Managing Channel Bonding with Clear Channel Assessment in 802.11 Networks

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***Abstract*—With the increasing demand for higher performance wireless local area networks (WLANs), channel bonding was first proposed in the IEEE 802.11n protocol to offer a higher data rate by combining two 20 MHz channels into one 40 MHz channel. Although much has been understood about channel bonding management, hardly any of these innovations have made it into today's IEEE 802.11 WLANs in a distributed manner. This paper presents the first step to fill the gap, by proposing a channel bonding management solution that can be readily implemented in today's commercial 802.11 devices. We conduct a measurement with off-the-shelf 802.11 devices in a real WLAN to characterize channel bonding, and then propose a channel bonding scheme based on adaptive channel clear assessment (CCA). We conduction evaluation under the typical IEEE 802.11 enterprise scenario, and the results show that our scheme improves the throughput by 37% and 46% compared to the traditional channel bonding scheme and the default CSMA/CA, respectively.**

I. Introduction

Recent development in wireless local area networks (WLANs) has provided opportunities for nodes to operate over wider channels to achieve higher transmission rates. IEEE 802.11n [1] enables *channel bonding*, which allows two 20MHz channels to combine into one 40 Mhz channel. IEEE 802.11ac [2] further extends channel bonding up to eight 20MHz channels. IEEE 802.11ac can operate on the 5GHz band that offers 24 non-overlapping 20 MHz channels in U.S. and up to 11, 5, 2 non-overlapping channels when carrying out channel bonding for 40 MHz, 80 MHz and 160 MHz, which substantially increases the opportunities of channel bonding compared to IEEE 802.11n.

Although channel bonding can offer a higher peak throughput, its merits are frequently compromised by reduced signal quality and potential interference over wider spectrum [3]. The IEEE standard [1] mandates that the total transmission power is limited by a threshold. As such, the power density is reduced by half when the channel width is doubled in channel bonding, which leads to decreased signal to noise ratio (SNR). Moreover, channel bonding increases the number of potential interfering links across consecutive channels. This susceptibility to interference increases the risk of starvation and collision.

A growing attempt has been devoted to exploring the usefulness of channel bonding in the context IEEE 802.11-based WLANs [4], [5]. Despite the fact that much has been understood through these studies, they cannot be directly applied to current standards. These studies either require a central controller to coordinate access points (APs) for channel allocation [4], or make assumptions about collisions and interferences that cannot be guaranteed in real networks [4]. These requirements limit their application in general IEEE 802.11-based WLANs.

The target of this paper is to fill the gaps in IEEE 802.11-compatible channel bonding management. We first characterize the effectiveness of channel bonding in different network topologies in a library 802.11n-based WLAN. We observe that the performance of channel bonding relies on the local topology, i.e., the link quality of the transmission pair and the interference from neighboring links. Therefore, we can make channel bonding decisions based on local link information without central coordination. To make our approach protocol-compatible, we manage channel bonding by tuning the clear channel assessment (CCA) threshold. The CCA adjustment is considered as a potential means to manage channel access in the coming IEEE 802.11 standard [6]. The CCA threshold controls the sensitivity of carrier sense, that is, a node with a higher CCA threshold can access channel with a higher interference/noise level.

In our approach, each node periodically independently adjusts its CCA threshold in channel bonding based on the link quality and interference conditions. For the nodes whose local topology offers potential gain for channel bonding, the CCA threshold is tuned to make its less sensitive to interference or noise, otherwise the CCA threshold is tuned to prevent channel bonding. However, setting different CCA thresholds incurs link unfairness. To solve this problem, we propose a fairness control scheme by periodically adjusting the CCA threshold based on throughput.

The main contributions are summarized as follows.

- We conduct a measurement study in a real IEEE 802.11n WLAN, and characterize suitable conditions for channel bonding. These observations have profound implications on the design of channel bonding schemes.
- We propose a distributed protocol-compatible channel bonding management approach through CCA adjustment. To the best of our knowledge, this is the first work that leverages the CCA adjustment to make effective channel bonding decisions.

