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RESEARCH ARTICLE

Throughput, energy efficiency and interference characterisation of 802.11ac

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ABSTRACT

This paper is the first of its kind in presenting a detailed characterisation of IEEE 802.11ac using real experiments. 802.11ac is the latest Wireless Local Area Network (WLAN) standard that is rapidly being adapted because of 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 Quadrature Amplitude Modulation (QAM)) and increased number of spatial streams for Multiple-input Multiple-output (MIMO). We provide an experiment evaluation of these factors and their impact using a real 802.11ac testbed. Our findings provide numerous insights on benefits and challenges associated with using 802.11ac in practice.

Because utilisation 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 utilising larger channel width is in general less energy efficient because of 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. Copyright © 2015 John Wiley & Sons, Ltd.

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1. INTRODUCTION

With tremendous increase in wireless access networks traffic, 802.11n-based WLANs have become increasingly popular. The next generation WiFi standard, 802.11ac, [1–4] builds on top of 802.11n to create even faster and more scalable WLANs. With higher throughput of 802.11ac, it is now possible to support more laptops and mobile devices from each Access Point (AP) as well as high data rate applications. Because of its potential of providing very high throughput, many of the leading smartphone and laptop manufacturers (Samsung Galaxy S4/S5 [5, 6], Apple MacBook Air/pro [7, 8] and HTC One [9]) have already adapted 802.11ac. Compared with 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 up to four SS.

This paper provides a performance characterisation of 802.11ac using experiments on a real testbed for both indoor and outdoor environments. 802.11ac is a Very High Throughput (VHT) amendment that has the potential to deliver a gigabit of throughput in WLANs. The newly introduced features also bring us new issues when we actually use them in real cases. To the best of our knowledge, this is the first work to present experimental evaluation and complete characterisation 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 utilising larger channel widths. The observed throughput when a 802.11ac link is operating at 80-MHz channel width (with 256 QAM and three SS) can reach up to 660 Mbps. With very high throughput as a known fact of 802.11ac, we centre 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 goal of this work is to provide a detailed understanding of 802.11ac using experiments and to identify how current wisdom about network planning should be adapted to take complete benefit of it. We present a comprehensive study of energy efficiency of 802.11ac using measurements on a smartphone. This understanding can be useful to devise strategies whereby choice of channel width, modulation and coding rate, and SS can be optimised to minimise power consumption while achieving higher throughput. We also show that while larger channel width can significantly improve the throughput, it gives rise to new kinds of fairness issues. We elaborate on the causes of these unfairness, and point out solutions for them. The presented findings can be used to derive physical/MAC layer protection or scheduling mechanisms that can resolve the issues.

The main contributions of this paper are as follows:

(1) We provide the first testbed-based performance characterisation of 802.11ac in both indoor and outdoor environments with and without interference. We verify that 802.11ac increases the throughput by 91 per cent compared with the best performance that 802.11n can achieve. We study various factors—modulation, SS and channel width—jointly and in isolation to characterise their impact on throughput. We find that no performance improvement can be gained using 256 QAM beyond 10 m, and majority of the throughput increase is attributed to larger channel width.

(2) We characterise 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 with 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 Modulation and Coding Scheme (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
► that in heterogeneous channel width environment where different links operate at different channel widths, competition to access the medium becomes increasingly 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 80-MHz 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 organised 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 3, we benchmark different characteristics of 802.11ac in ideal conditions. We also consider realistic scenarios with interference using a multi-node indoor testbed. Section 4 presents energy efficiency characterisation of 802.11ac. Interference characterisation and details of how dynamic channel width selection in 802.11ac works are provided in Section 5, followed by the related work in Section 7 and conclusions in Section 8.

2. OVERVIEW OF 802.11AC AND EXPERIMENT SETUP

In this section, we will give a brief overview about 802.11ac and highlight the new features it bring to us. Then, we will introduce the experiment devices and experiment layout we used in this paper.

