Supporting Throughput Fairness in IEEE 802.11ac Dynamic Bandwidth Channel Access: A Hybrid Approach

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***Abstract*—Wi-Fi enabled hand-held devices have quickly occupied the consumer market as a result of the remarkable customer acceptance of IEEE 802.11 standard. In this regard, the demand of high throughput introduces high throughput standards such as IEEE 802.11ac. It supports *Dynamic Bandwidth Channel Access (DBCA)*, where a wireless station selects channel bandwidth dynamically based on the availability of the secondary channels. But the widely-used contention based medium access mechanism provides an opportunistic access of secondary channels and affects the performance of DBCA. Consequently, unfairness in channel access is increased in DBCA, which further reduces average throughput of stations. In this paper, we develop a hybrid adaptive resource reservation mechanism, *Hybrid Adaptive DBCA (HA-DBCA)*, for supporting fair channel access in DBCA. In HA-DBCA, a polling based online learning mechanism is designed to avoid starvation of primary channel users. Through IEEE 802.11ac testbed implementation, we show that HA-DBCA improves throughput fairness in DBCA significantly along with other performance parameters.**

***Keywords*-IEEE 802.11ac; dynamic bandwidth channel access; fairness; multi-armed bandit**

I. Introduction

Wireless networks, build over the popular *Wireless Fidelity* (Wi-Fi) or IEEE 802.11 based technologies, have gradually captured the last mile communication paradigms for Internet connectivity and have become the most popular wireless technology to implement wireless local area networks (WLANs). With the growing demands for wireless capacity to support streaming and multimedia applications, IEEE has launched high throughput wireless extensions over IEEE 802.11 such as IEEE 802.11ac [1]. It supports a theoretical data rate of 7 Gbps over 5 GHz channel. At the physical (PHY) layer, IEEE 802.11ac introduces a feature of advanced channel bonding [2] which combines multiple 20 MHz channels to construct wider channels like 40 MHz, 80 MHz or 160 MHz. A station may not always need a wider channel. So, the concept of *primary* and *secondary* channels [2] have been introduced in IEEE 802.11ac, where a station acquires a 20, 40 or 80 MHz channel as the primary channel. Whereas, in the consecutive space, another extension of the same channel width is considered as the secondary channel.

To support channel reservation over dynamic channel bonding levels, IEEE 802.11ac introduces *Dynamic Bandwidth Channel Access (DBCA)* [3], where a wireless station extends the primary 20 MHz channel for data transmission, if other secondary 20 MHz channels are free during the time of communication. It is a feature of the Media Access Control (MAC) sublayer. DBCA is an extension of IEEE 802.11 Distributed Coordination Function (DCF) to handle both primary and secondary channels. In DBCA, a station applies the binary exponential back-off algorithm to acquire the primary channel by using a contention window (CW). In this back-off algorithm (similar to DCF), a station maintains the back-off time by using a contention window (CW). If the station finds the primary channel as idle, it attempts for a transmission.

In DCF, during an attempt of unsuccessful transmission, a wireless station chooses a value of back-off counter, which is selected randomly from $[0, CW]$. Then it waits for that number of slots before starting the next sensing of the primary channel. This mechanism is extended by DBCA as follows. After getting the access to the primary channel, the station attempts for a transmission after waiting for a time interval, called Distributed Inter-Frame Spacing (DIFS). Before initiating the transmission, the station also senses the secondary channel. If the secondary channel is free, the station transmits data in both the primary and the secondary channels. Otherwise, if the secondary channel is sensed as busy, it initiates transmission only at the primary channel. For the secondary channel, DBCA does not use any back-off counter. Thus, a station follows an instantaneous access to the secondary channel on the basis of its availability at the time of access of the primary channel. Therefore, an opportunistic access is followed in the secondary channel.

A few recent works like [4], [5] consider advanced PHY/MAC layer features of high throughput wireless amendments of IEEE 802.11 for evaluating their performances under various network scenarios. However, none of these works have

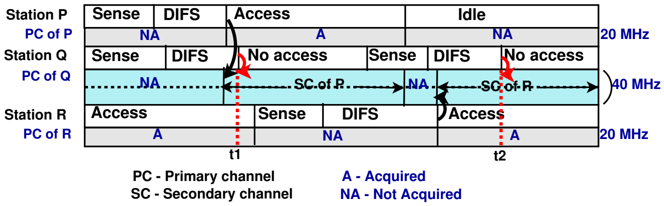

Fig. 1. Unfairness in channel access in DBCA

focused on DBCA to examine the impact of the secondary channel on the performance of throughput fairness of IEEE 802.11ac. As legacy IEEE 802.11 stations and other devices at the vicinity tend to acquire a 20 MHz channel for their data communications, the availability of a free secondary channel reduces. Since no back-off strategy is employed in the secondary channel, some stations may not get chance to access their primary channels. This is because their primary channels may be used to construct secondary channels which are acquired by some other stations at that time. Thus, the opportunistic nature of access of secondary channels blocks primary channels of some stations which repeatedly try to begin transmissions by contention method. This scenario is illustrated in Fig. 1 where the station Q wants to access its primary channel at time $t1$ and $t2$. But, Q's primary channel is used to create the secondary channel that is acquired by stations P and R at $t1$ and $t2$ respectively. Thus, Q can not access its primary channel. This situation leads to unfairness in channel access in DBCA.