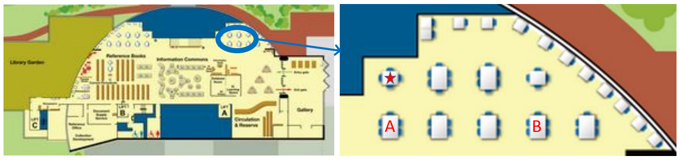


Fig. 1. Measurement topology.

- We implement the CCA-assisted channel bonding scheme on commercial off-the-shelf IEEE 802.11n NICs to validate our observation.
- We evaluate our approach under the standard scenario specified in IEEE 802.11 [7], and the results show that our approach improves network throughput by 37% and 46% compared to the traditional channel bonding scheme and the default 802.11 CSMA, respectively.

II. Characterizing Channel Bonding in IEEE 802.11

A. Channel Bonding in IEEE 802.11

Channel bonding was first proposed in IEEE 802.11n [1] and further developed in IEEE 802.11ac [2]. Senders first sense the primary channel via CCA, and then sense the secondary channel before the backoff counter counts down to zero. The CCA thresholds for primary and secondary channels are shown in Table I [2]. A device may: i) transmit on its primary channel when the primary channel is idle, or transmit on wider channel (40/80 MHz) when both the primary and secondary channels are idle. A channel is considered to be idle when the sensed energy is lower than the CCA thresholds.

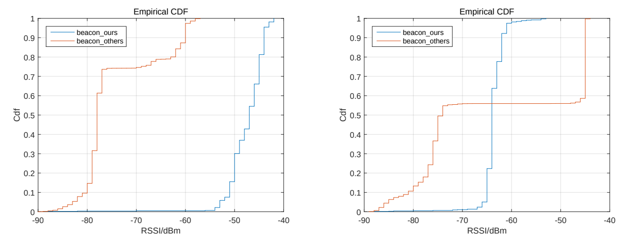
TABLE I
CCA sensitivity threshold in IEEE 802.11ac

Channel width(MHz)	threshold(primary)	threshold(secondary)
20	-82 dBm	-72 dBm
40	-79 dBm	-72 dBm
80	-76 dBm	-69 dBm

B. Measurement Study

Although channel bonding can boost the throughput by offering wider bandwidth, it also results in degraded signal quality and extra interference links in the secondary channel. The goal of our measurement study is to find in which cases channel bonding can do more good than harm. We analyze the performance gain of channel bonding in different cases to characterize the properties of channel bonding.

Measurement methodology. We conduct our measurement in a campus library as depicted in Fig. 1. To test the channel bonding performance in the library WLAN, we use an IEEE 802.11n TP Link router TL-WDR4300 as an AP and a laptop equipped with an Intel 2230 NIC as an STA. We put the AP at the position where the star in Fig. 1 is and put the STA at locations A and B respectively. We generate UDP traffic from AP to STA by using `Iperf` [8]. We set the frame length to be the MTU length and the CCA thresholds to different values by modifying the router's driver `Ath9k` [9] through `OpenWrt` [10]. The primary channel of AP is channel 6 in



(a) Location A (b) Location B

Fig. 2. Beacon strength.

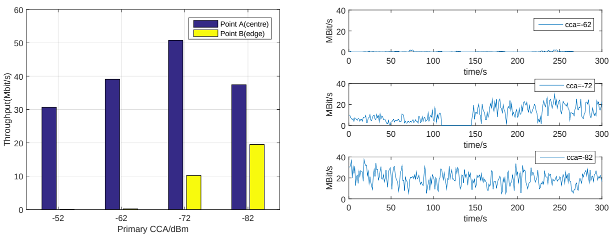
2.4Ghz band and 40 MHz channel bonding is enabled. We use the `wireshark` [11] on STA to capture all packets.

