Capacity Analysis of Opportunistic Channel Bonding Over Multi-Channel WLANs Under Unsaturated Traffic

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***Abstract*—In this paper, we analytically study the performance of opportunistic multi-channel bonding protocol supporting delay-sensitive multimedia services. We consider a multi-channel system shared by IEEE 802.11ac users who can transmit over multiple channels and legacy users who can only transmit over one single channel. By analyzing the channel bonding behavior of IEEE 802.11ac users and the random access of legacy users, bonding probability and successful bonding probability of IEEE 802.11ac users can be derived. Furthermore, the access delays of both legacy and 802.11ac users are analyzed. According to the analytical results, the network capacity which quantifies the maximum number of multimedia flows that can be supported with guaranteed delay is then presented. Additionally, the impacts of different parameters such as traffic data rate on the network capacity are investigated. Our analytical results show that channel bonding is favorable when the secondary channels are underutilized. But channel bonding should be disabled when there are already intense contentions from legacy users. Based on the analytical results, we propose a heuristic bonding policy which can provide important guidelines to control the number of flows to satisfy the QoS requirement and achieve the maximum network capacity. Extensive simulations have been conducted to validate the analytical results.**

***Index Terms*—Performance analysis, multi-channel bonding, unsaturated traffic, delay sensitive service.**

I. Introduction

According to Cisco's white paper, mobile video traffic will account for 82% of all consumer Internet traffic by 2021, up from 73% in 2016 [1]. The magnificent increase on the video demand is not only due to the increase of the number of mobile users, but also the launch of various applications requiring high resolution video streaming, e.g., virtual reality (VR) and augmented reality (AR). For example, a 720p VR video needs at least 50 Mbps bandwidth as each VR stream needs to be duplicated for both eyes [2]. Such emerging applications will pose new challenges on the network quality of service (QoS) provisioning in terms of both high bandwidth and low latency. Wireless Local Area Network (WLAN) is generally considered to be a wireless networking solution to support video services. However, the distributed coordination nature of WLAN can only provide the best effort performance which is not suitable to support the emerging high rate video services. To improve the network throughput, the idea of channel bonding is first introduced in the IEEE 802.11n and further enhanced in IEEE 802.11ac [3]–[5], which allows wireless users to opportunistically bond multiple channels.

Unlike the conventional WLAN transmitting over only one channel that has been extensively studied in the literature [6]–[12], multi-channel bonding is still not well investigated. Most existing works studying the channel bonding protocol are based on simulations [13]–[15]. Since simulation results cannot accurately predict the network performance when there is any change in the simulation scenarios, e.g., the number of users or traffic patterns, some analytical models have been developed [16]–[21] based on some simplified assumptions. For example, results in [16], [17] are too optimistic as collisions from random access are simply ignored. In our previous work [22], saturated throughput of multi-channel WLAN is analyzed, assuming all users always have data for transmissions. In [23], the performance of only two-channel WLAN is studied. Nevertheless, many realistic applications like video streaming do not have persistent traffic.

To our best knowledge, we believe there is no existing model that can be readily used to evaluate the performance of multi-channel bonding in support of unsaturated traffic.

In this paper, a general analytical model to evaluate the performance of multi-channel bonding protocol for supporting unsaturated traffic flows is developed by considering the coexistence of legacy users and IEEE 802.11ac users. We model the interactions between the legacy and IEEE 802.11ac users through channel bonding attempts and analyze the delay of both IEEE 802.11ac and legacy users. Legacy users refer to the legacy IEEE 802.11 users who can only transmit over one single channel by using CSMA/CA based channel access scheme. In contrast, IEEE 802.11ac users are capable of

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combining multiple adjacent channels to one single channel for data transmissions over a wider bandwidth. To ensure the QoS requirements of the delay sensitive traffic flows, we quantify the network capacity. The network capacity is important for admission control schemes to provision the QoS requirements of traffic flows.

Our main contributions in this paper can be summarized as follows:

- We develop a general mathematical model to study the performance of channel bonding protocol in terms of the channel bonding probability, the successful channel bonding probability of IEEE 802.11ac users, and the access delay of both legacy users and IEEE 802.11ac users carrying unsaturated traffic, characterizing the contentions among users in the same channel, and contentions between different users across multiple channels.
- The network capacity of multi-channel WLANs supporting unsaturated traffic flows is derived. The numerical results show that channel bonding can provide gain only if the secondary channels are underutilized, i.e., the number of legacy users is below a certain threshold. The impact of variable parameters such as video bit rates on the capacity is extensively investigated.
- The network capacity over multiple channels can be used to control the number of flows to be admitted to provision the QoS requirement of delay-sensitive services and to provide important guidelines on the channel bonding strategies to achieve the maximum capacity of the WLANs.

The remainder of this paper is organized as follows. We first summarize the related works in Section II. The system model is then presented in Section III, followed by the generic model to evaluate the performance of channel bonding in Section IV. Numerical results from both analyses and simulations are provided in Section V. Finally, the conclusion and future work are presented in Section VI.

II. Related Work

The performance of legacy IEEE 802.11 operating over a single-channel WLAN has been extensively studied in the literature. In [10], a two-dimensional discrete-time Markov chain was proposed to calculate the saturated throughput. The delay performance of a WLAN with saturated traffic was analyzed in [11]. In [12], an analytical model using renewal theory was developed to study the voice capacity of WLANs, considering non-saturated traffic. These prior analytical works of legacy IEEE WLAN characterize the detailed behavior of WLAN users using distributed CSMA/CA MAC operating over a single channel, yet they are not readily extensible for multi-channel WLAN analysis as they could not capture the inter-channel contentions among different users.

Several papers studied the performance of multi-channel WLAN via simulation or emulation experiments. It was found in [13] through simulations that dynamic bandwidth channel access scheme significantly outperforms static channel access in the dense network environment. In [14], it was found that bonding of two channels in IEEE 802.11n can greatly improve the network performance, and the bonding decision should be dependent on the received signal strength and the cross-channel interference measured at the receiver. It was shown in [15] that the spectrum utilization can be improved when the channel is divided into multiple narrow channels instead of a smaller number of wide channels. Based on the findings in [14], a network detector was introduced to identify interference conditions that affect channel bonding decisions in [24]. After realizing the importance of intelligent channel bonding, some works focused on the protocol design of channel bonding based on the experiment results. A channel bonding scheme based on adaptive channel clear assessment was proposed in [25]. In [26], a protection mechanism for medium access was proposed to tackle the problem of hidden node. To improve the channel efficiency, the authors in [27] evaluated the performance of a dynamic channel bonding protocol, which allows the users to increase the channel bandwidth whenever some channels become idle.

Besides the experiment-based performance studies, only a few works analytically studied the performance of channel bonding. A model using continuous-time Markov chain was proposed in [16] to investigate the system throughput of channel bonding, assuming that the collision probability is zero. However, it is well recognized that the collision probability is not negligible in a typical WLAN with random access protocol, thus the results in [16] were optimistic without considering collisions. Another model using a Markov chain was developed in [18] to derive the transmission probability along with the collision probability of static channel bonding in a two-channel case. Similarly in [19], a mathematical model was developed to analyze the performance of static channel bonding of four channels. In [28], a simplified analytical model was developed to compare the performance of channel bonding and multi-channel CSMA, considering no users operating in the secondary channels. The model proposed in [17] assumed that there was only one transmitter in the target WLAN so that no collision occurred in the primary channel. In our previous work [22], a generic model was developed to obtain the saturation throughput of channel bonding in a multi-channel WLAN shared by both IEEE 802.11ac and legacy users. It was found that channel bonding may degrade the overall throughput due to intense inter-channel contentions from 802.11ac users' bonding attempts in the saturation case. The maximum throughput can be achieved when the secondary channels are idle with no legacy users. In all these aforementioned models of multi-channel bonding, the users are assumed to have saturated traffic. In a realistic network, many multimedia applications such as voice and video may not be saturated, but transmitted at a certain bitrate. In [23], authors only studied the performance of two channel-WLAN in support of unsaturated traffic. To our best knowledge, all the existing works cannot be readily applied to analyze the performance of opportunistic multi-channel bonding in support of unsaturated traffic, e.g., video flows. Thus motivated, in this paper, we first develop an analytical model to evaluate the performance of dynamic channel bonding with unsaturated traffic. After obtaining the delay of all users, we plot the network capacity of multi-channel WLANs with guaranteed service delay.

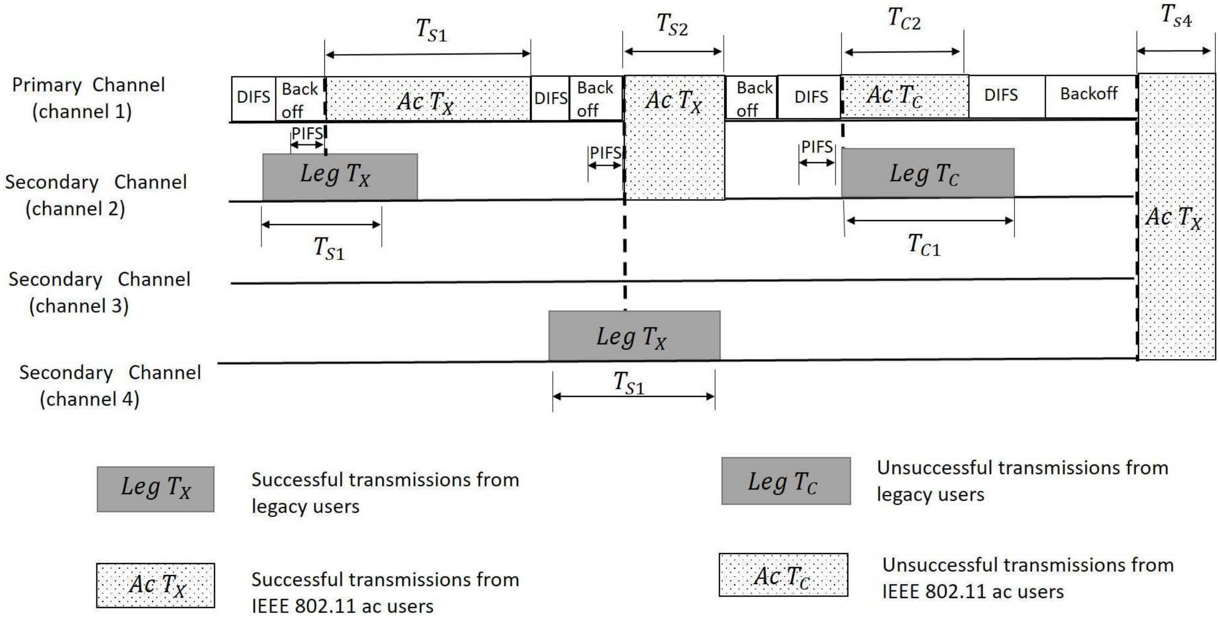


Fig. 1. Channel bonding over 4 channels.