In this paper, we consider fairness issue in DBCA and design an adaptive resource reservation mechanism for supporting fair channel access in DBCA, that can improve overall performance of IEEE 802.11ac networks. The proposed scheme, called *Hybrid Adaptive DBCA (HA-DBCA)*, is a hybrid approach where DBCA based channel access is utilized for contention based resource allocation. Whereas, a polling based online learning mechanism is developed to avoid starvation of primary channel users in DBCA due to opportunistic access of secondary channels by the higher channel bonding users. The performance of HA-DBCA is evaluated from both theoretical model as well as from practical experiments. We implement HA-DBCA in IEEE 802.11ac testbed and show that it provides a significant performance improvement in DBCA along with its throughput fairness.

II. Related Works

A few works have handled DBCA mechanism in IEEE 802.11ac. Authors in [6] evaluated performances of static and dynamic channel access mechanisms in IEEE 802.11ac. Deek *et al.* [7] designed a channel bonding scheme without employing dynamic channel access. In an another work [8], authors revealed that the application of DBCA can improve channel utilization significantly. An algorithm is developed in this work, which enables/disables dynamic bandwidth operation considering hidden interference. Kim *et al.* [9] proposed a delayed DBCA scheme along with virtual primary channel reservation. But, it does not focus on throughput fairness trade-off in DBCA. A new DBCA methodology proposed in [10] performs dynamic channel access for IEEE 802.11ac by applying conventional clear channel assessment approach that may increase protocol overhead. It deals with throughput enhancement without fairness in hybrid channel management. Using channel bonding, a fair channel access protocol is designed in [11]. However, DBCA is not employed in this scheme. Authors in [12] presented an analytical framework for analyzing the performance of dynamic channel bonding only, with carrier sensing. In [13], only the performance of a dynamic bandwidth mechanism is compared with a static bandwidth implementation.

III. Motivation: How Does DBCA Impact Short Term Fairness?

In this section, we show that DBCA results in severe unfairness in channel access, as we increase secondary channel users in the network. The analysis has been done over a IEEE 802.11ac testbed developed at the department of CSE, IIT Kharagpur, based on Broadcom BCM43602 IEEE 802.11ac chipset that works in 5 GHz, along with open source `brcmfmac` IEEE 802.11ac driver that supports three channel bonding levels – 20 MHz, 40 MHz and 80 MHz. We first discuss the detailed testbed setup, and then move towards analysis of the results from the testbed.

A. Testbed Setup

We have used 1 IEEE 802.11ac supported wireless routers, and 25 IEEE 802.11ac wireless stations to setup the testbed. The detailed configurations for the devices and the traffic generation models are as follows.

1) Device Details – Hardware, Drivers and Firmware: We use ASUS RT3200-AC routers for our testbed setup, which uses Broadcom BCM43602 IEEE 802.11ac chipset to transmit data at 5 GHz channel. We have used the open source `asus-wrt merlin`[1] firmware along with `brcmfmac`[2] driver for our implementation. The firmware release rt-7.14 has been used with Linux kernel version 2.6. For the router configuration, we have added a driver hook to switch on and switch off DBCA mode in the `brcmfmac` source that follows `cfg80211` driver framework for IEEE 802.11 supported devices. At the client side, we use ASUS USB-AC56 IEEE 802.11ac dongle that uses Realtek RTL8812AU chipset to support IEEE 802.11ac in station mode. Here we use open source `rtl8812au`[3] driver for configuring the chipset in wireless station mode.

2) Channel Configurations: We have done the experiments in two modes – (a) $20-40$ mode, where 10 wireless stations use 20 MHz primary channel for communication, and then we increase the 40 MHz stations (20 MHz primary, 20 MHz secondary) to check the impact of secondary channel access; and (b) $40-80$ mode, where 10 wireless stations use 40

[1]https://asuswrt.lostrealm.ca/ (last accessed: April 23, 2017)
[2]https://wikidevi.com/wiki/Brcmfmac (last accessed: April 23, 2017)
[3]https://github.com/gnab/rtl8812au (last accessed: April 23, 2017)

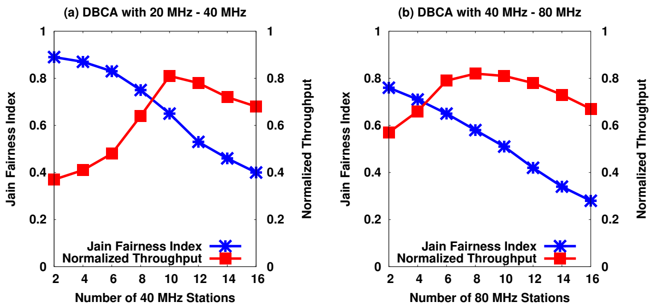

Fig. 2. Impact of Secondary Channel Access over Network Fairness and Normalized Throughput

