AU-ABQD frame is to allow the AP to probe the candidate downlink stations. In AU-ABQD frame, AP includes the association ID (AID) of STA-U. The probed downlink station, say STA-D, uses this STA-U's AID and checks whether it previously heard the original ADDBA frame request of STA-U. If STA-D has heard STA-U's ADDBA, it rejects the BA session request and notifies the AP. Then AP probes another station candidate by following the same procedure. The process continues until the timeout value is reached or until an STA-D candidate accepts the ACK invitation. This probing process plays as a second layer of protection against inter-node interference, as interference graph could be outdated due to mobility.

If an invited STA-D has not previously heard the ADDBA request of STA-U, it sends an ACK to AP, followed by the ADDBA Response frame, as recommended by the IEEE 802.11 standards. At this point of time, the AP needs to deliver two messages to STA-U and STA-D to respond and acknowledge them, respectively. To reduce the overhead, we define a new dual-purpose frame called 'ADDBA Response to uplink station - ACK downlink station' (ABRU-AD). This frame acts as an ADDBA response to STA-U and ACK for the ADDBA response of STA-D. Finally, STA-U replies with an ACK to the AP. In terms of overhead, the AFD-enabled BA session initiation adds only two frames (ACK and ADDBA response from STA-D) when compared to the HD case.

B. Data Transfer

After establishing an AFD-enabled BA session, the originator (STA-U) contends for the medium and sends an RTS to the AP, as shown in Figure 5. AP checks whether STA-D is still available for communication or not by sending an RTS frame. If STA-D is unavailable (e.g., sleep mode), then the AP skips the AFD mode for this specific TXOP after the CTS timeout. In this case, the AP replies with a CTS to STA-U

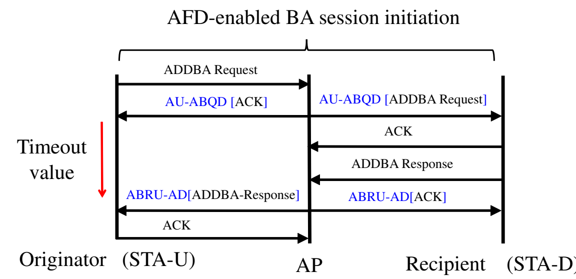


Fig. 4: AFD-enabled BA session initiation.

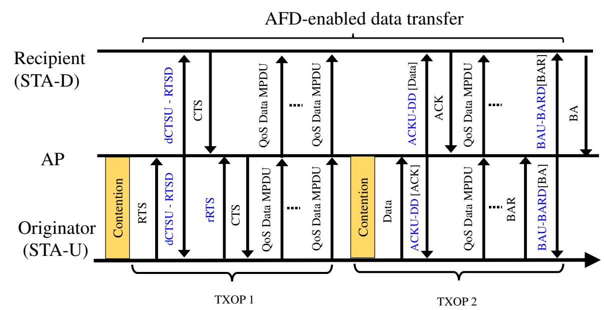


Fig. 5: Data transfer phase in AFD-enabled BA session.

and continues with the HD mode (i.e., UL-only). On the other hand, if STA-D is available, it replies with a CTS. Due to mobility, AP includes STA-U's AID in the RTS message of STA-D. If STA-D heard STA-U's RTS, it rejects the TXOP. Otherwise STA-D sends a CTS message to the AP. The AP then sends a CTS frame to STA-U informing it that both the AP and STA-D are ready to start this TXOP in AFD mode.

After this procedure, the AP starts transmitting DL frames to STA-D while receiving UL frames from STA-U on the same frequency. The AFD-mode ends when the TXOP limit specified by the AC is reached. Note that the mandatory short frame exchange at the beginning of the TXOP could be RTS/CTS or short Data/ACK message exchange. At the end of the block of data frames transmission (in Figure 5, the data block transfer spans two TXOPs), STA-U sends a BAR to the AP. The AP decodes the packet header and knows that the packet is not a QoS data MPDU but a BAR. Then, AP sends a new dual-purpose frame called 'BA to uplink station - BAR to downlink station' (BAU-BARD), which includes

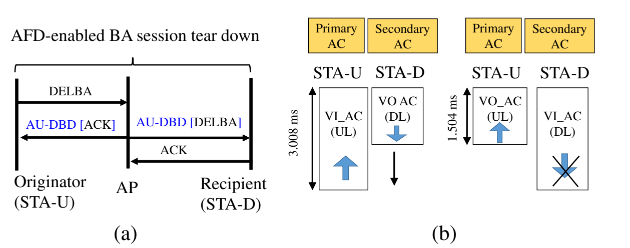


Fig. 6: (a) AFD-enabled BA session tear down, (b) possibility of having different ACs for both STA-U and STA-D.

the BA for STA-U and the BAR for STA-D. When STA-D replies with the BA, the TXOP ends. For the first TXOP (no BAR/BA exchange), there are two extra frames compared to the HD case (RTS/CTS or Data/ACK exchange between the AP and STA-D). For the second TXOP, in addition to the two aforementioned frames, there exists one more additional frame (BA from STA-D to the AP).