III. System Model

In the system, there are C, $C \in \{2, 4, 8\}$ channels, each of which is of 20 MHz bandwidth. In each channel, there are $N_{\ell g}(c)$ legacy users that adopt CSMA/CA based MAC to communicate with each other. Notice that a legacy user can be either an AP station (STA) or a non-AP STA, which only operates on one 20 MHz channel. An IEEE 802.11ac WLAN with one AP and multiple non-AP STAs with bonding capability co-exist with the legacy users over C channels. We do not differentiate AP and non-AP STAs in this paper because they use the same protocol parameters for channel access, as in other analytical works of WLANs [10]. It is assumed that all users in each channel, including both legacy users and IEEE 802.11ac users can hear each other and the channel is ideal and that transmission errors are only due to collisions. Legacy IEEE 802.11 users adopt the distributed coordination function (DCF) which employs the carrier sense multiple access with collision avoidance (CSMA/CA) for channel access. Specifically, a user will first sense the channel status for a DIFS duration before transmission. If the channel is sensed to be idle, the user will transmit the frame immediately. Otherwise, the user enters the backoff phase and randomly chooses a backoff counter from $[0, CW_j - 1]$, where CW_j is the contention window at stage j and it doubles when a collision happens. A wireless user will decrease backoff counter by one on every idle slot. When the backoff counter decrements to zero, the user can get the chance to transmit. But the transmission may fail when other users transmit at the same time. Notice that if the channel is sensed busy during the backoff phase, the backoff counters of all users need to be frozen and can be resumed until the channel is sensed idle for a DIFS duration again.

IEEE 802.11ac users are capable of performing opportunistic channel bonding, which allows IEEE 802.11ac users to combine multiple adjacent channels to one single channel with wider bandwidth for data transmissions. To guarantee backward compatibility with legacy users without channel bonding capability, control and management frames of IEEE 802.11ac users are transmitted only over a single basic channel which is called the primary channel. IEEE 802.11ac users first select a channel as the primary channel and adopt the legacy carrier sense multiple access with collision avoidance (CSMA/CA) for channel access in the primary channel. At the same time, IEEE 802.11ac users also do the sensing on other channels which are called secondary channels. IEEE 802.11ac users can combine the primary channel and secondary channels into one wider channel, only when the neighboring secondary channels are sensed idle for at least a PIFS duration before the backoff counter reaches zero in the primary channel.

To better illustrate the protocol, we depict the multi-channel bonding protocol in a 4-channel case in Fig. 1. It can be observed that IEEE 802.11ac users perform CSMA/CA in the primary channel (i.e., channel 1 in this example), and in the meantime sensing the adjacent secondary channels for a PIFS time before its backoff counter decrements to zero. If secondary channels are sensed idle, IEEE 802.11ac users bond available consecutive channels for transmission after a PIFS. As shown in Fig. 1, IEEE 802.11ac users can transmit over channel 1 and 2 when channel 2 is sensed idle. Notice that in the standard, IEEE 802.11ac users can only bond $2, 4$, and 8 channels. A bonded transmission fails if a collision happens in any of the channels including the primary channel and secondary channels.

Without loss of generality, in this paper, we consider that all IEEE 802.11ac users select channel 1 as the primary channel, and may bond $2, 4$, and 8 channels for transmissions. Each legacy user chooses only one channel to transmit. Let N_{ac} denote the number of IEEE 802.11ac users and $N_{\ell g}(c)$ the number of legacy users operating in channel $c \in \{1, 2, 3 \ldots 8\}$. λ_{ac} and $\lambda_{\ell g}(c)$ are the traffic arrival rate of IEEE 802.11ac users and that of legacy users in channel c, respectively.

TABLE I
LIST OF NOTATIONS

Description	Notation
The number of IEEE 802.11ac users	N_{ac}
The number of legacy users in channel c	$N_{\ell g}(c)$
The traffic arrival rate of one IEEE 802.11ac user	λ_{ac}
The traffic arrival rate of one legacy user in channel c	$\lambda_{\ell g}(c)$
The service rate of one IEEE 802.11ac user in channel 1	μ_{ac}
The service rate in the primary channel	μ_s
Channel bonding rate	μ
The service rate of one legacy user in channel c	$\mu_{\ell g}(c)$
Prob. of a user having backoff counter as b	$P_B(b)$
Prob. of a user having a backoff counter $\leq$ b	$P_{\text{ß}}(b)$
Transmission prob. of an IEEE 802.11ac user in channel 1	τ_{ac}
Transmission prob. of a legacy user in channel c	$\tau_{\ell g}(1)$
Successful bonding prob. on secondary channel c	P_{SCB_c}
Slot duration	σ
Probability of bonding c channels	$P_{CB}(c)$
Probability of successfully bonding c channels	$P_{SCB}(c)$

Although in the generic model, all users carry the unsaturated traffic, this model is also applicable to saturated traffic case and the details will be explained in the following sections.

IV. PERFORMANCE ANALYSIS

An analytical model to evaluate the performance of opportunistic channel bonding in multiple channels shared by IEEE 802.11ac and legacy users is presented in this section. By using both renewal theory and Markov chain, we characterize the competitions between IEEE 802.11ac users and legacy users across multiple channels. We first derive the channel bonding probability and the channel access delay. Based on the access delays of all users, we then obtain the network capacity. The main notations are listed in Table I.

A. Channel Bonding Analysis in a Two-Channel Case

We start from a case of two-channel bonding in Sec. IV-A and then extend it to multi-channel bonding in Sec. IV-B. In the two-channel case, there are N_{ac} IEEE 802.11ac users choosing channel 1 as the primary channel, and $N_{\ell g}(1)$, $N_{\ell g}(2)$ legacy users operating over channel 1 and 2. The channel bonding attempts from all IEEE 802.11ac users in channel 1 can be considered as one aggregated IEEE 802.11ac user with rate μ to bond the adjacent secondary channel. Therefore, there exist two kinds of users competing in channel 2. Besides the co-channel legacy users, the IEEE 802.11ac user who wins the chance to transmit in the primary channel may also compete with the legacy users for transmissions in the secondary channel. Notice that, in the secondary channel, the contentions between the legacy users and between the IEEE 802.11ac users and the legacy users are different from each other in the following aspects.

- An IEEE 802.11ac user only attempts to bond the secondary channel after it gets the chance to transmit in the primary channel.
- An IEEE 802.11ac user will neither enter the backoff phase nor retransmit in the secondary channel if the secondary channels are sensed busy for a PIFS duration.

We start with analyzing the performance of legacy users in the secondary channel, based on the model in [29]. Define $P_B(b)$ as the steady state probability that a legacy user has a backoff counter b, $b \in [0, W-1]$ where W represents the maximum backoff window size. Given the traffic arrival rate of a legacy user $\lambda_{\ell g}(2)$ and the service rate $\mu_{\ell g}(2)$, the probability that the user has a data in the queue for transmission is $\rho_{\ell g}(2) = min(1, \lambda_{\ell g}(2)/\mu_{\ell g}(2))$. Queue utilization ration $\rho_{\ell g}(2)$ is calculated when the network is stable. Thus, $\rho_{\ell g}(2)$ is only dependent on the mean value of the arrival rate and service rate. Notice that for saturated users, $\rho_{\ell g}(2) = 1$. In the IEEE 802.11ac standard, the time duration of a PIFS and a DIFS are $25\mu s$ and $34\mu s$, respectively. Therefore, a PIFS and a DIFS can be approximated as 3 slots and 4 slots given the duration of one slot is $9\mu s$. The one slot difference between DIFS and PIFS makes bonding attempts from IEEE 802.11ac users have a slightly higher priority than the legacy users in channel 2. Denote $P_{\text{ß}}(b)$ as the probability that a user would transmit before the end of $(b+4)$-th time slot, i.e., DIFS plus backoff slots. Only when the data queue is not empty and the backoff counter is smaller than or equal to b, the transmission of the tagged legacy user occurs before the $(b+4)$-th slot. Thus, we have

$$P_{\text{ß}}(b) = \rho_{\ell g}(2) \sum_{i=0}^{b} P_B(i). \quad (1)$$

In the case that the traffic of legacy users are saturated, i.e., $\rho_{\ell g}(2) = 1$, $P_{\text{ß}}(b) = \sum_{i=0}^{b} P_B(i)$.

Let $P_Q(b)$ be the probability that there is no other user transmitting before the $(b+4)$-th slot under the condition that the backoff counter chosen by the tagged legacy user is b. To ensure that the tagged user can transmit at the $(b+4)$-th slot, the backoff counter of all remaining legacy users should be larger or equal to b, and the bonding from all IEEEE 802.11ac users should not access channel 2 before $(b+4)$-th slot. Due to the one slot difference between DIFS and PIFS, IEEE 802.11ac users need to start sensing the secondary after the $(b+1)$-th slot. If the channel bonding rate from all IEEE 802.11ac users at any slot is given as μ, $P_Q(b)$ can be written as,

$$P_Q(b) = (1 - P_{\text{ß}}(b-1))^{N_{\ell g}(2)-1} \cdot (1-\mu)^{b+1}. \quad (2)$$

In the special case when the tagged legacy user chooses a backoff counter as zero. This tagged legacy user will win the competition and transmit after DIFS duration, only if no IEEE 802.11ac user transmits before the legacy user implies that IEEE 802.11ac user will not sense the channel in the first slot. Also, the tagged legacy user shall have a non-empty buffer. Thus, $P_Q(0) = 1 - \mu$. If $N_{\ell g}(2) = 1$, there must be no other legacy user transmitting before the tagged user. Thus $P_Q(b) = (1-\mu)^{b+1}$.