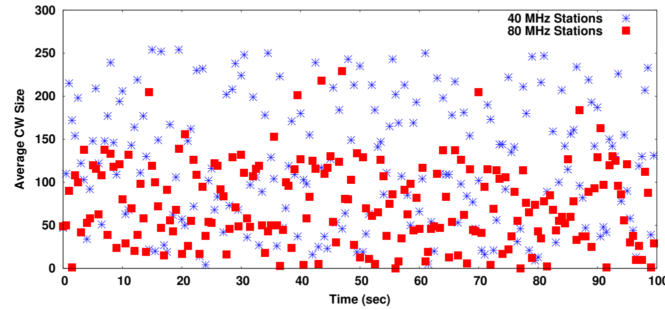

Fig. 3. CW Evolution for 40 MHz and 80 MHz Stations ($N_{40} = 10$ and $N_{80} = 10$)

MHz primary channel for communication, and we increase the number of 80 MHz stations (40 MHz primary and 40 MHz secondary bandwidth) to analyze the impact of secondary channel usage using DBCA. For $20-40$ mode configuration, we have used Channel 161 (frequency $5795-5815$ MHz, bandwidth 20 MHz) and Channel 165 (frequency $5815-5835$ MHz, bandwidth 20 MHz), where 20 MHz stations use Channel 165 for communication, whereas the 40 MHz stations use Channel 161 as the primary channel as Channel 165 as the secondary channel. On the other hand, for $40-80$ mode configuration, we use 5 GHz Channel 153 (frequency $5755-5775$, bandwidth 20 MHz), Channel 159 (frequency $5775-5815$, bandwidth 40 MHz), Channel 165 (frequency $5815-5835$ MHz, bandwidth 20 MHz), where the 40 MHz stations use Channel $5795-5835$ MHz, whereas the 80 MHz stations use Channel $5755-5795$ MHz for the primary channel, and Channel $5795-5835$ MHz as the secondary channel. It can be noted that the secondary channel for the high bandwidth stations is used as the primary channel for the low bandwidth stations. This configuration is used to understand how the opportunistic secondary channel access in DBCA impacts the primary channel users at the secondary channel for the high bandwidth stations. Apart from channel bonding, we configure the stations to use one spatial stream, as well as disable short guard interval (SGI) and frame aggregation features to ensure that we observe only the impact of channel bonding and DBCA on the stations' performance. Finally, we use 64-QAM with $2/3$ coding rate as the IEEE 802.11ac modulation and coding scheme, that supports 52 Mbps, 108 Mbps and 234 Mbps at 20 MHz, 40 MHz and 80 MHz, respectively.

3) Traffic Configurations: We use Linux tool `iperf` to generate traffic at the wireless stations. It can be noted that we keep the stations at fixed position so that mobility does not impact performance, and accordingly, we analyze the performance of DBCA. We use constant bit-rate traffic (CBR) at a rate of 5 Mbps at every station, so that the application traffic remains saturate, and we can measure the performance at the MAC layer.

B. Analysis of Fairness and Throughput

We measure average normalized MAC throughput at wireless stations and Jain's fairness index to analyze throughput performance and fairness. The normalized MAC throughput has been computed as the ratio of the computed throughput and the maximum channel capacity at the corresponding channel. The Jain's fairness index has been computed based on the normalized throughput. We measure the impact of secondary channel users on the performance of primary channel users by increasing the number of high bandwidth stations for the $20-40$ and the $40-80$ modes. The normalized throughput and the Jain's fairness index have shown in Fig. 2. We can observe from the figure that as we increase the number of secondary channel users, Jain's fairness index drops, whereas the normalized throughput also gets reduced after the saturation point. The impact of DBCA opportunistic access is severe for the $40-80$ mode, where Jain's fairness index drops significantly as we increase the number of secondary channel users.

Next, we analyze the behavior of secondary channel access to explore why the fairness index and normalized throughput drops as we increase the number of secondary channel users. For this, we plot the average CW values with respect to time (a bucketing of 0.5 seconds is used to plot the graphs), as shown in Fig. 3. We show the results for the $40-80$ mode, with the number of 40 MHz stations (N_{40}) as well as the number of 80 MHz stations (N_{80}) being 10 for both the cases. The figure indicates that the average CW for 40 MHz stations is high compared to the average CW for 80 MHz stations. This indicates that the average waiting time for the 40 MHz stations is comparatively higher compares to the average waiting time for 80 MHz stations.By thorough inspection of the channel access log, we observe that due to the opportunistic access of secondary channel based on DBCA, the 40 MHz stations suffers. Consequently, we observe reduced normalized throughput and drop in fairness index, as plotted in Fig. 2.

