IEEE 802.11ac DBCA: A Tug of War Between Channel Utilization and Fairness

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***Abstract*—IEEE 802.11ac supports *Dynamic Bandwidth Channel Access* (DBCA), where a wireless station dynamically selects the channel bandwidth based on the availability of the secondary channels. Although DBCA reduces the possibility of starvation due to non-availability of secondary channels, however, to the best of our knowledge, no existing works look into the performance benefits of IEEE 802.11ac DBCA based on theoretical modeling. In this paper, we develop a two dimensional Markov chain approach to model the performance of DBCA under various channel bonding conditions. We validate the proposed model based on a real testbed implementation. From the thorough analysis of the numerical results obtained from the model, we show that although DBCA improves channel utilization for secondary channels, it requires proper channel allocations and bonding level distributions across the wireless channels for reducing unfairness in the network. We observe that under certain circumstances, the secondary channel users can affect the throughput of primary channel users, which may introduce a short-term unfairness and a significant performance drop in the network.**

***Index Terms*—IEEE 802.11ac; DBCA; Throughput; Fairness**

I. Introduction

With the growing demands for wireless capacity to support streaming and multimedia applications, the community of wireless networks has standardized high throughput wireless extensions via IEEE 802.11ac [1] that supports around 7 Gbps data rate over 5 GHz channel. IEEE 802.11ac introduces advanced channel bonding [2] at the physical layer, where multiple consecutive 20 MHz channels are combined together to form wider channels ($40/80/160$ MHz). Considering the fact that a station may not need the full capacity of a wider channel always, IEEE 802.11ac introduces the concept of *primary* and *secondary* channels [2], where a station acquires a 20, 40 or 80 MHz channel as the primary channel, and another extension of the same channel width in the consecutive space is used as the secondary channel.

For effectively utilize the primary and secondary channel space, IEEE 802.11ac introduces *Dynamic Bandwidth Channel Access* (DBCA) [3] at the medium access control (MAC) layer, which is an extension of IEEE 802.11 distributed coordination function (DCF) to handle primary and secondary channels. In DBCA, a station uses the binary exponential back-off algorithm to access the primary channel. The back-off algorithm is similar to DCF, where a station uses a contention window (CW) to maintain the back-off time. At the beginning of transmission, every station selects a minimum CW value (CW_{min}), and senses the primary channel. If the primary channel is idle, the station attempts for a transmission. For every unsuccessful transmission attempts, the station doubles up the CW up to a maximum value (CW_{max}), where $CW_{max} = 2^m \times CW_{min}$, and m is the maximum back-off stage. During an unsuccessful transmission attempt, a wireless station selects a back-off counter value which is randomly chosen from the range 0 to CW, and waits for that many number of slots, before the next carrier sensing over the primary channel. DBCA extends this access methodology as follows. When a station gains access to the primary channel, that is it senses the primary channel to be free, and attempts for a transmission after waiting for a time duration called distributed inter-frame spacing (DIFS), it also senses the secondary channel. If it finds the secondary channel to be free, it transmits data in both the primary channel and the secondary channel, otherwise if the secondary channel is sensed busy, the station transmits only at the primary channel. It can be noted that, DBCA does not maintain any back-off counter value for the secondary channel, and the access to the secondary channel is instantaneous based on its availability during the access of the primary channel.

Starting from the pioneering work by Bianchi et al. [4], a group of researchers have focused on the performance modeling of IEEE 802.11 MAC considering the probabilistic aspects of the underlying binary exponential back-off algorithm and the wireless channel interference. These series of works, such as [5]–[13] and the references therein, have analyzed the performance of IEEE 802.11 and its advanced amendments from different aspects, like multi-hop ad-hoc networks, saturated and unsaturated traffic conditions, quality of service (QoS) conditions and so on. These models are mostly built over the Bianchi's model [4] and have provided different insights of IEEE 802.11 channel access protocols. A few recent mathematical models, like [14]–[18] consider advanced features of high throughput wireless extensions for understanding their performance under various aspects. However, none of these existing works have looked inside DBCA to understand the effect of *secondary channels* on the performance of IEEE 802.11ac. The availability of a free secondary channel depends on the number of legacy 802.11 devices that tend to grab a 20 MHz channel for data communication, as well as the other stations at the vicinity that use the same channel as the primary channel. For example, consider Fig. 1. A wireless

