A First Look at 802.11ac in Action: Energy Efficiency and Interference Characterization

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***Abstract*—This paper is first of its kind in presenting a detailed characterization of IEEE 802.11ac using real experiments. 802.11ac is the latest WLAN standard that is rapidly being adapted due to its potential to deliver very high throughput. The throughput increase in 802.11ac can be attributed to three factors - larger channel width (80/160 MHz), support for denser modulation (256 QAM) and increased number of spatial streams for MIMO. We provide an experiment evaluation of these factors and their impact using a 18-nodes 802.11ac testbed. Our findings provide numerous insights on benefits and challenges associated with using 802.11ac in practice.**

Since utilization of larger channel width is one of the most significant changes in 802.11ac, we focus our study on understanding its impact on energy efficiency and interference. Using experiments, we show that utilizing larger channel width is in general less energy efficient due to its higher power consumption in idle listening mode. Increasing the number of MIMO spatial streams is comparatively more energy efficient for achieving the same percentage increase in throughput. We also show that 802.11ac link witnesses severe unfairness issues when it coexists with legacy 802.11. We provide a detailed analysis to show how medium access in heterogeneous channel width environment leads to the unfairness issues. We believe that these and many other findings presented in this work will help in understanding and resolving various performance issues of next generation WLANs.

I. Introduction

With tremendous increase in wireless access networks traffic, 802.11n-based WLANs have become increasingly popular. 802.11ac [1]–[4] builds on top of 802.11n to create even faster and more scalable WLANs. 802.11ac is a Very High Throughput (VHT) amendment that has the potential to deliver a gigabit of throughput in WLANs. Many of the leading smartphone and laptop manufacturers (Samsung Galaxy S4 [5], Apple MacBook Air [6], HTC One [7]) have already adapted 802.11ac. Compared to current 802.11n, the performance gains of 802.11ac are due to three enhancements - (i) larger channel width and dynamic channel width selection, (ii) denser modulation and (iii) support for more spatial streams (SS) and Multi-user MIMO. First generation of 802.11ac products include the first two factors while supporting upto 4 SS.

This paper provides a performance characterization of 802.11ac using experiments on a real testbed of 18 nodes. To the best of our knowledge, this is the first work to present experimental evaluation and complete characterization of the standard. With larger channel width being one of the most significant changes in 802.11ac, the primary focus of our work is to find out pros and cons of utilizing larger channel widths. We center our study on two important issues of *energy efficiency* and *interference*, and provide novel insights on how larger channel width affects both of them. We have performed experiments on three different 802.11ac chipsets (on laptop and smartphone) to verify our results. The main contributions of this paper are as follows:

1) We provide the first testbed based performance characterization of 802.11ac in both indoor and outdoor environment with and without interference. We verify that 802.11ac increases the throughput by 91% compared to the best performance that 802.11n can achieve. We study various factors - modulation, SS and channel width - jointly and in isolation to characterize their impact on throughput. We find no performance improvement can be gained using 256 QAM beyond 10 meters, and majority of the throughput increase is attributed to larger channel width.
2) We characterize the power consumption of 802.11ac using measurements. We find that
   ► idle mode power consumption when a radio is operating at larger channel width is much higher, which makes larger channel width a less energy efficient option overall, and
   ► increasing SS is more energy efficient compared to doubling the channel width for achieving the same percentage increase in throughput.
   The energy efficiency analysis shows how optimal choice of channel width, SS and MCS can be made to meet the throughput requirement while lowering the energy consumption.
3) We identify new throughput and fairness anomalies that are introduced by using larger channel width. We show
   ► In heterogeneous channel width environment where different links operate at different channel widths, competition to access the medium becomes increasing unfair which results into starvation of the larger channel width links. As an example, we show that when a 20 MHz link is operating in secondary channels of an 80MHz 802.11ac link, the performance of the latter degrades severely.
   We provide a detailed analysis of the throughput anomaly issues and outline possible solutions.

The paper is organized as follows. We start out with providing an overview of new components of 802.11ac and our experiment setup in the following section. In Section

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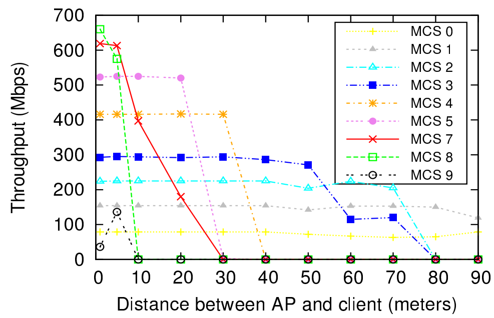
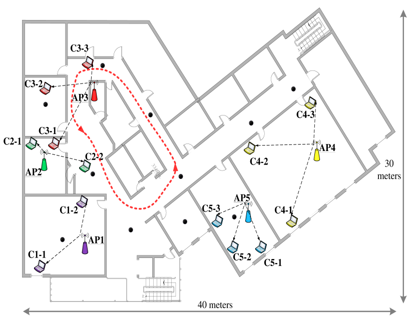
MCS	Modulation	Coding
0	BPSK	1/2
1	QPSK	1/2
2	QPSK	3/4
3	16-QAM	1/2
4	16-QAM	3/4
5	64-QAM	2/3
6	64-QAM	3/4
7	64-QAM	5/6
8	256-QAM	3/4
9	256-QAM	5/6

(a)



(b)



(c)

Fig. 1: (a) 802.11ac MCS index table, (b) Throughput with different MCS values when SS = 3, (c) Testbed of 18 802.11ac nodes used for the experiments.

III, we benchmark different characteristics of 802.11ac in ideal conditions. We also consider realistic scenarios with interference using a 18 nodes indoor testbed. Section IV presents energy efficiency characterization of 802.11ac. Interference characterization and details of how dynamic channel width selection in 802.11ac works are provided in Section V, followed by the related work in Section VII and conclusions in Section VIII.