C. Discussion and Opportunities for Improvement

From the above experiments, we observe that DBCA introduces unfairness in channel access which further reduces the average throughput for the stations. Therefore, we can conclude that there is a strong requirement for augmenting the DBCA mechanism to improve the throughput. This design is indeed complex because we need to deal with multiple trade-offs based on IEEE 802.11ac architecture. It is well known that channel bonding is one of the prior reason behind the high data rate communication [14], [15], and the static channel allocation with high bonding levels introduces severe channel underutilization [6]. Under station channel allocation with high bonding levels, the wireless stations contend for the wide channels, and the probability of a successful carrier sensing is reduced as the channel bonding level increases, which becomes severe for heterogeneous channel bonding environments. Therefore, IEEE 802.11ac introduces DBCA where a station does not wait for getting access to the secondary channel, and when it senses the secondary channel to be free, it starts transmitting data without going for further back-off. This opportunistic access of secondary channel introduces unfairness in channel access, as we show in the previous experiments.

The next question is as follows: *How can we overcome the problem of unfairness in secondary channel access?* One probable solution would be to develop a controlled channel access policy and enforce it over the network such that secondary channels for some wireless stations are not allocated as the primary channel for some other stations whenever possible, so that the unfairness scenario does not arise. However, such channel allocations are in general static, because dynamic channel allocation under wireless environment is known to be a hard problem, which can introduce high overhead under dynamic channel bonding scenarios. Finally, static channel allocation limits the scalability of the network.

Consequently, we develop an augmentation mechanism over DBCA, where we apply a methodology for *"starvation prevention"* rather than *"starvation avoidance"*; where we detect the stations under starvation that employs a high CW value due to contention, and then provide additional resources to the starved stations to improve their performance and balance the throughput across all the stations in the network. This methodology, called HA-DBCA, is discussed in details in the next section.

IV. HA-DBCA: Adaptive Resource Reservation for Supporting Fair Channel Access in DBCA

HA-DBCA employs a hybrid approach, where DBCA based channel access is utilized for contention based resource reservation, and a polling based adaptive mechanism (contention free access) is implemented to avoid the starvation of primary channel users. Although such hybrid access is proposed earlier for wireless channel access, such as [16]–[18] and the references therein, similar methodology is not directly applicable for IEEE 802.11ac because of two main reasons – (a) decision of contention free intervals is not straightforward under heterogeneous channel bonding, and (b) a detection methodology needs to be developed for identifying the stations under starvation in DBCA.

A. HA-DBCA: Overall Architecture and Protocol Internals

The proposed HA-DBCA methodology works as follows. We divide the time into periodic HA-DBCA intervals, where every HA-DBCA interval has two sub-intervals – DBCA interval and contention free (CF) interval; as shown in Fig. 4.

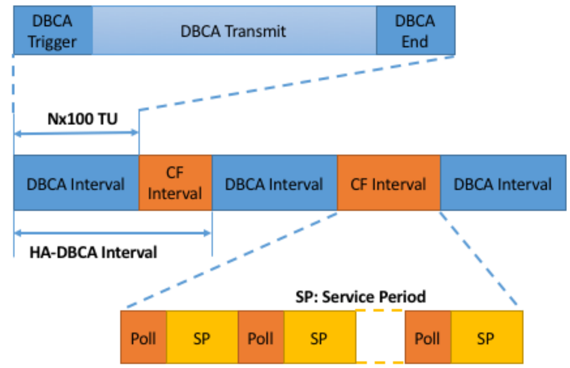

Fig. 4. Periodic DBCA and Contention Free (CF) Intervals in HA-DBCA

While the DBCA interval is kept fixed, the CF interval varies based on the number of starved stations at the beginning of the CF interval. DBCA interval has two components – DBCA trigger and DBCA transmit. During DBCA trigger, an IEEE 802.11ac supported AP broadcast a *DBCA Initiation Packet* (DIP) that indicates the start of a DBCA interval. Once the stations receive the DIP packet, they starts accessing the channel based on DBCA. At the end of DBCA interval (DBCA End), the AP again broadcast a *DBCA End Packet* (DEP). On receiving the DEP packet, the stations stop transmitting data using DBCA. The format of DIP and DEP is similar to IEEE 802.11 Beacon, except that we add two additional bits at the end of Beacon frames that indicate whether this is a regular Beacon frame (denoted by bit sequence 00), a DIP frame (denoted by bit sequence 01), or a DEP frame (denoted by bit sequence 10). To reduce the signaling overhead, we keep the DBCA intervals in sync with the *Target Beacon Transmission Time* (TBTT) of IEEE 802.11, which is by default 100 TUs. Accordingly, the DBCA interval is kept as the multiple of TBTT.