C. AFD-enabled BA Session Tear Down

To tear down the AFD-enabled BA session, the originator STA-U sends a DELBA to the AP, as shown in Figure 6(a). If the AP does not have more traffic to STA-D, it sends a new frame called 'ACK to uplink station - DELBA to downlink station' (AU-DBD). This frame has dual purpose, where it ACKs the DELBA frame of STA-U and includes a DELBA frame to STA-D. Finally, STA-D replies by an ACK whereby AFD-enabled BA session ends.

D. Special Cases in AFD-enabled BA Protocol

The difference in AC types, traffic loads, and ACK policies between AFD pair stations cast many complications on the design of the AFD-enabled BA protocol. We visit these differences and discuss them as follows:

1) Different ACs: Having STA-U and STA-D of different AC types leads to a problem because the two AC types will have unequal TXOP duration. We let the AC of STA-U be the 'primary AC', and that of STA-D be the 'secondary AC'. If the primary AC_VI (i.e., maximum TXOP duration is 3.008 ms), then the AP can select STA-D with AC_VO if no other downlink station with AC_VI exists, as shown in Figure 6(b). The AP treats the VO TXOP as AC_VI TXOP since the medium has been reserved by the STA-U for the longer TXOP duration. Hence, all network allocation vectors (NAVs) of the neighboring stations have been set to the 3.008 ms and therefore the AP can inform STA-D that its 1.504 ms TXOP (AC_VO) is now extended to 3.008 ms. However, the opposite is not true. If the AP cannot find a station with AC_VO (similar to STA-U's AC type), it proceeds with STA-U in an HD mode. It could also be possible to send a secondary AC of AC_VO and/or AC_VI with a primary AC_BE or AC_BK, given the TXOP of the primary AC is sufficiently longer than TXOP of the secondary AC.

2) Different Traffic Loads: When STA-U and STA-D have the same traffic loads, then BA sessions for both of them ends at the same time. However, in practice the two stations could have different traffic loads. Thus, two scenarios may occur. In the first scenario, the number of STA-U's data frames intended for the AP is larger than these of the AP intended for STA-D. In this case, the STA-U needs more TXOPs to finish its data transmission (see Figure 7). Thus, the AP could tear down the AFD-enabled BA session with STA-D using traditional DELBA/ACK method when no more traffic exists for STA-D. The AP continues the rest of the BA session with the STA-U using the traditional HD TXOPs or could invite a new downlink station. In the second scenario, STA-D could have more data frames to be served than STA-U. Therefor, when STA-U request to tear down the AFD-enabled BA session with AP, the AP continues the tear down the BA session with STA-U only using the traditional DELBA/ACK frame exchange. The AP may continue the rest of the AFD-enabled BA session in HD mode or poll another uplink station.

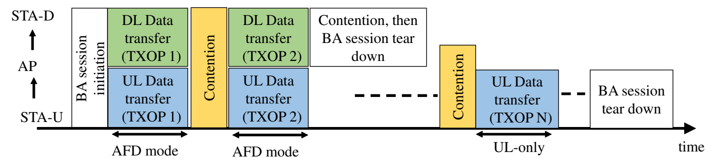


Fig. 7: AFD-pair (STA-U and STA-D) have different traffic loads.

3) Other ACK Policies: We discuss how different ACK policies, including 'No ACK' and 'Normal ACK' policies, can be incorporated in AFD-enabled BA sessions. In 'No ACK' policy, data transfer for the AFD mode follows to what we illustrated in Figure 5. In 'Normal ACK' policy, the AP should acknowledge STA-U and STA-D acknowledge AP. This can be enabled by following the communication modes presented in Figure 3, where the control phase can be used for acknowledgement and synchronization for AP as well as UL and DL stations. Our AFRA adaptation scheme considers 'Normal ACK' policy as we discuss in the next section.

VI. Asymmetric FD-Modes and Rate Adaptation (AFRA) Scheme

AFD-QoS framework aims at improving the AP cognition about interference and adaptability during the TXOP period through AFRA scheme. AFRA scheme starts once the AFD pair has been selected and after the BA session has been established and TXOP period started. It provides the AP with cognition about channel fading dynamics as well as inter-node and self-interference. AFRA scheme characterizes these channel dynamics and interference using a customized finite-state Markov channel (FSMC) model.

