# Performance Analysis of Channel Bonding in IEEE 802.11ac WLANs

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***Abstract*—Channel bonding is one of the strategies considered in IEEE 802.11ac to increase the performance of WLANs. However, besides the obvious gains from using wider channels in terms of higher achievable transmission rates, there are also several potential drawbacks that may seriously compromise the overall WLAN performance, most notably the higher probability to suffer from external interference. In this letter, we evaluate the performance of the two channel access protocols defined in IEEE 802.11ac to be used along with channel bonding using an analytical model. The presented analytical model is able to capture the relations between the different aspects that affect the WLAN performance when channel bonding is used, as well as the operation of both access protocols. The results obtained using the analytical model confirm that channel bonding is severely affected by the presence of other networks, even when the dynamic bandwidth channel access protocol is used, which excludes its applicability in crowded scenarios.**

***Index Terms*—IEEE 802.11ac, channel bonding, static and dynamic bandwidth channel access, WLANs**

## I. INTRODUCTION

One of the strategies considered in the IEEE 802.11ac amendment for increasing the throughput of WLANs is channel bonding [1]. Channel bonding simply consists in grouping several basic channels to obtain a wider one. However, the resulting wider channel may overlap with the channels used by other wireless networks in the vicinity, which may significantly compromise the performance of all of them. Therefore, effective channel access protocols must be considered along with the use of channel bonding.

Two channel access protocols are being considered for inclusion in the IEEE 802.11ac amendment: the Static Bandwidth Channel Access Protocol (SBCA), which requires finding the whole channel empty before starting a packet transmission; and the Dynamic Bandwidth Channel Access Protocol (DBCA), which is able to dynamically adapt the channel width to the instantaneous spectrum availability.

The performance of channel bonding in IEEE 802.11ac WLANs has been previously investigated by simulation in [3], [4], where both SBCA and DBCA protocols are considered. The results presented in [3], [4] show that channel bonding is able to provide significant throughput gains, but also corroborate that those gains are severely compromised by the activity of the overlapping wireless networks.

In this letter, we present an analytical model to evaluate the performance of both SBCA and DBCA protocols. The analytical model is then used to investigate the cases and conditions in which each channel access scheme is effective, namely in terms of the number of channels bonded, the activity from other wireless networks in those channels, and the position of the primary channel of the target WLAN. Unlike simulation, the presented analytical model can be applied only to a subset of representative cases. However, it have the advantage of highligthing the relations between parameters and the effect of tuning them.

The letter is structured as follows. In Section II, both SBCA and DBCA schemes are described. In Section III, the analytical model is presented, as well as the considerations and assumptions made to build it. In Section IV, we show the throughput of each scheme in terms of the number of channels bonded and the interferer's behavior, which allows us to determine in which conditions each scheme performs best. Finally, the conclusions of this paper and some future work directions are drawn in Section V.

## II. CHANNEL BONDING IN IEEE 802.11AC

An IEEE 802.11ac Basic Service Set (BSS) composed of an Access Point (AP) and a group of Stations (STAs) is considered. A set of predefined 20 MHz channels, to which we will refer as *basic channels* hereafter, are at the disposal of the BSS. When the BSS is initiated, it selects a channel $C$ of width $W$ comprising a contiguous subset of the basic channels. The width $W$ is selected based on the BSS's capabilities and can take values from $\mathcal{B} = \{20,\ 40,\ 80,\ 160\}$ MHz, as specified by IEEE 802.11ac. In other words, the selected channel $C$ can be composed of $N \in \{1, 2, 4, 8\}$ basic channels. A single basic channel within $C$ is set as the primary channel, and all the others are considered as secondary. The selected bandwidth, $W$, is the maximum allowed channel width, from which a contiguous subset of channels containing the primary are selected for each transmission, based on their availability and the channel access protocol used. We denote the channel selected for transmission by $c$, its width in MHz by $w$, and the number of basic channels it contains by $n$. Note that the values of $c$, $w$, and $n$ change for each transmission. In contrast, $C$, $W$, and $N$ are selected during the initialization and are fixed for all transmissions.