We first place the STA at location A in Fig. 1 and set the primary CCA threshold as -82 dBm, -72 dBm,-62 dBm, and -52 dBm successively. The secondary CCA is set at 10dBm higher than the primary CCA threshold as defined in IEEE 802.11. Then we let the AP transmit UDP traffic to the client for five minutes and record the corresponding averaged throughput. Then, we place the STA at location B and repeat the experiment. By analyzing the packet captured by wireshark, we find there are 6 APs and 118 clients at location A and 9 APs and 127 clients at location B. Fig. 2 shows the CDF of beacon strength. We can observe that there is an AP at location B has a strong beacon strength of around -46 dBm, which means that the AP is closer to our STA. In other word, the AP density is higher at location B. From Fig. 1, it is obvious that location A is at the centre of our AP while location B is at the edge of our AP.

Results. Now, we give the measurement results as shown in Fig 3(a). We find that the throughput of location A improves significantly when the CCA threshold is loosened to -72 dBm and the throughput of location B drops constantly when the CCA threshold increases. The results reveal that if the APs density is low or the STA is at the centre of the AP, a loose CCA threshold should be adopted to provoke channel bonding, otherwise a tight CCA threshold should be adopted to avoid channel bonding.

In addition, we also observe that the throughput of location A peaks at -72 dBm and starts to drop when the CCA threshold is any higher. In this case, an extremely high CCA results in collision at the beginning, which will double the back off counter and that will further increase the possibility of collision. The increased time of back off procedure and high probability of colliding will make the throughput drop constantly as shown in the cases where the CCA thresholds are set to -62 dBm and -52 dBm at location A.

It is worth noting that the throughput of location B drops sharply when the CCA threshold is higher than -72 dBm. This is because the beacon is sent every 0.1 s in IEEE 802.11 and location B suffers strong interference from more hidden terminals when the CCA threshold is constantly loosened, the beacon can be corrupted easily. That will cause the STA to disconnect from the AP. Fig 3(b) shows the instantaneous throughput at location B. We find that a disconnection occurs when the CCA threshold is at -72 dBm and seizes the most



(a) Averaged throughput (b) Instantaneous throughput at location B

Fig. 3. Throughput.

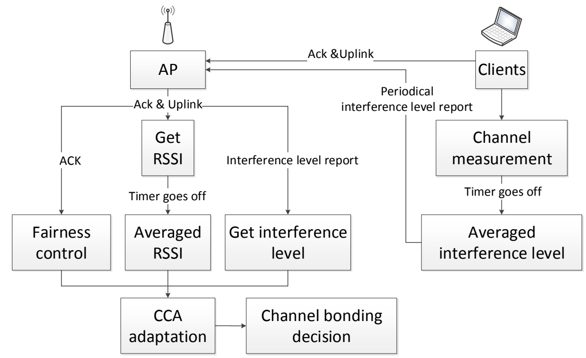


Fig. 4. Design overview.

traffic time when the CCA threshold is increased to -62 dBm. When the CCA threshold is -52 dBm, the STA cannot even resolve the AP's SSID to conduct the association process. In addition, we observe that there is a strong interference from Fig. 2(b), which means the hidden terminal may exist and that will cause collisions and result in a drop in throughput.

From the above results, we get two clues. First, channel bonding should be adopted if the STA is at the centre of the AP. The reasons behind that are (i) normally the STA at the centre of the AP has a good signal strength and is relatively far away from the other nodes; (ii) good signal strength can tolerate the drop in SNR when a wider channel is used; (iii) channel bonding can shorten the transmission range to enable concurrent transmission. Otherwise, channel bonding should be prohibited, because normally, the STA at the edge of the AP has a bad signal strength and is relatively near other nodes. Thus, the drop in SNR may not be tolerable when a wider channel is used. Also, the STA relatively nearer to the other nodes will cause strong interference to others during uplink transmission. In this case, channel bonding will incur strong interference to multiple channels which is harmful to spectrum reuse. Second, channel bonding should be adopted if the AP density is low, because channel bonding can shorten the transmission range so that some interference between different links can be eliminated to enable more concurrent transmission. If AP density is high, channel bonding should not be allowed, as channel bonding may incur new conflict links although the transmission range can be shortened.

