Throughput-fairness Tradeoff Evaluation for Next-generation WLANs with Adaptive Clear Channel Assessment

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Abstract—In order to meet the exponential increase in wireless demand, new technologies are being considered for next-generation Wi-Fi systems (e.g., IEEE 802.11ax). Among these technologies is the adaptation of *clear channel assessment* (CCA) thresholds for high-efficiency (HE) stations (STAs) according to the beacon's received signal strength indicator (RSSI). The motivation behind this approach is to enhance the network throughput by improving the spatial reuse (i.e., allowing simultaneous transmissions from nearby STAs). There exists an inherent tradeoff between increasing the network throughput, via adapting the CCA thresholds for HE STAs, and maintaining fairness between legacy and HE STAs. In this paper, we provide a theoretical framework to evaluate the aforementioned tradeoff. We also propose a *centralized fairness mechanism* (CFM), in which STAs switch between an adaptive phase (CCA adaptation is allowed) and a fixed phase (legacy and HE STAs use the same CCA threshold). We formulate an optimization problem with the objective of determining the optimal switching strategy that maximizes the network throughput while maintaining a lower bound on per-STA throughput. Finally, we validate the proposed mechanism using simulations.

Keywords—*IEEE 802.11ax, Clear channel assessment threshold adaptation, Network-throughput/fairness tradeoff.*

I. INTRODUCTION

The exponential increase in the number of mobile users and devices (e.g., smart phones, tablets, etc.) combined with emerging technologies and bandwidth-hungry applications (e.g., immersive multimedia), create a big challenge for the design of next-generation WLANs. It is forecasted that the wireless demand in 2020 will be 1000x the demand in 2010 (a.k.a., the 1000x challenge). Hence, new technologies and designs are needed to enhance the performance of wireless systems, including WLANs.

Next-generation WLANs (e.g., IEEE 802.11ax) aim to increase the network throughput, especially in dense environments. To achieve this objective, IEEE 802.11ax considers multiple technologies, including OFDMA and uplink (UL) multi-user MIMO. Another technique, currently under consideration, is adapting the clear channel assessment (CCA) thresholds for high-efficiency (HE) stations (STAs) according to different parameters (e.g., beacons' received signal strength indicator (RSSI)). CCA is executed by STAs or access points (APs) to determine whether the medium is free or busy before
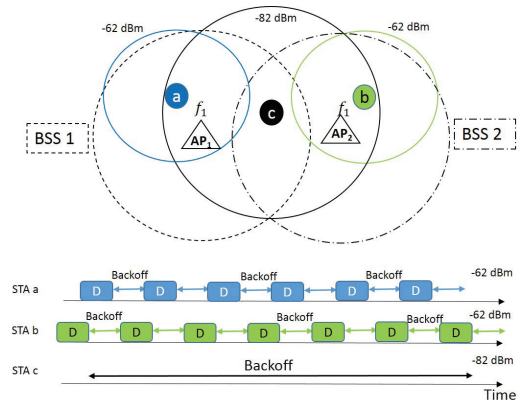
Fig. 1: Unfairness example for WLANs with adaptive CCA thresholds.

any transmission attempt. This is done by comparing the sensing outcome (usually the measured energy on a certain channel) with the CCA threshold. The potential enhancement in network throughput, under CCA threshold adaptation, results from the fact that STAs near to AP (or STAs with high channel gain) could have much higher throughput compared to other STAs. Increasing CCA thresholds for these STAs could increase their probabilities of using the spectrum and enable multiple concurrent transmissions, which eventually leads to higher network throughput.

We use the term 'legacy STA' to refer to a Wi-Fi device that implements either the 802.11ac standard or an earlier version. On the other hand, an 'HE STA' is a device that implements 802.11ax standards. While HE STAs are capable of adapting their CCA thresholds, legacy STAs use a fixed (minimum) CCA threshold value, typically set to -82 dBm.

Although adapting the CCA thresholds for some HE STAs can enhance the network throughput dramatically, legacy STAs (and possibly some other HE STAs) could suffer from unfairness and high blocking rates (i.e., not being able to access the medium). This motivates us to study the tradeoff between network throughput and fairness. To illustrate the unfairness problem in adapting the CCA thresholds, consider two overlapped basic service sets (OBSSs), as shown in Figure 1, where BSS i consists of AP_i and several Wi-Fi STAs, $i = 1, 2$. STAs a and b are communicating with AP_1 and AP_2, respectively, on channel f_1. After the association process, assume that STAs a and b adjust their CCA thresholds to -62 dBm because of their high RSSI. Then, they execute the CSMA/CA protocol

BSS is a set of STAs which can communicate with each other either through the AP (infrastructure BSS) or directly (independent BSS)

to communicate. Consider another STA c, which belongs to BSS 1, uses the default CCA threshold value of -82 dBm. Note that STA c could be a legacy STA that cannot adapt its CCA threshold or an HE STA with low RSSI. Under this situation, STA c has a lower probability of using channel f_1, as STAs a and b will be using the same channel more aggressively because of their higher CCA threshold values (equivalently, less sensitivity to channel activity, indicated by smaller sensitivity circles in Figure 1). Although this scenario could result in a high overall network throughput, some STAs may be blocked from using the channel.