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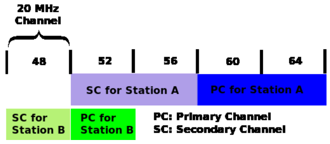

Fig. 1. Problem with DBCA: A secondary channel from one station can work as the primary channel for another station

station can use channels 60 and 64 as the 40 MHz primary channel (in the 5 GHz band) and the consecutive channels 52 and 56 as the 40 MHz secondary channel, whereas another station can use the channel 56 as a 20 MHz primary channel. Under such circumstances, it would be interesting to model the performance of DBCA, so that proper channel allocation methodologies can be designed while maximizing throughput and channel utilization.

This paper gives the first mathematical model to understand the performance of DBCA under heterogeneous channel bonding environment and also in the presence of legacy IEEE 802.11 stations. We develop a Markov chain based model to capture the impact of various channel bonding levels over the normalized throughput of the primary and the secondary channels, when DBCA is used to transmit data over a IEEE 802.11ac basic service set (BSS). We have validated the proposed model by comparing the numerical data obtained from the model with the results from a practical IEEE 802.11ac testbed. In a nutshell, this paper provides a mathematical framework that can be utilized for developing a proper channel allocation and channel bonding levels to maximize the channel utilization in a DBCA based environment.

II. Modeling DBCA using Discrete Time Markov Chains

In the proposed Markov chain based model, channel bonding level ℓ indicates that a station uses 2^ℓ number of consecutive channels as the primary channel to transmit data, with an effective bandwidth of $2^\ell \times 20$ MHz, where the width of a single channel is 20 MHz. If a station uses 2^ℓ number of channels as the primary channel bandwidth, it can also utilize the next 2^ℓ numbers of consecutive channels as the secondary channel bandwidth. We consider a heterogeneous environment, where there are 2^c numbers of channel available, where c is the maximum channel bonding level.

A. Channel Access Model

We consider a saturated network condition in this paper, where every station always has data to transmit, and they participate in the channel access procedure. Let p be the probability that a randomly chosen channel is busy. A station utilizes the primary channel with the channel bonding level ℓ if 2^ℓ numbers of consecutive channels are idle. Once it gets access to the primary channel, it also uses the secondary channel if all the consecutive $2^{\ell+1}$ channels are free, including the primary and secondary channel bandwidth; otherwise it only uses the primary channel to transmit. However, the interesting fact is that the stations maintain only a single CW which is corresponding to the primary channel only, and invariant of whether the secondary channel is free or not. Therefore, we can use this channel invariance model, where a station uses 2^ℓ numbers of consecutive 20 MHz channels, and therefore its channel bonding level is ℓ including primary and secondary channels. For instance, if $\ell = 2$, we consider that the station uses first 40 MHz as the primary channel bandwidth (first 2 consecutive 20 MHz channels) and the next 40 MHz as the secondary channel bandwidth (next 2 consecutive 20 MHz channels). The station can use 80 MHz as the primary bandwidth and another 80 MHz as the secondary bandwidth, if it can find out another 4 consecutive channels to be free. This channel invariance model helps to make the system tractable under heterogeneous channel bonding environment. Let p_ℓ denote the probability that a station utilizes channel bonding level ℓ for transmission. As every channel is independent, we can represent p_ℓ as follows when $\ell < c$.

$$p_\ell = \begin{cases} (1-p)^{2^\ell}(1-(1-p)^{2^\ell}) & \text{when } \ell < c \\ (1-p)^{2^c} & \text{when } \ell = c \end{cases} \tag{1}$$

This indicates that out of $2^{\ell+1}$ consecutive 20 MHz channels, the station has sensed the first 2^ℓ consecutive channels as idle, and at least one of the channels is sensed busy from the next consecutive 2^ℓ channels.