A. Finite-State Markov Chain-based SINR Model

We customize the FSMC model in [31] to characterize the instantaneous variation in SINR overtime (due to channel's shadowing and fading). Our customized FSMC SINR model accounts for SINR variations caused by inter-node and self-interference. Let us first construct the traditional FSMC SINR model. Let γ and $\bar{\gamma}$ be the instantaneous and mean values of SINR. Let ν_i be the probability that the instantaneous SINR γ takes a value in the interval $[g_i, g_{i+1})$, where g_i and g_{i+1} are two arbitrary SINR thresholds. By assuming a Rayleigh distribution for channel fading, then ν_i can be computed as $\nu_i = \Pr\left(g_i \leq \gamma < g_{i+1}\right) = \int_{g_i}^{g_{i+1}} p(\gamma) d\gamma$ where $p(\gamma) = \frac{\gamma}{\bar{\gamma}^2} e^{-\gamma^2/2\bar{\gamma}^2}$. The *level-crossing rate* L_i defines how often SINR passes a certain threshold g_i, and this rate depends on user's mobility, expressed in Doppler frequency f_d, as follows: $L_i = \sqrt{\frac{2\pi g_i}{\bar{\gamma}}} f_d e^{-g_i/\bar{\gamma}}$ [32]. We shortly use ν_i and L_i to derive transition probabilities in the customized FSMC SINR model.

1) States of FSMC SINR Model: We define the states in the FSMC model based on the values that the instantaneous SINR γ could take while considering its supported transmission rates, i.e., modulation and coding scheme (MCS) indices. We let the interval $[g_i, g_{i+1})$ represent the ith state of the FSMC model, where g_i and g_{i+1} boundaries are specified according to the ith and $(i+1)$th MCS indices. The IEEE 802.11ac standard specifies the *error-vector magnitude* (EVM) thresholds $\mathcal{E} = \{e_1, \cdots, e_M\}$ for all its supported M MCSs, $\mathcal{K} = \{1, \cdots, M\}$ [6], and these thresholds can be translated into SINR thresholds using the approximate relation $g_i \approx 1/e_i^2$ [33]. The EVM threshold specifies the maximum error in constellation points for each MCS index. Let the set $\mathcal{M}$ contain all states of the FSMC model $\mathcal{M} = \{1, \cdots, M_s\}$. The FSMC model has $M_s = M + 1$ possible states, where each state corresponds to the highest MCS index that could be supported, and the first state corresponds to the case when no MCS could be supported.

2) Outage-Indicator Function: An outage happens when the AP selects the MCS index whose SINR threshold is larger than the instantaneous value of SINR, i.e., $\gamma < g_i$. A transmitter should avoid using an MCS when the outage-indicator function is one. Let $\rho^{(i,k)}$ be the outage-indicator function when the transmitter chooses the kth MCS index while the SINR is at the ith state for any $k \in \mathcal{K}$ and $i \in \mathcal{M}$, then:

$$\rho^{(i,k)} = \begin{cases} 1 \quad , & i < k \\ 0 \quad , & i \geq k. \end{cases} \tag{3}$$

3) Transition Probabilities of FSMC SINR Model: The transition between the M_s states happens due to channel fading and/or self-interference and inter-node interference. To construct the transition probabilities between the M_s states, we follow the same line as in [32]. Let T_i be the average time for which SINR remains within state i, a.k.a, *average-fade duration*, then the nonzero transition probabilities are expressed as:

$$\tilde{q}_{i,i-1} = \frac{L_i T_i}{\nu_i}, \quad \tilde{q}_{i,i+1} = \frac{L_{i+1} T_i}{\nu_i}, \quad \tilde{q}_{i,i} = 1 - \tilde{q}_{i,i+1} - \tilde{q}_{i,i-1}. \tag{4}$$

