Performance Analysis of IEEE 802.11ac DCF with Hidden Nodes

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***Abstract*—Recently, the IEEE 802.11 standard based Wireless Local Area Networks (WLAN) have become more popular and are widely deployed. It is anticipated that WLAN will play an important rule in the future wireless communication systems in order to provide several gigabits data rate. IEEE 802.11ac is one of the ongoing WLAN standard aiming to support very high throughput (VHT) with data rate of up to 6 Gbps below the 6 GHz band. In the development of IEEE 802.11ac standard, several new physical layer (PHY) and medium access control layer (MAC) features are taken into consideration, such as employing wider bandwidth in PHY and incrementing the limits of frame aggregation in MAC. However, due to the newly introduced features, some traditional techniques used in previous standards could face some problems. This paper presents a performance analysis of 802.11ac Distributed Coordination Function (DCF) in presence of hidden nodes in overlapping BSS (OBSS) environment. The effectiveness of DCF in IEEE 802.11ac WLAN when using different primary channels and different frequency bandwidth has also been discussed. Our results indicate that the traditional RTS/CTS handshake mechanism faces shortcomings and needs to be modified in order to support the newly defined 802.11ac amendment.**

***Index Terms*—WLAN, Distributed Coordination Function, RTS/CTS, IEEE 802.11ac, Hidden Node**

I. INTRODUCTION

The IEEE 802.11 Wireless Local Area Networks (WLAN) is widely known and used for its convenience and low costs. It can be anticipated that WLAN will play an important role in the future wireless communication systems in order to provide data rate solutions of multi-gigabits transmission. So far, the current IEEE 802.11n can offer data rate up to 600 Mbps and IEEE 802.11ac is one of the ongoing WLAN standards aiming to support Very High Throughput (VHT) with data rate of up to 6 Gbps below 6 GHz band. In 1990's, the IEEE standardization group had defined the Distributed Coordination Function (DCF) as the fundamental medium access method, which is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) technique. Since then researchers have devoted a considerable amount of attentions on the MAC performance of IEEE 802.11 systems. The performance analysis of IEEE 802.11 DCF is presented by Bianchi in [1]. In this paper, the author proposed a bi-dimensional Markov chain model to study the performance of 802.11 DCF by assuming saturated traffic condition. Later on, [2] proposed an accurate unsaturated system analysis. The throughput analysis is shown in [3] by taking into account a Hidden Node (HN) scenario, which is an important problem inherent to the basic access scheme of DCF. With the ever increasing popularity of IEEE 802.11 standard based WLAN, it is highly probable that a station (STA) is in the coverage area of overlapping Basic Service Set (OBSS), which may result in a HN problem.

Meanwhile, due to the high speed development of WLAN technique, the performance of the most recent IEEE 802.11 system has drawn many interests. The IEEE 802.11ac is an ongoing next-generation WLAN standard which aims to offer data rate of up to 6 Gbps [4]. Although the performance of 802.11 DCF has been investigated [3] [5], new standard introduces several new PHY and MAC features into WLAN, e.g., usage of wider bandwidth from 40MHz in 802.11n to 80 MHz or 160 MHz. This brings different impacts on the performance of the DCF scheme. In this paper, we analyze the system performance of DCF with HN by taking into account some of the new 802.11ac PHY and MAC features. One key challenge of 802.11ac specification formulation is the indication and usage of different primary channels in different bandwidth, which have not been considered by current DCF researches. Therefore, we also present and analyze the results about the usage of different primary channels in OBSS.

The remainder of this paper is organized as follows: Section II gives an overview of the 802.11 DCF as well as the new features of PHY and MAC in 802.11ac. In Section III, we use the existing mathematical throughput analysis model for analyzing 802.11ac DCF. Simulation results and performance analysis are presented in Section IV and Section IV summarizes this paper.