### A. Channel Access Protocols

The two channel access protocols, SBCA and DBCA, share the same operation until their backoff counter reaches zero. When a node has a packet ready for transmission, it listens to the BSS's primary channel. Once the channel has been sensed free for the duration of an AIFS (Arbitration InterFrame Space), the node starts the backoff procedure by randomly

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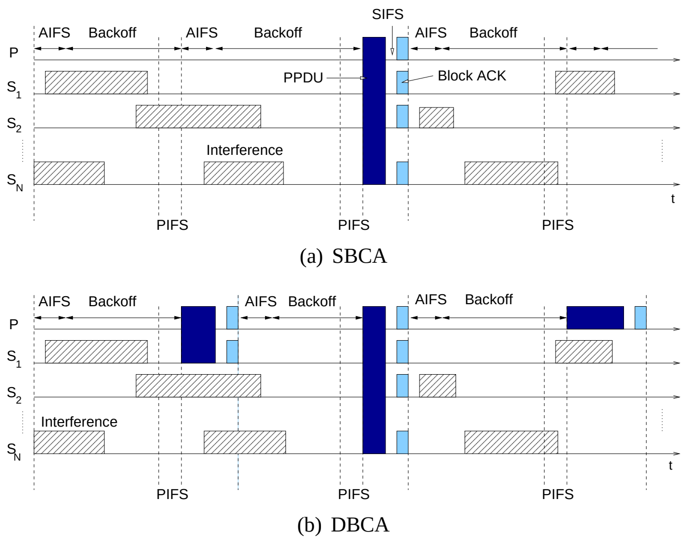



(a) SBCA

(b) DBCA

Fig. 1. Temporal evolution of the SBCA and DBCA. In the Figures, P indicates the primary and $S_i$ the secondary channels.

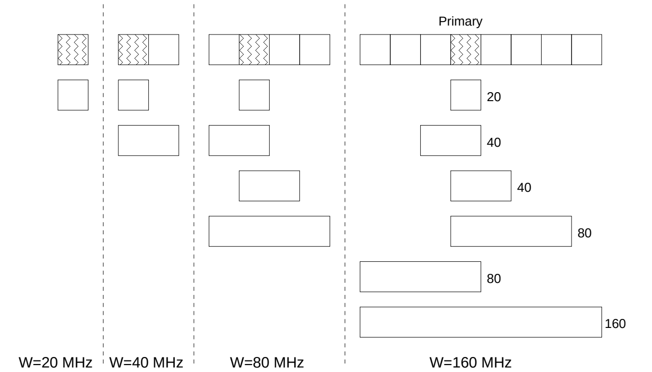



Fig. 2. The number of possible channel bonding combinations depends on the position of the primary channel (hashed) within $W$

initializing a counter. This counter will be decremented by one at each empty slot until it reaches zero, at which moment the node starts transmitting. The channel on which the packet will be transmitted is selected based on the status of the secondary channels, which are sensed for PIFS (Point coordination function Interframe Space) seconds before the backoff counter reaches zero. Based on the channel access protocol, the channel $c$ is selected as follows:

- **SBCA:** If all the channels in $C$ have been empty during the PIFS period, a packet transmission over the entire channel width will be initiated, i.e., $w = W$, or equivalently, $c = C$. Otherwise, the current transmission is deferred, and the entire procedure is repeated.
- **DBCA:** From the subset of channels that have been detected empty during the PIFS period, the largest contiguous group that has one of the allowed widths in $\mathcal{B}$ and includes the primary channel is chosen and used for the next transmission.

In Figure 1, the operation of both schemes is shown for a specific case. Unlike SBCA, DBCA is able to transmit at every attempt, although not always using all the basic channels in $C$. Note that if any interference appears in a secondary channel during a transmission, it may corrupt the ongoing packet transmission resulting in transmission errors.

### B. Position of the Primary Channel

When the DBCA is used, the position of the primary channel within $C$ is relevant. Selecting a channel in the center of $C$ as the primary channel, increases the chances of finding larger contiguous sets of basic channels that include the primary, as shown in Figure 2. For example, observe that for $W = 160$ MHz, by positioning the primary channel on the 4th basic channel within $C$, we can obtain two channels of $w = 40$ MHz and two of $w = 80$ MHz, instead of only one of each if we place the primary channel at the extremes of $C$.

## III. System Model and Performance Analysis

We focus on a single BSS in which all nodes are able to transmit and receive packets using a channel width of $W$. Only downlink traffic is considered, and the AP is assumed to be saturated, i.e., it always has packets to transmit. It is also assumed that the primary channel is only occupied by the target BSS. The $N-1$ secondary channels may be occupied by other networks, which act as interferers when the target BSS uses channel bonding.

