A Throughput Study for Channel Bonding in IEEE 802.11ac Networks

Mun-Suk Kim, Tanguy Ropitault, Sukyoung Lee, and Nada Golmie

***Abstract*— Several analytical models for the channel bonding feature of IEEE 802.11ac have previously been presented for performance estimation, but their accuracy has been limited by the assumptions that there are no collisions or all nodes are in saturated state. Therefore, in this letter, we develop an analytical model for the throughput performance of channel bonding in IEEE 802.11ac, considering the presence of collisions under both saturated and non-saturated traffic loads, and our numerical results were validated by a simulation study.**

***Index Terms*— Channel bonding, throughput, 802.11ac.**

I. Introduction

THE channel bonding technique was introduced in IEEE 802.11ac to use wider channels of 40, 80, and 160 MHz by grouping two, four, and eight basic 20 MHz channels, respectively [1]. In order to efficiently utilize these wider channels, IEEE 802.11ac defines two channel access protocols: static and dynamic channel access (SCA and DCA) schemes. Several letters including Park's [2] have evaluated the performance of SCA and DCA, mainly based on simulation studies. Although the performance gains of SCA are analyzed in Bellalta [3] and Faridi *et al.*'s [4] studies, the packet collision probability was not considered, and the saturated traffic condition was assumed in the latter study [4]. Han *et al.* [5] investigated the performance of opportunistic channel bonding under the saturated traffic condition, but saturation load models such as this have not been able to accurately predict the throughput of a wireless local area network (WLAN) because they have been unable to consider the effect of different traffic loads on the nodes associated with it. Thus, in this letter, to more accurately analyze the throughput performance of 802.11ac using SCA, we construct a Markov chain model for the backoff procedure of a node under both saturated and non-saturated traffic loads.

II. Performance Analysis of Channel Bonding

We consider a system with a group of WLANs, where all of the WLANs are within the carrier sense range of each other [3]. Each WLAN is assigned a set of contiguous basic 20 MHz channels after which the WLAN selects one basic channel as its primary channel (PCH) and the others as secondary channels (SCHs). We assume that the PCH of each WLAN is unique and each WLAN shares at least one SCH with the others [1]. Table I summarizes the notations.

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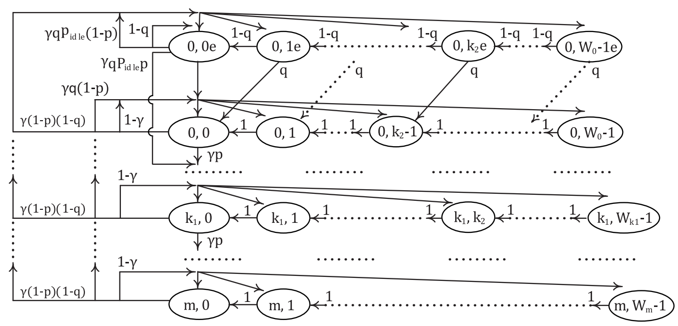

Fig. 1. A non-saturated Markov chain model for 802.11ac channel bonding.

TABLE I

Notations for the Proposed Analytical Model

Notation	Description
k_1 and k_2	The backoff stage and the backoff counter, respectively
q	The probability of at least one packet awaiting transmission at the start of each backoff counter decrement
p	The collision probability that a node and other nodes transmit at the same time in the PCH or SCHs resulting in a collision
$P[s_2\|s_1]$	The transition probability from state s_1 to state s_2
γ	The probability that all SCHs are sensed as idle for the PIFS
W_0	The minimum contention window size
W_{k_1}	The contention window size given k_1, i.e. $W_{k_1} = 2^{k_1} W_0$
m	The maximum value of the backoff stage
P_{idle}	The probability that the PCH is sensed as idle in a timeslot
τ	The probability that the node transmits in a timeslot
F	The ending timeslot number in the TP
L	The number of timeslots spent for a transmission or collision
n_D (n_P)	The number of timeslots spent for the DIFS (or the PIFS)
$\mathcal{T}_1$ ($\mathcal{T}_2$)	The probability that at least one WLAN1 (WLAN2) node attempts to sense SCHs in a timeslot
$P_K(\kappa\|F)$	The probability that WLAN1's nodes attempt to sense SCHs in the κ^{th} timeslot in the TP
$N_K(F)$	The mean number of times that WLAN1's nodes attempt to sense SCHs in the TP where the ending timeslot is the F^{th} timeslot
$\gamma(F)$	The probability that all SCHs are sensed as idle given WLAN1's nodes' attempt to sense SCHs in the TP where the ending timeslot is the F^{th} timeslot
$P_E(F)$	The probability that the ending timeslot is the F^{th} timeslot given that the starting timeslot is the 0^{th} one in the TP
n	The number of nodes associated with each WLAN