II. Overview of 802.11ac and Experiment Setup

A. What is new in 802.11ac?

A brief description of mechanisms that are used by 802.11ac to achieve higher throughput is as following.

Larger Channel Width: One of the most significant changes in 802.11ac is that it operates in 5 GHz band only, and not in much more crowded 2.4 GHz band. It has an added support for 80 MHz and 160 MHz (optional) channel widths.

Denser Modulation: 802.11ac introduces support for 256 QAM and also simplifies the MCS index (only 10 values). Fig.1a lists the MCS values and their corresponding modulation and coding rates. MCS 8 and 9 utilize 256 QAM which is the highest constellation density currently supported by any 802.11 standard. In 802.11n, the MCS index was used to indicate both the modulation/coding scheme and SS. In 802.11ac, the MCS indices are simplified to indicate just the modulation/coding scheme.

More MIMO: 802.11ac supports upto 8 SS, although we only use 3 SS for our experiments. Support for multi-user MIMO is also included but we do not include them in our study as none of the current 802.11ac products implement it.

B. Experiment Setup

We build our testbed using commercial 802.11ac hardware.

Access Points: We use ASUS-RT-AC66U router [8] as APs. The router is based on Broadcom BCM4360 chipset which can support 80 MHz channel width, upto 256 QAM and 3x3:3 MIMO. We run a Linux distribution (AsusWRT-Merlin 3.0) on the routers.

Clients: We use three different 802.11ac chipsets in our experiments. Repeating the experiments for different hardware ensures that we do not end up profiling a specific hardware. Instead, we profile the issues of 802.11ac which are common across all hardware. The chipsets and platforms we use are as following:

1) Asus PCE-AC66 [9]: 3 SS, mini PCI-E on laptop
2) Qualcomm Atheros QCA9880 in WLE900V5-18 NIC [10]: 3 SS, Ath10k Linux driver, mini PCI-E on laptop
3) Broadcom BCM4335: 1 SS, Samsung Galaxy S4 smartphone [5]

In the next three sections, we characterize the throughput performance, energy efficiency and interference of 802.11ac-based WLANs. We start with simpler and obvious results, and then proceed toward the intricate and critical characterization.

III. Performance Characterization

In this section, we first analyze the performance of an 802.11ac link in ideal RF settings using Asus PCE-AC66 adapter on laptop. We perform the experiments outdoors on the terrace of a parking lot which provides an LOS link for more than 100 meters without interference. We repeat the experiments at another parking lot for verification. We use this to benchmark 802.11ac's performance, and later use it for comparison in more complex scenarios.

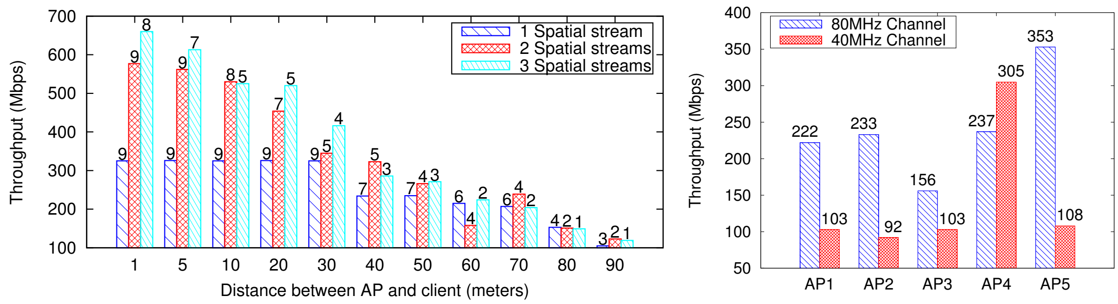
Unless mentioned otherwise, all experiments in this paper were repeated 10 times and average values are reported here. Each run of experiment involves running Iperf for anywhere between 3 to 10 minutes.

A. Performance of an Isolated 802.11ac Link

In this experiment, we fix the location of the client on one end of the parking lot and move the AP away from the client. We create a downlink (AP to client) Iperf UDP flow which sends data at maximum possible data rate.The best case throughput of 802.11ac is observed at 1 meter distance to be 661 Mbps. For comparison, at each distance, we repeat the experiments for 802.11n with 40 MHz channel width. Here, we use default rate adaptation to select the best MCS and SS combination. We found that operating in 80 MHz can improve the throughput by nearly 82% in first 30m, and 91% on an average across all distances (from 1m to 90m).

B. Characteristics of (MCS x SS)

Denser Modulation: 802.11ac introduces the use of 256 QAM (MCS 8 and 9 in Fig.1a). To study how well the 256 QAM works in real-world, we fix SS=1. These settings are referred as 8x1 or 9x1 in the format of MCSxSS. For comparison with 64 QAM, we also study 7x1 and 6x1 settings. The throughput results are shown in Table I. It is observed that 9x1 (256 QAM) gives upto 29% improvement over 7x1 (64 QAM). Also, higher coding rate (e.g. 5/6 for 9x1 and 7x1)



(a) (b)

Fig. 2: (a) Maximum throughput when SS = 1, 2 or 3 (MCS value labeled on top of each bar), (b) The aggregate throughput for each AP using 80 MHz and 40 MHz channel widths

improves the throughput by around 10% compared to lower coding rate (e.g. 3/4 used in 8x1 and 6x1).

TABLE I: Throughput of a link in Mbps when channel width = 80MHz, MCS = 6, 7, 8 or 9, and SS = 1

Distance	6x1	7x1	8x1	9x1
10m	228	252	297	325
20m	229	252	297	326
30m	223	252	297	325

Next, we fix the SS=3 and vary the MCS from $0 \rightarrow 9$. The results are shown in Fig. 1b. We see that although 256 QAM can achieve significant increase in throughput, it is practically useless since MCS 8 and 9 yield no throughput beyond 10 meters even in LOS and zero interference environment.