Once a station receives the DEP, it applies an online learning based estimation mechanism to compute whether it is in starvation. During the CF interval, the IEEE 802.11ac AP individually polls every station attached to it, and if the station is found to be under starvation during the previous DBCA interval, the AP allocates a channel to that station which is the maximum channel bonding level configured for that station. The channel is allocated for a fixed duration, called *Service Period* (SP). Note that if a station does not get starved during the previous DBCA interval, then SP=0 for that station in the corresponding CF interval. In our design, we assign 1 TU as the default SP for the CF interval duration for every starved station. It can be noted that there are possibilities of having legacy IEEE 802.11 stations in the vicinity, which are not under the control of the IEEE 802.11ac AP under consideration. Therefore, once the AP allocates channels to the stations, the station resets its congestion window value, and uses the standard IEEE 802.11 *Distributed Coordination Function* (DCF) based mechanism to transfer data to or from the AP. It can be noted here that although we call this as "contention free" channel access, it is not purely contention free because of the possibility of having legacy IEEE 802.11 stations in the vicinity, which might use the same channel for data transmission. In the next subsection, we give a brief description of the online learning mechanism that we apply for the detection of starved wireless stations in DBCA.

B. Detection of Stations under Starvation

As mentioned, we need to develop a mechanism to identify the stations under starvation due to primary channel blockage at DBCA by the secondary channel users. This detection is indeed challenging because of the following reasons;

- It is not possible to detect starvation just by observing whether a station has stopped transmitting data or whether the transmission rate of a station is less than a threshold. A station may not be transmitting data either because (i) it does not have sufficient data to transmit, or (ii) it is not able to get access to the channel due to channel blockage by the secondary channel users. Therefore, the AP cannot detect independently whether a station has starved or not.
- Similarly, a station cannot decide independently whether it is starved because of the uneven access of the channel that results in carrier sensing failure at the primary channel; or because of network saturation due to high traffic load.

Therefore, we need to develop a methodology based on coordination between the AP and the wireless stations. Accordingly, we develop an online learning, called *Multi Armed Bandit* (MAB), based estimation mechanism to identify whether a station is under starvation due to carrier sensing failure at the primary channel. Each station engages an agent that runs our proposed MAB-based adaptive learning algorithm to identify the stations which have been starved. This scheme selects the stations to be allowed for transmission in contention-free slot.

1) Multi-Armed Bandit: The MAB model uses an agent that always tries to balance exploration-exploitation dilemma, where the objective is to derive a balanced as well as optimized solution based on the history (exploitation) and the current observations (exploration). In MAB, the agent selects a single arm (an option) from a set of arms which have unknown characteristics initially. Each arm obtains a reward for every choice. The objective of each agent is to maximize the total acquired reward so far. The random bandit problem originally was proposed by Robbins (1952) [19].

The K-armed bandit problem can be defined by random variables $X_{i,n}$, where $1 \leq i \leq K$ for $n \geq 1$ (n is the total number of plays and each i denotes an arm of the MAB model). Successive plays of an arm i, produce rewards $X_{i,1}, X_{i,2}...$ which are independent and identically distributed according to an unknown distribution. Let the expectation of these rewards is μ_i. Also, let $\mu = \{\mu_1, \mu_2, ...\mu_K\}$ denote expected values of reward distribution. Let us consider $T_i(n)$ counts the number of times for which the arm i has been selected for playing during the first n number of plays. For arm i, the observed regret is defined as $(\mu^* - \mu_i)$, where $\mu^* = max_{1 \leq i \leq K} \mu_i$. At time t, let $r(t)$ specify the acquired reward. The expected regret value is given by, $E[R(n)] = \mu^* n - \sum_{t=1}^{n} E[r(t)]$. We have, $\sum_{t=1}^{n} E[r(t)] = \sum_{i=1}^{K} \mu_i E[T_i(n)]$ and thus, the regret can be expressed as $E[R(n)] = \mu^* n - \sum_{i=1}^{K} \mu_i E[T_i(n)]$.

We incorporate *Upper Confidence Bound* (UCB) model of MAB framework in the contention-free slots to select the stations which can transmit their data during the contention free access and reset their contention window to break the starvation.

2) Upper Confidence Bound (UCB): Being a MAB framework, UCB was derived from index-based policy of Agrawal (1995). In this policy, the index is the summation of two terms. The first term is the present average reward. The second term relates to the size of the one-sided confidence interval for the average reward. Each time an arm is chosen by observing confidence bounds of all arms. In UCB, rate of exploration and exploitation is updated dynamically with respect to the upper confidence bound of each arm. The algorithm is stated as follows [20].

UCB algorithm: At each time step, for each arm j, calculate confidence bound, $conf_j = \sqrt{\frac{2 \ln n}{n_j}}$, where n_j denotes the number of times arm j has been selected and played so far and n is the total number of plays. Choose the arm that maximizes $\hat{\mu_j} + conf_j$, where $\hat{\mu_j}$ is the average reward of arm j.