A. A Markov Model for a Node Using Channel Bonding

We developed a non-saturated Markov chain to model the backoff procedure of a node using SCA, as shown in Fig. 1. The Markov chain introduces two types of states, namely post-backoff and backoff, which are modeled by a pair of integers (k_1, k_2). The post-backoff states $(0, k_2)_e$ for $k_2 \in [0, W_0 - 1]$ represent a node whose buffer has no packets awaiting transmission. Conversely, the node must have a packet awaiting transmission in the backoff state, (k_1, k_2) for $k_2 \in [0, W_{k_1} - 1]$. Given k_1, the initial value of k_2 is a randomly selected integer in $[0, W_{k_1} - 1]$. While the PCH is sensed

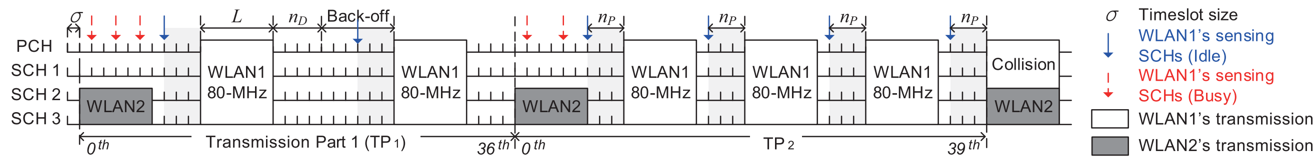

Fig. 2. An example of the timing of WLAN1's and WLAN2's transmissions in WLAN1's PCH and SCHs.

as idle, k_2 is decremented by 1 for every timeslot. Thus, the state transition probabilities for $0 < k_2 < W_{k_1}$, are

$$P[(k_1, k_2 - 1)|(k_1, k_2)] = 1 \quad (1a)$$
$$P[(0, k_2 - 1)_e|(0, k_2)_e] = 1 - q \quad (1b)$$
$$P[(0, k_2 - 1)|(0, k_2)_e] = q \quad (1c)$$

The node senses all of the SCHs for the point coordination function inter-frame space (PIFS) immediately before the PCH is sensed as idle for the distributed coordination function inter-frame space (DIFS) plus the backoff counter time, i.e. before the node is in the state $(k_1, 0)$. If all SCHs are sensed as idle for the PIFS, which occurs with probability γ, the node transmits; otherwise, it restarts the backoff procedure with a new k_2 chosen between $[0, W_{k_1} - 1]$. If a collision occurs in the PCH or SCHs with probability p, then k_1 is increased by 1 up to m; otherwise, if the node transmits successfully, it returns to the $(0, k_2)_e$ or $(0, k_2)$ state with the probability of $(1 - q)$ or q, respectively. Thus, we have

$$P[(0, k_2)_e|(k_1, 0)] = \frac{\gamma(1-p)(1-q)}{W_0} \quad (2a)$$
$$P[(0, k_2)|(k_1, 0)] = \frac{\gamma q(1-p)}{W_0} \quad (2b)$$
$$P[(k_1, k_2)|(k_1, 0)] = \frac{1-\gamma}{W_{k_1}} \quad (2c)$$
$$P[(\min(k_1+1, m), k_2)|(k_1, 0)] = \frac{\gamma p}{W_{\min(k_1+1,m)}} \quad (2d)$$