III. System Design

A. Design Overview

The crux of our system design is a low-overhead, protocol-compatible and efficient distributed channel bonding scheme. To meet this design requirement, we leverage the inherent C-CA process in IEEE 802.11 to automatically make an effective channel bonding decision. However, how to adjust the CCA threshold with limited information exchange is a non-trivial process, since exchanging information is very costly under a distributed design and fine-grained information exchange is nearly impossible when channel bonding is adopted. Last but not least, the CCA threshold has a very close connection to the network fairness issue. As the default setting in IEEE 802.11, all clients hold the same CCA threshold to guarantee fairness. Thus, it will result in unfairness between clients when they adopt different CCA thresholds of their own.

Fig. 4 illustrates the overview of the system design. Instead of leveraging a central controller or fine-grained information exchange process to do channel bonding, we chose to leverage the CCA process to make a channel bonding decision. The underlying reason is illustrate in Sec. III-B. As shown in fig. 4, The AP will set different CCA threshold for each client based on the information exchanged. Specifically, clients will measure the interference level periodically. The AP will infer the downlink RSSI information from the ack frame or uplink traffic due to link symmetry which gives an insight into the link signal quality. There is also a timer to control the frequency of information exchange. When the timer goes off, clients will calculate the average interference level during that interval, which reflects the surrounding network topology of the link. The AP will then calculate the average RSSI, which reflects the signal quality of the link. After that, the client will send an interference level report to the AP and the AP will feed the RSSI and interference information to the CCA adaptation unit to calculate a proper CCA threshold. There is also a fairness control unit which carries out statistical analysis on the channel occupancy time of every client based on the ack frame. It will periodically adjust the CCA threshold to keep fairness based on the statistics. It is worth mentioning that although we only analyze the downlink scenario of the system design, our scheme can also be applied to the uplink scenario if we report it from the view of sender and receiver instead of AP and client.

B. Channel Bonding Scheme

Channel bonding brings with it the benefits of wider bandwidth. According to the work in [12], a wider bandwidth can nearly double peak throughput and shorten the transmission range which means a higher throughput and the potential to enable concurrent transmission. However, in order to fully utilize the benefits of channel bonding, there are two main challenges to be settled. First, channel bonding also causes new interference to adjacent channels which may make any ongoing transmissions in the adjacent channels collide and result in dropping the aggregated throughput. Thus, finding cases suitable for channel bonding is challenging. Second, the network conditions are very complex and change very fast which makes the design of a light-weight distributed channel bonding scheme very challenging.

Now, we have clues about how to do channel bonding according to the network topology information as described earlier. The next challenge is how to design a distributed channel bonding scheme based on our observation. Notice that the result of CCA in IEEE 802.11 decides the availability of the channel and we can leverage the CCA process to control the channel bonding process. In this way, each node can make decision independently as today's DCF. Specifically, each node should periodically get an individual CCA threshold based on its topology information. For example, if the AP density is high and the STA is at the edge of the AP, the CCA threshold should be tightened to prohibit channel bonding. Otherwise, the CCA threshold should be loosened to provoke the AP to do channel bonding.

C. CCA Adaption

Recall that the CCA threshold should be set according to the topology information of the nodes, for example, the distance of the STA to the AP and the density of the APs. Intuitively, when the distance of the STA to the AP is increasing, the signal strength of the link will decrease and the interference level will increase. When the density of the APs becomes larger, the interference level will also increase. Therefore, we can leverage the signal strength level and interference level as an indicator of the topology information in a time interval T. Now we apply two intuitive criteria in adjusting the CCA threshold. First, we should set a higher CCA threshold for nodes with higher signal strength and lower interference levels. For nodes with lower signal strength and higher interference levels, a lower CCA threshold will be set. Second, the CCA threshold should monotonically increase as the signal strength level increases and monotonically decrease as the interference level increases. There may exist countless models to satisfy the criteria. Here we model the CCA threshold η of each node as