### A. Secondary Channels' Behavior

In the secondary channels, the behavior of the potential interferers is difficult to predict, as there can be different types of license-exempt wireless networks, including other WLANs, operating in those channels. Therefore, we cannot consider any specific behavior for the wireless networks operating in the secondary channels. For instance, they may not listen to the channel before transmitting or, may be in a position where they are not able to overhear the transmissions from the target BSS, and therefore, they will act as hidden nodes.

In such a scenario, we assume that all the wireless networks operating in the secondary channels are completely independent from the operation of the target BSS. Therefore, their activity, from the point of view of the target BSS, can be simply modeled by a two-state Markov chain **(reference?)**. A secondary channel will be in the *free* state if none of the wireless networks operating in it are transmitting. Otherwise, the secondary channel will be in the *busy* state.

The busy and free periods in secondary channels are then exponentially distributed with parameters $\lambda_\mathrm{b}$ and $\lambda_\mathrm{f}$ respectively. The fraction of time that the channel is busy and free are respectively $p_\mathrm{b} = \frac{\lambda_\mathrm{f}}{\lambda_\mathrm{f}+\lambda_\mathrm{b}}$ and $p_\mathrm{f} = 1 - p_\mathrm{b}$, and the average duration of busy and free periods is $T_\mathrm{b} = \frac{1}{\lambda_\mathrm{b}}$ and $T_\mathrm{f} = \frac{1}{\lambda_\mathrm{f}}$ respectively.

Finally, the probability that the AP of the target BSS finds a secondary channel empty is

$$\theta = p_\mathrm{f}\, e^{-\lambda_\mathrm{f} \cdot \mathrm{PIFS}} \tag{1}$$

which is the probability to find a channel free when the target BSS starts to sense it, times the probability that the channel remains free for a PIFS period.

### B. Performance Analysis

The throughput for channel scheme $\psi \in \{\text{SBCA}, \text{DBCA}\}$ when the primary channel is in position $k \in \{1, \dots, N\}$ within $C$ can be calculated as

$$S_k^\psi = \frac{\sum_{n=1}^N \phi_{n|k,N}^\psi \beta(n,L)L}{\sum_{n=1}^N \phi_{n|k,N}^\psi D_\psi(n,L)} \tag{2}$$

where $\phi_{n|k,N}^\psi$ is the probability that a transmission is done using $n$ basic channels, when the primary channel is the $k$th channel in $C$. Also, $\beta(n,L)$ is the probability that the transmission of a packet of length $L$ bits over the $n$ selected channels has not been corrupted by interference (i.e., all the channels used to transmit this packet have remained free for the entire transmission time). Finally, $D_\psi(n,L)$ is the expected transmission delay of the transmitted packet, from the moment it reaches the head of the line until it is successfully received.

The expected transmission delay when the protocol $\psi$ and $n$ channels are used is given by:

$$D_\psi(n,L) = \frac{1}{1-\alpha_\psi}(\text{AIFS} + T_{\text{backoff}}) + T(n,L) \tag{3}$$

where $\alpha_\psi$ is the probability that a transmission is deferred due to channel unavailability, and therefore, $1/(1-\alpha_\psi)$ is the expected number of attempts required for a successful channel access. $T_{\text{backoff}}$ is the average time spent in backoff at each attempt. Finally, $T(n,L)$ is the packet transmission duration, which for the IEEE 802.11ac is

$$\begin{aligned} T(n,L) = &\left(T_{\text{PHY}} + \left\lceil \frac{\text{SF} + (\text{MH} + L) + \text{TB}}{L_{\text{DBPS}}(n)} \right\rceil T_s\right) + \\ &+ \text{SIFS} + \left(T_{\text{PHY}}(1) + \left\lceil \frac{\text{SF} + L_{\text{BA}} + \text{TB}}{L_{\text{DBPS}}(1)} \right\rceil T_s\right) \end{aligned} \tag{4}$$

where $T_{\text{PHY}} = 40\mu$s is the duration of the PHY-layer preamble and headers and, $T_s = 4$ $\mu$s, the duration of an OFDM (Orthogonal Frequency Division Multiplexing) symbol. SF is the *service field* (16 bits), TB is the number of *tail bits* (6 bits), MH is the *MAC header* (288 bits), and $L_{\text{DBPS}}(n) = N_{\text{m}} \cdot N_{\text{c}} \cdot \xi(n)$ is the number of bits in each OFDM symbol, where $N_{\text{m}}$ is the number of bits per modulation symbol, $N_{\text{c}}$ is the coding rate, and $\xi(n)$ is the number of data subcarriers when $n$ basic channels are bonded together. Finally, the length of the $L_{\text{BA}}$ is 256 bits. The values are obtained from the IEEE 802.11ac draft [1].