Lastly, we consider the $(0, 0)_e$ state, where post-backoff is complete but the node's buffer has no packets awaiting transmission. We can suppose a scenario in which a packet arrives in the node's buffer in the $(0, 0)_e$ state. The node begins another stage-0 backoff $(0, k_2)$ if the PCH is sensed as busy during a typical timeslot or if the SCHs are sensed as busy; otherwise, the node transmits. If the transmission succeeds, the node returns to the $(0, k_2)_e$ state. However, if a collision occurs in the PCH or SCHs, the node begins another stage-1 backoff $(1, k_2)$. Thus, the transitions from the $(0, 0)_e$ state are

$$P[(0, 0)_e|(0, 0)_e] = 1 - q + \frac{\gamma q P_{idle}(1-p)}{W_0} \quad (3a)$$
$$P[(0, k_2)_e|(0, 0)_e] = \frac{\gamma q P_{idle}(1-p)}{W_0} \quad (3b)$$
$$P[(0, k_2)|(0, 0)_e] = \frac{q(1-P_{idle}) + qP_{idle}(1-\gamma)}{W_0} \quad (3c)$$
$$P[(1, k_2)|(0, 0)_e] = \frac{\gamma q P_{idle} p}{W_1} \quad (3d)$$

Let $b(k_1, k_2)$ and $b(0, k_2)_e$ be the stationary probabilities of being in states (k_1, k_2) and $(0, k_2)_e$, respectively, corresponding to post-backoff and backoff, respectively. Thus, we can obtain the following normalization condition:

$$\sum_{k_1=0}^{m} \sum_{k_2=0}^{W_{k_1}-1} b(k_1, k_2) + \sum_{k_2=0}^{W_0-1} b(0, k_2)_e = 1 \quad (4)$$

Using Eqs. (1), (2), and (3a), we can write all stationary state probabilities in terms of $b(0, 0)_e$ and then use the normalization equation in Eq. (4) to express $b(0, 0)_e$ in terms of q, p, m, W_0, P_{idle}, and γ in the same way as in [6].

A successful transmission occurs in the following two cases: (i) when a packet arrives in the buffer and all of the PCH and SCHs are sensed as idle in $(0, 0)_e$, and (ii) when all the SCHs are sensed as idle in $(k_1, 0)$ for $0 \le k_1 \le m$. Thus, the transmission probability is $\tau = q\gamma P_{idle} b(0, 0)_e + \gamma \sum_{k_1=0}^{m} b(k_1, 0)$ where $\sum_{k_1=0}^{m} b(k_1, 0) = b(0, 0) + \frac{b(1,0)}{1-p}$. As shown in Fig. 1, $b(1, W_1 - 1) = b(0, 0)\frac{\gamma p}{W_1} + b(0, 0)_e \frac{\gamma q p P_{idle}}{W_1} + b(1, 0)\frac{1-\gamma}{W_1}$, and hence $b(1, 0) = W_1 \cdot b(1, W_1 - 1) = b(0, 0)p + b(0, 0)_e q p P_{idle}$.

We also have $b(0, W_0 - 1)_e = b(0, 0)_e \frac{q\gamma(1-p)P_{idle}}{W_0} + \frac{\gamma(1-p)(1-q)}{W_0} \cdot \sum_{k_1=0}^{m} b(k_1, 0)$. In the $(0, k_2)_e$ chain, recursion from $k_2 = 0$ to $k_2 = W_0 - 1$, leads to $qb(0, 0)_e = b(0, W_0 - 1)_e \cdot (1 - (1 - q)^{W_0})/q$. Thus, $b(0, 0) = b(0, 0)_e \cdot \frac{q^2 W_0 - \gamma q P_{idle}(1-pq)(1-(1-q)^{W_0})}{\gamma(1-q)(1-(1-q)^{W_0})}$. Finally, τ is given by

$$\tau = b(0, 0)_e \left(\frac{q^2 W_0}{(1-p)(1-q)(1-(1-q)^{W_0})} - \frac{\gamma q^2 P_{idle}}{1-q} \right) \quad (5)$$

Using Eq. (5), we can express τ in terms of variables q, p, m, W_0, P_{idle}, and γ. We discuss how to model γ and p in Subsection II-B and P_{idle} in Subsection II-C.