A tagged legacy user with a backoff counter b will win the contention and transmit in the secondary channel, when no other users transmit before the tagged user. Accordingly, we can derive the transmission probability of a legacy user as,

$$P_{tr} = \sum_{b=0}^{W-1} P_B(b)\rho_{\ell g}(2)P_Q(b). \tag{3}$$

Generally, after a busy transmission which can be either a successful transmission or a collision, a legacy user will enter a backoff stage like j-th stage and then randomly chooses a backoff counter from $[0, CW_j - 1]$. Define P_{B_j} as the probability that a user is in the backoff stage j. Meanwhile, we denote $P_{B_j}(b)$ as the probability that a user chooses a backoff counter b at stage j. When a legacy user having a backoff counter as b, the user is likely to be in any of the backoff stages from $[j, m]$, where $j = \lceil \log_2(\lceil (b+1)/CW_0 \rceil) \rceil$ with probability P_{B_j} and m is the retry limit. For example, when a user chooses a backoff counter 45 and CW_0 is 16, the possible stage of 45 would be $[2, 7]$. Also, the probability that a user chooses backoff counter as b in stage j is $P_{B_j}(b) = P_{B_j}/CW_j$. Therefore, a user could choose a backoff counter as b after a busy transmission with the probability,

$$P(b) = \sum_{j=\lceil \log_2(\lceil (b+1)/CW_0 \rceil) \rceil}^{m} P_{B_j}(b) \tag{4}$$

We model the backoff process as a truncated geometric distribution,

$$P_{B_j} = \begin{cases} 1-p & j=0 \\ p^j(1-p) & 0 \le j \le m-1 \\ p^m & j=m \end{cases} \tag{5}$$

Denote p_c as the unconditional collision probability. A collision happens when two or more users transmit at the same slot. Thus, we have

$$p_c = \sum_{b=0}^{W-1} P_B(b)\rho_{\ell g}(2)P_T(b), \tag{6}$$

where $P_T(b) = P_Q(b) - P_Q(b+1)$ denotes the probability that besides the tagged user, at least one of remaining IEEE 802.11ac users and legacy users will transmit exactly at $(b+4)$-th slot. Given the probability that a user wins the competition and transmits is P_{tr} and the unconditional collision probability is p_c, the conditional collision probability can be expressed as $p = p_c/P_{tr}$. Generally, after a busy transmission whether from other users or the tagged user, the backoff counter of the tagged user could be b if the tagged user transmits in the previous transmission and selects a new backoff counter as b; or the tagged user with a backoff counter $(b+i)$ does not transmit in the previous busy transmission, and another user with a backoff counter i wins the competition so that the tagged user decrements its backoff counter from $b+i$ to b.

$$P_B(b) = P_{tr}P(b) + \sum_{i=0}^{W-1-b} P_B(b+i)\rho_{\ell g}(2)P_T(i) \tag{7}$$

But, there is a special case when b equals zero. Only one IEEE 802.11ac user who has just successful transmitted a frame is able to choose zero as the backoff counter. In this case, $P_B(0)$ is given by,

$$P_B(0) = P_{tr}P(0). \tag{8}$$

Based on the total probability theorem, we sum all $P_B(b)$ and get,

$$\sum_{b=0}^{W-1} P_B(b) = 1. \tag{9}$$

Solving (7) - (9), we can get the steady state probability $P_B(i)$. Using $P_B(i)$, the channel bonding probability can be derived. Denote t as the time instant that a transmission has just completes in channel 2. Given the backoff counters of all legacy users are equal or larger than b, the legacy users can not transmit before the $(t+b+4)$-th slots where 4 is the duration of DIFS. Therefore, if an IEEE 802.11ac user senses channel 2 and attempts to bond before $(t+b+1)$-th, the bonding must be launched with probability 1 as no legacy user will transmit before IEEE 802.11ac users. But if the bonding attempts are launched in the first or second slot, IEEE 802.11ac users will definitely bond the secondary channel no matter what value of b is chosen by the legacy users. Thus, given IEEE 802.11ac users transmit over the primary channel, the conditional channel bonding probability P_{CB_2} on channel 2 is given by,

$$P_{CB_2} = \frac{\sum_{b=1}^{W} \mu(1-\mu)^{b+1}[1 - P_{\text{ß}}(b-1)]^{N_{\ell g}(2)}}{P_t} + \frac{\mu + \mu(1-\mu)}{P_t}, \tag{10}$$

where $P_t = 1 - (\frac{\lambda_{ac}}{\mu_{ac}}\tau_{ac})^{N_{ac}}$ denotes the probability that at least one IEEE 802.11ac user is transmitting over the primary channel. The bonding attempt is guaranteed to be successful, when channel bonding attempts either arrive before $(t+b)$-th slot given the backoff counter of all legacy users is lager than $(b-1)$; or IEEE 802.11ac users launch the channel bonding attempts in the first slot. Notice that not all bonding attempts are successful as bonded transmission fails when it collides with transmission in either channel 1 or channel 2. Denote μ_s as the successful channel bonding rate from all IEEE 802.11ac users in channel 1 which means that each IEEE 802.11ac user not only wins the competition to transmit but also no other user has the same backoff counter as the tagged user. Thus, given IEEE 802.11ac users transmit over the primary channel, the probability of a successful bonding can be derived as follows,

$$P_{SCB_2} = \frac{\sum_{b=1}^{W} \mu_s(1-\mu_s)^b[1 - P_{\text{ß}}(b-1)]^{N_{\ell g}(2)} + \mu_s}{P_t}. \tag{11}$$

In the extreme case that $N_{\ell g}(2) = 0$, all the bonding attempts will be launched and successful. Thus we have $P_{CB_2} = 1$ and $P_{SCB_2} = 1$. Channel bonding probability is the probability that given the IEEE 802.11ac users transmit over the primary channel, the IEEE 802.11ac users also find the secondary channels idle and bond the secondary channels for transmissions. But the bonded transmissions may fail due to the collisions in either the primary channel or any of the secondary channels. Meanwhile, the successful bonding probability is the probability that given the IEEE 802.11ac users transmit over the primary channel, both transmissions on the primary channel and secondary channels of IEEE 802.11ac users are successful. Therefore, the successful bonding probability must be smaller than or equal to the bonding probability.

To calculate (11), we first need to calculate the channel bonding rate μ along with successful channel bonding rate μ_s from all IEEE 802.11ac users. In channel 1, both IEEE 802.11ac users and legacy users adopt the distributed DCF function namely CSMA/CA to access the channel. In the literature [10] [12], a large number of works studied the performance of CSMA/CA from the aspects of both delay and throughput. For an IEEE 802.11ac user, only when it wins the competition in the primary channel, the IEEE 802.11ac user can sense the secondary channel for bonding. To obtain the successful channel bonding rate from all IEEE 802.11ac users, we first need to calculate the service rate of a single IEEE 802.11ac user. Denote μ_{ac} as the service rate of a single IEEE 802.11ac user in the primary channel. There are N_{ac} IEEE 802.11ac users and $N_{\ell g}(1)$ legacy users competing in the primary channel. When a user is transmitting, any simultaneous transmission from the remaining users will inevitably lead to a collision. Denote p_{ac} and p_{lg} as the collision probability of IEEE 802.11ac users and legacy users in the primary channel. For the unsaturated traffic, one user could transmit only with non-empty queue. Therefore, the conditional collision probability of both users are,

$$p_{ac} = 1 - (1 - \frac{\lambda_{ac}}{\mu_{ac}}\tau_{ac})^{N_{ac}-1}(1 - \frac{\lambda_{\ell g}(1)}{\mu_{\ell g}(1)}\tau_{\ell g}(1))^{N_{\ell g}(1)}, \tag{12}$$

$$p_{\ell g}(1) = 1 - (1 - \frac{\lambda_{ac}}{\mu_{ac}}\tau_{ac})^{N_{ac}}(1 - \frac{\lambda_{\ell g}(1)}{\mu_{\ell g}(1)}\tau_{\ell g}(1))^{N_{\ell g}(1)-1}, \tag{13}$$

where $\tau_{\ell g}(1)$ and τ_{ac} are the transmission probability of legacy users and IEEE 802.11ac users in channel 1. Let $1/\mu_{ac}$ denote the average transmission interval of an IEEE 802.11ac user. According to the CSMA/CA algorithm, we summarize all the possible events could happen during $1/\mu_{ac}$: 1) successful transmissions from IEEE 802.11ac users; 2) collisions between different users; 3) channel idleness due to backoff.