II. PRELIMINARY

A. IEEE 802.11 Distributed Coordination Function

IEEE 802.11 DCF is based on CSMA/CA, which adopts carrier sensing to avoid channel collisions. It employs two techniques for the data transmission, the mandatory basic

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access scheme (Fig. 1) and optional request to Request-To-Send/Clear-To-Send (RTS/CTS) mechanism (Fig. 2). The default mode is base access scheme, which is a two-way atomic exchange sequence that allows each STA lock out the contention so that the atomic sequence is not interrupted by other contending STAs. A STA with new packets for transmitting will firstly monitor the channel. If the channel is sensed idle for an interval time exceeding the DCF Interframe Space (DIFS), the STA may starts the packet transmission immediately. Otherwise, the STA keeps monitoring the channel activity, then enters the back-off status and randomly (also uniformly) generates a back-off time within a Contention Window (CW) size before transmitting, e.g., in the range $[0, CW]$. The value of CW starts with a minimum value CW_{min}, which we denote as W_0. Then the value doubles after each unsuccessful transmission up to a maximum size CW_{max}. The relation between CW_{min} and CW_{max} could be defined as: $CW_{max} = 2^m CW_{min}$, where m is the maximum increasing factor. The back-off timer is decreased by one slot time if channel is sensed to be free in a slot time. If transmission is detected on the channel, then the back-off timer is frozen and restarted only when channel becomes idle for more than a DIFS period. When the back-off timer reaches zero, the STA starts transmission.

In 802.11ac, the sending STA will firstly send Block Acknowledgment Request (BAR) after Short Interframe Space (SIFS) period, then receiver responds with a Block Acknowledgment (BA) frame. If BA is not received by the sending STA, it will start its back-off procedure and double its current CW unless CW = CW_{max}. If BA is received or maximum retry limits is reached, the CW is always reset.

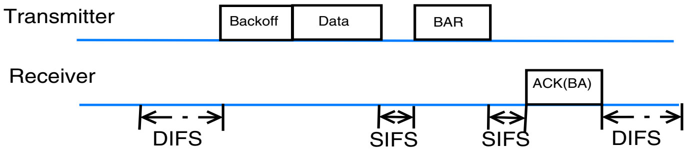


Figure 1: Basic access scheme

In the RTS/CTS mechanism, besides following the above mentioned basic access scheme, the sending STA will send a special RTS frame after medium is sensed to be free for a DIFS period. When the receiver receives the RTS frame, after a SIFS period it will respond with CTS frame. The transmission is started by sending STA only if the CTS frame have been received correctly. During the RTS/CTS exchange period, the other contending STAs also read the information of RTS/CTS frames and update their Network Allocation Vector (NAV) containing the information of which period the medium remains captured.

B. Hidden Node Problems

Carrier sensing mechanism or listen-before-talk scheme is critical for collision avoidance due to the inherent property of the DCF scheme. 802.11 employs both physical carrier sensing and virtual carrier sensing mechanisms. The carrier sensing mechanism is responsible for detecting the transmission of other STAs by using Clear Channel Assessment (CCA) function that resides in PHY. Hence, if another contending STA is out of sensing range of sending STA, then collisions could occur. Considering the situation in Fig. 3, there is data transmission between STA1 and Access Point (AP)1. The cycles are represented as the transmission range of STA3 and STA1, respectively. When STA2 wants to send data to AP1, it can detect the transmissions from STA1, and hence differs transmission. However, the distant STA3 is out of transmission range of STA1. Thus, when STA1 transmits data to AP1, STA3 would not be able to detect the transmission and consider channel to be free. Therefore, collision will occur at AP1 when STA3 starts the transmission at the same time. In such case, STA3 is called Hidden Node (HN) with respect to the communication between STA1 and AP1.

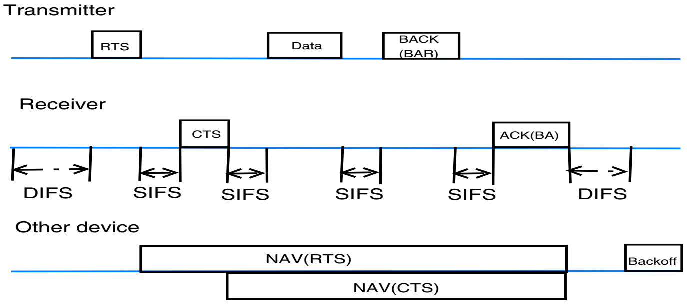


Figure 2: RTS/CTS access scheme

HN problem can't be solved by the basic backoff rules in MAC since STA fails to sense other existing transmissions. The RTS/CTS scheme, which relies on virtual carrier sensing mechanism, is one typical solution for HN problem. However, the exchange of RTS and CTS frames brings longer MAC overhead and costs more radio resource. The effectiveness of RTS/CTS is controversial, and it has been investigated in some papers with existing IEEE standard [5] [6].