CCA threshold adaptation has been studied in the literature [1–8]. In [1] and [3], methods for CCA adaptation were proposed which depends on the sensing outcomes and packet error rate (PER), respectively. To improve the downlink throughput, the authors in [2] proposed that the AP identifies the interferers' types, estimates their duty cycles, and adapts the CCA threshold accordingly. In [8], the authors evaluated the idea of adapting the CCA threshold according to the beacon's RSSI and found a 20% enhancement in the aggregate throughput compared with legacy WLANs. The authors in [7] proposed a channel-dependent CCA threshold adaptation scheme, with the goal of balancing different use cases in wireless networks. Specifically, channels with higher CCA thresholds could benefit from the spatial reuse; however, channels with low CCA thresholds could be used by low-power and/or low-bandwidth STAs (to provide more protection as the deferring area will increase). Although most of the aforementioned approaches are proposed to enhance network throughput, fairness in adapting the CCA threshold was not adequately studied in the literature. In [9], the authors showed that CCA adaptation can be exploited by selfish nodes to obtain an unfair share of the spectrum. The authors proposed a novel approach to detect this misbehavior. To ensure fairness in 802.11 WLANs, the authors in [10] proposed a combined method of adapting CCA thresholds and transmission power control.

The contributions of this paper are as follows. We propose a centralized fairness mechanism (CFM) for next-generation WLANs, where the AP dynamically switches between an adaptive phase, in which CCA threshold adaptation is allowed for HE STAs, and a fixed phase, in which all HE and legacy STAs use the same CCA threshold. To enable this mechanism, we propose to include a bit in the beacon frame, which we refer to as CCA threshold adaptation indication (CTAI). The CTAI bit informs HE STAs when to switch between the two phases. We formulate an optimization problem with the objective of determining the optimal switching time between the two phases, that maximizes the network throughput subject to constraints on STAs' individual rates. Finally, we discuss a practical algorithm for implementing the CFM and evaluate its performance using simulations.

The rest of the paper is organized as follows. The system model is presented in Section II. The CFM is discussed in Section III. We evaluate the performance of the CFM and conclude the paper in Sections IV and V, respectively.

II. SYSTEM MODEL

We consider a BSS that consists of an AP and N Wi-Fi STAs. The AP can support both HE STAs and legacy
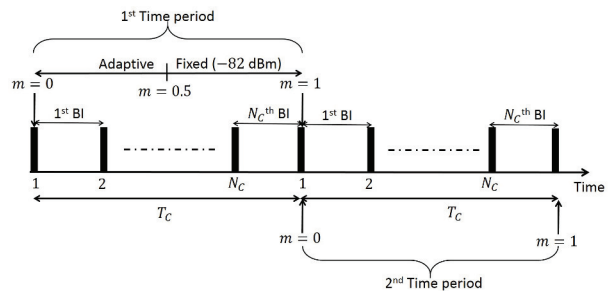
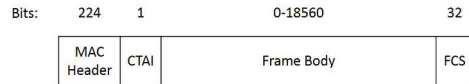Fig. 2: Illustration of time periods and beacon intervals (BIs).

Fig. 3: Management frame format (Beacon frame).

STAs. Specifically, the set of Wi-Fi STAs, $\mathcal{N} = \{1, 2, \ldots, N\}$, consists of N_L legacy STAs and N_H HE STAs. The AP updates the values of N_L and N_H in the association table after each association or disassociation process. Specifically, after exchanging the authentication/association frames between the AP and the STA, the AP saves the STA's association ID (AID) in the association table, along with the STA type (i.e., legacy or HE). To contend for the medium, STAs execute the traditional CSMA/CA before each transmission attempt. Let γ_j be the CCA threshold for STA $j, j = 1, 2, \ldots, N$. Note that $\gamma_j = \gamma_{\min} \stackrel{\text{def}}{=} -82$ dBm for $j = 1, 2, \ldots, N_L$, while $\gamma_{\min} \leq \gamma_j \leq \gamma_{\max}, j = 1, 2, \ldots, N_H$, where $\gamma_{\max}$ is the maximum allowed value for the CCA threshold.