$$\eta = K_0 + K_1 * R - K_2 I, K_1 > 0, K_2 > 0, \qquad (1)$$

where RSSI R stands for the average signal strength of the link in a time interval T. The interference I represents the average interference level to the link. The AP can get the RSSI information from the ack or uplink traffic due to link symmetry, while the interference level can only be measured on the STA side. The STA can distinguish the traffic from the OBSS by decoding the MAC header. However, if the channels of two nodes are partially overlap, they cannot decode the MAC header of the opponent to judge whether they belongs to the same BSS or not. Fortunately, in order to be compatible with legacy devices, a node will transfer duplicated preambles in each 20 MHz sub band and there are at least 5 reserved bits in the L-SIG filed and VHT-SIG-A filed as shown in Fig. 5. The 5 reserved bits can be enough to distinguish different APs among the same contention domain. Thus, the node can encode the ID of its AP in those reserved bits. In this way, two nodes even with partially overlapped channels can decode the ID information in duplicated preamble to judge whether the ongoing traffic belongs to an OBSS or not. After that, the STA will record the interference level from the OBSS and send the averaged interference level periodically to the AP. Once the AP receives the interference report, it will update the CCA threshold on the primary channel for that STA according to Eq. 1. The CCA threshold on the secondary channel is set based on the difference between the primary CCA and the secondary CCA in IEEE 802.11 protocol, as illustrated in table II. It is almost same for the uplink traffic analysis, with the only difference being that AP will broadcast the averaged interference level to all of its clients so that every client can update its own uplink CCA threshold.

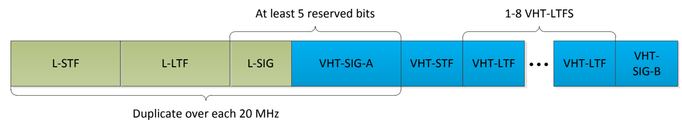


Fig. 5. Reserve bits in the duplicated preambles

TABLE II
DIFFERENCE BETWEEN PRIMARY CCA AND SECONDARY CCA

Bandwidth(MHz)	Primary CCA(dBm)	Secondary CCA(dBm)
20	Th	Th+10
40	Th+3	Th+10
80	Th+6	Th+13

D. Fairness Control

Although we can change the CCA threshold to make effective channel bonding decisions, there is still another issue to be solved: link fairness. It is obvious that our scheme will give those potentially good links a looser CCA threshold and a tighter CCA threshold for the bad links. This means the links with looser CCA thresholds have more opportunity to access the channel while the links with tighter CCA thresholds will spend more time waiting to access a channel, thus incurring unfairness between different clients. To solve this problem, we have come up with a simple but effective fairness control scheme via adjusting the CCA threshold.

First, we use time fairness to evaluate the fairness. The channel occupancy time is calculated based on the packet length and data rate. The AP will maintain a channel occupancy time table which records the channel occupancy time of each client. Suppose the CCA threshold is adjusted every T seconds, then the AP will look up the table to check the time that each client occupies the channel for every $t = \frac{T}{N}$ seconds (here we choose $N = 5$). According to the table, the top P percent (here we choose $P = 50$) will return to the default CCA threshold in IEEE 802.11, the bottom P percent will return to use the adjusted CCA threshold generated by Eq. (1).

IV. EVALUATION

The scenario is a typical enterprise scenario specified by IEEE 802.11 [7]. As illustrated in Fig. 6, there are 8 offices for each floor. Every office is a 20m × 20m square. Inside each office, there are 64 cubicles. Each cubicle is a 2m × 2m square containing one randomly placed STA. There are

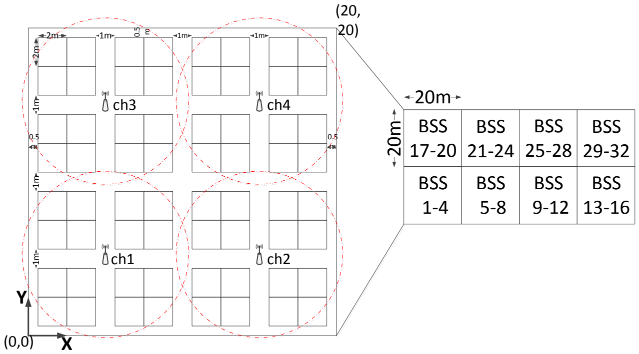


Fig. 6. Deployment layout in the enterprise scenario.

four APs installed on the ceiling at different positions (AP1: (x=5,y=5,z=3), AP2: (x=15,y=5,z=3), AP3: (x=5,y=15,z=3), AP4: (x=15,y=15,z=3)). APs in the same office operate on different non-overlapping primary channels when transmitting with 20 MHz bandwidth only. For APs in different offices, those in the same relative position share the same channel. The specific parameters are summarized in Table III. We choose the CSMA/CA, channel bonding scheme in the existing IEEE 802.11 protocol and CSMA/CA with CCA adaptation as baselines.