3) Exploiting UCB in Detection of IEEE 802.11ac Stations under Starvation: We propose a distributed mechanism where each station tries independently to come out from starvation by utilizing UCB learning scheme. In our proposed approach, let an <u>arm</u> represent a <u>station</u> which is contending for accessing the channel. For station j, let us consider, n denotes the total number of attempts taken by it to access the channel. Also, let station j has accessed the channel n_j number of times. Following UCB, the confidence bound is $conf_j = \sqrt{\frac{2 \ln n}{n_j}}$. Now, if μ_j specifies Head-of-Line (HOL) delay for station j, we define α as the *confidence factor* and the confidence factor α_j of node j is as follows.

$$\alpha_j = \mu_j + conf_j$$

. Now, let $\mathcal{T}$ denote the probability of transmission and it is defined as given in the following.

$$\mathcal{T} = (1 - \frac{1}{\alpha}) \times \text{access channel} + \frac{1}{\alpha} \times \text{not access channel} \tag{1}$$

At the end of DBCA period, all the stations calculate their confidence factors. After that, each station computes its probability of data transmission by applying Eq. (1). From this equation, it can be observed that the probability of accessing channel increases as α gets high. For any station j, as it enters into starvation, $(n - n_j)$ increases. Consequently, $conf_j$ is also increased. Further, μ_j is enhanced in this situation. As a result, $\mathcal{T}$ increases. Thus, the stations which are waiting for a long time to access the channel (i.e., in starvation) get higher opportunities to acquire the channel in the contention-free period. At any time, if M number of stations are in starvation out of N number of stations, M stations will get the first chance to access the channel according to Eq. (1). These stations are allocated a service period at the CF interval, and they transmit data as well as reset their CW value to break the starvation, as we discussed earlier.

V. Theoretical Modeling of HA-DBCA

In our model, the HA-DBCA interval (HDI) (T_{HDI}) is variable depending on the number of IEEE 802.11ac stations getting starved in the DBCA interval under that HDI. We consider N numbers of IEEE 802.11ac stations that are attached to an IEEE 802.11ac AP. We assume that the data packets are of fixed length L (measured in terms of seconds based on the data rate of the corresponding channel bonding level used by the station) and are generated at each station following a Poisson process with mean arrival rate λ. We assume that the stations have serial IDs from 1 to N. Let the CF period be divided into N number of Poll intervals of length L_p. We further assume that the SP durations are multiple of L for a given station, and we consider it to be L_m. Therefore a CF interval has the length $NL_p + ML_m$, where M is the number of starved stations in the DBCA interval. In our model M is variable based on the success probability at the corresponding DBCA interval.

A. *Worst Case Delay Analysis for a Packet in HA-DBCA*

Here, we analyze the delay of the N^{th} station. Due to the inherent ordering of SP allocation being followed by the IEEE 802.11ac AP, the delay of the N^{th} station is statistically the worst case delay with respect to the other stations. However, this assumption of ordering of SPs has been relaxed in the later section, and we analyze the average delay for random ordering of the SPs. Consider a packet in the N^{th} station, and we term this packet as the *target packet*. It may happen that the target packet is served in a DBCA interval if the station does not get starved. However, we assume that the target packet gets served in a CF interval, in order to calculate the worst case delay for the starved stations.

1) Delay Experienced in the HA-DBCA Where the Target Packet is Transmitted at the CF Interval: Let the random variable $\mathcal{J}$ denote the number of stations having reservation other than the N^{th} station in the CF interval in which the target packet is being transmitted. It can be noted that based on the serializability of the stations, where we assume that the SPs are in the order of the stations' ID, there are $N-1$ number of stations that get an opportunity to transmit before the N^{th} station. Then the random variable $\mathcal{J}$ follows a binomial distribution with parameters $N-1$ and ρ, where ρ denotes the probability of a station having reservation in the CF interval. The probability mass function of $\mathcal{J}$ can be given by the following equation.

$$P\{\mathcal{J}=j\} = \binom{N-1}{j} \rho^j (1-\rho)^{N-1-j} \tag{2}$$

The expected value of $\mathcal{J}$, $E[\mathcal{J}]$ is given as follows.

$$E[j] = (N-1)\rho \tag{3}$$

Then, the amount of delay that the target packet experiences in the CF interval can be given by the following equation.

$$D_F = B + NL_p + jL_m \tag{4}$$

where B is the duration of the DBCA interval, NL_p is the total duration of the poll intervals in the CF interval, as shown in Fig. 4, and jL_m denotes the total time taken for transmitting packets from all the j stations (other than the N^{th} station) that got starved during the DBCA interval, and have got a SP in the current CF interval. Averaging over j, the expected delay $E[D_F]$ can be obtained as follows.

$$E[D_F] = B + NL_p + (N-1)\rho L_m \tag{5}$$

2) M/G/1 Model for Computing the Value of ρ: We define a queuing system that models the behavior of a packet in HA-DBCA. Considering that the packet arrival follows a Poisson distribution, we model the system as a M/G/1 queue. In HA-DBCA, a packet can be scheduled only when the station can get access to the channel, either in the DBCA interval, or in the CF interval. Therefore, the average service time ($E[s]$) for that packet can be given as follows.

$$[E(s)] = (L_T + 2L_T + ... + NL_T)/N = L_T(N+1)/2 \tag{6}$$

where $L_T = L_p + L_m$. Based on this, we can compute ρ as follows.