B. Idle Probability of the SCH

To simplify the analysis, we consider an example scenario in which WLAN1 shares its 2nd and 3rd SCHs with WLAN2, as shown in Fig. 2. We assume that the time is allotted with timeslot size σ, and that both WLAN1's and WLAN2's nodes are allowed to transmit only at the beginning of each timeslot although their actual transmissions may occur at any point during a timeslot. Because the transmission timing error is less than $\sigma/2$ under this assumption, it has little effect on the estimation of γ. We assume that the nodes associated with each WLAN have the same value of q.

For the example in Fig. 2, we obtain $\gamma = \frac{6}{11}$ for WLAN1's node, because the total number of times that WLAN1's nodes attempt to sense SCHs is 11, and the number of times that all SCHs are sensed as idle for the PIFS is 6. Let us solve this example in a different way to derive a general equation for γ. The value of γ depends on when WLAN1's node attempts to sense its SCHs between two consecutive transmissions of WLAN2's nodes. Thus, we divide Fig. 2

into two transmission parts (TPs), denoted by TP_1 and TP_2. Each TP is separated by two timeslots in which WLAN2's nodes transmit. In Fig. 2, the 0^{th} and 36^{th} (0^{th} and 39^{th}) timeslots are the starting and ending ones in TP_1 (TP_2), respectively. Let $P_K(\kappa)$ be the probability that WLAN1's nodes attempt to sense SCHs in the κ^{th} timeslot in a TP, and let $P_I(\kappa)$ be the probability that all SCHs are sensed as idle for the PIFS given that WLAN1's nodes attempt to sense them in the κ^{th} timeslot. Subsequently, for TP_1, we can write $\gamma = \sum_{\kappa=0}^{36} P_K(\kappa)P_I(\kappa) = 3\cdot(\frac{1}{5}\cdot 0)+2\cdot(\frac{1}{5}\cdot 1) = \frac{2}{5}$. Likewise, in TP_2, $\gamma = \sum_{\kappa=0}^{39} P_K(\kappa)P_I(\kappa) = 2\cdot(\frac{1}{6}\cdot 0)+4\cdot(\frac{1}{6}\cdot 1) = \frac{4}{6}$. The numbers of times that WLAN1's nodes attempt to sense SCHs are 5 and 6 in TP_1 and TP_2, respectively, thus we can obtain the mean probability $\gamma^{avg} = \frac{5\cdot\frac{2}{5}+6\cdot\frac{4}{6}}{5+6} = \frac{6}{11}$.

In the same way as in the above example, we consider a TP divided by two of WLAN2's transmissions where the starting and ending timeslots are the 0^{th} and F^{th} ones, respectively. We obtain γ for WLAN1's node by considering the status of WLAN1's transmission in every timeslot in the TP. Let $s_{1,z} \in \{-1, 0, 1\}$ be a state variable to indicate the status of WLAN1's transmission in the z^{th} timeslot. Specifically, $s_{1,z} = -1$ if WLAN1's nodes are unable to transmit in the z^{th} timeslot because the transmissions of other nodes are in progress. Conversely, $s_{1,z} = 0$ if WLAN1's nodes are able to transmit in the z^{th} timeslot but do not do so; otherwise, if WLAN1's nodes transmit in the z^{th} timeslot, then $s_{1,z} = 1$. Let $\mathcal{S}$ denote a set of $s_{1,z}$, for $0 \le z \le F$, which obeys the rules of SCA. Thus, the set $\mathcal{S} = \{s_{1,z}|0 \le z \le F\}$ satisfies the following (**Condition 1**):

(i) WLAN1's nodes are allowed to transmit after its PCH is sensed as idle for a duration greater than the DIFS, as shown in Fig. 2. Thus, $s_{1,z} = -1$ if $\exists s_{1,z'} = 1$ for $z' > 0$ and $z-(L+n_D) < z' < z$; otherwise, $s_{1,z} \in \{0, 1\}$.
(ii) WLAN1's transmission must not be in progress for the PIFS immediately before WLAN2's transmission in the F^{th} timeslot. Thus, $s_{1,z} = 0$ if $s_{1,z} \neq -1$ by (i) and $F-(L+n_P) < z < F$.