Since our interest is to ensure fairness among legacy and HE STAs, we focus on UL transmissions from STAs to the AP. We assume that both legacy and HE STAs always have packets to send. The signal-to-interference-plus-noise ratio (SINR) at the AP for a signal from STA j can be expressed as $\text{SINR}_j = P |h_j|^2 / (\sigma^2 + I_j)$, where P is the fixed transmission power of Wi-Fi STAs, h_j is the channel gain between STA j and the AP, I_j is the interference signal at the AP for STA j transmission, and σ^2 is the noise power.

Define T_C to be a time period that consists of N_C beacons (see figure 2). A typical value for the beacon interval (BI) is 100 ms. Hence, if $N_C = 10$, for example, $T_C = 1$ sec. As explained in Section III, we propose that the AP uses the broadcasted beacons to inform the STAs about the fixed and adaptive CCA threshold periods. Define $0 \leq m \leq 1$ as the fraction of the time period T_C that is allocated to the adaptive phase. Figure 3 shows the general frame format for management frames (e.g., beacons, association/authentication frames, etc.). A management frame consists of the MAC header, frame body, and frame check sequence (FCS), which uses CRC to validate the integrity of the packet.

III. CENTRALIZED FAIRNESS MECHANISM (CFM)

In this section, we discuss the proposed CFM, which is applied by the AP to balance the tradeoff between network throughput maximization and ensuring fairness between different STAs' types. To achieve this objective, we propose to split time into two alternating phases. The first phase is the adaptation phase, where HE STAs are allowed to adapt their CCA thresholds according to the RSSI, or any other parameters. The second phase is the fixed CCA threshold

Performance metrics	IEEE 802.11ac	IEEE 802.11ax	11ax + CFM.
Network throughput	✓	✓✓✓	✓✓
Fairness	✓✓✓	✓	✓✓

TABLE I: IEEE 802.11ac vs. IEEE 802.11ax vs. CFM

phase, where all HE and legacy STAs use a fixed CCA threshold value (-82 dBm) to ensure fair spectrum share. There are a couple of issues that needed to be addressed. First, how the AP will inform associated STAs about the start and end of the adaptive and fixed phases? Second, for a time period T_C, what is the optimal time instant to switch from the first phase to the second phase in order to achieve the target tradeoff between network throughput and fairness?

A. CCA Threshold Adaptation Indication

To enable the AP to inform HE STAs about the durations of the adaptive and fixed phases, we propose to include a new field in the beacon frame body that determines whether CCA adaptation is allowed or not in the next BI. Define a CCA threshold adaptation indication (CTAI) field (1 bit) in the beacon frame body (see Figure 3) that informs the STAs about the CCA threshold adaptation status (CTAI = 1 means that the adaptive CCA threshold is enabled, while CTAI = 0 means that it is disabled).

Before the start of a time period T_C (see Figure 2), the AP determines the optimal percentage of T_C that will be allocated to the adaptive phase. Once, the AP determines this value, it includes it in the broadcasted beacons. For example, if $N_C = 10$ and the ratio of adaptive to fixed phases is $0.3 : 0.7$, then the AP will set the CTAI in the first 3 beacons to one, and sets it to zero in the remaining 7 beacons. Whenever an STA receives a beacon, it checks the CTAI bit to determine whether CCA threshold adaptation is allowed or not (in case of transmission).

Another potential approach for informing the STAs about the sharing ratio is to include it once at the first beacon in each time period T_C as STAs know that the adaptive phase is the first phase. Although, this approach may reduce the overhead, it may increase latency. Specifically, new STAs who join the BSS after the transmission of the first beacon (or STAs in sleep mode) will not be able to utilize the remaining time in T_C as they may not know whether it is allowed to adapt the CCA threshold or not. One solution to this problem is to let those STAs to act conservatively and use the minimum CCA threshold value for the rest of T_C.

B. Switching between Adaptive and Fixed Phases

In this section, we determine the optimal switching instant between the fixed and adaptive phases. Recall that $0 \leq m \leq 1$ is the fraction of T_C that is allocated to the adaptive phase (see Figure 2). At $m = 0$, no CCA threshold adaptation is allowed in time period T_C, however, at $m = 1$, STAs can adapt their CCA threshold for the whole T_C period. At $0 < m < 1$, CCA adaptation is allowed only for a duration of mT_C. Note that the proposed CFM converges to the 802.11ac systems at $m = 0$, (fair system but with low network throughput) and converges to 802.11ax systems at $m = 1$, (high network throughput but unfair system). Table I compares the performance metrics of 11ac, 11ax (in case CCA threshold adaptation is included in the standards), and 11ax with CFM. We formulate an optimization problem with the objective of finding the optimal value of m