MCS x SS: We repeat the experiments for all possible combinations of MCS x SS at each distance point, and the results are presented in Fig.2a. For clarity, we only present 3 results for each distance showing the MCS value that achieves the maximum throughput when using 1, 2 and 3 SS. As we can see, adding an additional SS increases the throughput but the increase is not 100% except for the shorter distances.

An interesting observation from Fig.2a is that for many distances there exists combinations of MCS x SS that can yield comparable throughput. For example, at 10m distance, 8x2 and 5x3 achieve almost the same throughput. This is especially important as it shows that the choice of MCS x SS should not be clearly driven by achievable throughput, and other factors such as client's power consumption can also be considered.

Findings: We observed that newly introduced MCS 8 and 9 have limited usefulness in most practical cases. We also showed that many possible combinations of MCS x SS can achieve similar throughput. In such cases, the choice of MCS x SS can be based on other factors such as their power consumption.

C. Performance Characterization in Indoor Environment

We now characterize the performance of an 802.11ac link indoors in a university building. Note that the campus WiFi network was operating in 5 GHz band but the activity was negligible, especially during night time when our experiments were carried out. First, we fix the location of the AP at location AP2 in Fig. 1c. We then vary the location of the client at 11 different locations (marked with black circles in Fig.1c), and start downlink Iperf flow at maximum rate. We observe the maximum measured throughput to be 643 Mbps, the minimum throughput of 253 Mbps while the average throughput being 463 Mbps.

Next, to evaluate the impact of larger channel width on mobility, we move the client around the AP at walking speed for five minutes. The track of mobility is shown in Fig.1c with a red dotted line. The average throughput of three such experiments was observed to be 491 Mbps. No significant impact of larger channel width is observed on throughput variation at walking speeds.

We also create a scenario where a total of 18 nodes (5 APs and 13 clients) are deployed as shown in Fig.1c. Here, maximum of 3 clients connect to each AP. Each AP creates a downlink Iperf flow to each of its clients and sends packets to them simultaneously. We repeat the experiments for 80 and 40 MHz channel widths. The throughput measurements are presented in Fig.2b. During the experiments of 80 MHz, (AP1, AP2, AP3) pick the same channel while (AP4, AP5) pick another non-overlapping channel. In the case of 40 MHz, (AP1, AP2, AP3, AP5) and AP4 operate on distinct channels. Also, we tried multiple layout configurations and inferred that the throughput variation is strongly dependent on the topology and how channels are shared/divided.

IV. Energy Efficiency of 802.11ac

Energy efficiency has become a crucial design factors when building newer standards of communications for mobile devices. With more and more smartphones and laptops adapting 802.11ac, it is imperative to study the energy efficiency of 802.11ac.

To this end, we perform the experiments on two different 802.11ac chipsets, i.e. Atheros QCA9880 in a laptop and Broadcom BCM4335 in a smartphone. We use Monsoon power monitor [11] to bypass the power supply in both cases and measure the power consumption.

802.11ac is the first standard to introduce 80 MHz channel width for commercial use. To our knowledge, this is the first work to explore the trade-off between power consumption and throughput when using 80 MHz channel width.

A. Idle Listening - A Dominant Factor

First of all, we try to understand how utilizing different channel widths differs in terms of their resultant power consumption. For this, we perform an experiment on the laptop with QCA9880 where we fix Iperf's source rate S = 1 Mbps, MCS = 7 and SS = 2. We then vary the channel width (20, 40

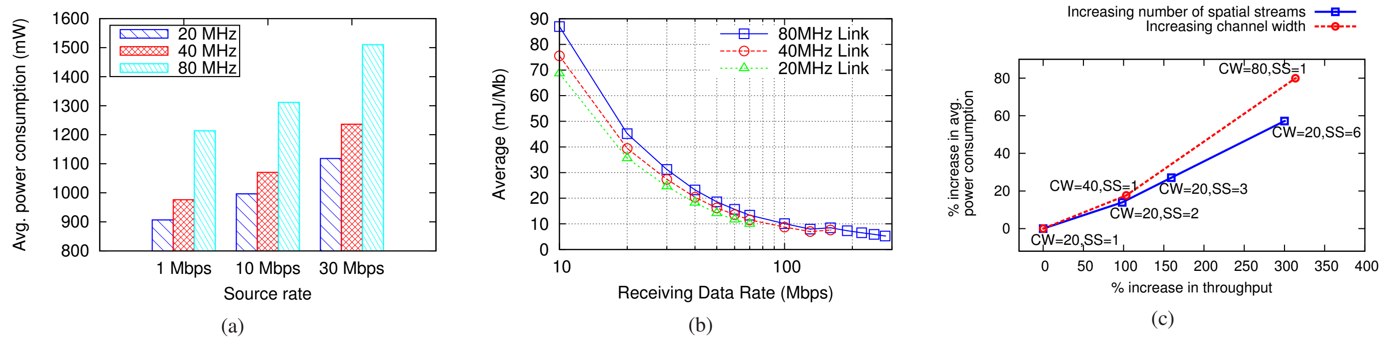


Fig. 3: (a) Power consumption of the most energy efficient setting in different channel widths at different source rates, (b) Comparison of per megabit energy cost between different channel widths, (c) Comparison of percentage increase in power consumption with increasing SS or increasing channel width

and 80 MHz) of the link. The results are presented in Table II.

TABLE II: Detailed power consumption of QCA9880 when operating on different channel widths

CW (MHz)	P_{active} (mW)	T_{active} (%)	P_{idle} (mW)	T_{idle} (%)	$P_{average}$ (mW)
20	948.72	26	894.19	74	908.29
40	1119.02	9	966.55	91	979.31
80	1468.07	5	1196.12	95	1208.37

Average power consumption ($P_{average}$) can be calculated using

$$P_{average} = P_{active} \cdot T_{active} + P_{idle} \cdot T_{idle} \tag{1}$$

where P_{active} and T_{active} are the average power consumption and the percentage of the time when the radio is active (sending or receiving); P_{idle} and T_{idle} are the average power consumption and the percentage of the time when the radio is idle. Here, we determine whether the radio is idle or not by analyzing power measurement samples. If a sample is below the pre-selected threshold, we consider it as an idle sample; otherwise we consider it as an active sample.