B. Collision and Transmission Models

Let a station $\mathcal{S}$ select a channel bonding level dynamically from c numbers of available bonding levels. Let τ be the probability that a station transmits in a randomly chosen slot. Here, we use a virtual slot duration similar to the one as given in [4]. This transmission is successful if the station transmits with channel bonding level $\ell \leq c$, and none of the 2^ℓ channels experiences a collision. Assume $\mathcal{E}_i$ is the event that a station uses i number of consecutive channels, and $\mathcal{E}_i^{\text{free}}$ is the event that all consecutive i channels are free, that is they do not experience a collision. Let $\mathcal{T}_S$ be the probability that a transmission from $\mathcal{S}$ is successful. Then,

$$\mathcal{T}_S = \sum_{i=0}^{c} P[\mathcal{E}_i^{\text{free}} | \mathcal{E}_i]$$

Let q be the probability that there is a collision at any randomly chosen channel. We can represent $\mathcal{T}_S$ as follows.

$$\mathcal{T}_S = p_0(1-q) + p_1(1-q)^2 + p_2(1-q)^4 + \\ ... + p_\ell(1-q)^{2^\ell} + ... + (1-p)^{2^c}(1-q)^{2^c} \tag{2}$$

Similarly, let us assume that $\mathcal{T}_C$ be the probability that there is a collision when $\mathcal{S}$ attempts to transmit a data packet. When channel bonding level is ℓ, there would be a collision in transmission if there is a collision in any of the 2^ℓ available channels. Let q_ℓ be the probability that there is a collision in any of the available 2^ℓ channels. Then, $q_\ell = 1-(1-q)^{2^\ell}$. We can represent $\mathcal{T}_C$ as follows.

$$\mathcal{T}_C = p_0 q_0 + p_1 q_1 + ... + p_\ell q_\ell + ... + (1-p)^{2^c} q_c \tag{3}$$

With the values of $\mathcal{T}_S$ and $\mathcal{T}_C$, we now develop the Markov model for DBCA.

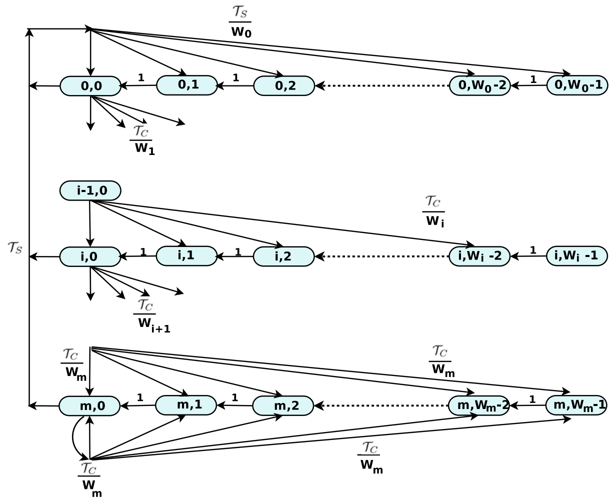

Fig. 2. Markov Chain Model for DBCA with Dynamic Channel Bonding

C. Markov Model for DBCA

The Markov model for DBCA is shown in Fig. 2, which is a two-dimensional Markov chain, where every state is represented as two tuples $(s(t), b(t))$ where $s(t)$ is the process denoting the evolution of back-off stages, and $b(t)$ is the process for evolution of the back-off counter. Let W_i be the maximum contention window size at back-off stage i, that is $W_i = 2^i CW_{min}$. At every back-off stage, each station uses average success probability ($\mathcal{T}_S$) and average collision probability ($\mathcal{T}_C$) for a transmission, as derived in Eqs. (2) and (3), respectively.

D. Packet Transmission Probability

From the channel independence model, the only non null one step transition probabilities in the Markov chain, given in Fig. 2, are as follows.

$$\begin{cases} P\{i,k|i,k+1\} = 1 & k \in (0, W_i - 2), i \in (0, m) \\ P\{0,k|i,0\} = \frac{1-\mathcal{T}_C}{W_0} & k \in (0, W_0 - 1), i \in (0, m) \\ P\{i,k|i-1,0\} = \frac{\mathcal{T}_C}{W_i} & k \in (0, W_i - 1), i \in (1, m) \\ P\{m,k|m,0\} = \frac{\mathcal{T}_C}{W_m} & k \in (0, W_m - 1) \\ P\{i,0|0,k\} = \frac{\mathcal{T}_S}{W_0} & k \in (0, W_0 - 1), i \in (1, m) \end{cases} \tag{4}$$