that maximize the total network throughput of HE and legacy STAs subject to lower bound constraints on the throughput per STA. Formally:

$$
\begin{aligned}
\underset{m}{\text{maximize}} \quad & R_{\text{tot}} \\
\text{subject to} \quad & R_j^{(L)} \geq R_{th} \ \forall j = 1, 2, \ldots, N_L \\
& R_j^{(H)} \geq R_{th} \ \forall j = 1, 2, \ldots, N_H \\
& 0 \leq m \leq 1
\end{aligned}
\tag{1}
$$

where R_{tot} is the total network throughput, $R_j^{(L)}$ is the throughput for the jth legacy STA, $j = 1, 2, \ldots, N_L$, and $R_j^{(H)}$ is the throughput for the jth HE STA, $j = 1, 2, \ldots, N_H$. All the aforementioned parameters are averaged over the two phases of the T_C period. R_{th} is a lower bound threshold on the STA's throughput. The throughput for the jth legacy STA, $j = 1, 2, \ldots, N_L$, depends on the achieved throughput in both phases (i.e., adaptive and fixed phases), which in return depends on the value of m. Hence, $R_j^{(L)}$ can be formulated as follows:

$$
R_j^{(L)} = m R_j^{(\text{LA})} + (1 - m) R_j^{(\text{LF})}
\tag{2}
$$

where $R_j^{(\text{LA})}$ and $R_j^{(\text{LF})}$ are the jth legacy throughput at the adaptive and fixed phases, respectively. We assume that STAs' throughput remains the same during a given phase. As discussed above, an STA can only start transmitting if the CCA returns a free channel (i.e., received energy of the sensed channel is below a given threshold). Hence, the legacy STA's throughput can be formulated as follows:

$$
\begin{aligned}
R_j^{(L)} = & \, m \Pr.\left[D_j^{(\text{LA})} \leq \gamma_{\min} \right] \log \left(1 + \text{SINR}_j^{(\text{LA})} \right) \\
& + (1 - m) \Pr.\left[D_j^{(\text{LF})} \leq \gamma_{\min} \right] \log \left(1 + \text{SINR}_j^{(\text{LF})} \right)
\end{aligned}
\tag{3}
$$

where $D_j^{(\text{LA})}$ and $D_j^{(\text{LF})}$ are the decision metrics that results from sensing the spectrum in the adaptive and fixed phases, respectively. For energy detection, $D_j^{(\text{LA})}$ (or $D_j^{(\text{LF})}$) is the average energy in the received signal, which could be noise if no other STA is transmitting.

The time-average throughput for the jth HE STA, $j = 1, 2, \ldots, N_H$ can be formulated similarly as follows:

$$
\begin{aligned}
R_j^{(H)} = & \, m R_j^{(\text{HA})} + (1 - m) R_j^{(\text{HF})} \\
= & \, m \Pr.\left[D_j^{(\text{HA})} \leq \gamma_j \right] \log \left(1 + \text{SINR}_j^{(\text{HA})} \right) \\
& + (1 - m) \Pr.\left[D_j^{(\text{HF})} \leq \gamma_{\min} \right] \log \left(1 + \text{SINR}_j^{(\text{HF})} \right)
\end{aligned}
\tag{4}
$$

where $R_j^{(\text{HA})}$ and $R_j^{(\text{HF})}$ are the jth HE throughput at the adaptive and fixed phases, respectively. $D_j^{(\text{HA})}$ and $D_j^{(\text{HF})}$ are the decision metrics in the adaptive and fixed phases for the HE STA, respectively. Note that in the adaptive phase of the above equation, the HE STA uses a CCA threshold γ_j which could be higher than the minimum CCA threshold, $\gamma_{\min}$. The time-average total network throughput can be expressed as:

$$
R_{\text{tot}} = \sum_{j=1}^{N_L} R_j^{(L)} + \sum_{j=1}^{N_H} R_j^{(H)}.
\tag{5}
$$

In (1), we define a lower bound on each STA's throughput.