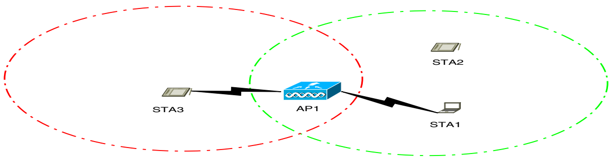


Figure 3: Hidden node problem

C. Overview of Key PHY Features and MAC Enhancement of 802.11ac

IEEE 802.11ac, which aims to provide VHT below the 6 GHz band, is currently under development. It could be viewed as an extension of the existing 802.11n standard, where basic notions of Multiple Input Multiple Output (MIMO) and wider channel bandwidth are enhanced generally. An overview of the key PHY features and MAC enhancements of 802.11ac are introduced in the following.

1) Mandatory and Optional PHY Features: The key feature that makes 802.11ac different from 802.11n in PHY is the support for 80 MHz or 160 MHz channel bandwidths. Usage of 80 MHz channel can approximately double the data rate as compared to 802.11n where 40 MHz is the largest channel bandwidth. As a result, only one spatial stream is mandatory in 802.11ac instead of one or two spatial streams as specified in 802.11n. As an optional feature, the support of 160 MHz channel is also defined in 802.11ac for another two-fold increase in data rate over 80 Mhz channel bandwidth which is mandatory. Another feature of 802.11ac is that 256QAM is added as an optional modulation scheme in order to support peak data rates of close to 7 Gbps transmission while 64QAM is the highest modulation scheme specified in 802.11n.

In order to support wider channel bandwidths, 802.11ac defines its channelization for 20, 40, 80, and 160 MHz channels as shown in Fig. 4. For example, a 40 MHz band is formed by two contiguous 20 MHz bands, and 80 MHz transmission band is formed by two contiguous 40 MHz bands, where one of the 20 MHz bands is the primary channel and the others are secondary channels. However, unlike only one 20 MHz channel is specified in 802.11a, how to utilize and support the multi-channel are still critical for the development of 802.11ac specifications.

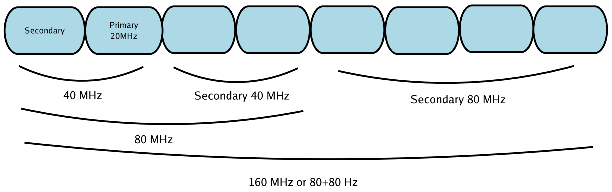


Figure 4: Channelization in the draft IEEE 802.11ac standard

2) MAC Enhancements: 802.11n introduces two kinds of frame aggregations comprising Aggregated MAC Protocol Data Unit (A-MPDU) and Aggregated MAC Service Data Unit (A-MSDU) to enhance its MAC efficiency. It is also possible to combine both which is referred as hybrid A-MSDU/A-MPDU aggregation hereinafter. Due to multiple channels are defined, the key MAC enhancements of 802.11ac are centered around its capability of multi-channel operations. More details of the MAC layer enhancement as well as PHY features could be found in [7].

III. SYSTEM ANALYSIS

We recall the Markov chain model in [1]. STA starts transmission in a generic time slot with probability τ, and the transmission suffers from the collision with probability p. We assume saturated traffic condition, hence τ and p can be expressed as [1] :

$$\tau = \frac{2(1-2p)}{(1-2p)(W_0+1)+pW_0(1-(2p)^m)}, \tag{1}$$

$$p = 1-(1-\tau)^{n-1}, \tag{2}$$

where n is the number of contending STAs, $W_0 = CW_{min}$ and m is the maximum increasing factor. The transmission probability τ and collision probability p can be calculated by solving the nonlinear equations of (1) and (2) numerically using fixed point iteration technique. It can be proved that the system has unique solutions [1]. The normalized system throughput S, which is defined as the ratio of the average number of successfully transmitted bits in a slot time over the average slot time, can be calculated as :

$$S = \frac{P_{tr}P_sE[P]}{T}, \tag{3}$$

where P_{tr} is the probability that there is at least one transmission is occurred on the channel in the considered slot time, P_s is the probability that the transmission occurred is successful, and $E[P]$ is the average payload size. Since there are n contending STAs on the channel and each of them transmits with τ, so we have $P_{tr} = 1-(1-\tau)^n$.