Firstly, we calculate the time due to the successful transmissions in the duration of $1/\mu_{ac}$. Because of the long term fairness, as long as the tagged IEEE 802.11ac user transmits a successful frame, each of the remaining IEEE 802.11ac users should also successfully transmit λ_{ac}/μ_{ac} frames, which will contribute to a total successful transmission time of $(N_{ac}-1)\lambda_{ac}/\mu_{ac}\widehat{T_s}$. In addition to the IEEE 802.11ac users, each of the legacy users also transmits $\lambda_{\ell g}(1)/\mu_{ac}$ frames which contributes $\lambda_{\ell g}(1)/\mu_{ac}N_{\ell g}(1)T_s$ frames in total. While T_s denotes the successful transmission time in the basic mode, and $\widehat{T_s}$ denotes the average or expected successful transmission time of IEEE 802.11ac users. With the capability of channel bonding, IEEE 802.11ac user can successfully transmit the packet using either one or two channels. Let T_{s1} and T_{s2} denote the duration of a successful transmission when transmitting over one and two channels, respectively. T_{s1} is the same as T_s in the basic access mode. In the basic access mode, T_s consists of packet transmission time, a SIFS, an ACK frame, and a DIFS and is expressed as,

$$T_{s1} = T_s = T_{data} + SIFS + T_{ACK} + DIFS. \tag{14}$$

The difference between T_{s1} and T_{s2} is the duration of packet transmission. When the packet is transmitted using two channels, the packet transmission time T_{s2} is half of T_{s1},

$$T_{s2} = \frac{T_{data}}{2} + SIFS + T_{ACK} + DIFS. \tag{15}$$

Given the transmission is successful, the probability that the packet is transmitted by one and two channels are $(1-P_{SCB_2})$ and P_{SCB_2}. And P_{SCB_2} can be calculated using (11). Thus, the expected duration of a successful transmission from IEEE 802.11ac users is given by,

$$E[T_s] = T_{s2}P_{SCB_2} + T_{s1}(1 - P_{SCB_2}). \tag{16}$$

Next, we calculate the collision time. In the primary channel, there are three types of collisions depending on the contenders. The collisions can occur between two IEEE 802.11ac users, between two legacy users, or between one legacy user and one IEEE 802.11ac user. If the collision involves one legacy user, the collision time is T_c which is the same as in the basic mode. But when the collisions only occur due to IEEE 802.11ac users, the collision time is different based on the number of channels used to transmit. When both IEEE 802.11ac users bond two channels, the collision time is T_{c2}. When both ac users find the secondary channel is busy, the collision time is T_{c1}. Similar to T_{s1} and T_{s2}, the collision time between two IEEE 802.11ac users in such two cases are

$$T_{c1} = T_{data} + ACK_{timeout} + DIFS, \tag{17}$$

$$T_{c2} = \frac{T_{data}}{2} + ACK_{timeout} + DIFS. \tag{18}$$

Given there is an unsuccessful transmission between only IEEE 802.11ac users, the probability that this transmission transmitting in two channels is P_{CB_2} which can be found in (10). Thus, the expected collision time between two IEEE 802.11ac user is given by

$$E[T_c] = T_{c2}P_{CB_2} + T_{c1}(1 - P_{CB_2}). \tag{19}$$

Denote P_{inv} as the probability that one collision involves one legacy user given the collision already involves one IEEE 802.11ac user. Define $E[A_{ac}]$ as the average number of transmissions of IEEE 802.11ac users during $1/\mu_{ac}$. Given there are N_{ac} IEEE 802.11ac users in channel 1, during $1/\mu_{ac}$ the number of collisions involving an IEEE 802.11ac user is $N_{ac}(E[A_{ac}] - 1))/2$. Among these collisions, if the collision involves with a legacy user the collision time is T_{c1};

otherwise the collisions are between two IEEE 802.11ac users with length $E[T_c]$. Given the collision occurs when one IEEE 802.11ac user is transmitting, the number of users will collude with is $N_{\ell g}(1)+N_{ac}-1$. And the number of possible collisions involving legacy users is $N_{\ell g}(1)$. In addition, we need to consider the difference between the arrival rate of IEEE 802.11ac users and legacy users. Thus the probability that a collision involves a legacy user is,

$$P_{inv} = \frac{N_{\ell g}(1)\lambda_{\ell g}(1)}{N_{\ell g}(1)\lambda_{\ell g}(1) + (N_{ac}-1)\lambda_{ac}}. \tag{20}$$

During one cycle which is $1/\mu_{ac}$, each IEEE 802.11ac user has $E[A_{ac}]$ transmissions which consists of one successful transmission and $(E[A_{ac}]-1)$ collisions. For the remaining ac users, each of them would have $\lambda_{ac}/\mu_{ac}(E[A_{ac}]-1)$ collisions during $1/\mu_{ac}$. With probability P_{inv} the collision involving one IEEE 802.11ac user and one legacy user which takes T_{c1}, and the remaining collisions occur due to two IEEE 802.11ac users which take $E[T_c]$. Also each of the legacy user would have $\frac{\lambda_{\ell g}(1)/\mu_{ac}(E[A_{\ell g}(1)]-1)}{2}$ collisions during $1/\mu_{ac}$. Therefore the total collision time during $1/\mu_{ac}$ is

$$\begin{aligned} T_{ct_a} = &\frac{(E[A_{ac}]-1)[(N_{ac}-1)\frac{\lambda_{ac}}{\mu_{ac}}+1]}{2}[(1-P_{inv})E[T_c] \\ &+ P_{inv}T_{c1}] + \frac{(E[A_{\ell g}(1)]-1)N_{\ell g}(1)\frac{\lambda_{\ell g}(1)}{\mu_{ac}}T_{c1}}{2} \end{aligned} \tag{21}$$

Similarly, the total collision time during $1/\mu_{lg1}$ can be derived by

$$\begin{aligned} T_{ct_{lg_1}} = &\frac{(E[A_{ac}]-1)N_{ac}\frac{\lambda_{ac}}{\mu_{\ell g}(1)}}{2}[(1-P_{inv})E[T_c] + P_{inv}T_{c1}] \\ &+ \frac{(E[A_{\ell g}(1)]-1)[(N_{\ell g}(1)-1)\frac{\lambda_{\ell g}(1)}{\mu_{\ell g}(1)}+1]T_{c1}}{2} \end{aligned} \tag{22}$$

When a user is in the backoff stage, it may make multiple transmissions until it successfully transmits a frame or the maximum retry limit is reached. From (12) and (13), the collision probability of both IEEE 802.11ac users and legacy users in primary channel can be obtained. Thus, on average, the number of transmissions of IEEE 802.11ac users $E[A_{ac}]$ and legacy users $E[A_{\ell g}(1)]$ are given by:

$$E[A_{ac}] = \frac{1-p_{ac}^{m+1}}{1-p_{ac}}, \tag{23}$$

$$E[A_{\ell g}(1)] = \frac{1-p_{\ell g}(1)^{m+1}}{1-p_{\ell g}(1)}. \tag{24}$$

Denote the average backoff time of IEEE 802.11ac users and legacy users as $\overline{W_{ac}}$ and $\overline{W_{lg_1}}$, respectively. The backoff window size will be doubled when a collision occurs. Given the maximum retry limit is m, the average backoff time is given by,

$$\overline{W_{ac}} = \sum_{i=0}^{m-1} p_{ac}^i(1-p_{ac})\sum_{j=0}^{i}\frac{CW_j}{2} + p_{ac}^m\sum_{j=0}^{m}\frac{CW_j}{2}, \tag{25}$$

$$\begin{aligned} \overline{W_{lg_1}} = &\sum_{i=0}^{m-1} p_{\ell g}(1)^i(1-p_{\ell g}(1))\sum_{j=0}^{i}\frac{CW_j}{2} \\ &+ p_{\ell g}(1)^m\sum_{j=0}^{m}\frac{CW_j}{2}, \end{aligned} \tag{26}$$

where CW_j denotes the backoff window size at the jth stage.

After obtaining the average backoff time, we can derive the probability τ_{ac} that an IEEE 802.11ac user transmits over a random slot. Since in the duration of $\overline{W_{ac}}$, an IEEE 802.11ac user gets to transmit $E[A_{ac}]$ times on average. Thus τ_{ac} can be derived as,

$$\tau_{ac} = \frac{E[A_{ac}]}{\overline{W_{ac}} + E[A_{ac}]}. \tag{27}$$

Similarly, the transmission probability of a legacy user is given by,

$$\tau_{\ell g}(1) = \frac{E[A_{\ell g}(1)]}{\overline{W_{lg_1}} + E[A_{\ell g}(1)]}. \tag{28}$$

Summing up the time duration of all these events during $1/\mu_{ac}$ and $1/\mu_{\ell g}(1)$, we can have

$$\begin{aligned} \frac{1}{\mu_{ac}} &= [1+(N_{ac}-1)\frac{\lambda_{ac}}{\mu_{ac}}]E[T_s] + \frac{\lambda_{\ell g}(1)}{\mu_{ac}}N_{\ell g}(1)T_{s1} \\ &\quad + \overline{W_{ac}} + T_{ct_a}, \end{aligned} \tag{29}$$

$$\begin{aligned} \frac{1}{\mu_{\ell g}(1)} &= [1+(N_{\ell g}(1)-1)\frac{\lambda_{\ell g}(1)}{\mu_{\ell g}(1)}]T_{s1} + N_{ac}\frac{\lambda_{ac}}{\mu_{\ell g}(1)}E[T_s] \\ &\quad + \overline{W_{lg_1}} + T_{ct_{lg1}}. \end{aligned} \tag{30}$$

When the service rate of each IEEE 802.11ac user is larger than its arrival rate, the successful channel bonding access rate μ_s is the same as the sum of arrival rate of all IEEE 802.11ac users which is $N_{ac}\lambda_{ac}$. Notice that when the service rate of any user is less than its arrival rate, then the successful channel bonding access rate will be $N_{ac}\mu_{ac}$. In other words, all IEEE 802.11ac users in channel 1 will make the channel bonding attempts on the secondary channels with a rate of $\mu_s = N_{ac}\min(\lambda_{ac},\mu_{ac})$ which is calculated based on the channel is saturated or not. Accordingly, we calculate the channel bonding rate μ which includes both the successful and the unsuccessful transmission attempts. During each transmission cycle, an IEEE 802.11ac user will transmit $E[A_{ac}]$ times on average including collisions and successful transmissions. Among $E[A_{ac}]$ transmissions, there are $(E[A_{ac}]-1)$ unsuccessful transmissions due to two users transmitting concurrently and one successful transmission. Therefore, the channel bonding rate from all IEEE 802.11ac users is given by

$$\mu = \min(\lambda_{ac},\mu_{ac})(N_{ac} + \frac{(E[A_{ac}]-1)N_{ac}}{2}). \tag{31}$$

Next, we analyze the delay of legacy users in the secondary channel. Let $\mu_{\ell g}(2)$, $\lambda_{\ell g}(2)$ be the service rate and arrival rate of legacy users. During $1/\mu_{\ell g}(2)$ the events may occur are listed as follows,

- Successful transmissions from $N_{\ell g}(2)$ legacy users and $\mu_s P_{SCB_2}/\mu_{\ell g}(2)$ successful channel bonding attempts from IEEE 802.11ac users, as $\mu_s P_{SCB_2}$ is the successful channel bonding rate;

- Collisions involving legacy users, and among two IEEE 802.11ac users; (As long as the collisions involving a legacy user, the collision time is T_{c1}, otherwise it is T_{c2}.)
- The average backoff time.