As we can see in Table II, T_{active} decreases as expected when we increase the channel width. Also, as we expect, P_{active} increases since the same amount of data is being sent over a smaller time period when using larger channel widths.

What is surprising to see is that even though the radio spends more time in idle mode when operating at larger channel widths, the actual power consumption during the idle mode (P_{idle}) is much higher. This results in an overall increase of power consumption ($P_{average}$) even though the radio is idle majority of the time. We repeat the same experiments for the smartphone with the same settings except that it supports only one SS. The results are shown in Fig. 4 where we observe the same phenomenon - idle listening at larger channel widths dominates the overall power consumption. We observe that when receiving at the same data rate, using 80 MHz channel width consumes 14% more power compared to 40 MHz. Similarly, it consumes 12% more power when running at 40 MHz compared to operating at 20 MHz.

The "race to sleep" heuristic which is studied in [18] also holds true in our case although we do not consider the sleep state in this work. It is obvious that, for a given amount of data,

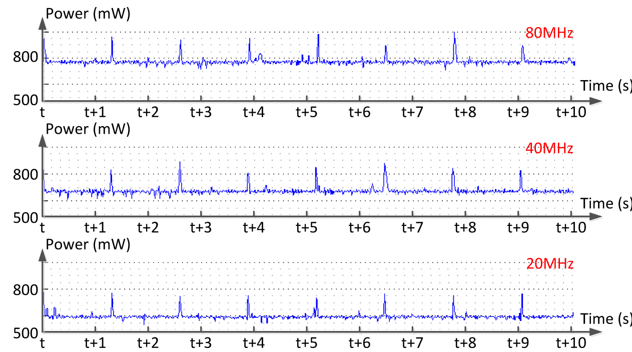


Fig. 4: Comparison of dynamic power consumption between different channel widths (with 1 Mbps receiving rate constantly) on smartphone (the periodic spikes indicate transmission or reception of a packet)

a larger channel width would allow the transfer to complete faster and radio can return to sleep mode sooner, reducing the overall energy consumption. However, here we focus on comparison based on a given input rate as it is more useful in practical scenarios.

Findings: *Since larger channel widths allow a radio to send/receive at faster rates, one might expect that overall power consumption will be reduced because the radio can spend more time in idle mode. Although this is true, the power consumption in idle mode is much higher at larger channel widths which in fact dominates the overall power consumption, making larger channel widths a less energy efficient option. It is necessary to devise intelligent power saving schemes that can reduce the power consumption of idle mode operations in larger channel widths.*

B. Impact of Rate & Channel Width Adaptation:

In practice, the physical layer data rate of the link is adapted based on the channel condition. Various rate control schemes are designed to adapt MCS x SS with the objective being maximization of the throughput [12]–[15]. Recent work such as [16], [17] have proposed rate adaptation schemes that try to minimize the energy consumption. Here, we seek the answer for a simple question: can joint rate and channel width adaptation (finding CW x MCS x SS) yield additional energy benefits compared to performing just the energy-efficient rate adaptation (MCS x SS)?

To understand this, we perform a set of experiments where we try to find the most energy efficient MCS x SS combination using a brute-force approach. For each channel width, we try out all combinations of MCS ($0 \rightarrow 9$) and SS ($1 \rightarrow 3$) and find out the most energy efficient combination that can satisfy a given source rate. Since the source rate is fixed, power consumption results will be equivalent to energy results. We repeat the experiments for several different source rates, and the results are shown in Fig.3a.

As we see in Fig. 3a, the power consumption of the most energy efficient MCS x SS combination for a larger channel width is always higher than that of a smaller channel width. In the experiments, a higher MCS value (either 7 or 8) and one SS is observed to be the most energy efficient in most cases. This is in line with [18] which suggests that choice of higher MCS is more energy efficient.

This results show that a larger channel width consumes more power, and it is more energy efficient to use smaller channel width if the source rate can be satisfied by doing so.

We repeat the experiments for many different source rates on the smartphone and observe the same phenomenon where power consumption proportionally increases as the channel width increases. The results are presented in Fig. 3b. Note that for a fair comparison at different source rates, we present the energy consumption values in Mega-Joule/Megabit (mJ/Mb) as a unit of comparison. Here, mJ/Mb can be calculated as mJ/Mb = (Power consumption in mW)/(Goodput in Mbps).

Findings: For the throughput values that can be achieved with both larger and smaller channel widths, utilizing larger channel width consumes more power. Since the power consumption increases proportionally with channel width, no additional energy benefits can be achieved with joint channel width and rate adaptation.

Control Message Overhead: Since 802.11ac mandates the use of RTS/CTS (discussed in Section VI-A), one potential reason of this higher power consumption can be that 80 MHz width requires 4 times more RTS/CTS compared to 20 MHz. To verify if the power consumption is actually due to these added RTS/CTS overhead, we repeat the same experiments using 802.11n with RTS/CTS disabled. We observe that even in 802.11n, when smartphone uses 40 MHz, it also consumes more power compared to when operating in 20 MHz. This proves that additional power consumption is not due to increased overhead of RTS/CTS when using larger channel width.

C. Channel Width vs. Spatial Streams

Two main factors responsible for throughput gains of 802.11ac are more SS and larger channel width. Both of these factors achieve a similar increase in throughput - e.g. increasing SS from 1 to 2 nearly doubles the throughput, similarly, doubling the channel width from 40 Mhz to 80 Mhz also has the same effect on throughput. We raise a simple question, since the throughput increase of both mechanisms is comparable, how different are they in terms of their power consumption?