Since the capture effect is not considered, the probability that a packet is not corrupted by interference is the probability that no secondary channel changes from the free to the busy state during the packet transmission, which is given by:

$$\beta(n,L) = e^{-(n-1)\lambda_f T(n,L)} \tag{5}$$

In the next subsections, $\phi_{n|k,N}^\psi$ and $\alpha_\psi$ are derived for each channel-access scheme.

### C. SBCA

In this case, $\alpha_{\text{SBCA}} = 1 - \theta^{N-1}$, which is the probability that at least one secondary channel is detected busy when the backoff counter reaches zero.

To find $\phi_{n|k,N}^{\text{SBCA}}$, we have to take into account that SBCA only transmits when all channels are free, which means that $n = N$. Therefore, the position of the primary channel becomes irrelevant, and we get

$$\phi_{n|k,N}^{\text{SBCA}} = \begin{cases} 1, & n = N, \forall k \\ 0, & \text{otherwise} \end{cases} \tag{6}$$

### D. DBCA

For DBCA, even if all secondary channels are busy, the primary channel can be selected as the transmission channel ($n = 1$). Given that the primary channel is assumed to never suffer external interference, no transmission is ever deferred and $\alpha_{\text{DBCA}} = 0$.

Furthermore, as it was shown in Figure 2, the position of the primary channel is relevant in this case. The probability to make a transmission using $n \le N$ basic channels for DBCA is the probability to find a contiguous set of $n \in \{1,2,4,8\}$ free basic channels containing the primary (recall that the transmission channel width, $w$, is required to be in $\mathcal{B}$). This probability can be calculated as follows

$$\phi_{n|k,N}^{\text{DBCA}} = \sum_{l=n}^{\min(2n-1,N)} p_{l|k,N} \tag{7}$$

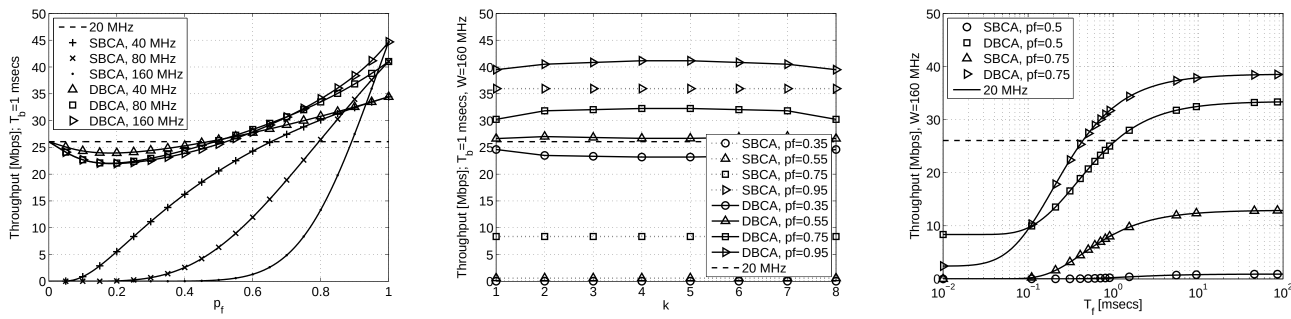
where $p_{l|k,N}$, is the probability that a contiguous set of exactly $l$ basic channels containing the primary are empty, given by

$$p_{l|k,N} = \theta^{l-1}\left(b_2(l) + (1-\theta)b_1(l) + (1-\theta)^2 b_0(i)\right) \tag{8}$$

where, for given $k$ and $N$, $b_i(l)$ is the number of possible contiguous sets containing $l$ basic channels, including the $k$th, within $C$ that share $i \in \{0,1,2\}$ of their boundaries (leftmost and rightmost basic channels in each set) with $C$. In other words, $b_0(l)$ is the number of possible sets of $l$ basic channels containing $k$ that do not contain neither the 1st nor the $N$th basic channel in $C$, $b_1(l)$ is the number of such sets that contain either the 1st or the $N$th basic channel (but not both) in $C$, and finally, $b_2(l)$ is the number of such sets that contain both the 1st and the $N$th basic channels in $C$.

$$\begin{aligned} b_2(l) &= I\{l = N\} \\ b_1(l) &= I\{l \neq N\}\left(I\{k \le l\} + I\{k > N-l\}\right) \\ b_0(l) &= [\min(k, N-l) - \max(2, k-l+1) + 1]^+ \end{aligned} \tag{9}$$

where $I\{x\}$ is the indicator function, which is equal to 1 when the condition $x$ is true and is 0 otherwise, and $[x]^+$ is the non-negative part of $x$, which is equal to $x$ when $x \ge 0$ and is zero otherwise.