Therefore, the average service time of a legacy user in channel 2 is calculated as,

$$\begin{aligned}\frac{1}{\mu_{\ell g}(2)} &= \frac{\mu_s P_{SCB_2}}{\mu_{\ell g}(2)} E[T_s] + [(N_{\ell g}(2)-1)\frac{\lambda_{\ell g}(2)}{\mu_{\ell g}(2)} + 1]T_{s1} \\ &\quad + (\mu - \mu_s) P_{CB_2} T_{c2} + \overline{W_{lg2}} \\ &\quad + \frac{T_{c1}(E[A_{\ell g}(2)]-1)((N_{\ell g}(2)-1)\frac{\lambda_{\ell g}(2)}{\mu_{\ell g}(2)}+1)}{2}.\end{aligned} \tag{32}$$

Notice that $E[A_{\ell g}(2)]$ is dependent on $p_{\ell g}(2)$ of legacy user. In channel 2, given a legacy user is transmitting, a collision will happen if any of the remaining IEEE 802.11ac users and legacy users is transmitting. Additionally, we can calculate the number of active contenders in channel 2 as $(N_{\ell g}(2)+P_{CB_2}N_{ac})$. Therefore, we can calculate the collision probability of a legacy user,

$$p_{\ell g}(2) = 1-(1-\frac{\lambda_{\ell g}(2)}{\mu_{\ell g}(2)}\tau_{\ell g}(2))^{(N_{\ell g}(2)-1+N_{ac}P_{CB_2})}, \tag{33}$$

where

$$\tau_{\ell g}(2) = \frac{E[A_{\ell g}(2)]}{\overline{W_{lg_2}} + E[A_{\ell g}(2)]}. \tag{34}$$

After obtaining the service rate of all users, we are able to derive the capacity of a multi-channel WLAN. For a delay sensitive service, only when the traffic service rate is larger than the arrival rate, the data queue is stable and the delay requirement can be satisfied. Otherwise, the queue will build up, and the video service will experience ever-increasing queuing delay and packet loss. In other words, any user in the system needs to have a stable queue to ensure the delay is bounded.

B. Generic Model of Multiple Channels

Now, we extend our analysis from the case of two-channel to a more general case which consists of multiple channels. Given that channel 1 is chosen by N_{ac} IEEE 802.11ac users as the primary channel and $N_{\ell g}(c)$ legacy users are operating only in channel c, both P_{SCB_c} and P_{CB_c} can be derived. As specified in the standard, IEEE 802.11ac users can only bond neighboring channels up to eight channels. The probability of bonding all eight channels is the product of the corresponding P_{CB_c}. But, to get the probability to transmit over four or two channels, we need to subtract the probability that all eight or four channels are available to transmit. Given the number of bonded channels is x, $P_{CB}(x)$ and $P_{SCB}(x)$ denote the probability to bond x channels and successfully bond x channels. When the total number of available channels is C, $C \in \{2,4,8\}$ channels, the bonding probability and successful bonding probability to bond x channels can be written as,

$$P_{CB}(x) = \prod_{c=2}^{x} P_{CB_c} + i(x-C)\prod_{c=2}^{2x} P_{CB_c}, \quad x \in \{2,4,8\}\, and\, x \le C \tag{35}$$

$$P_{SCB}(x) = \prod_{c=2}^{x} P_{SCB_c} + i(x-C)\prod_{c=2}^{2x} P_{SCB_c}, \quad x \in \{2,4,8\}\, and\, x \le C \tag{36}$$

where $i(x)$ is given by,

$$i(x) = \begin{cases} -1 & if\, x<0 \\ 0 & if\, x=0 \end{cases} \tag{37}$$

In general, given the total number of channels available in the system as C, there are $i = (\log_2(C)+1)$ types of T_c and T_s. For example, if $C=8$ there are $T_{c1}, T_{c2}, T_{c4}, T_{c8}$ and $T_{s1}, T_{s2}, T_{s4}, T_{s8}$. Thus, we can define a set $\mathcal{I}_C$,

$$\mathcal{I}_C \in \{2^x; x = 1, 2 \ldots \log_2(C)\}. \tag{38}$$

According to the analysis in Sec.IV-A, the average delay of a single IEEE 802.11ac user in the primary channel is,

$$\frac{1}{\mu_{ac}} = [1+(N_{ac}-1)\frac{\lambda_{ac}}{\mu_{ac}}]E[T_s] + \frac{\lambda_{\ell g}(1)}{\mu_{ac}}N_{\ell g}(1)T_{s1} + \overline{W_{ac}} + T_{ct_a} \tag{39}$$

where

$$\begin{cases} E[T_s] = \sum_{i\in\mathcal{I}_C}(P_{SCB}(i)T_{si}) + (1-\sum_{i\in\mathcal{I}_C}P_{SCB}(i))T_{s1} \\ E[T_c] = \sum_{i\in\mathcal{I}_C}(P_{CB}(i)T_{ci}) + (1-\sum_{i\in\mathcal{I}_C}P_{CB}(i))T_{c1}. \end{cases} \tag{40}$$

Note that when the channel bonding is disabled, $P_{SCB}(i) = 0, P_{CB}(i) = 0$ for $\forall i \in \mathcal{I}_C$.

In (40), the successful transmission time T_{si} and collision time T_{ci} are both dependent on the number of bonded channels. Thus T_{si} and T_{ci} are,

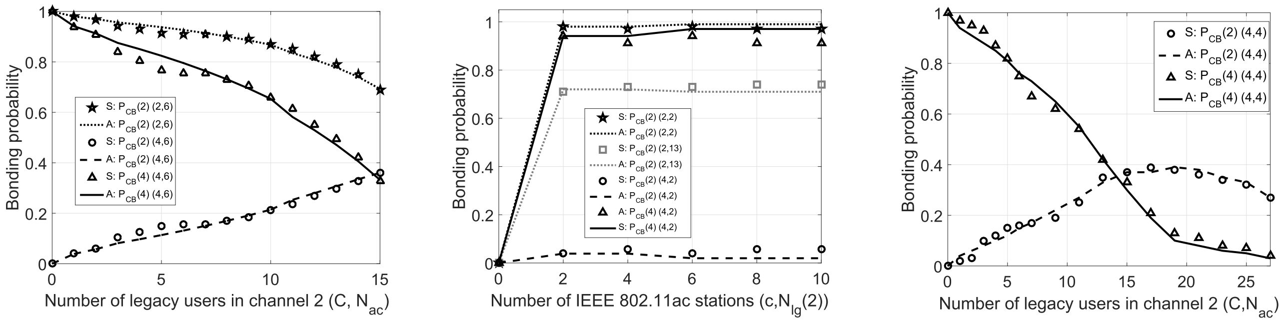
$$T_{si} = \frac{T_{data}}{i} + SIFS + T_{ACK} + DIFS \quad i \in \mathcal{I}_C, \tag{41}$$

$$T_{ci} = \frac{T_{data}}{i} + ACK_{timeout} + DIFS \quad i \in \mathcal{I}_C. \tag{42}$$

Denote the service rate of one tagged legacy user in channel c as $\mu_{\ell g}(c)$. Based on the previous analysis, we know that the legacy users in channel 1 compete with IEEE 802.11ac users with CSMA/CA, while the legacy users in other channels compete with channel bonding attempts. Therefore, $1/\mu_{\ell g}(c)$ is

$$\begin{aligned}\frac{1}{\mu_{\ell g}(c)} &= \frac{\sum_{i=2^{\lceil \log_2(c)\rceil}..2^{\log_2(z)}} \mu_s P_{SCB}(i)T_{si}}{\mu_{\ell g}(c)} \\ &\quad + [(N_{\ell g}(c)-1)\frac{\lambda_{\ell g}(c)}{\mu_{\ell g}(c)}+1]T_{s1} + \overline{W_{lg_c}} \\ &\quad + \frac{(E[A_{lg_c}]-1)((N_{\ell g}(c)-1)\lambda_{\ell g}(c)/\mu_{\ell g}(c)+1)}{2T_{c1}} \\ &\quad + \frac{\sum_{i=2^{\lceil \log_2(c)\rceil}..2^{\log_2(z)}}(\mu-\mu_s)P_{CB}(i)T_{ci}}{\mu_{\ell g}(c)} \quad (c \ne 1)\end{aligned} \tag{43}$$

$$\frac{1}{\mu_{\ell g}(c)} = [1+(N_{\ell g}(c)-1)\frac{\lambda_{\ell g}(1)}{\mu_{\ell g}(1)}]T_{s1} + N_{ac}\frac{\lambda_{ac}}{\mu_{\ell g}(c)}E[T_s] + \overline{W_{lg_c}} + T_{ct_{lgc}} \quad (c=1). \tag{44}$$



(a) Under different $N_{\ell g}(2)$ (b) Under different N_{ac} (c) Under different $N_{\ell g}(2)$

Fig. 2. Bonding probability.

TABLE II
PARAMETERS

Parameters	Value
PLCP/PHY/MAC Header	128/128/34 Bytes
ACK	240 bits
SIFS/PIFS/DIFS	16/25/34 μs
a Slot time size	9 μs
Channel bit rate	54Mbps
Maximum packet size	1000 Bytes
Average video data rate from trace [30]	1.1 Mbits/s

In a special case, when IEEE 802.11ac users disable the channel bonding, $P_{CB}(i)$ and $P_{SCB}(i)$ for $\forall i \in \mathcal{I}_C$ become zero in (43) and (44).