The first equation in Eqs. (4) accounts for the fact that, at the beginning of each slot time, the back-off time is decremented. The second equation accounts for the fact that a new packet, following a successful packet transmission, starts with back-off stage 0, and thus, the back-off is initially uniformly chosen in the range $(0, W_0 - 1)$. The other cases model the system after an unsuccessful transmission. In particular, as considered in the third equation of Eqs. (4), when an unsuccessful transmission occurs at the back-off stage $i - 1$, the back-off stage increases, and the new initial back-off value is uniformly chosen from the range $(0, W_i)$. Finally, the fourth equation models the fact that once the back-off stage reaches the value m, it is not increased in subsequent packet transmissions. We assume that at the maximum back-off stage, a station keeps on trying for retransmitting the packet with the back-off counter uniformly chosen from $(0, W_m - 1)$, where $W_m = CW_{max} = 2^m CW_{min}$. The last equation in Eqs. (4) indicates a successful transmission using one of the channel bonding level.

Let $b_{i,k} = \lim_{t\to\infty} P\{s(t) = i, b(t) = k\},\ i \in (0, m),\ k \in (0, W_i - 1)$ be the stationary distribution of the chain. We now compute a closed-form solution for the Markov chain shown in Fig. 2. First, note that,

$$\begin{aligned} b_{i-1,0} \cdot \mathcal{T}_C = b_{i,0} \rightarrow b_{i,0} = \mathcal{T}_C^m b_{0,0} \quad 0 < i < m \\ b_{m-1,0} \cdot \mathcal{T}_C = (1 - \mathcal{T}_C) b_{m,0} \rightarrow b_{m,0} = \frac{\mathcal{T}_C^m}{1 - \mathcal{T}_C} b_{0,0} \end{aligned} \tag{5}$$

Owing to the chain regularities, for each $k \in (1, W_i - 1)$, we derive the following set of equations.

$$b_{i,k} = \frac{W_i - k}{W_i} \cdot \begin{cases} (1 - \mathcal{T}_C) \sum_{j=0}^{m} b_{j,0} & i = 0 \\ \mathcal{T}_C \cdot b_{i-1,0} & 0 < i < m \\ \mathcal{T}_C \cdot (b_{m-1,0} + b_{m,0}) & i = m \end{cases} \tag{6}$$

Based on Eq. (5), and using of the fact that $\sum_{i=1}^{m} b_{i,0} = \frac{b_{0,0}}{(1-\mathcal{T}_C)}$, we can rewrite Eq. (6) as follows.

$$b_{i,k} = \tfrac{W_i - k}{W_i} b_{i,0} \quad i \in (0, m), \quad k \in (0, W_i - 1) \tag{7}$$

Therefore, by Eq. (5) and Eq. (7), all the values $b_{i,k}$ are expressed as functions of the value $b_{0,0}$ and of the conditional collision probability $\mathcal{T}_C$. $b_{0,0}$ is finally determined by imposing the normalization condition, that simplifies as follows.

$$\begin{aligned} 1 &= \sum_{i=0}^{m} \sum_{k=0}^{W_i - 1} b_{i,k} = \sum_{i=0}^{m} b_{i,0} \sum_{k=0}^{W_i - 1} \frac{W_i - k}{W_i} \\ &= \frac{b_{0,0}}{2} \left[W \left(\sum_{i=1}^{m-1} (2\mathcal{T}_C)^i + \frac{(2\mathcal{T}_C)^m}{1 - \mathcal{T}_C} \right) + \frac{1}{1 - \mathcal{T}_C} \right] \end{aligned} \tag{8}$$

Here, W is the average contention window size. From Eq. (8), we compute $b_{0,0}$ as follows.

$$b_{0,0} = \frac{2(1 - 2\mathcal{T}_C)(1 - \mathcal{T}_C)}{(1 - 2\mathcal{T}_C)(W + 1) + \mathcal{T}_C W (1 - (2\mathcal{T}_C)^m)} \tag{9}$$

Let τ be the probability that a station transmits in a randomly chosen slot duration. As any transmission occurs when the back-off counter reaches zero regardless of the back-off stage, we can represent τ as follows.

$$\begin{aligned} \tau &= \sum_{i=0}^{m} b_{i,0} = \frac{b_{0,0}}{1 - \mathcal{T}_C} \\ &= \frac{2(1 - 2\mathcal{T}_C)}{(1 - 2\mathcal{T}_C)(W + 1) + \mathcal{T}_C W (1 - (2\mathcal{T}_C)^m)} \end{aligned} \tag{10}$$