(a) Different $p_f$ values

(b) Position of the Primary Channel

(c) Different $T_\mathrm{f}$ values

Fig. 3. Achievable Throughput for the target WLAN

TABLE I
PARAMETER VALUES BASED ON IEEE 802.11AC [1]

| Parameter | Notation | Value |
|---|---|---|
| Channel width (Number of data subcarriers) | $W(\xi)$ | 20 (52), 40 (108) 80 (234), 160 (468) |
| Modulation (64-QAM) | $N_m$ | 6 bits |
| Coding Rate | $N_c$ | 5/6 bits |
| Packet Length | $L_d$ | 12000 bits |
| Backoff Contention Window | CW | 16 slots |
| Average time spent in backoff | $T_\mathrm{backoff}$ | $\frac{CW}{2} \cdot 9$ $\mu$s |
| AIFS | - | 34 $\mu$s |

## IV. Numerical Results

In this section, we plot and compare the achievable throughput of a IEEE 802.11ac WLAN using channel bonding. The values for the parameters used are shown in Table I. It is worth to remark here that the considered scenario, described in Section III, is the worst-case one in terms of the behavior of the external interference, as it assumes that all the activity in the secondary channels comes from nodes that are hidden to the target WLAN, or not use carrier sense to access the channel.

Figure 3(a) shows the throughput versus $p_\mathrm{f}$, the probability that a secondary channel is free, achieved by SBCA and DBCA schemes for $T_\mathrm{b} = 1$ msec, respectively. In all the plots related to the DBCA protocol, the primary channel has been placed in the position that maximizes the number of possible channel bonding combinations (i.e., $k = \lfloor N/2 \rfloor$). It can be observed how DBCA outperforms SBCA for all $p_\mathrm{f}$ values. For the DBCA, the use of channel bonding is only recommended for $p_f > 0.5$, as otherwise using a single basic channel (i.e., no channel bonding) provides the best performance. Furthermore, for the DBCA scheme, given that channel bonding is effective, the best option is to set $W$ always to 160 MHz, and take advantage of the adaptation capabilities of the DBCA protocol.

Figure 3(b) shows the throughput achieved by SBCA and DBCA schemes versus the position of the primary channel for $T_\mathrm{b} = 1$ msec and $W = 160$ MHz. As expected, the position of the primary channel only affects the performance of the DBCA scheme. However, from the results, it can be concluded that the impact it has on the DBCA performance is low. In the one hand, the throughput does not scale linearly with the channel width, as protocol and frame overheads are not affected by the use of wider channels. In the other hand, using wider channels increases the probability that a transmission is corrupted by external interference. This effect is clearly observed for low $p_f$ values. In that case, placing the primary channel in the $k = \lfloor N/2 \rfloor$ basic channel is detrimental in terms of throughput, as the extra packets that can be transmitted per second do not compensate the higher packet losses caused by the external interference.

Finally, Figure 3(c) shows the throughput for both SBCA and DBCA protocols versus $T_\mathrm{f}$ for $W = 160$ MHz. As it can be observed, when the secondary channels have long free and busy periods, both SBCA and DBCA protocols perform better in terms of throughput compared to the case when the secondary channels change rapidly between both states.

## V. Conclusions and Final Remarks

We have presented an analytic model to evaluate the performance of channel bonding in IEEE 802.11ac WLANs. Results show that channel bonding can offer some interesting performance gains, although only in scenarios where the secondary channels are mostly empty.

The use of channel bonding in combination with the new mechanisms defined in IEEE 802.11ac must be also evaluated in future works, as there are several tradeoffs to be considered. For instance, for a given transmission power, the use of wider channels imply that the Signal to Noise ratio per subcarrier will be lower, which may result in the selection of lower transmission rates. Furthermore, in case that Multi-user Beamforming is considered, the use of wider channels require a higher amount of Channel State Information to be fedback from the STAs to the AP, hence increasing the network overheads.

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