C. Proposed Bonding Policy

As the wireless network has limited capacity in support of delay sensitive users, it is of critical importance to apply admission control to guarantee that all admitted users have a bounded delay. According to the analysis in Section IV.A-B, the number of users can be supported with bounded delay is dependent on the channel bonding decision. To improve the network capacity, the bonding feature should be activated when the secondary channel are underutilized; and be disabled when excessive contentions in the secondary channels degrade the service rate of legacy users to a certain threshold. Therefore, we propose an algorithm that incorporates the bonding decision and admission control to achieve the maximum network capacity. The detailed procedure is described in Algorithm 1.

V. PERFORMANCE EVALUATION

To validate the analytical results, we implement the multi-channel bonding protocol in an event-driven network simulator (NS-3). In the experiments, we set up a single-hop WLAN with multiple channels, and all users carry video flows. The video flow is generated based on real video trace file obtained from [30]. We list the main parameters used in the experiments in Table II.

A. Bonding Probability

The channel bonding probabilities in the two-channel setting and the four-channel setting are shown in Fig. 2. To simplify the figure illustration, we set the number of legacy users in all the secondary channels to be the same. And C in the legend denotes the number of available channels in the system. In Fig. 2(a), we can observe that the channel bonding probability $P_{CB}(2)$ under the two-channel case becomes smaller if we increase $N_{\ell g}(2)$ in the secondary channel. Because, the secondary channel is more likely to be busy with more legacy users. Additionally, $P_{CB}(2)$ under two-channel case is always larger than that under four-channel case due to the transmissions over four channels. In other words, the preliminary condition to bond four channels is that both the primary channel and the first secondary channel are idle. From Fig. 2(b), we can observe that the number of IEEE 802.11ac users will not change bonding probability much when the number of IEEE 802.11ac users is larger than two. This is because the bonding probability is conditioned on the transmissions of IEEE 802.11ac users over the primary channel. Therefore, the bonding probability is mainly dependent on the number of legacy users in the secondary channels. Thus, the number of IEEE 802.11ac users does not change the bonding probability much. But channel bonding probability changes significantly when we vary $N_{\ell g}(2)$ which equally changes the channel occupancy in channel 2. In the four-channel case, there are two channel bonding options, i.e., two channels or four channels. IEEE 802.11ac users are more likely to bond four channels than two channels when there are only a small number of legacy users in the secondary channels which is shown in Fig. 2(c). But when the number legacy user increases, it is more likely that some channels, channel 3 or 4 will be occupied by legacy transmissions. Given that channel two is idle, IEEE 802.11ac users still have chance to bond two channels. It is also observed in Fig. 2(c) that the probability of bonding two channels increases, yet that of bonding four channels decreases when the number of legacy users increases. In addition, we observe that when $N_{\ell g}(2)$ is larger than 14, $P_{CB}(2)$ is larger than $P_{CB}(4)$.

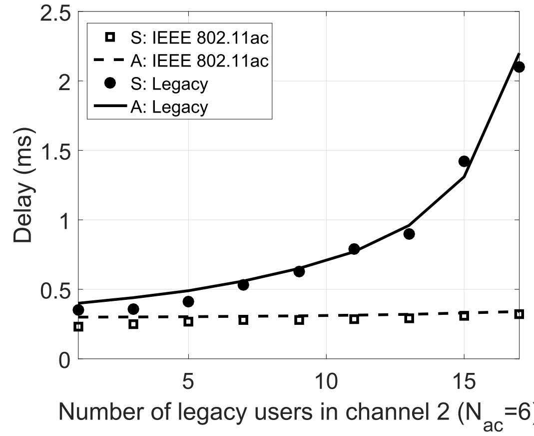
B. Delay Performance

In Fig. 3, we plot the delay when the service rate is larger than the arrival rate for both IEEE 802.11ac users and legacy users. In the two-channel case, it is shown in Fig. 3(a)

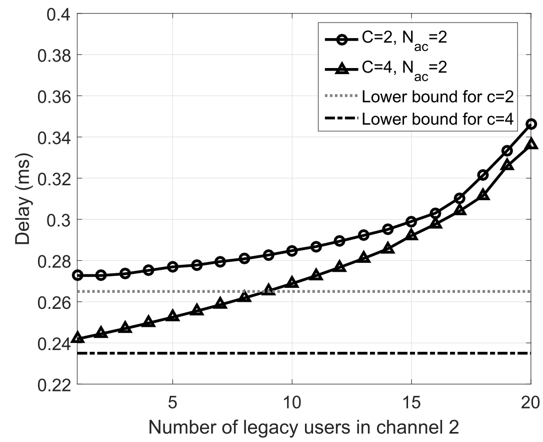
Algorithm 1 Channel Bonding and Admission Control Algorithm

Input:
C: the number of available channels;
N_{ac}: the number of IEEE 802.11ac users;
$N_{\ell g}(c)$, $c \in \{1, \dots C\}$: the number of legacy users in all channels;
λ_{ac}: the arrival rate of IEEE 802.11ac users;
$\lambda_{\ell g}(c)$, $c \in \{1, \dots C\}$: the arrival rate of legacy users in all channels;
Output:
(A,B_i): Admit the new user and allow IEEE 802.11ac users to bond up to i channels, i $\in$ {2,4,8} and i≤C;
(A,B_0): Admit the new user and disable the bonding feature;
R: Reject the new user;
Procedure:
Receive a request to join the network;
if *the request is from a legacy user in channel* c^* **then**
  $N_{\ell g}(c^*)++$;
else
  $N_{ac}++$;
end
Calculate $\mu_{\ell g}(c)$ in all channels when channel bonding is enabled using (39)-(44);
if $\forall c \leq C, \mu_{\ell g}(c) \geq \lambda_{\ell g}(c)$ *and* $\mu_{ac} \geq \lambda_{ac}$ **then**
  Return (A,B_C) ;
else if $\mu_{\ell g}(2) > \lambda_{\ell g}(2)$ **then**
  C_m=min$\big(c >= 2 | \mu_{\ell g}(c) < \lambda_{\ell g}(c)\big)$;
  Return $(A,B_{2^{\lfloor \log_2 C_m \rfloor}})$;
else
  Calculate μ_{ac} and $\mu_{\ell g}(c^*)$ when channel bonding is disabled using (39)-(44);
  if $\mu_{ac} \geq \lambda_{ac}$ *and* $\mu_{\ell g}(c^*) \geq \lambda_{\ell g}(c^*)$ **then**
    Return (A,B_0);
  else
    Return R;
  end
end

that the delay of legacy users increases with the number of legacy users in the secondary channel while the delay of IEEE 802.11ac users does not increase much. Due to increased contentions from legacy users in channel 2 and channel bonding attempts from IEEE 802.11ac users, legacy users in channel 2 experience a longer delay with a larger $N_{\ell g}(2)$. The contentions in the primary channel do not change, yet the heavily loaded secondary channel reduces the bonding opportunities for IEEE 802.11ac users, and the delay slightly increases. The delay of an IEEE 802.11ac user is much lower than that of a legacy user. Fig. 3(b) compares the delay of IEEE 802.11ac users operating over $C = 2$ channels and $C = 4$ channels. It is found that the delay of IEEE 802.11ac users operating over two channels is larger than that of four channels, especially when $N_{\ell g}(2)$ is small, due to a lower bandwidth of bonded transmissions. The dashed lines represent



(a) Legacy users and IEEE 802.11ac users



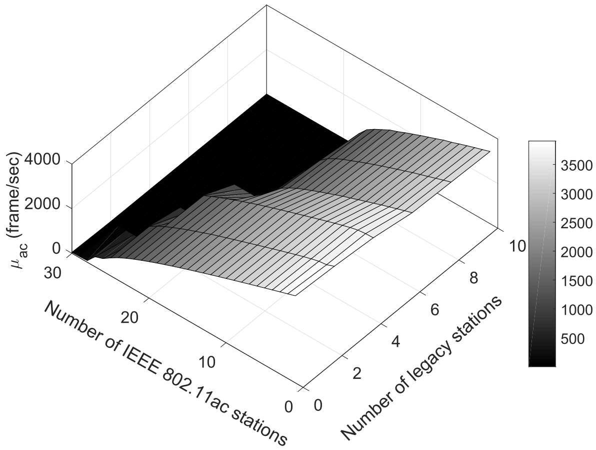
(b) IEEE 802.11ac users

Fig. 3. Delay performance.

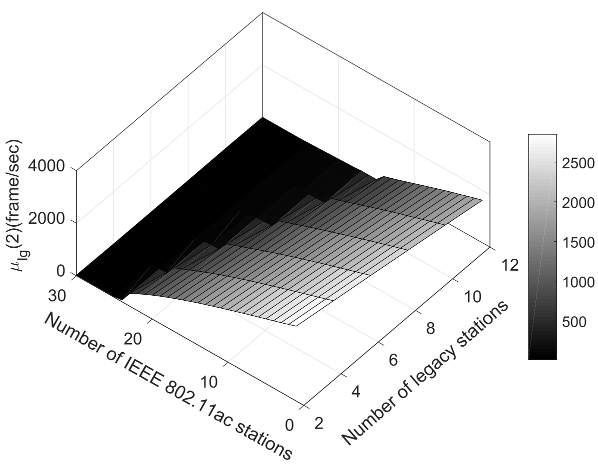
the lower bound of delay when there is no legacy user in all secondary channels for $C = 2$ and $C = 4$ cases. For a larger number of legacy users, the bonding probability of IEEE 802.11ac user decreases, and the delay gap operating over two and four channels becomes smaller. The simulation results validate our analysis.