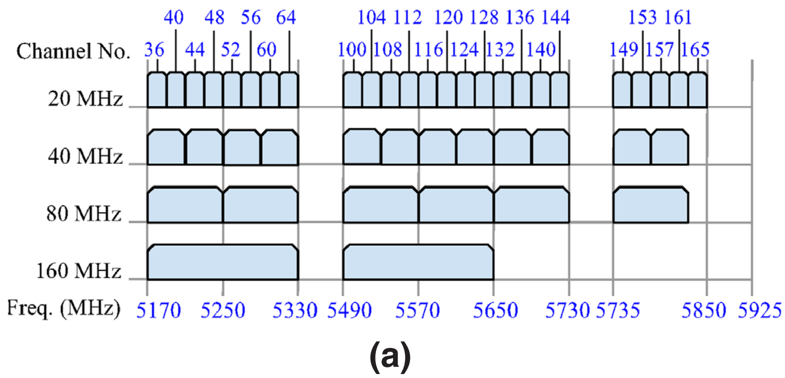
2.1. What is new in 802.11ac?

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

Larger channel width: One of the most significant changes in 802.11ac is that it operates in a 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. Figure 1(a) shows the 5-GHz spectrum for the USA along with non-overlapping channels for different channel widths. As we can see, 5-GHz band has 25 non-overlapping 20-MHz channels, which provide us a much larger band compared with 2.4 GHz. However, because of fragmentation, only a few 80-MHz and 160-MHz channels are available. There can be at most six non-overlapping 80-MHz (or two 160-MHz) channels in this band. Also, some channels (such as 120, 124 and 128) cannot be used to avoid interference with weather radar systems.

Even if a 802.11ac AP is using 80-MHz channel width, it still utilises 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. First, it is used to determine the channel width (20, 40, 80 or 160) in real time depending on the current interference. As we will be discussed in Section 5, an enhanced Request to Send/Clear to Send (RTS/CTS) protocol is used for dynamic channel width selection. Second, 802.11a/n clients, which are capable of operating at a maximum of 40/20-MHz channels, can still receive the beacons and connect to a 802.11ac AP.

Denser modulation: 802.11ac introduces support for 256 QAM and also simplifies the MCS index (only 10 values). Figure 1(b) lists the MCS values and their corresponding modulation and coding rates. MCS 8 and 9 utilise 256 QAM, which is the highest constellation density currently supported by any 802.11 standard. In 802.11n,



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

(b)

Figure 1. (a) FCC 5-GHz unlicensed band channel map. There are 25 20-MHz bands, 12–40-MHz bands, six 80-MHz bands and two 160-MHz bands in this band. (b) 802.11ac MCS index table. The table is simplified to have only 10 values, and the spacial streams information is not indicated in this table.

the MCS index was used to indicate both the modulation and coding scheme and SS. In 802.11ac, the MCS indices are simplified to indicate just the modulation and coding scheme.

More MIMO: 802.11ac supports up to eight SS, although we only use three SS for our experiments. Support for multi-user MIMO, which enables a single AP to transmit to multiple clients simultaneously in the same channel, is also included, but we do not include them in our study as none of the current 802.11ac products implement it.

2.2. Experiment setup

We build our testbed using commercial 802.11ac hardware.

Access points: We use ASUS-RT-AC66U router [10] as APs. The router is based on Broadcom BCM4360 chipset, which can support 80-MHz channel width, up to 256 QAM and 3×3:3 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 follows:

(1) Asus PCE-AC66 [11]: three SS, mini Peripheral Component Interconnect Express (PCI-E) on laptop
(2) Qualcomm Atheros QCA9880 in WLE900V5-18 Network Interface Card (NIC) [12]: three SS, Ath10k Linux driver, mini PCI-E on laptop
(3) Broadcom BCM4335: one SS, Samsung Galaxy S4 smartphone [5]

In the line-of-sight (LOS) scenario, one link (AP–client pair) was deployed on terrace of a university parking lot.