Let $P_1(s_{1,z})$ be the probability for the status of WLAN1's transmission in the z^{th} timeslot, then the probability of $\mathcal{S}$ in the TP is given by $\prod_{z=0}^{F} P_1(s_{1,z})$. Let $I_K(\kappa|\mathcal{S})$ be the function which indicates if WLAN1's nodes are able to attempt to sense the SCHs in the κ^{th} timeslot given set $\mathcal{S}$. To obtain $I_K(\kappa|\mathcal{S})$, we verify if WLAN1's nodes are able to transmit in the $(\kappa+n_P)^{th}$ timeslot by referring to **Condition 1**. Accordingly,

- $I_K(\kappa|\mathcal{S}) = 0$ if $\exists s_{1,z} = 1$ for $\kappa+n_P-(L+n_D) < z < \kappa+n_P$ or $\kappa > F-(L+2\cdot n_P)$; otherwise, $I_K(\kappa|\mathcal{S}) = 1$.

Thus, $P_K(\kappa|F)$ can be obtained as

$$P_K(\kappa|F) = \sum_{\mathcal{S}}\left(I_K(\kappa|\mathcal{S})\cdot\mathcal{T}_1\cdot\prod_{z=0}^{F} P_1(s_{1,z})\right) \tag{6}$$

where $s_{1,0} \in \{0, 1\}$, and the value of $P_1(s_{1,z})$ is 1, $(1-\mathcal{T}_1)$, and $\mathcal{T}_1$ when $s_{1,z}$ is -1, 0, and 1, respectively. We can obtain $\mathcal{T}_1$ from τ in Eq. (5), as presented in Subsection II-C.

Using Eq. (6), $N_K(F) = \sum_{\kappa=0}^{F-1} P_K(\kappa|F)$. All SCHs must be sensed as idle between the L^{th} and $(F-n_P)^{th}$ timeslots because there is no WLAN2 transmission in these; however, SCHs must be sensed as busy in the other timeslots due to WLAN2's transmissions in the 0^{th} and F^{th} timeslots. Thus, $\gamma(F) = \sum_{\kappa=L}^{F-n_P} P_K(\kappa|F)/N_K(F)$.

Next, we calculate $P_E(F)$ by considering the statuses of WLAN1's and WLAN2's transmissions in every timeslot between the 0^{th} and the F^{th}. Let $s_{2,z}$ be a state variable to indicate the status of WLAN2's transmission in the z^{th} timeslot with reference to the definitions of $s_{1,z}$ in Eq. (6). Note that $P_E(F)$ is the probability that there are no WLAN2 transmissions between the $(L+n_D)^{th}$ and $(F-1)^{th}$ timeslots and WLAN2 nodes transmit in the F^{th} timeslot. Thus, we assume $s_{2,z} \in \{-1, 0\}$ for $L+n_D \le z < F$ and $s_{2,F} = 1$. In addition, $s_{2,z} = -1$ for $0 \le z < L+n_D$ due to WLAN2's transmission in the 0^{th} timeslot. Let $\hat{\mathcal{S}}$ denote a set of $(s_{1,z}, s_{2,z})$ for $0 \le z \le F$, which obeys the rules of SCA. Thus, the set $\hat{\mathcal{S}} = \{(s_{1,z}, s_{2,z})|0 \le z \le F\}$ satisfies the following (**Condition 2**):

(i) $s_{1,z}$ for $0 \le z \le F$ obeys the rules of **Condition 1**.
(ii) WLAN2's nodes cannot transmit if WLAN1's transmission was sensed within the PIFS, thus $s_{2,z} = -1$ if $\exists s_{1,z'} = 1$ for $z-(L+n_P) < z' < z$; otherwise, $s_{2,z} = 0$.