C. Network Capacity With and Without Channel Bonding

In this subsection, we will first plot the service rate of both IEEE 802.11ac users and legacy users. Then, based on the service rate of both users, the network capacity which quantifies the maximum number of traffic flows can be admitted with a bounded delay of a multi-channel network with or without channel bonding can be obtained. Thereafter, we will investigate the impact of different parameters on the capacity. As shown in Fig. 4, the service rate of IEEE 802.11ac users and that of legacy users decrease when N_{ac} becomes larger due to the increased contentions in both primary channel and secondary channel. Similarly, the service rate of both legacy and IEEE 802.11ac users decreases when $N_{\ell g}(2)$ increases. Because, when the number of legacy users increases, the IEEE 802.11ac users are less likely to bond the secondary channel which decreases the service rate.



(a) Service rate of IEEE 802.11ac users



(b) service rate of legacy users

Fig. 4. Service rate of legacy users and IEEE 802.11ac users.

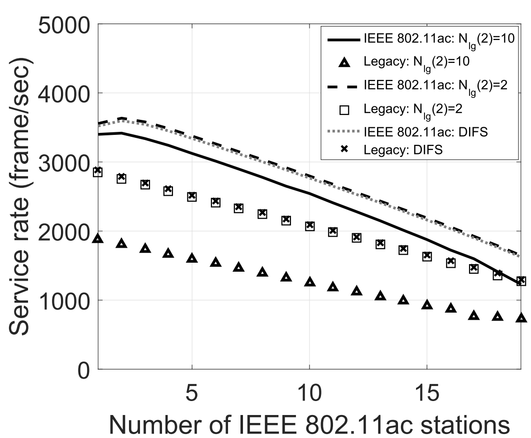


Fig. 5. Service rate Vs number of IEEE 802.11ac users.

IEEE 802.11ac users achieve a higher service rate compared with legacy users due to the bonding capability. But the service rate of IEEE 802.11ac users decreases faster than that of legacy users when the number of IEEE 802.11ac users increases, as shown in Fig. 5. This is because, when the number of IEEE 802.11ac users increases by one, the increased bonding attempts to a secondary channel can be approximated by $P_{CB}(2) * 1 < 1$. Thus, more contention increases in the primary channel compared with that in the secondary channel.

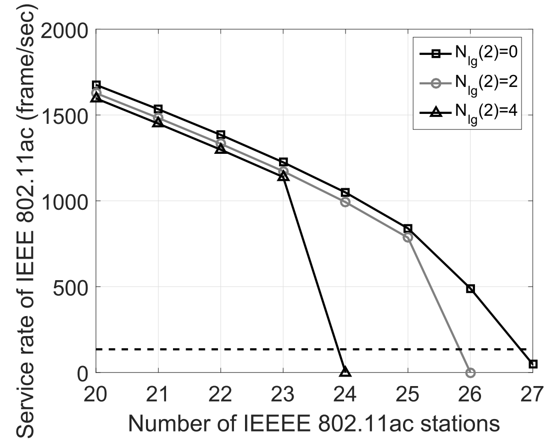


Fig. 6. Service rate of IEEE 802.11ac users (μ_{ac}).

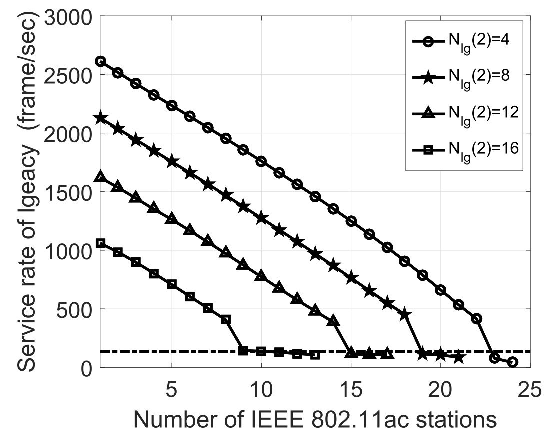


Fig. 7. Service rate of legacy users in channel 2 ($\mu_{\ell g}(2)$).

Accordingly, the service rate of IEEE 802.11ac users decreases faster than that of legacy users. We have also found that PIFS introduces a minor priority difference for IEEE 802.11ac users to access secondary channels as there is only one slot difference between a PIFS and a DIFS, as shown in Fig. 5. To guarantee the delay is bounded, it is critical to ensure that the service rate of all users are larger than their traffic arrival rate. Because, a user will have an unstable data queue which leads to unbounded delay when the arrival rate is larger than the service rate. As shown in Fig. 6, in the two-channel case and when there is no legacy user, 26 IEEE 802.11ac users can be supported; the service rate of 802.11ac users becomes lower than the arrival rate when the 27-th user joins the network. When $N_{\ell g}(2)$ equal to two and four, the maximum number of IEEE 802.11ac users can be supported are 23 and 25, respectively. However, for four legacy users, when the 23rd IEEE 802.11ac user joins the network, although the data queue of IEEE 802.11ac users is still stable, the data queue of legacy users becomes unstable as the service rate of legacy users becomes lower than the traffic arrival rate. Thus, the network capacity is four legacy users and 22 IEEE 802.11ac users. In the case when there are more legacy users, the network capacity is mainly determined by the service rate of legacy users which is shown in Fig. 7.

To guarantee the delay is bounded, we should make sure that the service rates of all users are larger than the traffic arrival rates. Thus, the capacity over a two-channel WLAN

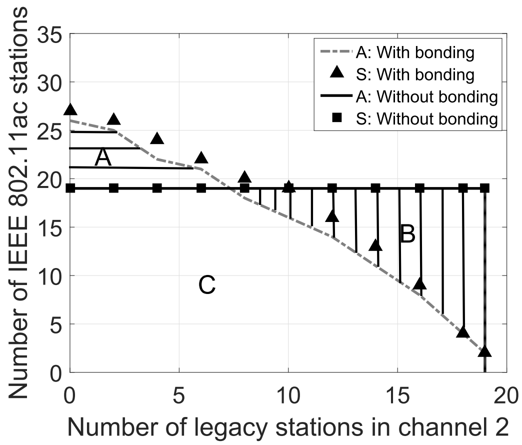


Fig. 8. Network capacity of two-channel WLANs.

supporting unsaturated video services can be derived. It can be seen in Fig. 8 that when $N_{\ell g}(2)$ is small, more IEEE 802.11ac users can be admitted to transit in a two-channel WLAN compared with legacy MAC with no channel bonding.

But when $N_{\ell g}(2)$ becomes larger, legacy users will have a longer delay, thus channel 1 can only allow a smaller number of IEEE 802.11ac users to transmit to ensure the delay of legacy users is bounded. For example, when $N_{\ell g}(2)$ equals 10, no more than 16 IEEE 802.11ac users should transmit in channel 1 to ensure the delay is bounded. Meanwhile, 19 legacy users can be admitted in one channel with bounded delay. In the above example, we can find that channel bonding does not consistently provide gain but also loss. It is observed in Fig. 8 that channel bonding is only preferred when it can provide capacity gain (in A) when $N_{\ell g}(2)$ is less than 8. But, as long as $N_{\ell g}(2)$ is above 8, the capacity will become smaller (in B). Thus, when $N_{\ell g}(2)$ reaches a certain threshold, we should better disable the feature of channel bonding, as the increased contentions will lower the network capacity. We further investigate the impact of other parameters on the network capacity. Since data rate is calculated using two parameters, i.e., the traffic arrival rate and the average packet size, thus users having the same data rate can have different arrival rate and data packet size. We use the online video trace [30] as the baseline, but the arrival rate and the average packet size of data flows can be varied for performance comparison. From Fig. 8, we find that the region can be divided into 3 sub-regions denoted as A, B and C. Area A is the bonding gain region; area B is bonding loss region; while area C is the same as that of legacy WLAN without bonding. In a two-channel case, when channel bonding is disabled, the maximum number of users that can be supported with QoS guarantee is 19 in each channel. In area A, when there are a small number of legacy users in the secondary channel, more IEEE 802.11ac users can be supported with a bounded delay. For example, if there are two legacy users in the secondary channel, 25 IEEE 802.11ac users can be supported in the primary channel with channel bonding. Thus, area A is the region that a bonding gain can be achieved. When the number of legacy users increases to a certain threshold, channel bonding increases the inter-channel contentions that may degrade the network performance. Thus, the channel bonding enters the channel loss region which is area B. For example, if there are 10 legacy users in the secondary channel, only 16 IEEE 802.11ac users can be supported with a bounded delay; while 19 IEEE 802.11ac users can be supported w/o bonding. In this case, bonding feature should be disabled due to the bonding loss. Then, we investigate the impact of different parameters on the maximum capacity.

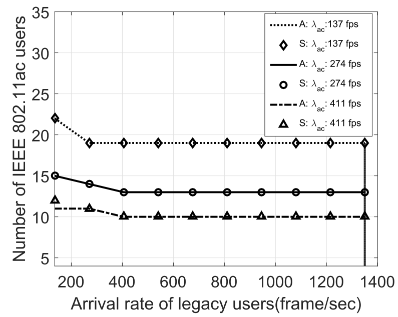


Fig. 9. Impact of arrival rate and payload size.