If we denote $p' = 1-p$ as the probability that transmission is successful without collision. Then P_s can be expressed as:

$$P_s = \frac{n\tau p'}{P_{tr}} = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n}. \tag{4}$$

The average slot time T can be calculated as [1]:

$$T = (1-P_{tr})\sigma + P_{tr}P_sT_s + P_{tr}(1-P_s)T_c, \tag{5}$$

where σ is the duration of an empty slot time, T_s and T_c are the average times that channel is busy because of successful transmission and collisions respectively. For the basic access mechanism, T_s and T_c are expressed as:

$$T_c^b = T_s^b = T_{data-ba} + DIFS \tag{6}$$

For the RTS/CTS scheme,

$$\begin{aligned} T_c^{rts} &= T_{phy} + T_{rts} + DIFS, \\ T_s^{rts} &= 2T_{phy} + T_{rts} + 2SIFS + T_{cts} + T_{data-ba} + DIFS, \end{aligned} \tag{7}$$

where T_{rts} and T_{cts} are the transmission time for RTS and CTS frame respectively. $T_{data-ba}$ is the time for transmitting data and BAR frames as well as receiving BA frame. We assume that collision occurs only to the RTS frame, and propagation delay is not taken into account accordingly. We have

$$T_{data-ba} = 3T_{phy} + 2SIFS + T_{data} + T_{BAR} + T_{BA}, \tag{8}$$

$$T_{data} = T_{phy} + T_{sym}N_{sym}, \tag{9}$$

where T_{sym} is the tranmission time for a symbol and N_{sym} is the number of symbols.

IV. PERFORMANCE ANALYSIS

A. Simulation Description

In this section, we investigate the performance of DCF with basic access scheme and RTS/CTS scheme under various

Table I: Simulation parameters

Name	Description	802.11ac
R_{data}	Data rates	var.
$R_{control}$	RTS CTS ACK rates	6 Mbps
SIFS	SIFS duration	16 μs
DIFS	DIFS duration	34 μs
L_{rts}	RTS frame size	20 bytes
L_{cts}	CTS frame size	14 bytes
L_{bar}	MAC compressed BAR frame size	24 bytes
L_{ba}	MAC compressed BA frame size	32 bytes
L_{MAChdr}	MAC overhead	34 bytes
$CW_{min,max}$	Contention window size	{15,127}
N_{AMPDU}	Number of aggregated MPDU	1/10(for simulation)
N_{AMSDU}	Number of aggregated MSDU	1/2(for simulation)
L_{SER}	Length of service bits	16 bits
L_{TAIL}	Length of tail bits	6 bits
N_{ES}	Number of encode stream	2 (for simulation)
T_{phy}	VHT-PHY and legacy preamble and header time	68.8 μs

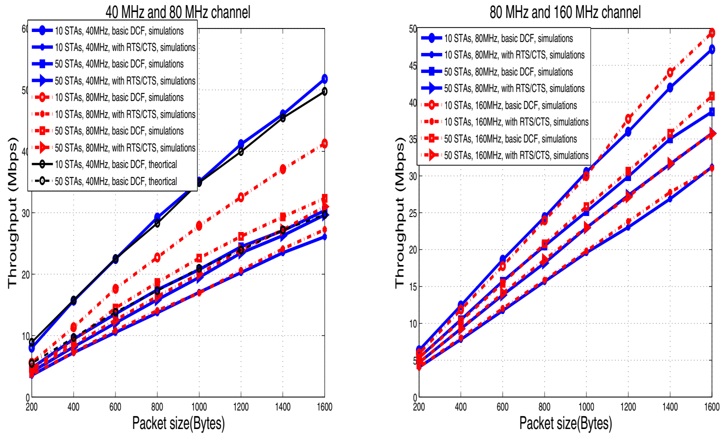
simulation scenarios. To evaluate the performance of DCF within 802.11ac environment, we propose different scenarios with different data rates. At first we validate our numerical simulation results by considering single AP and various numbers of STAs. The results also show the effectiveness of DCF scheme in contending node scenario with wider channel bandwidth. The we present the OBSS scenario including HN to examine the performance of DCF and the usage of different primary channels in multiple APs. In all these simulations, we set Transmit Opportunity (TXOP) limit to be zero. Channel propagation is modeled by using the IEEE TGac specifications [4]. The channel bandwidth varies from 40 MHz to 160 MHz. Note that if 40 MHz is used, the transmission is based on the 802.11n HT-mixed format while others are based on the 802.11ac VHT format [7].