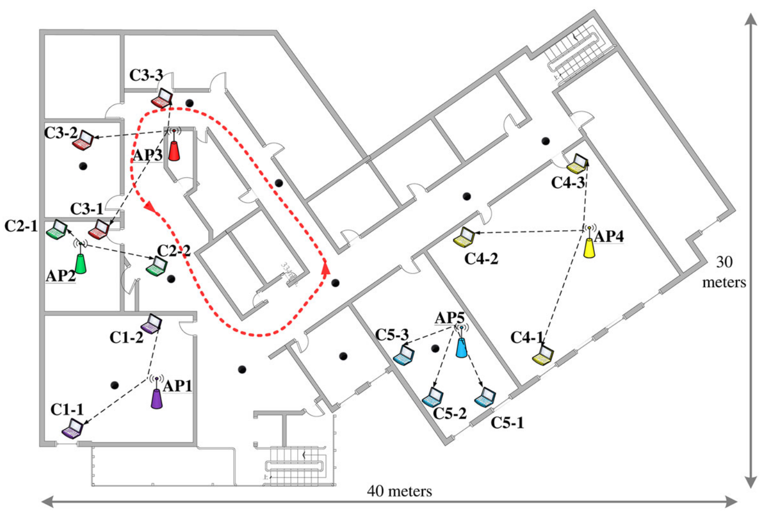


Figure 2. Testbed of 18 802.11ac nodes used for the experiments. We use this 18 nodes to do the experiments for the indoor characterisation only. The outdoor measurement, energy efficiency and interference cases are not included in this figure.

The experiments were repeated on another parking lot for verification. These locations were chosen as they provided an LOS link for up to 100 m without any external interference in 5 GHz. In the second scenario, a total of 18 nodes (five APs and 13 clients) were deployed indoors in a university building (Figure 2) to create a more practical scenario of non-LOS links. Although campus WiFi network was operating in 5-GHz band, the activity was negligible, especially during night time when our experiments were carried out. Unless explicitly mentioned, all the experiments presented in this work were repeated 5–10 times for increased confidence in results. Each run of experiment involves running Iperf for anywhere from 3 to 5 min.

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

3. PERFORMANCE CHARACTERISATION

In this section, we first analyse the performance of an 802.11ac link using Asus PCE-AC66 adapter on laptop in ideal Radio Frequency (RF) settings where there is an LOS link with no other interference. We use this to benchmark 802.11ac's performance, and later use it for comparison in more complex scenarios.

3.1. 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 a maximum possible data rate. The measurements of throughput are presented in Figure 3(a). Here, 802.11ac is operating in 80-MHz channel with 'auto' mode, which means that the MCS value and the number of SS are chosen automatically. The best case throughput of 802.11ac is observed at a 1-m 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. As shown in Figure 3(a), we found that operating in 80 MHz can improve the throughput by nearly 82 per cent in the first 30 m, and 91 per cent on an average across all distances (from 1 to 90 m).

3.2. Characteristics of (MCS x SS)

Denser modulation: 802.11ac introduces the use of 256 QAM (MCS 8 and 9 in Figure 1(b)). To study how well the 256 QAM works in real world, we fix SS = 1. These settings are referred as 8×1 or 9×1 in the format of MCS $\times$ SS. For comparison with 64 QAM, we also study 7×1 and 6×1 settings. The throughput results are shown in Table I. It is observed that 9×1 (256 QAM) gives up to 29 per cent improvement over 7×1 (64 QAM). Also, higher coding rate (e.g. 5/6 for 9×1 and 7x1) improves the throughput by around 10 per cent compared with lower coding rate (e.g. 3/4 used in 8×1 and 6×1).

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

MCS $\times$ SS: We repeat the experiments for all possible combinations of MCS $\times$ SS at each distance point, and the results are presented in Figure 4(a). For clarity, we only present three results for each distance showing the MCS

Table I. Throughput (Mbps) of a link when channel width = 80 MHz, MCS = 6, 7, 8 or 9 and SS = 1.

Distance (m)	6×1	7×1	8×1	9×1
10	228	252	297	325
20	229	252	297	326
30	223	252	297	325