Let $P_2(s_{2,z})$ be the probability of $s_{2,z}$, then the probability of $\hat{\mathcal{S}}$ is given by $\prod_{z=0}^{F} P_1(s_{1,z})P_2(s_{2,z})$. Hence, we can obtain

$$P_E(F) = \sum_{\hat{\mathcal{S}}}\left(\prod_{z=0}^{F} P_1(s_{1,z})P_2(s_{2,z})\right) \tag{7}$$

where the value of $P_2(s_{2,z})$ is 1, $(1-\mathcal{T}_2)$, and $\mathcal{T}_2$ when $s_{2,z}$ is -1, 0, and 1, respectively.

When the ending timeslot is the F^{th} one in the TP, F can be any integer between $[L+n_D, \infty]$. Considering all of the TPs, the mean probability of γ is

$$\gamma^{avg} = \sum_{F=L+n_D}^{\infty} \frac{P_E(F)\cdot N_K(F)\cdot\gamma(F)}{N_K^{avg}} \tag{8}$$

where $N_K^{avg} = \sum_{F=L+n_D}^{\infty} P_E(F)\cdot N_K(F)$.

In addition, we can estimate the collision probability at WLAN1's node, p. As in Eq. (6), we first calculate p based on the set of WLAN1 transmissions in the TP. To this end, we sum up two collision probabilities (i) that at least one WLAN1 node transmits in the starting and ending timeslots, and (ii) that two or more WLAN1 nodes transmit in the other timeslots in the TP. Then, referring to Eq. (8), we obtain the mean collision probability p^{avg} considering all of the TPs.

C. Throughput Analysis

To calculate the throughput of WLAN1's node, we let τ' be the probability that a node of WLAN1 attempts to sense SCHs in a timeslot. We can express $\tau' = \tau/\gamma$ because the node transmits under the condition where all SCHs are sensed as idle for the PIFS, then $\mathcal{T}_1 = 1-(1-\tau')^n$ and $\mathcal{T}_2$ is obtained from τ' of WLAN2's node. Variable P_{idle} is simply the probability that the PCH is sensed as idle in the next timeslot, thus $P_{idle} = (1-\tau)^{n-1}$. We employ the following two steps to determine γ, p, and τ for WLAN1 and WLAN2:

- Step 1: Estimate γ^{avg}, p^{avg}, and P_{idle} for each WLAN as described in Section II-B using τ and γ calculated and used in Step 2, respectively.

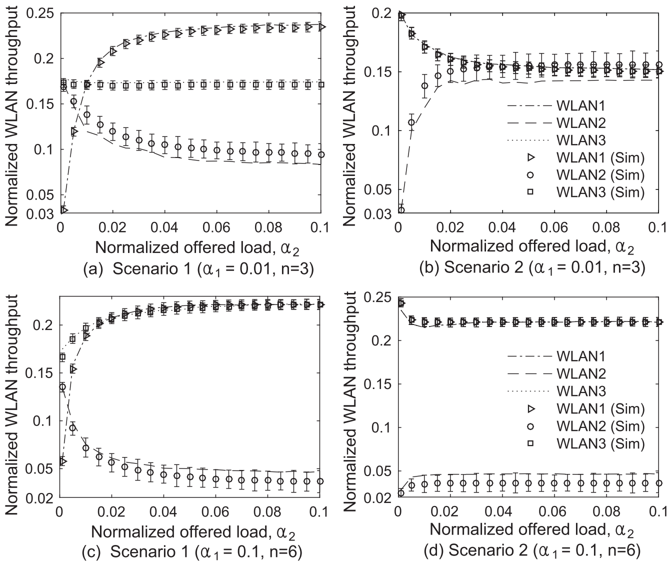

Fig. 3. Normalized throughput of each WLAN when $\alpha_1 = 0.01$ and 0.1.

- Step 2: Calculate τ for each WLAN from Eq. (5) using γ^{avg}, p^{avg}, and P_{idle} estimated in Step 1.

We repeat these steps until γ used in Step 1 for both WLAN1 and WLAN2 is closest to γ^{avg} estimated in Step 1.