E. Modeling Dynamic Channel Bonding

Now, for the ease of representation and analysis, we use a special case when $c = 1$, that means we have two channels c_1 and c_2, each of width 20 MHz. There would be three types of stations in this case – (a) stations that transmit at 20 MHz with c_1 as the primary channel (**Group 1 stations**), (b) stations that transmit at 20 MHz with c_2 as the primary channel (**Group 2**

stations), and (c) stations that transmit at 40 MHz, with c_1 as the primary channel and c_2 as the secondary channel (**Group 3 stations**). Let τ_1, τ_2 and τ_3 be the probabilities that a Group 1, Group 2 and Group 3 station transmit in a randomly chosen slot, respectively. We can represent τ_1, τ_2 and τ_3 as follows.

$$\tau_1 = \frac{2(1-2P_{c_1})}{(1-2P_{c_1})(W+1)+P_{c_1}W(1-(2P_{c_1})^m)} \quad (11)$$
$$\tau_2 = \frac{2(1-2P_{c_2})}{(1-2P_{c_2})(W+1)+P_{q_2}W(1-(2P_{c_2})^m)} \quad (12)$$
$$\tau_3 = \frac{2(1-2\mathcal{T}_C)}{(1-2\mathcal{T}_C)(W+1)+\mathcal{T}_C W(1-(2\mathcal{T}_C)^m)} \quad (13)$$

Here, P_{c_1} and P_{c_2} are the probabilities of collisions for channel c_1 and channel c_2, respectively, given that a station transmits a packet in the respective channel. Now, assume that N_1, N_2 and N_3 are the number of stations in Group 1, Group 2 and Group 3, respectively, with total number of stations $N = N1 + N2 + N3$. Then we can compute P_{c_1} and P_{c_2} as follows.

$$P_{c_1} = 1-\left[(1-\tau_1)^{N_1-1}\cdot(1-\tau_3)^{N_3}\right] \quad (14)$$
$$P_{c_2} = 1-\left[(1-\tau_2)^{N_2-1}\cdot(1-\tau_3)^{N_3(1-q)}\right] \quad (15)$$

For a DBCA station, there can be two types of packet collisions. Consider a packet from a station of Group 1. The packet can get collided either with a packet from another station of Group 1, or a packet from a station of Group 3. We express these two probability components as Q_1 and Q_2, where Q_1 denotes the probability that a station collides with another station from the same group, and Q_2 denotes the probability that it collides with a station which uses a higher channel bonding level (Group 3 in this case). We compute Q_1 and Q_2 as follows.

$$Q_1 = 1-\left[(1-\tau_1)^{N_1}\cdot(1-\tau_3)^{N_3-1}\right] \quad (16)$$
$$Q_2 = 1-\left[(1-\tau_1)^{N_1}\cdot(1-\tau_2)^{N_2}\cdot(1-\tau_3)^{N_3-1}\right] \quad (17)$$

Now, we can compute the values of all the probabilities based on fixed point iterations over Eqs. (11)-(17).

F. Throughput Estimation for DBCA

Next, we estimate the throughput for channel c_1 and channel c_2. Let P_{tr_1} and P_{tr_2} be the probabilities that there is at least one transmission in a randomly chosen slot for channels c_1 and c_2. P_{tr_1} and P_{tr_2} can be computed as follows.

$$P_{tr_1} = 1-\left[(1-\tau_1)^{N_1}\cdot(1-\tau_3)^{N_3}\right] \quad (18)$$
$$P_{tr_2} = 1-\left[(1-\tau_2)^{N_2}\cdot(1-\tau_3)^{N_3(1-q)}\right] \quad (19)$$

Let P_{s_1} and P_{s_2} be the conditional probabilities that a transmission is successful at channel c_1 and channel c_2, respectively. These probabilities are computed as follows.