These transition probabilities account only for fading dynamics. Switching between the different AFD communication modes also changes the SINRs at UL and DL receivers, and thus modulates these transition probabilities. We redefine these transition probabilities to account for such changes as follows. Let Δ_p and Δ_d be the respective change in the states of the FSMC SINR model due to the switching from communication mode a to a', then:

$$\Delta_i = \begin{cases} -\delta_i \text{ , } a \in \{\text{UL-only, DL-only}\}, a' = \text{AFD} \\ \delta_i \quad \text{ , } a = \text{AFD}, a' \in \{\text{UL-only, DL-only}\} \\ 0 \quad \text{ , otherwise,} \end{cases} \tag{5}$$

where $i \in \{p, d\}$, δ_p and δ_d represent the transitions in the states of SINR due to the self- and inter-node interference, respectively. It should be noted that by switching from either UL-only or DL-only mode to the AFD mode we trigger new transitions between the states of the FSMC model. These new transitions happen due to the reduction in the SINRs caused by the inter-node interference and self-interference. However, switching the communication mode from the AFD mode to either UL-only or DL-only mode triggers transitions in the opposite direction, and this justifies the negative and positive signs in (5). The nonzero transition probabilities of our customized FSMC model while the self-interference and inter-node interference are included become:

$$q_{i,i+\Delta_c-1}^{(a,a')} = \frac{L_{i+\Delta_c} T}{\nu_{i+\Delta_c}}, \qquad q_{i,i+\Delta_c+1}^{(a,a')} = \frac{L_{i+\Delta_c+1} T}{\nu_{i+\Delta_c}},$$
$$q_{i,i+\Delta_c}^{(a,a')} = 1 - q_{i,i+\Delta_c+1}^{(a,a')} - q_{i,i+\Delta_c-1}^{(a,a')}, \tag{6}$$

When $\Delta_c = 0$, these probabilities reduce to those in (4). To account for the joint variations in SINRs at both AP and DL receivers, we extend our customized FSMC model into a two-dimensional one. Let (i, m) be the joint state for which SINRs at the AP and DL receivers are at the ith and mth states of the one dimensional FSMC model in 6, respectively. The transition probability from state (i, m) to state (j, n) is written as:

$$p_{(i,m),(j,n)}^{(a,a')} = q_{i,j}^{(a,a')} q_{m,n}^{(a,a')}. \tag{7}$$

B. AFRA POMDP-based Design

For the AP to adapt the communication modes and their associated transmission rates during the AFD-enabled TXOP period, it requires knowledge about the channel gains and SINRs for UL and DL connections. Although this knowledge could be hidden, the AP could infer it partially by decoding UL frames sent by STA-U and monitoring the ACKs sent by STA-D. Because the AP can only obtain partial knowledge about SINRs and the SINRs vary in a Markov-based fashion, AFRA utilizes the POMDP to help the AP decide the optimal communication modes and their associated transmission rates during the TXOP period. Next, we introduce the main POMDP elements, including state, action, and observation spaces. We also introduce the reward and value function formulations, and explain how to obtain the optimal policy.

1) POMDP Elements: We consider a discrete *time horizon* $\mathcal{T} = \{1, \cdots, L\}$ that corresponds to the TXOP period with L time slots. The *action space* $\mathcal{A}$ includes the three possible communication modes: AFD, UL-only, and DL-only modes, associated with their transmission rates. When the SINR becomes too low for both UL and DL connections, it is better to quit the TXOP earlier, hence, we add another action BO for the AP to backoff earlier. We define the action space as $\mathcal{A} = \{\text{AFD}_{k_u,k_d}, \text{UL}_{k_u}, \text{DL}_{k_d}, \text{BO} : \forall k_u, k_d \in \mathcal{K}\}$, where k_u and k_d are the MCS indexes assigned for UL and DL connections, respectively. Let $a_t \in \mathcal{A}$ be the action taken at time slot t for $t \in \mathcal{T}$.

We define the *state space* $\mathcal{S} := \mathcal{M} \times \mathcal{M}$ to include all possible SINR values of UL and DL connections quantized according to the two-dimensional FSMC model presented in Section VI-A. The joint state $(i, m) \in \mathcal{S}$ indicates that the SINRs at AP and STA-D receivers are at the ith state and the mth state, respectively. The transition probabilities $p_{s',s}^{(a_{t-1},a_t)}$ between any two arbitrary states $s, s' \in \mathcal{S}$ and any two arbitrary actions $a_{t-1}, a_t \in \mathcal{A}$, are as defined in (7).

The *observation space* $\mathcal{O}$ consists of all possible outcomes that the AP would receive after taking an action. Each action $a \in \mathcal{A}$ has its own specific set of observations. For instance, when the AP takes an action that involves the AFD mode, the AP either decodes (D) or fails (F) to decode the UL frame, and either receives an ACK or NACK from STA-D for its transmitted DL frame. The BO action has no observations because the AP terminates the TXOP period. These observations constitute the observation space defined as $\mathcal{O} = \{(\mathrm{D}, \mathrm{ACK}), (\mathrm{D}, \mathrm{NACK}), (\mathrm{F}, \mathrm{ACK}), (\mathrm{F}, \mathrm{NACK}), (\mathrm{F}), (\mathrm{D}), (\mathrm{ACK}), (\mathrm{NACK})\}$. We define $r_{s,o_t}^{(a_t)}$ to be the probability of receiving an observation o_t when the AP takes an action a_t while the SINRs are at the sth joint state. These probabilities for various actions/observations are defined as follow:

$$r_{(i,m),o_t}^{\mathrm{AFD}\,k_u,k_d} = \begin{cases} (1-\rho_u^{(i,k_u)})\,(1-\rho_d^{(m,k_d)}) & \text{, for } o_t = (\mathrm{D}, \mathrm{ACK}) \\ (1-\rho_u^{(i,k_u)})\,\rho_d^{(m,k_d)} & \text{, for } o_t = (\mathrm{D}, \mathrm{NACK}) \\ \rho_u^{(i,k_u)}\,(1-\rho_d^{(m,k_d)}) & \text{, for } o_t = (\mathrm{F}, \mathrm{ACK}) \\ \rho_u^{(i,k_u)}\,\rho_d^{(m,k_d)} & \text{, for } o_t = (\mathrm{F}, \mathrm{NACK}) \end{cases} \tag{8}$$

$$r_{(j,n),o_t}^{\mathrm{UL}\,k_u} = \begin{cases} 1-\rho_u^{(j,k_u)} & \text{, for } o_t = (\mathrm{D}) \\ \rho_u^{(j,k_u)} & \text{, for } o_t = (\mathrm{F}), \end{cases} \tag{9}$$

$$r_{(k,\ell),o_t}^{\mathrm{DL}\,k_d} = \begin{cases} 1-\rho_d^{(\ell,k_d)} & \text{, for } o_t = (\mathrm{ACK}) \\ \rho_d^{(\ell,k_d)} & \text{, for } o_t = (\mathrm{NACK}), \end{cases} \tag{10}$$

$$r_{(i,m),o_t}^{\mathrm{BO}} = \frac{1}{|\mathcal{O}|}, \forall\,(i,m) \in \mathcal{S}, \forall o_t \in \mathcal{O}, \tag{11}$$

where $\rho_u^{(i,k_u)}$ and $\rho_d^{(m,k_d)}$ are the outage-indicator functions for uplink and downlink communications defined in (3).

AP cannot monitor the true values of SINRs, and thus it assigns beliefs for them. These beliefs are simply the probabilities of being in one of the SINR states. Let Ω be the probability space $\Omega = \{\omega : \omega \in [0,1]\}$. We define the *state-belief space* as $\mathcal{B} := \mathcal{S} \times \Omega$. At the end of the tth time slot, we assign each state in $\mathcal{S}$ a belief value $\pi_{s,t} \in \Omega$. We let $\bar{\pi}_t = \langle \pi_{1,t}, \cdots, \pi_{|\mathcal{S}|,t} \rangle$ be the *belief vector* at the end of the tth time slot. After taking an action $a_t \in \mathcal{A}$ at the start of the tth time slot and getting an observation $o_t \in \mathcal{O}$, the AP updates its belief about each state using the following Bayes rule:

$$\pi_{s,t} = \frac{\sum_{s' \in \mathcal{S}} \pi_{s',t-1} p_{s',s}^{(a_{t-1},a_t)} r_{s,o_t}^{(a_t)}}{\sum_{s \in \mathcal{S}} \sum_{s' \in \mathcal{S}} \pi_{s',t-1} p_{s',s}^{(a_{t-1},a_t)} r_{s,o_t}^{(a_t)}}. \tag{12}$$

The belief vector is a sufficient statistic that helps AP trace the state of the environment without need to keep record for all previous actions and their resultant observations [34].

2) Immediate Reward Formulations: We define the reward that the AP receives at the end of each time slot to be the amount of data communicated successfully minus a cost defined by the associated power consumption. Wi-Fi frames are OFDM modulated and the amount of data that can be accommodated in one time slot is $R_k = N_o N_c b_k c_k$, where N_o is the number of OFDM symbols that fit in one time slot, N_c is the number of OFDM subcarriers, b_k is the modulation order, and c_k is the coding rate c_k of the kth MCS. Let $W_{o_t}^{(a_t)}$ be the reward that the AP receives after taking an action a_t and receiving an observation o_t:

$$W_{o_t}^{\mathrm{AFD}\,k_u,k_d} = \begin{cases} R_{k_u} + R_{k_d} - \eta(P_\mathrm{a} + P_\mathrm{u}) & \text{, for } o_t = (\mathrm{D}, \mathrm{ACK}) \\ R_{k_u} - \eta(P_\mathrm{a} + P_\mathrm{u}) & \text{, for } o_t = (\mathrm{D}, \mathrm{NACK}) \\ R_{k_d} - \eta(P_\mathrm{a} + P_\mathrm{u}) & \text{, for } o_t = (\mathrm{F}, \mathrm{ACK}) \\ -\eta(P_\mathrm{a} + P_\mathrm{u}) & \text{, for } o_t = (\mathrm{F}, \mathrm{NACK}), \end{cases} \tag{13}$$

$$W_{o_t}^{\mathrm{UL}\,k_u} = \begin{cases} R_{k_u} - \eta P_\mathrm{u} & \text{, for } o_t = (\mathrm{D}) \\ -\eta P_\mathrm{u} & \text{, for } o_t = (\mathrm{F}), \end{cases} \tag{14}$$

$$W_{o_t}^{\mathrm{DL}\,k_d} = \begin{cases} R_{k_d} - \eta P_\mathrm{a} & \text{, for } o_t = (\mathrm{ACK}) \\ -\eta P_\mathrm{a} & \text{, for } o_t = (\mathrm{NACK}), \end{cases} \tag{15}$$

$$W_{o_t}^{\mathrm{BO}} = \eta(P_\mathrm{a} + P_\mathrm{u}), \text{ for } \forall o_t \in \mathcal{O}, \tag{16}$$

where η is a scaling coefficient that we use to match data and power terms. We include the power as a cost to penalize the AP when communication becomes unsuccessful due to outages. When the AP takes an action at the start of the tth time slot it does not know whether this action would result in a successful transmission or not. Therefore, we define the *expected immediate reward* as the average reward over all possible outcomes and beliefs. Let $D^{(a_t)}$ be the expected immediate reward of the a_t action:

$$D^{(a_t)} = \mathrm{E}[W_{o_t}^{(a_t)}] = \sum_{o_t \in \mathcal{O}} \sum_{s \in \mathcal{S}} \sum_{s' \in \mathcal{S}} \pi_{s',t-1} p_{s',s}^{(a_{t-1},a_t)} r_{s,o_t}^{(a_t)} W_{o_t}^{(a_t)}. \tag{17}$$

3) Value Function Formulation: Our goal is to maximize the accumulated reward that the AP receives along all time slots during the TXOP period. The actions that the AP takes at the start of the TXOP affects its subsequent belief updates, impacting the actions to be selected subsequently. Therefore, it is important to pick the most suitable action at the start of the TXOP period. To account for this issue, we have to consider both the expected immediate reward and the *expected long-term reward*. We define the *value function* to combine the two rewards and optimize them during the TXOP. The optimal value function at the tth time slot can be written as in the following recursive relation:

$$V_t(\bar{\pi}_{t-1}) = \max_{a_t \in \mathcal{A}} \Big[D^{(a_t)} + \kappa \sum_{o_t \in \mathcal{O}} \sum_{s \in \mathcal{S}} \sum_{s' \in \mathcal{S}} \pi_{s,t-1} p_{s,s'}^{(a_{t-1},a_t)} r_{s',o_t}^{(a_t)} V_{t+1}(\bar{\pi}_t) \Big], \tag{18}$$

where $V_{t+1}(\bar{\pi}_t)$ is the value function at the $(t+1)$th time slot, and κ is known as the discount factor. The discount factor characterizes how much future rewards are important. The optimal policy maps the beliefs $\bar{\pi}_t$ about the SINRs to the optimal actions that maximizes the value function in (18) (i.e., $\mu_t^* : \mathcal{B} \mapsto \mathcal{A}$).

4) Solving POMDP: To determine the optimal policy μ^*, we need to solve for the sequence of optimal actions that optimizes (18) over the TXOP period. This optimization can be solved through dynamic programming. However, the large dimensionality of the state-belief space makes solving such a problem daunting and obtaining the optimal policy may

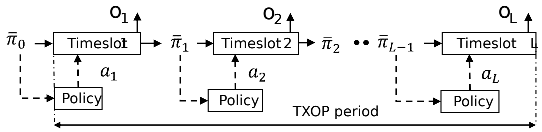


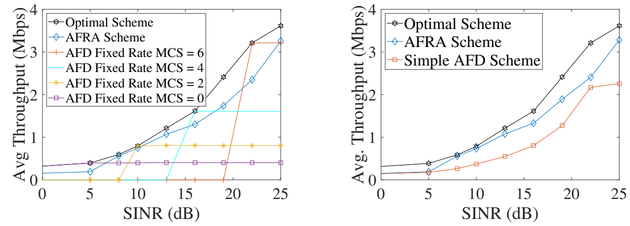
Fig. 8: POMDP operation during the TXOP period of L time slots.