To understand this, we perform an experiment where we fix the MCS and configure Iperf to send at maximum possible source rate. We then perform two sets of operations. In the first one, we double the channel width while keeping SS the same. In the second, we increase SS while keeping the channel width unchanged. In both cases, we observe the percentage increase in throughput and power consumption. The results are presented in Fig. 3c, which shows that increasing channel width consumes much more energy (primarily due to reasons described above) compared to increasing SS. Note that since none of the current hardware supports 6 SS, we use interpolation to find its power consumption.

Findings: Increasing SS is a more energy efficient alternative compared to doubling the channel width for achieving the same percentage increase in throughput.

V. Interference Characterization

We now look at the details of how 802.11ac operates when operating in presence of other 802.11a/n/ac links. Note that even if an 802.11ac AP is using 80 MHz channel width, it still utilizes a 20 MHz channel inside the 80 MHz as a control channel. This channel is referred as the *primary channel*. Beacons and management frames are sent over the primary channel. The purpose of using the primary channel is twofold.

(1) Primary channel is used to determine the channel width (20, 40, 80 or 160) in real time depending on the current interference. An Enhanced RTS/CTS protocol is used for dynamic channel width selection. The Enhanced RTS/CTS utilizes explicit message exchange for dynamic channel width selection and collision avoidance. We study this in details in Sec. VI-A.

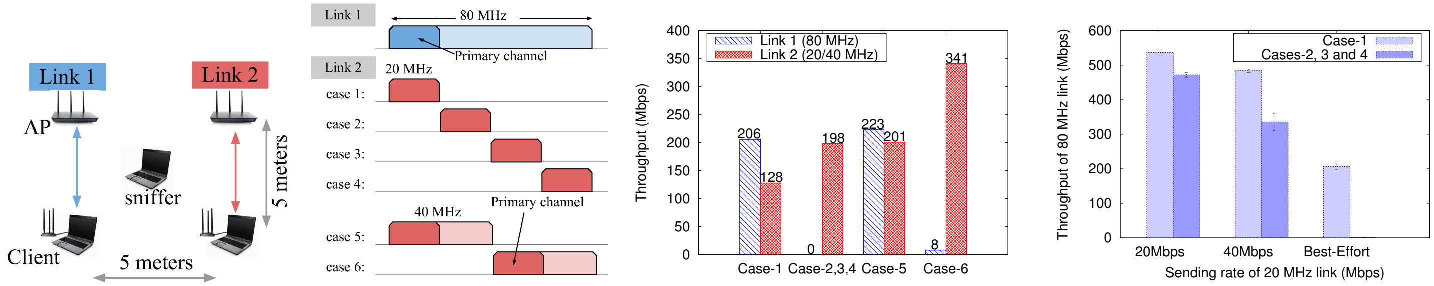
(2) 802.11a/n clients capable of operating at maximum of 40/20 MHz channels can still receive the beacons and connect to an 802.11ac AP. 802.11ac uses the same preamble as 802.11a/n and can detect other 802.11a/n nodes and their activity during Clear Channel Assessment (CCA).

Indoor Setup: The selection of primary channel and the channel widths play crucial roles in determining how the spectrum is sliced between different links. We now focus on the experiments where two links can use different channel widths and can have the same or distinct primary channels. For these experiments, we deploy two 802.11ac links indoors as shown in Fig.5a using Asus PCE-AC66 as clients. In order to monitor how management frames are exchanged, we use an additional laptop that is equipped with four wireless cards. All four interfaces are tuned to different 20 MHz sub-channels of 80 MHz band. Their role is to sniff the MAC frames over the air on four sub-channels. Sniffers can only sniff the management frames, and any data frame that is sent over 20 MHz channels.

A. Throughput Anomalies with Heterogeneous Channel Widths

Using the setup of Fig. 5a, we fix Link 1 to operate on 80 MHz and Link 2 to operate on 20 MHz. We now consider two scenarios where both links have same or different primary channels.

Same Primary Channel: In the first scenario, when both 80 MHz link and 20 MHz link have the same primary channel, the resultant throughput of both the links is shown in Case-1



(a) (b) (c) (d)

Fig. 5: (a) Indoor setup of 2 links and a sniffer, (b-d) Link 1 is operating in 80 MHz fixed channel width and Link 2 is operating on 40/20 MHz width. When Link 2's primary channel is the same as that of Link 1, both link share the medium proportionally (Case 1 or Case 5). On the other hand, when Link 2's primary channel falls within secondary channels of Link 1, severe degradation of throughput is observed for Link 1.

of Fig. 5b. It can be observed from Fig. 5c that when 20 MHz channel is overlapping with the primary channel of Link 1, throughput of both the links decrease but the decrease is more or less proportional.

Different Primary Channel: Cases 2, 3 and 4 of Fig. 5b show the scenario when a 20 MHz link is operating in the secondary channels of the 80 MHz link. As we can see from Fig. 5c, when Link 2 is sending at best-possible rate, throughput of Link 1 becomes zero. This is surprising to see because this means that co-existence of 80 MHz and 20 MHz links can deteriorate throughput of large channel width link significantly. We repeat the experiments with 20 MHz link reducing its sending rate. The results are presented in Fig. 5d. It is observed that when the sending rate of Link 2 is less (20 Mbps), the relative decrease in Link 1's performance is not significant. As we increase the rate of Link 2 (40 Mbps as shown in Fig. 5d), the performance of 80 MHz link starts degrading. Further increasing the rate of Link 2 to its maximum (Best-Effort as shown in Fig. 5d) causes complete blockage of the 80 MHz link.