We define the threshold on the minimum achieved throughput per STA to be a portion of the total network throughput, which depends on the number of Legacy and HE STAs. Formally,

$$R_{th} = \frac{1}{\alpha_L N_L + \alpha_H N_H} R_{\text{tot}} \qquad (6)$$

where $\alpha_L \geq 1$ and $\alpha_H \geq 1$ are two adjustable parameters that determine how legacy and HE STAs will share the throughput. For example, if $N_L = N_H = 1$, then $\alpha_L = 1$ and $\alpha_H = 2$, means that the minimum throughput that has to be achieved for each STA is $1/3$ of the total throughput. From a practical point of view, it may be difficult for the AP to get real-time update for the instantaneous throughput value for each STA including the channel state information (CSI). Hence, we convert our optimization problem shown in (1) to the following:

$$\begin{aligned} \underset{m}{\text{maximize}} \quad & \bar{R}_{\text{tot}} = N_L R^{(L)} + N_H R^{(H)} \\ \text{subject to} \quad & R^{(L)} \geq \frac{\bar{R}_{\text{tot}}}{\alpha_L N_L + \alpha_H N_H} \\ & R^{(H)} \geq \frac{\bar{R}_{\text{tot}}}{\alpha_L N_L + \alpha_H N_H} \\ & 0 \leq m \leq 1 \end{aligned} \qquad (7)$$

where $R^{(L)}$ and $R^{(H)}$ are the expected throughput for legacy and HE STAs, respectively. For simplicity, we represent the average values for different parameters by dropping the STA's index. We assume that the AP collects periodically different statistics from both HE and legacy STAs (e.g., locations, channel gains, interference, data traffic) which enables it to estimate the average throughput for each STA type and for each phase. This information could be learned from the initial connectivity (authentication/association) and the communication between the AP and STAs (e.g., piggybacked with ACKs). Recall that, the AP knows the exact number of HE and legacy STAs as well as the type of each associated STA. In the following analysis, we assume that the variation in the SINR from the fixed to the adaptive phases is small compared to the variation in the probabilities of using the spectrum (i.e., probability of getting an idle/busy channel after executing spectrum sensing). The justification of our assumption is that adapting the CCA threshold for some HE STAs should affect the probability of spectrum access (i.e., spectrum sensing process) for neighbor STAs. This spectrum sensing process takes place before the actual data transmission according to the CSMA/CA protocol, hence the dominant effect will be on the spectrum access probability. Second, we assume that $N_H \geq N_L \neq 0$.

Lemma 1: $R^{(L)}$ is a linear decreasing function of m, while $R^{(H)}$ is a linear increasing function of m.

Proof: The expected throughput for legacy STAs can be expressed as follows:

$$R^{(L)} = m\left(R^{(\text{LA})} - R^{(\text{LF})}\right) + R^{(\text{LF})} \qquad (8)$$

As discussed above, the CCA threshold is fixed for both the adaptive and fixed phases for legacy STAs. Furthermore, the average received energy during spectrum sensing in the adaptive phase is higher than that of the fixed phase (i.e., $D^{(\text{LA})} > D^{(\text{LF})}$) because in the adaptive phase, HE STAs are allowed to increase their CCA thresholds which results in more concurrent transmissions and hence an increment in the energy of the sensed signals. Therefore, $\text{Pr.}\left[D^{(\text{LA})} \leq \gamma_{\min}\right] < \text{Pr.}\left[D^{(\text{LF})} \leq \gamma_{\min}\right]$. Hence, equation (8) has a negative slope (i.e., $\left(R^{(\text{LA})} - R^{(\text{LF})}\right) < 0$). This means that the spectrum access probability for the legacy STAs in the adaptive phase is lower than that of the fixed phase, which is intuitive.

Second, the average throughput for HE STAs can be expressed as follows:

$$R^{(H)} = m\left(R^{(\text{HA})} - R^{(\text{HF})}\right) + R^{(\text{HF})}. \qquad (9)$$

Since the CCA threshold for HE STAs in the adaptive phase is higher than that of the fixed phase (i.e., $\gamma > \gamma_{\min}$), then $\text{Pr.}\left[D^{(\text{HA})} \leq \gamma\right] > \text{Pr.}\left[D^{(\text{HF})} \leq \gamma_{\min}\right]$. Hence, equation (9) has a positive slope (i.e., $\left(R^{(\text{HA})} - R^{(\text{HF})}\right) > 0$). Note that, although $D^{(\text{HA})} > D^{(\text{HF})}$ (i.e., more potential interference in the adaptive phase compared to the fixed phase), $\gamma - \gamma_{\min} \gg D^{(\text{HA})} - D^{(\text{HF})}$, which means that the amount of increase in the CCA threshold when switching from the fixed to the adaptive phase is much larger than the induced interference between the two phases. This is an essential requirement in system design (i.e., the mapping from the RSSI to the CCA threshold) to get the benefit of CCA threshold adaptation. For example, $\gamma - \gamma_{\min}$ is in the range of 30 dB. $\square$

Note that Lemma 1 is intuitive. It simply says that legacy (HE) STAs' throughput in the fixed phase is higher (lower) than that of the adaptive phase because in the adaptive phase, only HE STAs are allowed to increase their CCA thresholds (and hence higher spectrum access probabilities) while legacy STAs are not. However, in the fixed phase, all STAs have the same spectrum access probabilities.