require days. Many algorithms were proposed in literature to solve such a program in exact form, while others followed approximate and heuristic approaches. A comparison between all of these approaches and their relative computational complexities can be found in [35]. We solved our problem using an approximate point-based POMDP solver called SARSOP [36]. SARSOP improves the computational efficiency for solving (18) by sampling a few initial values of the Belief space $\mathcal{B}$, and checking for the optimal solutions reachable from these initials. Point-based algorithms have a polynomial time complexity, and are efficient when the problem have tens of states. We solve for the optimal policy μ^* offline. The optimal policy can be saved as a lookup table in the AP memory. The process of computing the policy takes place offline. Once the AP occupies the channel and starts the TXOP, it initiates beliefs $\bar{\pi}_0$ about SINRs at UL and DL receivers; see Figure 8. AP consults with the policy for an action a_1 to be taken, and at the end of the first time slot it receives observation O_1. AP uses this observation to update its beliefs $\bar{\pi}_1$, and consults a gain with the policy and takes a new action a_2 for the next time slot. The same process repeats again until the end of TXOP. In [1] (Section IV-B), we provide an arbitrary example of AFRA scheme operation in AFD-enabled TXOP.

VII. Performance Evaluation

A. Simulation Setup

We consider a Wi-Fi system that consists of an FD-enabled AP and a set of HD STAs, contending using the EDCA channel access scheme on UNII Channel 100 of 20 MHz bandwidth at 5.5 GHz. We consider a channel model with path-loss exponent of 4 and Rayleigh fading with mean value of 10 dB. We focus on evaluating the performance while involving the impact of EDCA contention, and report the average sum-throughput of UL and DL links. To simulate multiple SINRs, we fix the distance between UL and DL stations pair and vary their locations with respect to AP, and repeat the simulation for 100 times. On each run, we evaluate the minimum average fade duration, and compute the number of frames (i.e., the number of time slots) that can be exchanged over an AFD-enabled TXOP period of 3 milliseconds. We set the residual self-interference to be 5 dB above the AP noise floor, unless otherwise specified. The discount factor in (18) is set to $\kappa = 0.95$. We consider eight MCS indices $k \in \{0, \cdots, 7\}$ with modulation index $b_k \in \{1, 1, 2, 2, 4, 4, 6, 6\}$ and coding rate $c_k \in \{0.5, 0.75, 0.5, 0.75, 0.5, 0.75, 0.666, 0.75\}$. The EVM thresholds for these MCSs are $\mathcal{V} \in \{-5, -8, -10, -13, -16, -19, -22, -25\}$ dB [6].



(a) (b)

Fig. 9: Average network throughput vs. SINR (number of Wi-Fi STAs = 6).

B. Evaluating AFRA Scheme Spectrum Efficiency

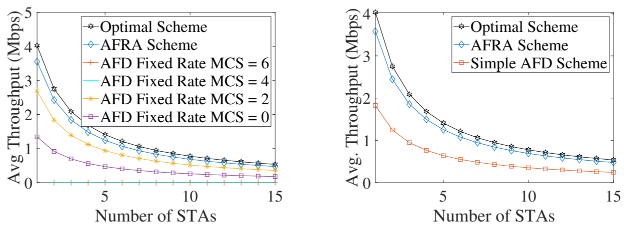
Theoretically, full-duplex communications have the potential to double the link throughput. However, in a practical network setup, achieving twice the throughout is extremely challenging, if not impossible, due to residual self-interference and interference generated by nearby transmissions. Therefore, it is not possible to quantify the gain of AFD network analytically. In an attempt to evaluate the gains provided by our framework, we compared the throughput achieved by our algorithms with other two AFD-based schemes. In the first scheme, the AP has complete knowledge of the interference levels at UL and DL receivers, and hence it can pick the best combination of transmission rate and communication mode (i.e., UL-only, DL-only, and AFD modes) that provides the highest sum-utilities of UL and DL links. We label this scheme as ‘Optimal scheme’ because the AP is capable of AFD and has full knowledge about network setting as well as interference sources, enabling it to take the optimal action. In the second scheme, called ‘Simple scheme’, the AP is AFD-enabled but it is agnostic about network setting and interference sources. AP attempts to maximize its sum-utility in an ad-hoc fashion by increasing (decreasing) transmission rate after successful (failed) transmissions. We decided to evaluate our framework against these two schemes because they represent two extreme cases in our model.