TABLE III
EVALUATION PARAMETERS

Parameter	value
Number of APs	32
Number of clients	512
Transmission power	20 dBm
Noise level	-95 dBm
SIFS duration	16 µs
DIFS duration	34 µs
Slot time	9 µs
MCS	[0-6]
Simulation time	10s

Performance under different traffic models. First, we evaluate how the different traffic models impact on the performance of our scheme. For each client, the traffic arrives at a constant rate, then, we change the traffic interval to infer the corresponding performance under different types of web services (e.g., $600\mu s$ for HDTV and $20ms$ for VOIP). Fig. 7 shows the performance under different traffic intervals. When the traffic is very dense (e.g. traffic interval = 1ms), it becomes saturated for all schemes. Our scheme can improve the throughput by around 27.7%, 36.6% and 45.8% compared to the CSMA/CA scheme with CCA adaptation, channel bonding scheme in existing IEEE 802.11 protocol and CSMA/CA respectively under saturated traffic. When the traffic becomes light, each scheme is gradually able to handle all traffic. The results demonstrate that our scheme is more effective compared with others even with different traffic models. Our scheme can also improve the performance a lot especially for services with heavy workload.

Performance under different packet lengths. As the packet length will have an effect on MAC efficiency, we evaluate our scheme under different packet lengths in Fig. 8.

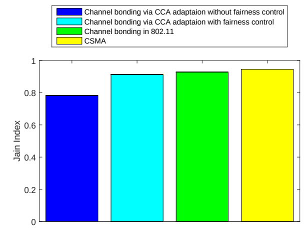


Fig. 10. Jain index of time-based fairness.

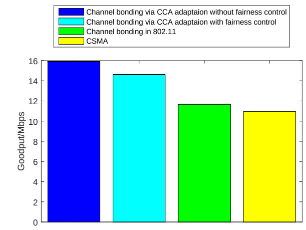


Fig. 11. Throughput under fairness control.

The results reveal that the performance of all schemes degrade as the packet length decreases, which tallies with the fact that MAC efficiency drops as packet length decreases. Our scheme outperforms the channel bonding scheme in existing IEEE 802.11 protocol and the CSMA/CA scheme in all cases demonstrated. Thus, we can see that compared to the channel bonding scheme in IEEE 802.11, our scheme still has a good performance even the packet length is short. This is mainly because exposed terminal exists between different rooms, our CB scheme can use wider bandwidth more intelligently.

Performance under different node densities. In Fig. 9, we set the number of clients in each cubicle to be 5 and 10 to vary the node density. The results show that there is no obvious change in the throughput of each scheme even if the node becomes denser in a cubicle. The main reason is that the cubicle is very small so that the nodes in the same cubicle experience very similar path loss, which makes the nodes in the same cubicle will have similar throughput as well. Thus, the throughput per AP nearly stays the same. This phenomenon further demonstrates that our scheme is still effective even if the node density becomes higher.

Throughput with fairness control. We validate the effectiveness of our fairness control scheme under saturated traffic with the packet length of 1500 Bytes. We use Jain's index [13] to evaluate the time-based fairness. From Fig. 10, we find that changing the CCA threshold indeed results in an unfairness problem. Compared to the CSMA/CA, Jain's index value of our scheme drops nearly 18%. However, when we adopt the fairness control scheme, Jain's index value increases from 0.7836 to 0.9132, which is very close to the CSMA/CA scheme. It is also common sense that we cannot optimise throughput and fairness at the same time, thus, we further compare the throughput of our scheme after adopting fairness control. From Fig. 11, we observe that the throughput of our scheme drops by nearly 10% while it still outperforms the baselines. The results demonstrate that our fairness control scheme is able to strike a balance between the fairness issue and throughput performance.