$$P_{s_1} = \left[\frac{N_1\tau_1(1-\tau_1)^{N_1-1}\cdot(1-\tau_3)^{N_3}}{P_{tr_1}} + \frac{N_3\tau_3(1-\tau_1)^{N_1}\cdot(1-\tau_3)^{N_3-1}}{P_{tr_1}}\right] \quad (20)$$
$$P_{s_2} = \left[\frac{N_2\tau_2(1-\tau_2)^{N_2-1}\cdot(1-\tau_3)^{N_3(1-q)}}{P_{tr_2}} + \frac{N_3\tau_3(1-\tau_2)^{N_2}\cdot(1-\tau_3)^{N_3(1-q)-1}}{P_{tr_2}}\right] \quad (21)$$

Let S_1 and S_2 be the normalized throughputs for channel c_1 and channel c_2, respectively. Following the model given in [4], we compute the channel throughputs as follows. Let $E[P]$ be the average packet payload size. Then the average amount of payload information successfully transmitted in a slot time is $P_{tr_1}P_{s_1}E[P]$, since a successful transmission occurs in a slot time with probability $P_{tr_1}P_{s_1}$. The average length of a slot time is readily obtained considering that, with probability $1-P_{tr_1}$, the slot time is empty; with probability $P_{tr_1}P_{s_1}$, it contains a successful transmission, and with probability $P_{tr_1}(1-P_{s_1})$, it contains a collision. Hence, S_1 is computed as follows.

$$S_1 = \frac{P_{tr_1}P_{s_1}E[P]_1}{(1-P_{tr_1})\sigma + P_{tr_1}P_{s_1}T_{s_1} + P_{tr_1}(1-P_{s_1})T_{x_1}} \quad (22)$$

Here, T_{s_1} and T_{x_1} are the average times the channel c_1 is sensed busy because of a successful transmission, and a collision, respectively. σ is the duration of an empty slot time. Of course, the values $E[P], T_{s_1}, T_{x_1}$, and σ must be expressed with same unit.

Similarly, we can express S_2 as follows.

$$S_2 = \frac{P_{tr_2}P_{s_2}E[P]_2}{(1-P_{tr_2})\sigma_2 + P_{tr_2}P_{s_2}T_{s_2} + P_{tr_2}(1-P_{s_2})T_{x_2}} \quad (23)$$

Here, T_{s_2} and T_{x_2} are the average times the channel c_2 is sensed busy because of a successful transmission, and a collision, respectively.

III. Model Validation and Analysis

The IEEE 802.11ac testbed is developed using IEEE 802.11ac supported ASUS AC-3200RT wireless router flushed with `asus wrt-merlin` firmware. We have used ASUS USB-AC56 dongles as the wireless stations. The traffic is generated using `iperf` tool. We have configured the wireless router to work in two modes 20 MHz and 40 MHz over 5 GHz channel. The router operates in ‘monitor’ mode. We have used channel 116 (center frequency 5580 MHz) and channel 118 (center frequency 5590 MHz). The various parameters used in the testbed are summarized in Table I. Every individual scenario has been executed for continuous 12 hours.

Model validation: Fig. 3 compares the numerical results obtained from the proposed model with the testbed results. We have computed the results for multiple scenarios, by varying the values of $N1$, $N2$ and $N3$ (number of nodes for the three

TABLE I
PARAMETERS USED FOR MODEL ANALYSIS

Feature	Value	Feature	Value
Packet Payload	65535 bytes	MAC Header	304 bits
PHY Header	128 bits	ACK	112 bits + PHY Header
Bit Rate(20MHz)	234.0 MBit/s	Bit Rate(40MHz)	486.0 MBit/s
Propagation Delay	1 μs	Slot time	9 μs
SIFS	16 μs	DIFS	34 μs