We repeat the same experiments with Link 2 now operating on 40 MHz channel width (Cases 5 and 6 in Fig. 5b). As in the case of 20 MHz, when Link 2 is overlapping with Link 1's primary channel, the throughput is proportionally divided. On the other hand, if Link 2 is not overlapping with Link 1's primary channel, the throughput of Link 1 degrades severely.

Findings: When a 20/40 MHz link is operating in secondary channels of another 80 MHz link, the throughput performance of the latter link degrades severely.

Causes of Throughput Degradation: We believe that this throughput anomaly when using heterogeneous channel widths is due to two main reasons - (i) 802.11ac channel access procedure and, (ii) difference in CCA sensitivity thresholds. Next, we discuss both of them in details.

1) 802.11ac Channel Access Procedure: 802.11ac supports both static and dynamic channel width access methods. In the experiments discusses above, the link is set to operate at fixed 80 MHz channel. This means that only when the entire 80 MHz channel is idle, it is possible to send any data over the link. The procedure, that is used to determine if the larger channel is idle or not, is described in Algorithm-1 (extracted from [1]).

Algorithm 1 802.11ac Channel Access Procedure

1) An 802.11ac node senses the primary channel for DIFS time;
2) **If** the primary channel is idle for the DIFS time, then the node chooses a random backoff time from its current contention window.
   Else go back to Step-1;
3) During the backoff time, if the primary channel is sensed to be busy, the node freezes the backoff counter, and keeps sensing until it is idle again. When the channel is idle, it resumes the backoff counter
4) The secondary channels are simultaneously sensed for PIFS time just preceding the end of backoff timer.
5) **If** all the secondary channels are reported idle, the transmission is initiated immediately.
   Else if *channel-access* == *static*
      Go back to Step 1.
   Else if *channel-access* == *dynamic*
      Transmit using the idle 20 MHz or 40 MHz channel containing the primary channel

Smaller Sensing time for secondary channels: From the channel access procedure of Algorithm-1, we see that primary channel performs sensing for DIFS (Distributed Inter-Frame Space) and backoff time, however the secondary channels are only sensed for PIFS (Point Inter-Frame Space) time. This way, sensing time for the primary channel is much larger than that of the secondary channels. Furthermore, once the secondary channel is sensed busy (during PIFS), the station will exit the current cycle of access, and will return back to primary channel sensing the medium for DIFS time. This is shown in Fig. 6. The PIFS and DIFS are calculated as Equations 2 and 3 where aSIFSTime refers to a SIFS (Short Inter-Frame Space) duration. The backoff time is a random number selected from 0 to the current contention window size multiplied with the slot time (aSlotTime).

$$\mathrm{PIFS} = \mathrm{aSIFSTime} + \mathrm{aSlotTime} \tag{2}$$

$$\mathrm{DIFS} = \mathrm{aSIFSTime} + (2 \times \mathrm{aSlotTime}) \tag{3}$$

The main issue with operation of Algorithm-1 is that when a secondary channel is sensed busy, instead of freezing the backoff counter of primary channel, the transmission is aborted

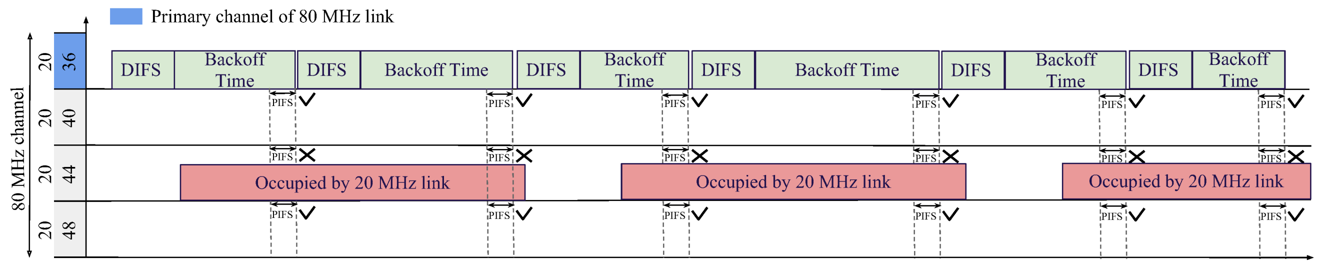


Fig. 6: Different physical carrier sensing time and CCA methods in primary channel and secondary channels cause the 80 MHz link to continuously back off

and the cycle is re-initiated. Note that the freezing of backoff counter is indeed implemented for primary channel but not for secondary channels. This on top of smaller sensing time for secondary channel makes it very difficult for a 80 MHz link to gain access to medium and transmit. We believe that increasing the sensing time and implementing freezing of counter for secondary channels can significantly improve 80 MHz link's throughput as it requires medium access for a very small fraction of time (due to high data rate).

Findings: Since backoff timer of primary channel is not frozen when secondary channels are found busy and secondary channels are only sensed for a small amount of time, a larger channel width link does not get useful medium access which results into severe throughput reduction.

2) CCA Thresholds: From [1], we know that the primary channel and the secondary channel use different CCA mechanisms. The primary channel utilizes a full CCA including preamble packet detection, and performs both physical carrier sensing and virtual carrier sensing. In other words, the primary channel will decode the detected PLCP (Physical Layer Convergence Protocol) preamble and use that information to set the NAV (Network Allocation Vector) counter. However, the secondary channel implements a *reduced* CCA and does not set the NAV counter.

Difference in CCA procedure and thresholds between primary and secondary channels is another reason of throughput degradation observed in Fig. 5c. Since 802.11ac supports larger channel widths, it enforces much stricter requirements of CCA procedure. As before CCA in 802.11ac consists of two parts - signal detection (SD) and energy detection (ED).

SD is used only when the detected channel activity is decodable (PLCP preamble detected), while the ED is used when signal can not be decoded. Furthermore, the signal detection thresholds for primary channel and secondary channel are different due to different CCA methods. We summarize the CCA thresholds used in 802.11ac in Table III. In the table, P-20 refers to primary channel of 20 MHz, and similarly S-20 refers to secondary channel of 20 MHz. Also, SD-th denotes signal detection threshold while ED-th denote energy detection threshold.