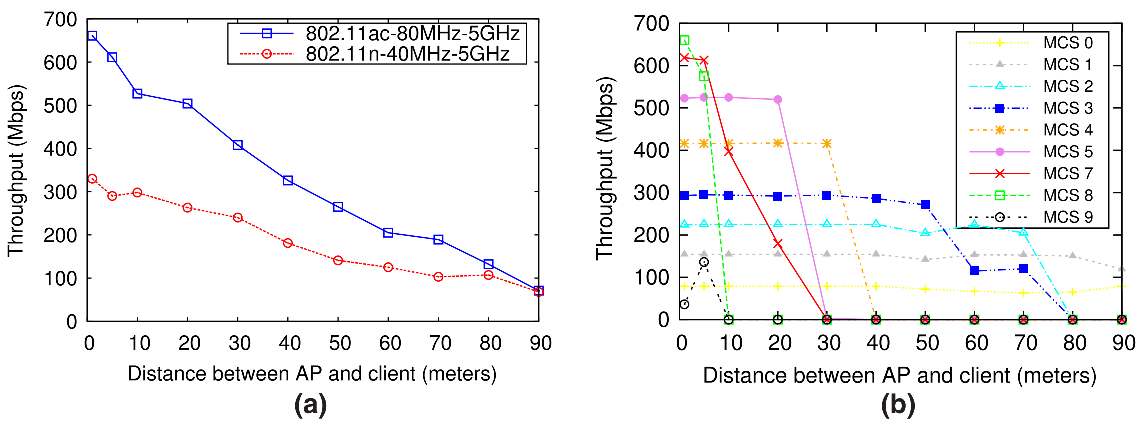


Figure 3. (a) Throughput comparison between 802.11ac and 802.11n, (b) throughput with different MCS values when SS = 3.

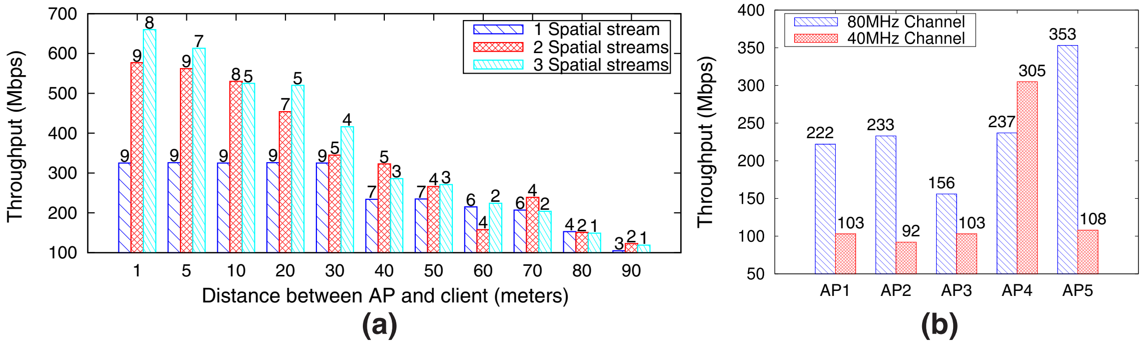


Figure 4. (a) Maximum throughput when SS = 1, 2 or 3 (MCS value labelled on top of each bar), (b) the aggregate throughput for each AP using 80-MHz and 40-MHz channel widths.

Table II. Throughput (Mbps) comparison between 802.11ac at 80 MHz and 802.11n at 40 MHz in indoor environment.

Standard	Average	Max	Min
802.11ac	463	643	253
802.11n	247	358	127

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 per cent except for the shorter distances.

An interesting observation from Figure 4(a) is that for many distances, there exist combinations of MCS × SS that can yield comparable throughput. For example, at 10-m distance, 8 × 2 and 5 × 3 achieve almost the same throughput. This is especially important as it shows that the choice of MCS × 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 × SS can achieve similar throughput. In such cases, the choice of MCS × SS can be based on other factors such as their power consumption.

3.3. Performance characterisation in indoor environment

We now characterise the performance of 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 Figure 2. We then vary the location of the client at 11 different locations (marked with black dots in Figure 2), and start downlink Iperf flow at a maximum rate. We observe the maximum measured throughput to be 643 Mbps, the minimum throughput to be 253 Mbps while the average throughput being 463 Mbps. We also repeat the experiment for 802.11n, and the comparison is shown in Table II, where we observe that 802.11ac almost doubles the average throughput comparing with 802.11n.

Next, to evaluate the impact of larger channel width on mobility, we move the client around the AP at walking speed for 5 min. The track of mobility is shown in Figure 2 with a red dotted line. The average throughput of three such experiments was observed to be 491 Mbps for 802.11ac with 80-MHz channel width. No significant impact of larger channel width is observed on throughput variation at walking speeds comparing with the stationary cases. We repeat the same experiment using 802.11n with 40-MHz channel width, and the average throughput is 223 Mbps.