First, we compare the performance of AFRA scheme with the ‘AFD Fixed Rate’ scheme. In ‘AFD Fixed Rate’ scheme, AP always operates in AFD mode with fixed transmission rate. In Figure 9a, we plot the average sum-throughput of UL and DL links versus SINR at the AP receiver (we set the average SINRs for UL and DL links to be similar). ‘AFD Fixed Rate’ scheme outperforms our scheme only when SINR keeps constant, but fails to react to SINR changes. In contrast, our scheme adapts to these changes, and approaches the optimal performance.

We compare AFRA scheme against the ‘Simple’ scheme in Figure 9b. Our scheme outperforms the ‘Simple’ scheme due to the fact that AFRA is based on POMDP, providing awareness about the predicted channel changes that might happen in the future. The ‘Simple’ scheme adapts transmission rates opportunistically without considering how SINRs would change overtime, resulting in too conservative actions in some situations and too aggressive actions in others. We report the sum-throughput of the ‘Simple’ and AFRA schemes when

TABLE II: Avg. throughput normalized by the throughput of the 'Optimal' scheme

SINR (dB)	5	8	10	13	16	19	22	25
AFRA (%)	48	95	93	83	78	77	76	92
Simple (%)	47	43	46	45	42	54	67	60



(a) (b)

Fig. 10: Average network throughput vs. number of Wi-Fi STAs (SINR at uplink and downlink = 13 dB).

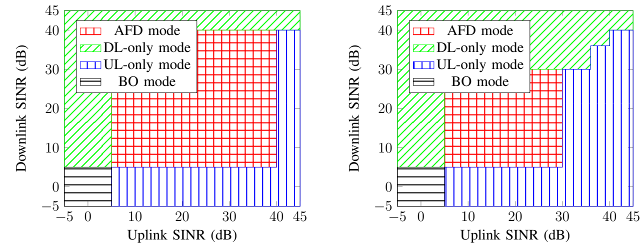
normalized to the 'Optimal' scheme in Table II. The AFRA scheme sometimes achieve throughput above 90% of the 'Optimal' scheme performance, while the 'Simple' scheme achieves at the best about 67% of it.

C. Evaluating the Impact of EDCA Contention on AFRA Scheme Performance

We also evaluate the impact of EDCA contention on AFRA scheme and compare it with other schemes, as shown in Figures 10a and 10b. We plot the average sum-throughput achieved by UL and DL links versus the number of contending STAs. Although increasing the number of contending stations reduces the network throughput achieved by all schemes, we notice that AFRA scheme maintains good performance when compared to the Simple and AFD Fixed Rate schemes.

D. Evaluating AFRA Scheme Policies as Function of Inter-node and Self-Interference

We investigate how the self-interference and inter-node interference affects AFRA adaptation policies. We evaluate the expected immediate rewards as in (17), and plot the optimal communication mode regions versus SINRs at UL and DL receivers, as shown in Figures 11a and 11b. In Figure 11a, we set the self-interference and inter-node interference to 2 dB above noise floor, and investigate the resultant policy, while in Figure 11b we increase the self-interference and inter-node interference to 8 dB above noise floor. We conclude the following key findings. First, the AFD mode is only limited to certain region because the self-interference and inter-node interference lowers the maximum SINRs that can be achieved. For example in Figure 11a, the maximum SINRs in UL and DL connections with AFD mode are 40 dB, however, if the AP switches to DL-only or UL-only, then higher SINR values could be achieved, and thus these modes becomes more preferred. This shows that AFRA policies are aware of the self-interference and inter-node interference present in the network. Second, we notice that the policy shrinks the region of the AFD mode when the self-interference and inter-node



(a) (b)

Fig. 11: Expected immediate reward policies vs. SINRs at UL/DL receivers, with self-interference & inter-node interference $(2, 2)$ dB in (a) and $(8, 8)$ dB in (b) above receiver noise floor.

interference increase (see the AFD mode region in Figure 11b and compare it with that in Figure 11a). This increase in inter-node interference and self-interference reduces the efficiency of the AFD mode, because they limit the possibility of reaching high SINR states, and thus the policy limits the applicability of this mode.

VIII. Conclusions

In this paper, we introduced AFD-QoS, a cognitive and intelligent framework for supporting QoS applications in AFD-enabled WLANs. Our framework consists of three components for selecting AFD pairs to be involved in AFD communications, AFD-enabled block acknowledgement (BA) session initiation and termination protocols, and a cognitive communication mode and transmission rate adaptation scheme. We explained these three components in details and illustrated their applicability in Wi-Fi systems. We conducted various simulations to study how our adaptation schemes perform and compared its performance with other traditional schemes. AFD-QoS has the potential of achieving 90% throughput of the optimal performance in AFD-enabled WLANs under certain conditions.

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