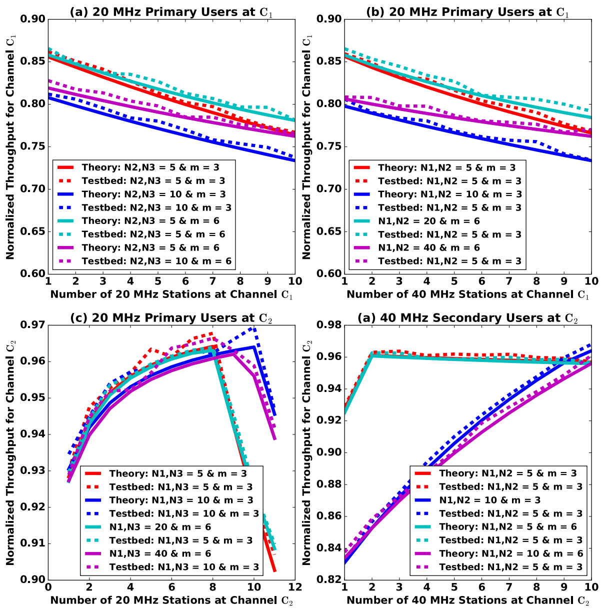

Fig. 3. Theory versus Testbed Results

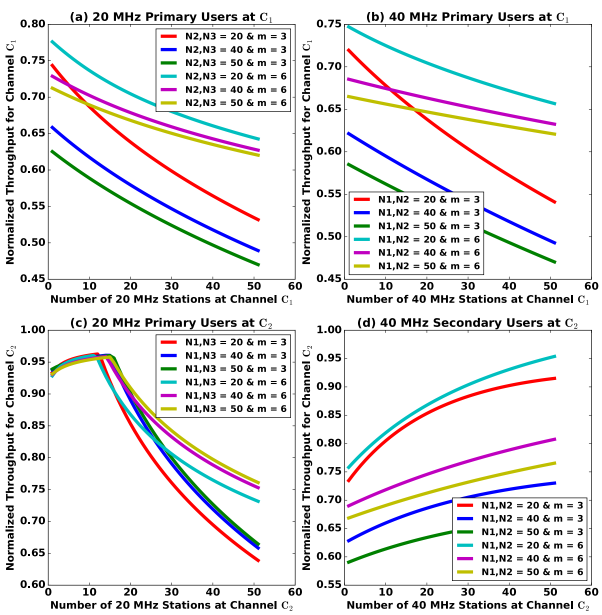

Fig. 4. Normalized Throughput with respect to Number of Stations ($W = 32$)

groups of stations as discussed during the model development) and for various values of back-off stage m. Here, we consider CW size (W) = 32.

Analysis of Normalized Throughput: From Fig. 4(a), it is

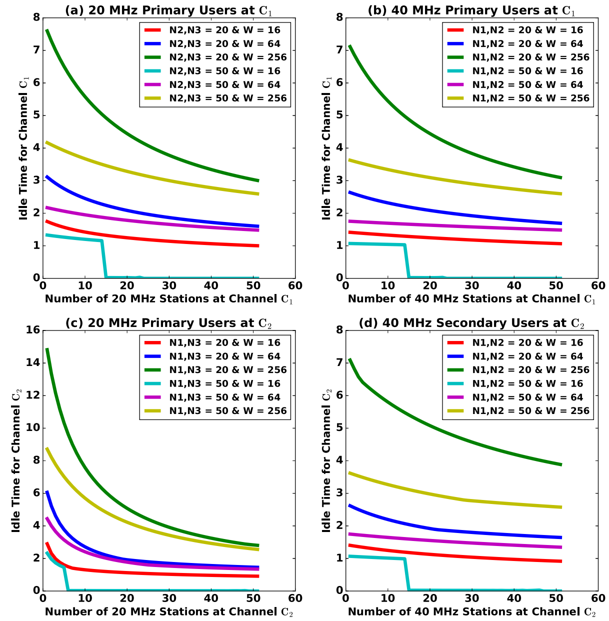

Fig. 5. Idle Time with respect to the Number of Stations ($m = 6$)

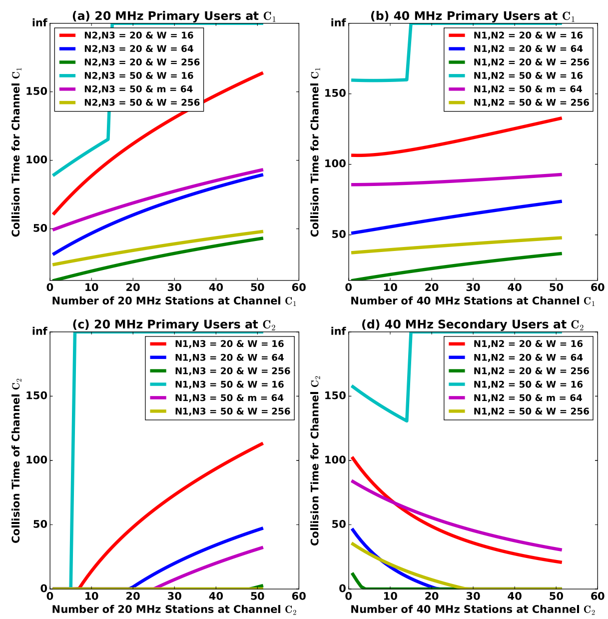

Fig. 6. Collision Time with respect to the Number of Stations ($m = 6$)