TABLE III: CCA Thresholds (dBm)

CCA mode	P-20	P-40	P-80	S-20	S-40	S-80
SD-th	-82	-79	-76	-72	-72	-69
ED-th	-62	/	/	-62	-59	-56

CCA in Cases 1 and 5: In Cases 1 and 5, since the primary channel is overlapped, Link 1 can detect 20 or 40 MHz signal of Link 2, and similarly Link 2 can detect Link 1's signal (beacons on primary channel). This way, both the links use signal detection thresholds for CCA which results in nearly fair CSMA medium access.

CCA in Cases 2, 3, 4 and 6: On the other hand, when Link 2 operates in secondary channels of Link 1 (Cases 2, 3, 4 and 6), Link 2 will use energy detection threshold (-62 dBm) to perform CCA because it can not decode the signal of Link 1's 80 MHz data. However, Link-1 can decode Link 2's preamble and uses a more sensitive threshold of -72 dBm to do CCA. This will increase Link 2's chances of medium access substantially while starving Link 1. Here, we believe the CCA threshold for Link 2 in Case-2,3,4 is -62 dBm which is different with what Park said (-82 dBm) in [2]. The reason for this is that 20 MHz link can not decode 80 MHz PPDU from the secondary channel as there are not beacons.

Additionally, when the received interference power at each 20 MHz channels of the 802.11ac link is above the primary channel CCA threshold (i.e. -82 dBm) but below the secondary channel CCA threshold (here is -72 dBm), Park [2] showed the simulation results that the 20 MHz link (Link 2) will significantly back off and have an extremely low throughput. However, when we move the 20 MHz link (Link 2) away from the 80 MHz link (Link 1) which is equivalent to decreasing the received interference power for both links, we observe that the throughput of 80 MHz link gradually increasing from 0 to 400 Mbps, but the throughput 20 MHz link decreases only a little. This way, in out experiments, the significant back-off issue (as presented in [2]) does not happen. We attribute this to difference between simulation and real-world experiments.

Findings: We showed that the larger channel accessing method and the difference in CCA thresholds does not work well when using larger and heterogeneous channel widths because it creates an unfair competition for medium access.

VI. Dynamic Channel Width Access

A. Enhanced RTS/CTS Protocol

We consider an example as shown in Fig. 7 to discuss the operations of Enhanced RTS-CTS (E-RTS/CTS). First, let us consider an 802.11ac AP (AP-1) that is using channel 36 as its primary channel. When it has data to send to a client, it can use an 80 MHz channel given that the entire channel is idle for communication. If the part of the channel is busy due to other ongoing transmission, this should be detected to reduce the channel width and avoid collisions. This is precisely the purpose of E-RTS/CTS protocol.

In this case, AP-1 will first carrier sense to see if the primary channel is idle or not. If there is any ongoing activity on the primary channel, AP-1 will defer its communication. Now, if the primary channel is idle and all the three secondary channels are also idle. Instead of sending the data directly, AP-1 first sends out RTS messages. What is interesting to note is that instead of sending an RTS message one time (as in 802.11a/b/g/n), the AP replicates the same RTS message on all four channels (Fig.7). When the client receives the 4 RTS messages, it interprets AP's intention to send data on an 80 MHz channel. The client follows up by detecting if the four channels are idle or not. Depending on which channels are busy or idle, the client broadcasts CTS messages. For now, let us assume that all the four channels are also idle for the client. In this case, when AP receives CTS messages on all four channels, it moves ahead by sending data on all four channels (80 MHz). Of course, when sending the data, the entire 80 MHz channel is treated as one channel and no replication of data is done.

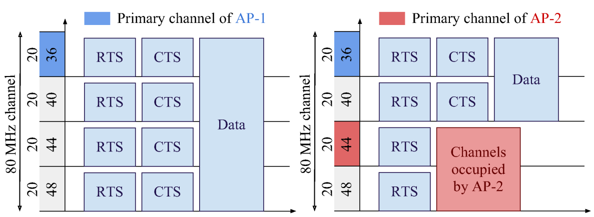


Fig. 7: E-RTS/CTS protocol

Now let us consider the cases where there is some activity on secondary channels. If another AP (AP-2) operates using 44 as its primary channel and has an ongoing communication on channels 44 and 48. If AP-1 detects this activity, it will not send RTS messages on channels 44 and 48. This means that in ideal case, it will use only 40 MHz non-interfering band for its communication. Let us assume that AP-1 does not detect AP-2's activity but client of AP-1 does. In this case, after receiving four RTS messages from AP-1, the client will only reply back with 2 CTS messages on channels 36 and 40. AP-1 will interpret this information to send data on 40 MHz channels only. This is shown in Fig. 7.

By using E-RTS/CTS mechanism, sender and receiver can distributively come to a consensus on what channel and channel width to use for communication. It is worth noting that no matter what channel width is used (20, 40, 80 or 160 MHz), the channel must include the 20 MHz primary channel.

B. Sharing or Dividing 80 MHz

To test the E-RTS/CTS protocol, we experiment with setup of Fig.5a. We fix the channel widths for both the links to be 80 MHz, and their primary channels to be the same.

We now send data at maximum possible rate on both the links. Fig. 7 shows how RTS/CTS messages are exchanged to use the 80 MHz channel. Since the primary channel is the same, both the links use the 80 MHz channel in a time divided manner. The average throughput of the links is shown in Case 1 of Fig. 8b.

To study the impact of selecting different primary channels, we assigned different primary channels for both the links. Here, there are two possibilities where links can share the 80 MHz channel in time divided manner or they can divide the channel in two parts of 40 MHz, and use them in parallel. We observe that instead of dividing the 80 MHz channel into two 40 MHz channels, both links still use the same 80 MHz channel in time divided manner. The results of average throughput are given in Case 2 of Fig. 8b.