1) Impact of the arrival rate
   Fig. 9 shows the impact of traffic arrival rate on the maximum capacity. For video flows of 1.1 Mbps, the payload size can be adjusted according to the traffic arrival rate, e.g., a video frame of 500 bytes and an arrival rate of 274 frame/second achieves $274 \cdot 8 \cdot 500 \approx$ 1.1 Mbps. It is observed that the maximum number of IEEE 802.11ac users that can be supported decreases when the arrival rate of legacy users increases. The increasing arrival rate leads to more collisions which lowers the service rate of legacy users. To achieve the maximum capacity for a given arrival rate of IEEE 802.11ac as 137 frame/sec, the bonding feature should be disabled when the arrival rate of legacy users is larger than 137 frame/sec. Additionally, we vary the arrival rate of IEEE 802.11ac users. It can be found that a smaller number of IEEE 802.11ac users can be accommodated when the arrival rate of IEEE 802.11ac stations increases.
2) Impact of the data rate
   The impact from traffic data rate on the maximum capacity is shown in Fig. 10. For the same packet size of 1000 bytes, we adjust the traffic arrival rate to achieve different traffic data rate, e.g., a video frame of 1000 bytes and an arrival rate of 137 frame/second achieves $137 \cdot 8 \cdot 1000 \approx 1.1$ Mbps. When there is only one legacy user in the secondary channel, channel bonding feature should be enabled when the data rate of legacy users is larger than 2.2 Mbps given the data rate of IEEE 802.11ac users is 1.1 Mbps. Because when the data rate is larger than 2.2 Mbps, the number of IEEE 802.11ac users that can be supported in the primary channel is much lower than 19 which is the number of IEEE 802.11ac users can be supported using one channel. Additionally, we vary the data rate of 802.11ac users. It can be observed that the maximum number of traffic flows can be supported drops from 23 to 11 when the data rate of IEEE 802.11ac users increases to 2.2 Mbps. Therefore, the maximum capacity becomes

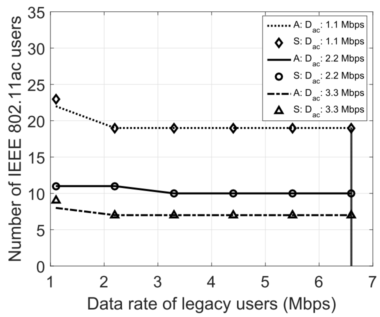


Fig. 10. Impact of data rate.

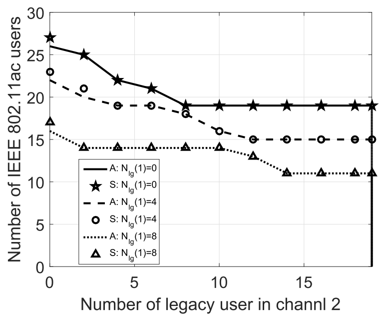
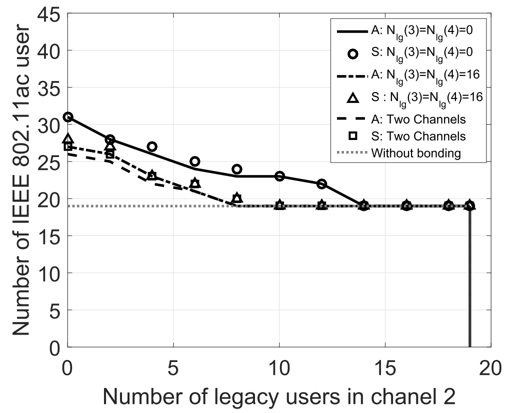
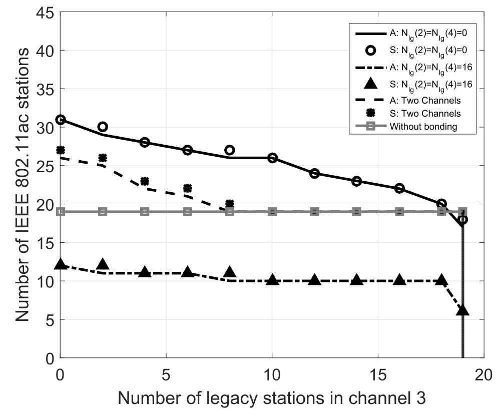


Fig. 11. Impact of $N_{\ell g}(1)$.



(a) $N_{\ell g}(3) = N_{\ell g}(4)$ case



(b) $N_{\ell g}(2) = N_{\ell g}(3)$ case

Fig. 12. Network capacity of four-channel WLANs.

smaller when the data rate of IEEE 802.11ac users increases.

3) Impact of $N_{\ell g}(1)$

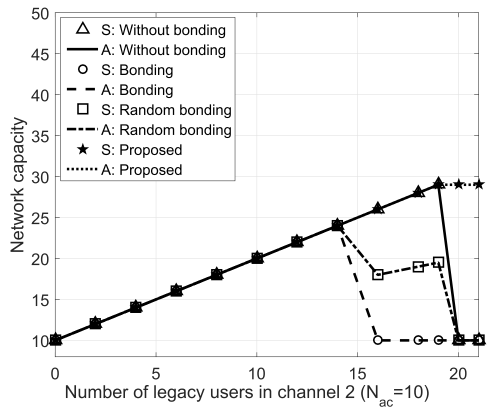
Then, we study the impact of the number of legacy users competing with IEEE 802.11ac users in channel 1. Fig. 11 shows that the number of IEEE 802.11ac users can be supported decreases when $N_{\ell g}(1)$ increases, due to the increased contentions from the legacy users in channel 1. When $N_{\ell g}(1)$ is 0 as only IEEE 802.11ac users are competing in channel 1, the channel bonding feature should be disable when $N_{\ell g}(2)$ is larger than or equal to 8; Meanwhile when $N_{\ell g}(1)$ increases from 0 to 4, the range of legacy users $N_{\ell g}(2)$ to disable the channel bonding feature increases from 8 to 12. When there are more legacy users transmitting in the primary channel, channel bonding is more likely to improve the capacity comparing with legacy MAC with no bonding. Therefore, channel bonding can improve the capacity especially when there are more legacy users in the primary channel.

We further analyze the network capacity when there are four channels. To simplify the illustration, we set the number of legacy users in channel 3 and channel 4 to be the same and vary the value of $N_{\ell g}(2)$ in Fig. 12(a). It can be found in Fig. 12(a) that the network capacity is slightly larger than that of two channels when $N_{\ell g}(2)$ is small and $N_{\ell g}(3) = N_{\ell g}(4) = 0$. This is because transmissions of legacy users in channel 2 may prevent IEEE 802.11ac users from channel 1 to bond multiple channels. But still it is possible that an IEEE 802.11ac user may find a chance to transmit over 4 channels to achieve a higher capacity. But when $N_{\ell g}(3) = N_{\ell g}(4) = 16$, the maximum number of IEEE 802.11ac users can be supported is similar to the case of two channels as IEEE 802.11ac users are more likely to bond two channels or no channels instead of four channels. In another case, we set $N_{\ell g}(2) = N_{\ell g}(3) = 0$. It can be seen from Fig. 12(b) that four channel bonding can significantly improve the network capacity when $N_{\ell g}(2) = N_{\ell g}(3) = 0$ as the bonding of two channels is always guaranteed, and also there is a good chance for four channel bonding when $N_{\ell g}(4)$ is small. When $N_{\ell g}(2) = N_{\ell g}(3) = 16$, the maximum number of IEEE 802.11ac users can be supported is mainly determined by $\mu_{\ell g}(2)$. Therefore, the key factor to decide whether we should enable or disable the bonding feature in a four-channel WLAN is the value of $N_{\ell_g}(2)$ or the contention level in the first secondary channel.

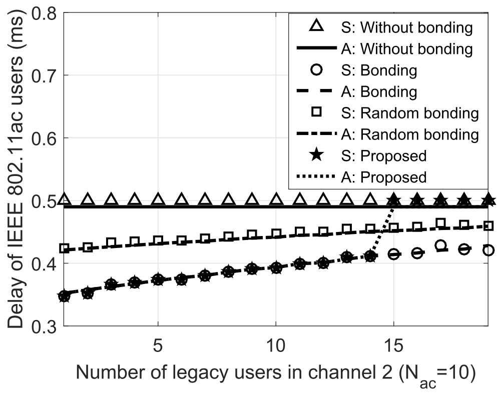
D. Performance of the Proposed Bonding Policy

The performance of the proposed policy in the two-channel case is compared with persistent bonding policy, no bonding policy and random policy in Fig.13. In persistent bonding policy, the channel bonding feature is always activated, while in no bonding policy all IEEE 802.11ac users disable the bonding feature and transmit only on the primary channel. In random policy, IEEE 802.11ac users randomly choose bonding or no bonding.

As shown in Fig.13(a), given that the traffic arrival rates of both legacy users and IEEE 802.11ac users are 137 frames/sec



(a)



(b)

Fig. 13. Performance of the proposed policy.

and N_{ac} is 10, the maximum number of users that can be supported with guaranteed delay are the same for four policies as all users are admitted when the network is lightly loaded, e.g., $N_{\ell g}(2) < 14$. Yet in low load case it is also observed that bonding can improve the delay performance of IEEE 802.11ac users, as shown in Fig.13(b). Therefore, the bonding feature should be activated when $N_{\ell g}(2)$ is smaller than 14. When $N_{\ell g}(2)$ is larger than 14, no bonding policy and the proposed policy can achieve better performance compared with the other two policies. This is because, when $N_{\ell g}(2)$ is larger than 14, channel bonding will make the service rate of legacy users in channel 2 smaller than the arrival rate. For a delay sensitive service, when the service rate is smaller than the arrival rate, the data queue becomes unstable, which leads to unbounded delay. Additionally, the 20-th legacy user is rejected as one more user admitted in the system will degrade the service rates of all existing users, and will lead to unbounded service delay.

VI. CONCLUSION

In this work, we have developed a mathematical framework to study the performance of opportunistic channel bonding specified in the IEEE 802.11ac standard. Specifically, we consider a multi-channel scenario where IEEE 802.11ac users and legacy users are coexisting in all channels including primary and secondary channels. The successful channel bonding probability along with the bonding probability of IEEE 802.11ac users and the service delay of both IEEE 802.11ac users and legacy users have been derived. We further define the network capacity which quantifies the maximum number of traffic flows can be served with guaranteed delay. Numerical results reveal that channel bonding may not always provide gain on network capacity. To achieve the maximum capacity, we should disable the bonding feature when the contentions from legacy users reach a certain threshold in the secondary channels. Additionally, to maximize the network capacity, we propose a bonding policy.

In our future work, we will consider a wireless fading channel and heterogeneous traffic patterns of wireless users. Additionally, we will design an algorithm to select the best primary channel for IEEE 802.11ac users to obtain the maximum throughput.

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