We also create a scenario where a total of 18 nodes (FIVE APs and 13 clients) are deployed as shown in Figure 2. Here, a maximum of three 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-MHz and 40-MHz channel widths. The throughput measurements are presented in Figure 4(b) and Table III. During the experiments of 80 MHz, (AP1, AP2 and AP3) pick the same channel, while (AP4 and AP5) pick another non-overlapping channel. In the case of 40 MHz, (AP1, AP2, AP3, AP5) and AP4 operate on distinct channels. However, we tried multiple layout configurations, but no meaningful patterns in the throughput variation were found. The potential factors affecting the throughput could be the topology or how channels are shared/divided between different links. More experiments are required for a clear understanding, and we leave it for the future work.

4. ENERGY EFFICIENCY OF 802.11AC

Energy efficiency has become a crucial design factor 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.

Table III. Throughput (Mbps) of different clients when multiple APs simultaneously transmit.

Channel width (MHz)	C1-1	C1-2	C2-1	C2-2	C3-1	C3-2	C3-3	C4-1	C4-2	C4-3	C5-1	C5-2	C5-3
80	112	110	117	116	54	52	50	80	76	81	117	120	116
40	52	51	45	47	43	39	31	102	100	103	36	36	36

To this end, we perform the experiments on two different 802.11ac chipsets, that is, Atheros QCA9880 in a laptop and Broadcom BCM4335 in a smartphone. We use Monsoon power monitor [13] 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.

4.1. Idle listening—a dominant factor

First of all, we try to understand how utilising 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 and 80 MHz) of the link. The results are presented in Table IV.

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

$$P_{average} = P_{active} \cdot T_{active} + P_{idle} \cdot T_{idle} \quad (1)$$

Table IV. Detailed power consumption of QCA9880 when operating on different channel widths.

CW (MHz)	P_{active} (mW)	T_{active} (Percent)	P_{idle} (mW)	T_{idle} (Percent)	$P_{average}$ (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

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); and 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 analysing 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. The detail about how these thresholds are selected and the power samples distributions for 20-MHz, 40-MHz and 80-MHz channels are shown in Figure 5(a)–5(c). From [14], we can obtain the theoretical way to calculate T_{active} (percentage of active time) as

$$T_{active} = \lambda_g \cdot T_L \quad (2)$$

where λ_g is the frame generation rate, and $T_L = T_{PLCP} + (H+L)/R_{PHY}$ is the time required for transmitting a frame. Here, L is the frame size; H is the MAC layer overhead; R_{PHY} is determined by MCS, SS and channel width; and T_{PLCP} is the time for transmitting Physical Layer Convergence Protocol (PLCP) preamble, which is usually sent at a low PHY rate. However, the theoretical values calculated using Equation 2 are much lower than the values we obtain in Table IV. The reason is that 802.11ac requires RTS/CTS as a mandatory part to determine channel width, and RTS/CTS frames are sent in an 802.11a Physical Protocol Data Unit format with 20 MHz, which uses a low PHY rate [1, 3]. In this way, the actual percentage of active time can be much higher than the theoretical value.

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

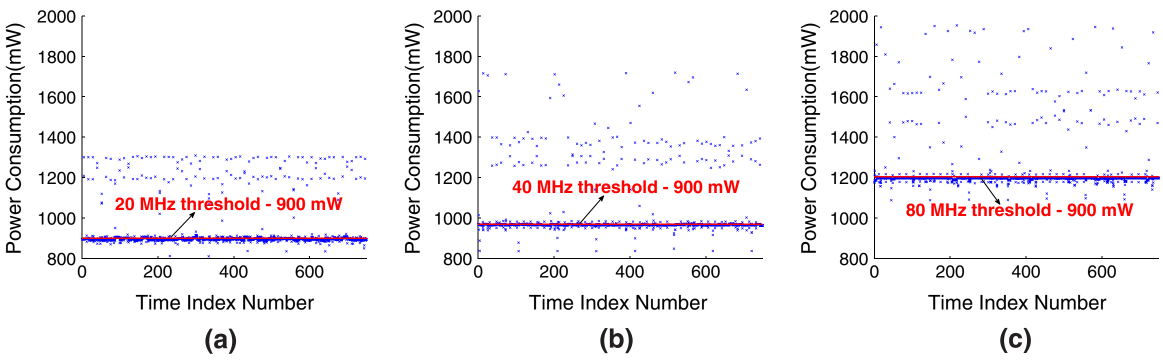


Figure 5. Power consumption samples with idle to active threshold line for 20-MHz (a), 40-MHz (b) and 80-MHz (c) channel widths. The power measurement sampling rate is 50 Hz.