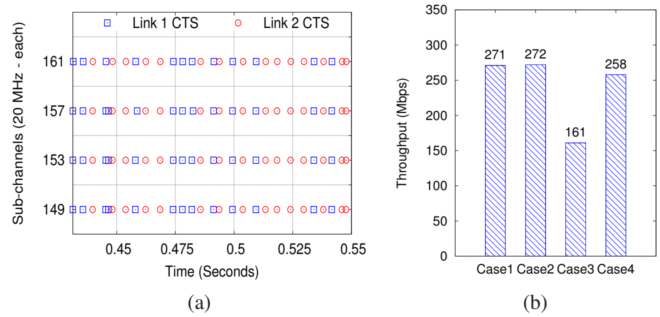


Fig. 8: (a) RTS-CTS packets captured by sniffer (b) Throughput comparison of 4 cases where two links (Case-1): share 80MHz with same primary channel, (Case-2): share 80MHz with different primary channel, (Case-3): divide 80 MHz into adjacent 40MHz channels, (Case-4): divide 80 MHz into non-adjacent 40MHz channels

To further understand why sharing of 80 MHz was chosen over dividing it, we perform two additional experiments in the same settings. In Case 3, we force the links to operate on two non-overlapping and adjacent 40 MHz channels. We observe a significant degradation of throughput even though both the links were operating on two different channels. In Case 4, we repeat the same experiments but instead choose two non-adjacent 40 MHz channels. In this case, we find that throughput of two 40 MHz links sum up to 80 MHz (with some difference due to overhead).

Findings: This shows that due to adjacent channel interference, it is not possible to use two adjacent non-overlapping 40 MHz channels to best of their capacity. In such case, choosing non-adjacent channels or in fact utilizing a larger channel width in time-divided manner is a better option.

C. 80 MHz channel interference pattern

In order to further understand the difference between 40 MHz and 80 MHz interference range, we setup two 802.11ac links (similar to Fig.5a). We then increase the distance between the two links and observe how throughput is affected on both the links. The measurements are presented in Fig.9. As we expect, when both links operate at 80 MHz, their mutual interference reduces faster with distance. Because of this, we observe a faster increase in the throughput of both links as they move apart. However, if we operate both links on 40 MHz, the increase is slower in comparison because of larger interference range at smaller channel widths. This shows that to provide better coverage, it is better to deploy a denser network of AP when they operate on 80 MHz. Although, this denser deployment demands further complicates the interference management as there will be more neighboring cells for each AP.

VII. Related Work

802.11n is the most prevalent standard used in current WLANs. Compared to other WLAN standards (802.11a/b/g),

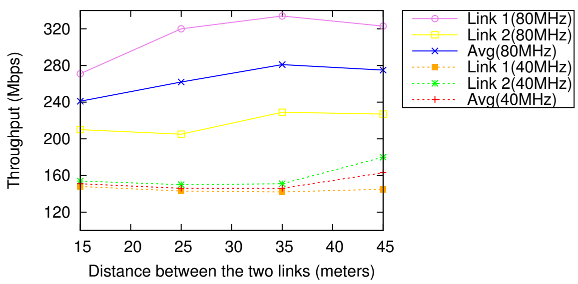


Fig. 9: Two 802.11ac links - comparison of interference pattern between two cases, case 1 when both links operate on 80 MHz and case 2 when both links operate on 40 MHz.

802.11n introduced MIMO and frame aggregation as new features for throughput enhancement. Many previous research studies [19]–[21] provide an overview of these features of 802.11n. A detailed experimental evaluation of 802.11n is provided in [22]. It observed that throughput of an 802.11n link degrades severely in presence of an 802.11g link. Our observation about degradation of 802.11ac link performance is largely due to heterogeneous channel widths as we discussed. The work of Pelechrinis et al. [23] characterizes the influence of MIMO to the link quality. They show that MIMO highly increases the physical layer rate but produces more losses at high SNR values if packet size adaptation is not used. More recently, Kriara et al. [24] use regression analysis based on the testbed data to show that how these new features work independently to optimize the overall performance. But, all above testbed works are based on 802.11n and they didn't cover the effects and issues introduced by 802.11ac with larger channel width and denser modulation, and the coexistence between links of different channel widths.

Although some white papers [3], [4] provide an overview of 802.11ac standard, no experiment evaluation is presented. To our knowledge, our paper provides first testbed based detailed evaluation of 802.11ac. Some previous research [2] has explored the benefit of dynamic channel switching in 802.11ac. However, some of their simulation results contradict what we get using real testbed. In our paper, we use multiple experiments to illustrate the nature behind the throughput gain and the potential issues of 802.11ac.

In terms of power consumption characterization, Carcia-Saaverdra et al. [25] presents a new energy consumption model to measure the per-frame energy cost with higher accuracy and confidence. Halperin et al. [18] investigate the power consumption of 802.11 NICs and mainly focus on the effect of MIMO on energy cost. However, different from their work, our work focuses on the effect of larger channel width and denser modulation on power consumption of mobile devices especially for 802.11ac.

VIII. Conclusions

In this paper, we presented a performance characterization of 802.11ac standard. We identified what is the impact of utilizing larger channel width on energy efficiency and interference. We showed that 80 MHz channel width yields substantial throughput improvement but the improvements come at the cost of higher power consumption. This is mainly due to higher idle mode power consumption of larger channel widths. We also showed that increasing the number of spatial streams is more energy efficient compared to increasing the channel width in achieving the same percentage increase in throughput. Also, our interference characterization showed that unplanned selection of primary channels and channel widths can severely degrade the throughput of links operating at larger channel widths. This requires that a careful interference management scheme should be designed for the success of 802.11ac. Integrating energy efficiency of mobile devices with interference management forms an important direction of future work.

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