obvious that as N_1 increases, due to collisions at the channel c_1, the throughput reduces. We have similar observations for Fig. 4(b), where the 40 MHz stations use channel c_1 as the primary channel. From Fig. 4(c), we observe that the channel throughput drops after the bandwidth gets saturated. We have an interesting observation from Fig. 4(d). The 40 MHz stations use channel c_2 as the secondary channel. As the number of 40 MHz stations increases, the additional capacity available at channel c_2 gets utilized. Further, although the throughput for c_2 slowly moves towards saturation, the performance does not drop as the 40 MHz stations utilize channel c_2

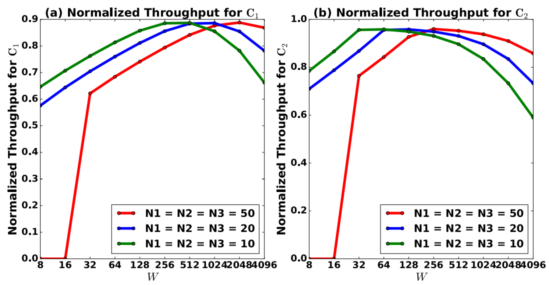

Fig. 7. Normalized Throughput with respect to CW Size ($m = 6$)

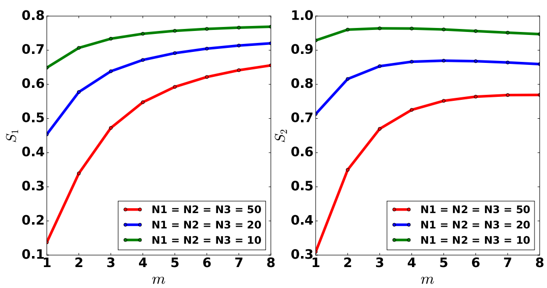

Fig. 8. Throughput with respect to Back-off Stage

opportunistically. On contrary, the increase in 20 MHz primary stations at channel c_2 results in a sharp drop in saturation throughput, as we observe from Fig. 4(c).

We observe the idle time and collision time for the two channels, as shown in Fig. 5 and Fig. 6. Idle time indicates the average number of slots a channel remains idle, and collision time is the average number of slots for which the channel bandwidth is wasted due to collision. As the secondary channel is used opportunistically, a 40 MHz station grabs the secondary channel when it senses the channel to be free, without going for a back-off. Because of this particular behavior at DBCA, the primary users get affected, because they sense the channel to be busy, and then go for the back-off. This introduces a type of starvation in the channel, which results in short-term unfairness. As the primary users use back-off to get access to the channel, at every iteration, they increase the back-off stage as well as the back-off counter. Consequently, they experience sharp drop in throughput, as we observe from Fig. 4(c).

Effect of CW Size and Back-off Stage: We observe that after a CW threshold, the normalized throughputs for both the channels drop (Fig. 7). This is because high value of the CW increases waiting time for carrier sensing, and this can reduce the utilization of the channel. Further, the drop is more in c_2, because the primary users at c_2 need to wait more for a high CW, when they experience a collision in the channel. Finally, we analyze the effect of back-off stage (m) on channel throughput, as shown in Fig. 8. In a nutshell, a proper distribution of channel bonding levels and controlled allocation of primary and secondary channels are required to ensure short-term fairness in the network.

IV. Conclusion

This paper provides the first mathematical model to analyze the performance of DBCA for high throughput wireless access networks. We have developed a Markov chain based model to understand the impact of primary and secondary users on primary and secondary channel throughput. The proposed model is validated based on real experimental results over a testbed. We observed that although the secondary users can improve channel throughput by reducing the channel idle time, they have a significant impact on the performances of the primary users for those channels. The proposed model in this paper can act as a baseline for such performance optimization over IEEE 802.11ac based networks.

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