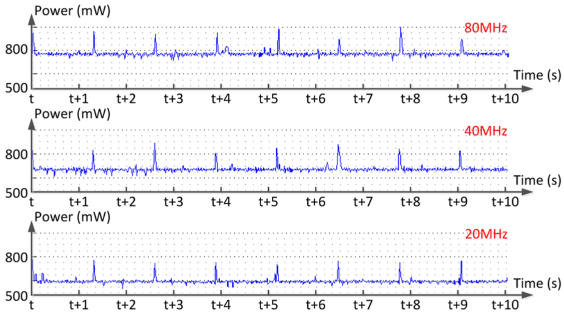


Figure 6. Comparison of dynamic power consumption between different channel widths (with 1 Mbps receiving rate constantly) on smartphone.

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 smartphone with the same settings except that it supports only one SS. Note that we consider the whole system's power consumption, which includes both NIC and CPU for smartphone. Because it is a relatively more complicated system, we do not apply a threshold to smartphone's data. Instead, we have confirmed the idle listening power to be the smooth line between spikes in Figure 6 by making the phone idle and measuring its power. The results are shown in Figure 6 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 per cent more power compared with 40 MHz. Similarly, it consumes 12 per cent more power when running at 40 MHz compared with operating at 20 MHz.

The 'race to sleep' heuristic, which is studied in [15] 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, 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: Because 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.

4.2. Impact of rate and 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 × SS with the objective being the maximisation of the throughput [16–19]. Recent work such as in [20, 21] have proposed rate adaptation schemes that try to minimise the energy consumption. Here, we seek the answer for a simple question: can joint rate and channel width adaptation (finding CW × MCS × SS) yield additional energy benefits compared with performing just the energy-efficient rate adaptation (MCS × SS)?

To understand this, we perform a set of experiments where we try to find the most energy-efficient MCS × SS combination using a brute-force approach. For each channel width, we try out all combinations of MCS (0 → 9) and SS (1 → 3) and find out the most energy-efficient combination that can satisfy a given source rate. Because 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 Figure 7(a).

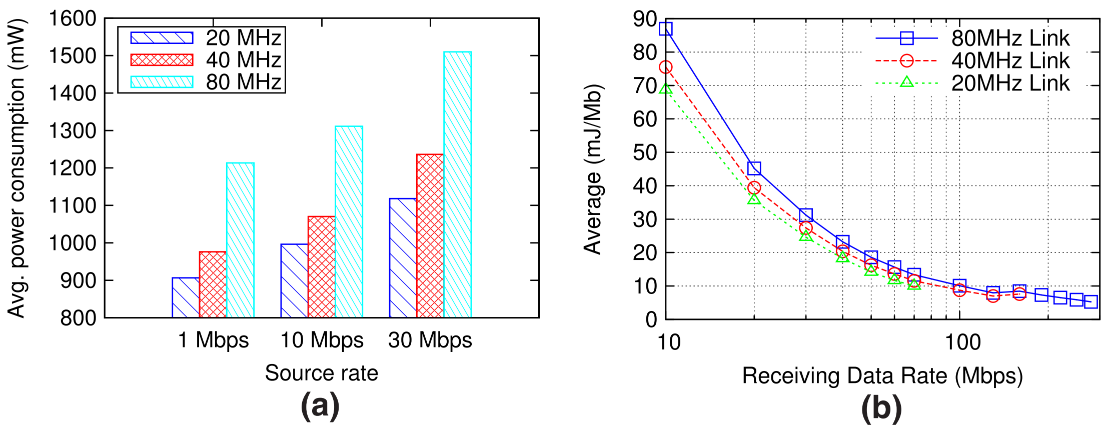


Figure 7. (a) Power consumption of the most energy-efficient setting in different channel widths at different source rates, (b) comparison of per megabit energy cost between different channel widths.

As we see in Figure 7(a), the power consumption of the most energy-efficient MCS × 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 are observed to be the most energy efficient in most cases. This is in line with the work in [15], which suggests that the choice of higher MCS is more energy efficient.

These 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 Figure 7(b). Note that for a fair comparison at different source rates, we present the energy consumption values in megajoule/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, utilising larger channel width consumes more power. Because 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: Because 802.11ac mandates the use of RTS/CTS (discussed in Section 6.1), one potential reason of this higher power consumption can be that 80-MHz width requires four times more RTS/CTS compared with 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 with 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.