Lemma 2: $\bar{R}_{\text{tot}}$ is a linear increasing function of m.

Proof: Since the energy of the sensed signal is only phase-dependent (i.e., $D^{(\text{HA})} = D^{(\text{LA})}$ and $D^{(\text{HF})} = D^{(\text{LF})}$), $\gamma - \gamma_{\min} \gg D^{(\text{HA})} - D^{(\text{HF})}$, and since $N_H \geq N_L$. Therefore, the increment in the total throughput for HE STAs, while switching from the fixed to the adaptive phase, is higher than the decrement in the total throughput of legacy STAs (i.e., $N_H\left(R^{(HA)} - R^{(HF)}\right) > N_L\left(R^{(LF)} - R^{(LA)}\right)$). The interpretation of this lemma is as follows. First, the spatial reuse increases in the adaptive phase compared to the fixed phase is due to using higher CCA threshold for HE STAs and hence enabling multiple concurrent transmissions. Second, HE STAs are using the spectrum more frequent in the adaptive phase compared to legacy STAs, and hence boosting the network throughput compared to the fixed phase. Hence, R_{tot} is an increasing function of m (see (11)). $\square$

$$\begin{aligned} \bar{R}_{\text{tot}} = m &\left[N_L\left(R^{(LA)} - R^{(LF)}\right) + N_H\left(R^{(HA)} - R^{(HF)}\right)\right] \\ & + N_L R^{(LF)} + N_H R^{(HF)} \end{aligned} \qquad (11)$$

Theorem 1: The optimization problem in (7) is a linear programming problem, where the optimal switching point m^* can be expressed generally as in (10). The optimal strategy can be expressed as follows:

$$\text{Optimal strategy} = \begin{cases} m^* = 0 \, (.11ac) & \text{if } R_{th} \geq R^{(L)} \; \forall m \\ m^* = 1 \, (.11ax) & \text{if } R_{th} \leq R^{(L)} \; \forall m \\ m^* & \text{otherwise.} \end{cases}$$

$$m^* = \frac{(\alpha_L N_L + \alpha_H N_H) R^{(\text{LF})} - \left(N_L R^{(LF)} + N_H R^{(HF)}\right)}{N_L \left(R^{(LA)} - R^{(LF)}\right) + N_H \left(R^{(HA)} - R^{(HF)}\right) - (\alpha_L N_L + \alpha_H N_H)\left(R^{(LA)} - R^{(LF)}\right)} \tag{10}$$
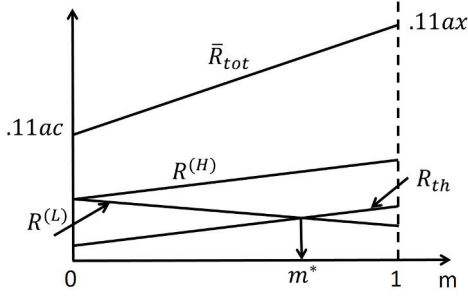

Fig. 4: Illustration of the feasible region of the optimization problem in (7).

Proof: The first step in the proof is to determine the feasible region, where all the constraints in (7) are satisfied. We notice that the first constraint (lower bound on the legacy STAs' throughput) is the bottle neck who directly affects the optimal value for m (see Figure 4). The reasons for this are as follows:

- At $m = 0$, $R^{(H)} = R^{(L)} = R^{(HF)} = R^{(LF)}$. This is because at $m = 0$, all HE and legacy STAs are using fixed CCA threshold and are sharing the spectrum fairly (i.e., system converges to 802.11ac). Hence, the expected throughput is the same.

- $R^{(L)}$ is a decreasing function of m and $R^{(H)}$ is an increasing function of m (lemma 1).

- $R_{th} = \bar{R}_{\text{tot}}/\left(\alpha_L N_L + \alpha_H N_H\right)$ is an increasing function of m (direct result from lemma 2).

- At $m = 0$, $R_{th} \leq R^{(L)}$. The justification of this inequality is as follows. Let $\alpha_L = \alpha_H = 1$, then at $m = 0$, $R_{th} = \frac{N_L R^{(LF)} + N_H R^{(HF)}}{\alpha_L N_L + \alpha_H N_H}$, which is equal to the average throughput per STA in the fixed phase. However, since at $m = 0$, $R^{(H)} = R^{(L)} = R^{(HF)} = R^{(LF)}$, then the equality of the aforementioned inequality holds. Since $\alpha_L \geq 1$ and $\alpha_H \geq 1$, then the inequality also holds.