B. Simulation Results

The parameters that are used in the simulation are based on the draft IEEE 802.11ac standard as shown in Table I.

1) Single AP with varying contending nodes: We show the effectiveness of DCF by taking into account a single AP and different numbers of STAs. For validating our simulator, we also show the numerical results for the basic access scheme. Fig. 5a plots the uplink throughput of whole BSS against the different STA packet sizes in an error-prone channel, where collision is the only reason that causes packet error. The goal is to investigate the performance of DCF with 80 MHz channel bandwidth. To fulfill this goal, we compare it with 40 MHz channel with 64QAM modulation scheme, which provides the highest data rate for 802.11n. The data rate considered in simulations is 270 Mbps for both 40 MHz and 80 MHz channels. We do not use aggregation scheme here. First, we can see that the theoretical results match the simulation results very well. Generally, we observe that, the throughput of basic access scheme outperforms the RTS/CTS scheme, especially with fewer STAs. The difference is not so obvious when more STAs are considered. We notice that the usage of 80 MHz channel provides only a little improvement (about 2 Mbps) comparing to the usage of 40 MHz channel in the case of 50 STAs. However, in the case of 10 STAs, the usage of 40 MHz can provide a larger throughput of up to 10 Mbps.

We also compare the throughput performance between 80 MHz and 160 MHz channels with data rates of 270 Mbps in Fig. 5b. The main target for this simulation is to investigate the effectiveness of newly defined 80 MHz/160 MHz channels as well as 256QAM modulation scheme. Although 160 MHz channel is an optional PHY feature for the ongoing 802.11ac standardisation, the effectiveness of DCF in 160 MHz channel remains relevant. Here, the usage of 80 MHz and 160 MHz have almost the same performance in error-prone channel. Similarly, the throughput of the basic access scheme outperforms RTS/CTS mechanism.



(a) 40 MHz and 80 MHz channels (b) 80 MHz and 160 MHz channels

Figure 5: Error-prone channel

2) OBSS with hidden node case: One of our main goal is to investigate the effectiveness of current DCF in OBSS with different usages of primary channels. One simplified scenario is shown in Fig. 6:

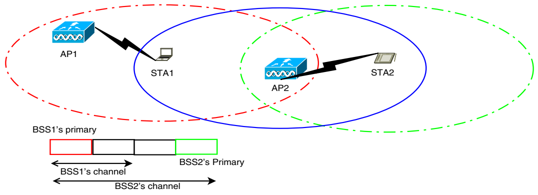


Figure 6: OBSS with hidden node case

In Fig. 6, we consider AP1-STA1 pair as BSS1 and AP2-STA2 pair as BSS2, and note that STA1 and STA2 are hidden from each other due to limitation of sensing range. Fig. 6 shows that one STA is associating with one AP, but it can be extended readily to multiple STAs associating with same AP. Since we assume that AP2 can still hear the transmission of BSS1, the transmission between STA2 and AP2 could be interfered by STA1's transmission. We consider uplink transmissions only, and hence APs do not send any data to its STA but only control frames, such as CTS and BACK. The number of A-MPDU and A-MSDU are 10 and 2, respectively.

Fig. 7 shows the throughput performance of both BSSs when 40 MHz and 80 MHz channels are used. Both BSSs are using the same primary channel and an error-prone channel model is considered. The goal is to study how collision caused by HN problem affects the transmission of OBSS. Generally, we can see that BSS2 has worse throughput performance due to the HN problem. This is due to the fact that the transmissions from STA2 to AP2 could be interfered by the transmissions of BSS1 but not vice versa. The RTS/CTS scheme actually degrades the performance of BSS1 and preserve the transmissions of BSS2. In Fig. 7, we notice that how frequent collisions happen during transmission since the throughput of BSS2 is almost zero when basic access scheme is used. Although the RTS/CTS scheme improve the throughput of BSS2 by up to 40 Mbps due to its ability to mitigate HN problem, such effect is limited and the usage of the RTS/CTS scheme could degrade the throughput performance of BSS1. The usage of 80 MHz channel can offer throughput performance of up to 25 Mbps as compared to 40 MHz channel for BSS1, but not for BSS2.