Let P_{tr} be the probability that at least one WLAN1 node attempts to transmit in a timeslot, which is given by $P_{tr} = (1-\tau)^n$. Subsequently, the mean timeslot length of the states is $E_s = (1-P_{tr}) \cdot 1 + P_{tr}(L+n_D)$. Thus, the normalized throughput of WLAN1's node is as follows:

$$T = \frac{P_{tr}(1-p) \cdot L_{data}}{n \cdot E_s} \tag{9}$$

where L_{data} is the number of timeslots spent for transmitting payload data. The throughput of WLAN1 is $T_1 = n \cdot T$.

III. Simulation Results and Discussion

We developed multi-channel bonding in the C++ language to validate the proposed analytical model. We setup WLAN1, WLAN2, and WLAN3 with an operating channel bandwidth of 80 MHz and the number of nodes associated with each WLAN was 3 and 6. WLAN2 shared at least one SCH with both WLAN1 and WLAN3, but WLAN1 did not share any of its SCHs with WLAN3. Our analysis uses the variable q as the normalized offered load of each node, and placing the node in saturation by taking the limit $q \to 1$ as in [6]. Using α_1 and α_2 to denote the fixed offered load and the offered load increased in the range $[0.001, 0.1]$, respectively, i.e. $q = \alpha_1$ or α_2, we simulated the following two scenarios:

- Scenario 1 (Scenario 2): The offered load of WLAN2's (WLAN1's) or WLAN3's node was fixed as α_1, and the offered load of WLAN1's (WLAN2's) node was α_2.

The transmission rate of all of the nodes was 117 Mbit/s. Other parameters were defined as follows: $W_0 = 16$, $m = 5$, $\sigma = 9\ \mu s$, $n_D = 4$, $n_P = 3$, $L = 22$, and $L_{data} = 12$ [1], [3].

Fig. 3 plots the normalized throughput of each WLAN versus the offered load of WLAN1 and WLAN2 in Scenarios 1 and 2, respectively, with 95 % confidence intervals shown. Figs. 3 (a) and (c) show that as the offered load of WLAN1 increased, its throughput increased whereas WLAN2's throughput decreased, and there was little effect on WLAN3's throughput due to the fact that it did not share any SCHs with WLAN1. It can be seen in Figs. 3 (b) and (d) that with an increase in WLAN2's offered load, its throughput increased whereas the throughputs of both WLAN1 and WLAN3 decreased because their collision probabilities with WLAN2's transmissions increased as WLAN2's offered load increased. Fig. 4 shows that the normalized total system throughput depended on the offered load distribution among the WLANs given that the total offered load remained the same in the system. In the case of $\alpha_1 = 0.01$, WLAN2's offered load was higher than those of both WLAN1 and WLAN3 in two situations: (i) when α_2 increased up to 0.01 in Scenario 1 and (ii) when α_2 increased from 0.01 to 0.1 in Scenario 2. Fig. 4 (a) shows that the total system throughput of Scenario 1 was lower than Scenario 2 as α_2 increased up to 0.01, and thereafter was higher than Scenario 2. The same phenomenon was observed when $\alpha_1 = 0.1$, as shown in Fig. 4 (b). These results indicate that if WLANs with high offered loads shared at least one of their SCHs with more than one other WLAN, the collision probability increased and the transmission probability decreased in the system, which means that in such a situation, the total system throughput decreased.

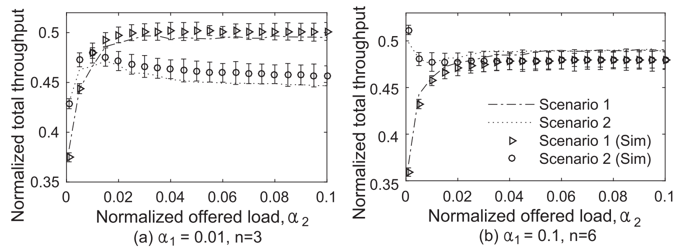

Fig. 4. Normalized total system throughput when $\alpha_1 = 0.01$ and 0.1.

IV. Conclusion

We derived the throughput of 802.11ac using SCA. Via numerical and simulation results, we studied the effect that the traffic load distribution among WLANs has on the system throughput and showed that it decreased as WLANs with high load shared their SCHs with more than one other WLAN even though the total system load remained the same.

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