Therefore, the optimal switching point (m^*) is the solution of $R^{(L)} = R_{th}$, which is represented by (10). Note that, if $R_{th} \geq R^{(L)} \forall m$, then the optimal strategy converges to the 802.11ac system (i.e., $m^* = 0$). On the other hand, if $R_{th} \leq R^{(L)} \forall m$ (which means that the minimum throughput is achieved for all m values), then the optimal strategy converges to the 802.11ax system (i.e., $m^* = 1$). If neither conditions are met, then the optimal strategy is $0 < m^* < 1$. □

C. CFM Algorithm

Algorithm 1 shows the main steps of the CFM. The AP starts first with the initialization process, where both legacy and HE STAs associate with the AP. The AP gathers and estimates multiple parameters about the associated STAs (e.g., traffic, RSSI, etc.). The time domain is then divided into periods, each of duration T_C. Before the beginning of each period, the AP checks its association table to determine N_L and N_H and estimate the average throughput for each STA type and for each phase. Using these parameters, the AP calculates the expected network throughput, and R_{th} as functions of m.

The AP then checks the relation between R_{th} and $R^{(L)}$ to determine the optimal switching point. If $R_{th} \geq R^{(L)} \forall m$, then the CFM converges to the 802.11ac system (i.e., $m^* = 0$) and the AP sets CTAI to zero in all the N_C beacons within the current T_C period. On the other hand, if the threshold value on the per STA throughput is satisfied for all m values, then the CFM converges to the 802.11ax system (i.e., $m^* = 1$) and the AP sets CTAI to one in all the N_C beacons within the current T_C period. If neither cases occur (i.e., CCA adaptation is permitted for only portion of T_C), the AP calculates the optimal switching point m^* using (10) and adjust the CTAI bit accordingly in the beacons. At the end of the T_C period, the AP updates different parameters and statistics for both HE and legacy STAs (e.g., traffic distribution, interference, etc.) and repeat the algorithm again starting at step 4.

Algorithm 1 CFM

1: Initialization:
2:     HE/legacy STAs associate with the AP
3:     AP gathers/estimates STAs' parameters
4: **for** each time period T_C **do**
5:     AP checks the association table & updates N_L and N_H
6:     AP estimates $R^{(L)}, R^{(H)}$ and $\bar{R}_{\text{tot}} \rightarrow$ calculates R_{th}
7:     **if** $R_{th} \geq R^{(L)} \ \forall m$ **then**
8:         $m^* = 0$
9:     **else if** $R_{th} \leq R^{(L)} \ \forall m$ **then**
10:        $m^* = 1$
11:     **else**
12:        AP calculates $\hat{m}$ in (10)
13:     **end if**
14:     $t = 0$
15:     **for** beacon $i, i = 1, 2, \ldots, N_C$ **do**
16:        **if** $t < m^* T_C$ **then**
17:            Set CTAI = 1 in the beacon frame body
18:        **else**
19:            Set CTAI = 0 in the beacon frame body
20:        **end if**
21:        $t = t + BI$
22:     **end for**
23:     AP updates STAs' parameters
24: **end for**

IV. PERFORMANCE EVALUATION

In this section, we evaluate the performance of our proposed CFM via simulations and compare it with 11ac and 11ax systems. Since our focus is to optimize the CCA adaptation process, we did not implement all the new technologies considered in the 11ax system. However, we only focus on the CCA adaptation feature. For the simulations, we use dynamic time-driven Wi-Fi system simulator. The simulator has fully 11ac compliant MAC features. Physical layer functions are abstracted using SINR-to-PER mapping tables. We consider two simulation scenarios. The first scenario is a single BSS, with the AP at coordinates $(0, 0, 1.5)$, one HE STA at $(-20, 0, 1.5)$, and one legacy STA at $(20, 0, 1.5)$. All distances are in meters. The second simulation scenario is four OBSSs, where each BSS consists of an AP, an HE STA, and a legacy STA, which are located 20 m apart from the AP similar to the first scenario (i.e., HE STA is on the left and the legacy is on the right). The x-coordinate of the four APs are $-85, 0, 85$, and 170 meters.
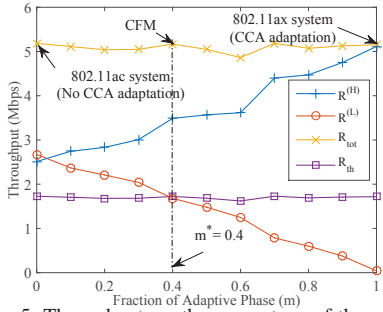
Fig. 5: Throughput vs. the percentage of the adaptive phase, m (One BSS, with $N_L = N_H = 1, \alpha_L = 1, \alpha_H = 2$).