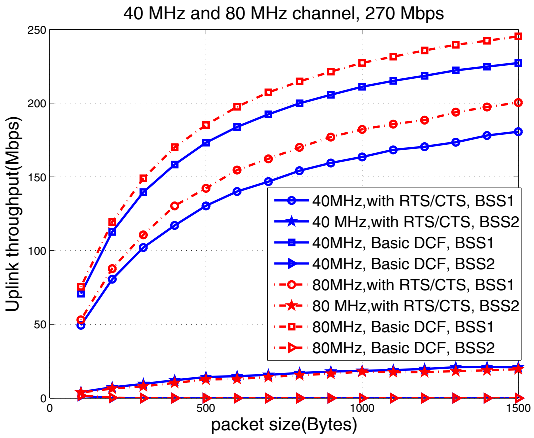
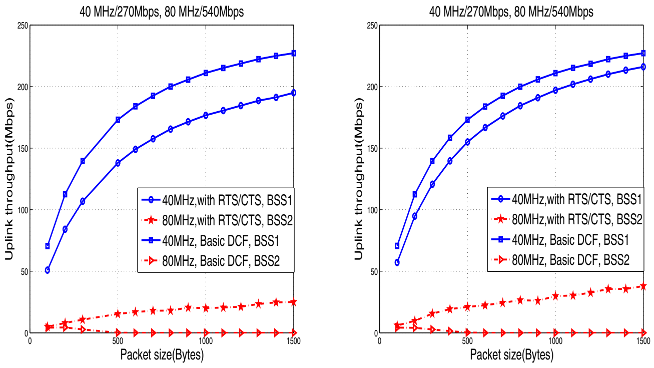


Figure 7: Same primary channel

Since the question of how to effectively support for multi-channels is critical for future WLAN research, we extend our work to the study of usage of different primary channels in OBSS. We assume BSS1 uses only 40 MHz channel, while BSS2 is using 80 MHz channel and their primary channels are different. The data rates for BSS1 and BSS2 are 270 Mbps and 540 Mbps respectively.

The considered scenario in Fig. 8a is that BSS2 uses secondary channel of BSS1 as its primary channel, while in Fig. 8b, the primary channel of BSS2 does not lie on the channel bandwidth scale of BSS1. From Fig. 8, we see that the throughput performance is similar to the one in Fig. 7 though the data rate is doubled for BSS2. The reason is that the current RTS/CTS scheme makes BSS2 fail to know the transmission of BSS1. Therefore, although BSS2 is using different primary channel and bandwidth for transmission, it still suffers from the transmission of BSS1. In Fig. 8b, we can notice that if the primary channel of BSS2 does not lie on the channel bandwidth of BSS2, the throughputs of both BSSs become better (around 10 Mbps comparing to Fig. 8a) for the case with RTS/CTS support. Therefore, we can conclude that the current DCF cannot fully preserve the throughput performance of BSS2 as well as effectively utilizing the newly defined 802.11ac amendments.



(a) 40Hz/270Mbps, 80MHz/540Mbps (b) 40Hz/270Mbps, 80MHz/540Mbps

Figure 8: Different primary channel

V. CONCLUSION AND FUTURE

In this work, we have studied the effect of current DCF access mechanism in 802.11ac scenarios. The target for gigabit transmission and the support for multi-channel operations bring challenges for the emerging 802.11ac standardization. The impact of using the RTS/CTS and basic access schemex in VHT WLAN has been examined in the context of an OBSS in this work. We have concluded that the throughput performance of overall VHT WLAN system suffers from the drawbacks of current DCF scheme. The benefits of wider channel bandwidth, different primary channel and higher order modulation scheme can't be utilized ultimately without enhancement of RTS/CTS scheme, e.g. in [8]. For future work, we planned to investigate an effective RTS/CTS scheme that can fully support multi-channel feature and preserve transmissions in the upcoming IEEE 802.11ac standard .

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