$$\rho = [E(s)] \times \lambda = (L_T(N+1)\lambda)/2 \tag{7}$$

3) Effect of Heterogeneous Data Arrival Rates at the Wireless Stations: Next, we present the worst case delay analysis for HA-DBCA when the packet arrival rates at different stations are different. Let the arrivals of packets at the i^{th} station follows Poisson distribution with rate λ_i. Using the M/G/1 queuing model for each station, the utilization factor for the i^{th} station (ρ_i) can be given as follows.

$$\rho_i = (L_T(N+1)\lambda_i)/2 \tag{8}$$

Accordingly, we derive the worst case delay for a packet transmission . Let S_k denote the set of stations (apart from the N^{th} station) having reservation in the current CF interval, and S'_k denote the complement of the above set. Let $|S_k| = \beta$ is the number of stations having SP allocation in the CF interval before the N^{th} node. The expected delay in the CF interval in which the target packet is transmitted can then be written as follows.

$$E[D_F] = B + NL_p + E[j]L_m \tag{9}$$

We now proceed to derive $E[\beta]$, the expected number of stations that use a SP in the CF interval to transmit data. We can say that ρ_i is the probability that the station i has a packet to transmit at the CF interval, and hence a SP has been allocated to it. Considering β as a random variable, the probability mass function of β can now be derived as follows. Let $\mathcal{E}$ be the event that a station j transmits before the N^{th} node. Then,

$$P[\mathcal{E}] = \sum_{|S_k|=0}^{N-1} \sum_{k=1}^{\binom{N-1}{|S_k|}} \prod_{r \in S_k} \rho_r \prod_{r \in S'_k} (1-\rho_r) \tag{10}$$

Based on the derivation given in [5], we compute the average of β as follows.

$$E[\beta] = \sum_{i=1}^{N-1} \rho_i \tag{11}$$

Therefore, the delay in the last CF interval for the heterogeneous traffic arrival can be derived as follows.

$$E[D_F] = B + NL_p + \left(\sum_{i=1}^{N-1} \rho_i\right) L_m \tag{12}$$

4) Effect of Random Ordering of SP Allocation: Finally, we relax the assumption of fixed ordering of the stations and present the modified expression of the worst case delay. We consider the homogeneous system model and allow the allocation of SP in any random order. We first evaluate the delay of the target packet in the last CF interval where it gets the SP. The probability of r nodes (not including the target node) having SP allocated in the CF interval, denoted by an event $\mathcal{Z}_r$, can be given as follows.

$$P[\mathcal{Z}_r] = \binom{N-1}{r} \rho^r (1-\rho)^{N-1-r}; \quad \forall r \in [0, N-1] \tag{13}$$

The target packet can occupy any slot out of the $r+1$ SP slots uniformly with a probability $\frac{1}{r+1}$.

$$E[\mathcal{Z}_r] = \frac{\rho^2(N-1)}{2}[(N-2)\rho + 3] \tag{14}$$

Hence using the above modifications, the delay in the last CF interval ($E[D_F]$) can be given by Eq. 15.

$$E[D_F] = B + NL_p + \frac{\rho^2(N-1)}{2}[(N-2)\rho + 3]L_m \tag{15}$$

B. Numerical Analysis

Next, we validate the theoretical model and show the impact of HA-DBCA in terms of channel access delay compared to the standard DBCA protocol. For numerical validation and analysis, we consider that the primary channel users transmit using 20 MHz bandwidth, whereas the secondary channel users transmit using 40 MHz bandwidth. We increase the number of stations and consider that 50% of the total stations use 20 MHz and rest use 40 MHz. Let M be the total number of stations, and P_s be the probability of success at the DBCA channel access, then $M \times P_s$ number of stations participate in the CF interval. For a given number of stations, we compute P_s based on the model given in [21]. We consider $CW_{min} = 32$, $CW_{max} = 256$, packet length (L) = 1024 bytes, $L_m = 10$ TUs, $L_p = 1$ TU, $B = 100$ TUs, and packet generation rate follows a Poisson distribution with mean 1000 packets per second.

To validate the theoretical bound, we first implement the similar scenario over the testbed discussed earlier, and compute the average channel access delay with the similar number of stations as well as with other settings. The results are plotted in Fig. 5(a). We observe that the average channel access delay from the theory and from the simulation follows similar trend, which validates the proposed model. Further, it can be seen

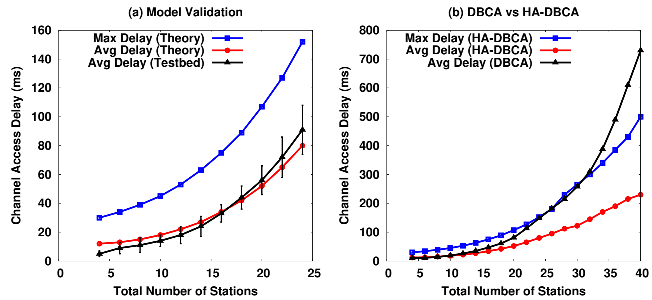

Fig. 5. Numerical Analysis of Channel Access Delay

from the figure that the average channel access delay for HA-DBCA is almost half of the worst case channel access delay.