Fig. 6: Throughput vs. the percentage of the adaptive phase, m (Four BSSs, with $N_L = N_H = 4, \alpha_L = 1, \alpha_H = 4$).

Fig. 7: Throughput vs. the percentage of the adaptive phase, m (Four BSSs, with $N_L = N_H = 4, \alpha_L = 1, \alpha_H = 4$).

For both scenarios, we assume that all STAs have full buffer traffic at the UL. For the wireless channels, we consider a pathloss propagation model (TGac Indoor) with exponent equal to 3.5. STAs follow traditional CSMA/CA protocol to access the spectrum and transmit unicast packets. The AP replies with an ACK for each successful transmission. The transmission power of the AP and STAs are 20 dBm. No walls are simulated in the system. We assume that no link adaption is used, hence STAs and AP are using BPSK modulation scheme with a coding rate of $1/2$. Finally, RTS/CTS is disabled.

Figure 5 shows the results for the first scenario (i.e., one BSS). At $m = 0$, both HE and legacy STAs are sharing the spectrum fairly because no CCA thresholds' adaptation is allowed. As m increases, the adaptation phase duration increases, which in return increase the HE STA's throughput and decreases that of the legacy STA. At $m = 1$ (most unfair point), the HE STA is using the medium very aggressively (fixed phase vanishes) to get the maximum throughput, while the legacy STA is getting very low throughput ($\approx$ zero). This is the situation that we need to fix using the CFM, where the optimal switching point, under this scenario, is $m^* = 0.4$. At this point, the AP maximizes the total network throughput while maintaining a lower bound on the per-STA throughput. The AP can then adjust the parameters α_L and α_H to balance the tradeoff between network throughput and fairness. Note that, the benefit of increasing the network throughput is not very clear in Figure 5 because we only consider one BSS, hence the benefit of the spatial reuse is not achieved. This benefit will be much clearer in the second simulation scenario.

Figures 6 and 7 shows the results for the second simulation scenario (four OBSSs case). Figure 6 shows the variation of the HE and legacy STAs' throughput with m. As it was shown in the analysis, the HE STAs' throughput increases with m, while the legacy STAs' throughput decreases with m. In contrast to the one BSS case, the total network throughput at $m = 1$ (i.e., 11ax system) is higher than that of the 11ac system due to the exploitation of the spatial reuse. Note that the network throughput should be higher if we enable link adaptation. Figure 7 shows the average HE and legacy throughput vs. m. According to the simulations, the optimal switching point is at $m^* = 0.62$, where the network throughput is maximized while satisfying the minimum throughput requirement for the STAs.

V. CONCLUSIONS

Motivated by the exponential increase in the number of mobile users and devices, and the potential adaptation of
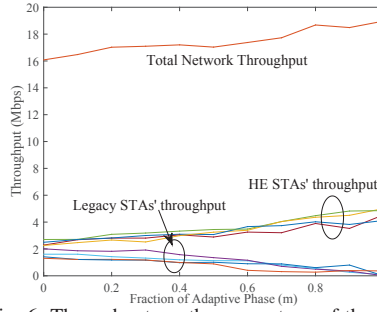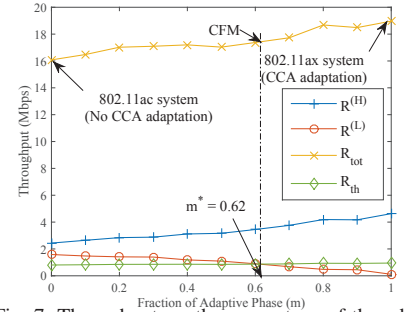
the CCA thresholds in next-generation Wi-Fi networks, we devise a centralized fairness mechanism to achieve the balance between network throughput (i.e., high spatial reuse) and fairness between Wi-Fi STAs. Specifically, we propose that the AP dynamically switches between an adaptive phase (CCA threshold adaptation is allowed for HE STAs), and a fixed CCA threshold phase. We determine the optimal switching point between the two phases that maximizes the network throughput subject to constraints on the per STA throughput. To enable this mechanism, we propose to include an indication bit (CTAI) in the beacons which informs HE STAs whether CCA threshold adaptation is allowed or not in the following beacon interval. One direction for future work is to design a distributed fairness mechanism. Furthermore, we are working on developing the proposed centralized mechanism to include different traffic models, more relaxed assumptions regarding the available information at the AP and the SINR models, etc.

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