V. RELATED WORK

Channel bonding was first proposed in IEEE 802.11n [1] protocol where two 20 MHz channels can be aggregated to get a 40 MHz channel. IEEE 802.11ac [2] further extends this technology to support an even wider bandwidth (e.g. 40 MHz, 80 MHz, 160 MHz) by grouping more 20 Mhz channels together. In the literature related to channel bonding

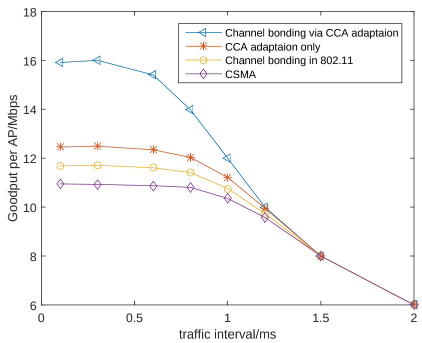


Fig. 7. Performance under different traffic intervals.

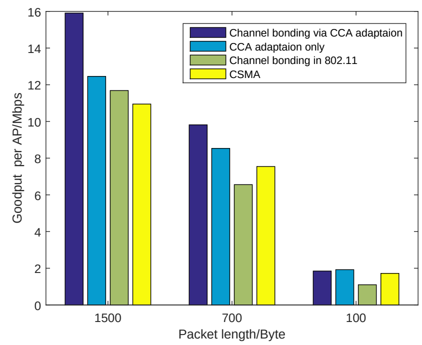


Fig. 8. Performance under different packet length.

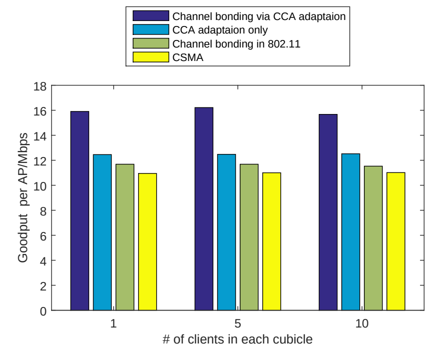


Fig. 9. Performance under different node density.

performance, one of the first studies of channel bonding is SampleWidth [12]. SampleWidth first quantifies the impact of channel width on throughput, range, and power consumption, and demonstrates that a wider bandwidth can get higher peak throughout with a smaller transmission range by detailed measurements using commodity IEEE 802.11 hardware. Deek et al. [4] further investigate the merits and issues of channel bonding in larger 802.11 networks. Bellalta et al. [5] analyze the interactions between a group of neighboring WLANs that use channel bonding and evaluate the impact of those interactions on the achievable throughput. The impact of hidden nodes was evaluated and a protection mechanism by exchanging RTS/CTS was proposed in [14]. Different from these studies, this paper explores using CCA adaptation to manage channel bonding in a distributed manner.

Our work is also related to spectrum management. Rayanchu et al. [15] develop a modeling framework to efficiently construct a conflict graph, and then propose a centralized algorithm to enable flexible channelization based on the conflict graph. However, flexible channelization is difficult to implement on an off-the-shelf IEEE 802.11 device. Yun et al. [16] propose an approach to adapt the spectrum on a per-frame basis. However, it requires modification in the PHY which is incompatible with the IEEE 802.11 protocol. Our work differs from these proposals in that our solution is readily implemented on commercial off-the-shelf devices and is fully compatible with the IEEE 802.11 PHY.

VI. Conclusion

In this paper, we have proposed a practical distributed protocol-compatible channel bonding scheme. We observe that a channel bonding decision should be made according to the topology information and the CCA process can be leveraged to control the channel bonding process. We have also conducted a measurement study with off-the-shelf IEEE 802.11 devices to demonstrate the correctness of our observation under a real-world environment. Extensive evaluation is conducted in a typical IEEE 802.11 enterprise scenario, and the results show that our scheme significantly improves the network throughput under various traffic models without sacrificing fairness. We hope that our investigation on the impact of CCA adaptation and the proposed channel bonding scheme can provide some implications for future designs.

Acknowledgment

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