Next we compare the performance of DBCA and HA-DBCA based on the theoretical model. The results for DBCA is computed based on the model proposed in [21]. It can be noted that the model given by [21] can compute only the average channel access delay, and therefore we show the average channel access delay in Fig. 5(b) for DBCA, and plots the maximum as well as average channel access delay for the proposed HA-DBCA mechanism. We observe that the proposed HA-DBCA can significantly reduce the channel access delay. As we increase the number of stations in the network, the average channel access delay for DBCA increases exponentially, and even goes beyond the maximum channel access delay for HA-DBCA, when number of stations is more than 32. This theoretical model shows the advantage of HA-DBCA and also provides a theoretical bound on the worst case performance. Next, we do a detailed performance analysis of HA-DBCA from the testbed.

VI. Performance Evaluation from Testbed

We finally evaluate the performance of the proposed HA-DBCA from the testbed as discussed in Section III. We used similar testbed configuration and similar traffic generation scenarios, and observe how good the proposed methodology for IEEE 802.11ac channel access can perform in comparison with the standard DBCA mechanism. For HA-DBCA implementation, we set the duration for DBCA intervals, Poll intervals and SPs as 1000 TUs, 1 TUs and 10 TUs , respectively. As earlier, we do the experiments under $20-40$ and $40-80$ modes of operations. In each scenario, we keep 10 low channel bonding stations fixed, and increase the high channel bonding stations gradually to measure the effect. We execute every experiment for at least 10 different times; while every instance of the experiments have been executed for at least 2 hours continuously. We plot the average results along with the confidence interval (standard deviation of results for different runs).

Fig. 6 compares the two methodology, DBCA and HA-DBCA in terms of normalized throughput. We observe that when number of secondary channel users are less, HA-DBCA perform marginally less than DBCA. However, as we increase the number of stations that uses the secondary channel, the

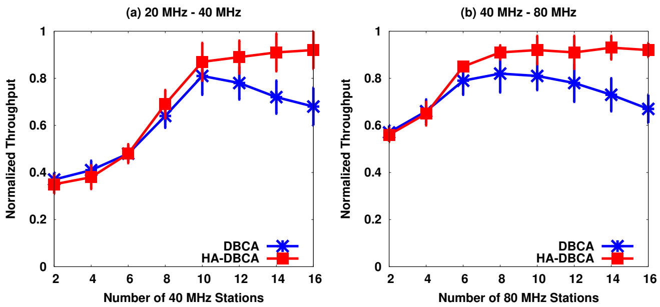

Fig. 6. Comparison of Normalized Throughput

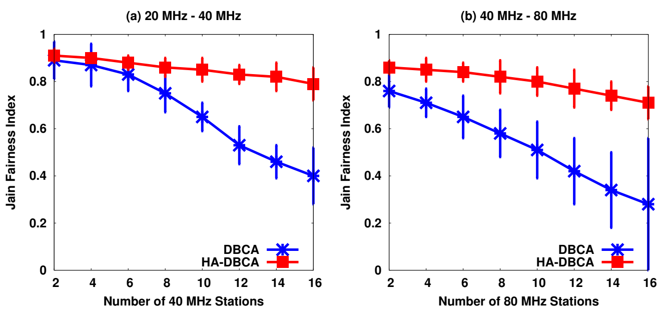

Fig. 7. Comparison of Fairness Index

throughput performance of HA-DBCA improves significantly. The marginal drop in performance for HA-DBCA with less number of secondary channel users is because some of the bandwidth for DBCA interval remains underutilized, as we keep the DBCA interval fixed at 1000 TUs, and the overhead for HA-DBCA (poll intervals) is little more. However, the performance of HA-DBCA improves significantly as the secondary channel users in the network increases.

Finally we compare the performance of the two schemes in terms of fairness, as shown in Fig. 7. The figure clearly indicates that the proposed HA-DBCA methodology can significantly boost up the fairness among the contending wireless stations. HA-DBCA reduces the starvation of stations by granting them extra slots for communication, which in turns improve the average throughput for the stations, as we observed earlier in Fig. 6.

VII. Conclusion

In this paper, we have addressed the issue of unfairness in IEEE 802.11ac DBCA, and designed a hybrid adaptive resource reservation mechanism, HA-DBCA, for supporting fair channel access. It utilizes contention based resource reservation for implementing DBCA. Additionally, we have employed a polling based online learning mechanism, UCB, to avoid starvation of primary channel users due to opportunistic access of secondary channels by the higher channel bonding users. We have developed a theoretical model, as well as implemented HA-DBCA in IEEE 802.11ac testbed. The results from the testbed have shown that it provides a significant better performance compared to DBCA along with fairness.

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