4.3. Channel width versus spatial streams

Two main factors responsible for throughput gains of 802.11ac are more SS and larger channel width. Both factors achieve a similar increase in throughput—for example, increasing SS from 1 to 2 nearly doubles the throughput, similarly, doubling the channel width from 40 to 80 Mhz also has the same effect on throughput. We raise a simple question, because 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 a 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.

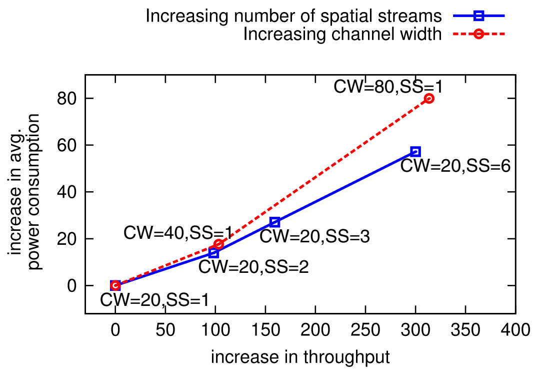


Figure 8. Comparison of percentage increase in power consumption with increasing SS or increasing channel width.

The results are presented in Figure 8, which shows that increasing channel width consumes much more energy (primarily due to reasons described earlier) compared with increasing SS. Note that because none of the current hardware supports six SS, we use interpolation to find its power consumption.

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

5. INTERFERENCE CHARACTERISATION

We now look at the details of how 802.11ac operates when operating in the presence of other 802.11a/n/ac links. Note that even if an 802.11ac AP is using 80-MHz channel width, it still utilises 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) The 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 utilises explicit message exchange for dynamic channel width selection and collision avoidance. We study this in details in Section 6.1.
(2) 802.11a/n clients capable of operating at a 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 activities during clear channel assessment (CCA).

Indoor setup: The selection of the primary channel and the channel widths plays crucial roles in determining how the spectrum is sliced between different links. We now focus on the experiments where two links can use different

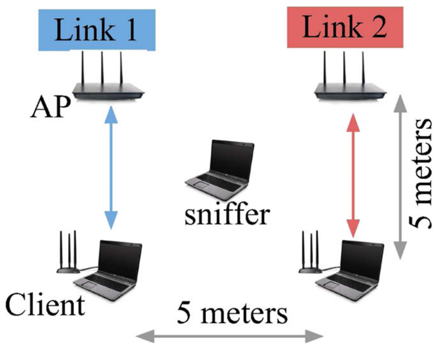


Figure 9. Indoor setup of two links and a sniffer.

channel widths and can have the same or distinct primary channels. For these experiments, we deploy two 802.11ac link indoors as shown in Figure 9 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.

5.1. Throughput anomalies with heterogeneous channel widths

Using the setup of Figure 9, 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 the same or different primary channels.

Same primary channel: In the first scenario, when both 80-MHz and 20-MHz links have the same primary channel, the resultant throughput of both links is shown in case 1 of Figure 10(a). It can be observed from Figure 10(b) that when 20-MHz channel is overlapping with the primary channel of link 1, the throughput of both links decreases, but the decrease is more or less proportional to its throughput without interference. In other words, neither link 1 nor link 2 severely decreases or even gets blocked.

Different primary channels: Cases 2, 3 and 4 of Figure 10(a) show the scenario when a 20-MHz link is operating in the secondary channels of the 80-MHz link. As we can see from Figure 10(b), when link 2 is sending at the best possible rate, throughput of link 1 becomes 0. This is surprising to see because this means that co-existence of 80-MHz and 20-MHz links can deteriorate the throughput of large channel width link significantly. We repeat the experiments with 20-MHz link reducing its sending rate. The results are presented in Figure 10(c). 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 Figure 10(c)), the performance of 80-MHz link starts degrading. Further increasing the rate of link 2 to its maximum (best effort as shown in Figure 10(c)) 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 Figure 10(a)). 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.

<u>Findings:</u> *When a 20/40-MHz link is operating in the 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 (Section 5.2) and (ii) difference in CCA sensitivity thresholds (Section 5.3). Next, we discuss both of them in details.

5.2. 802.11ac channel access procedure

802.11ac supports both static and dynamic channel width access methods. In the experiments discusses earlier, 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

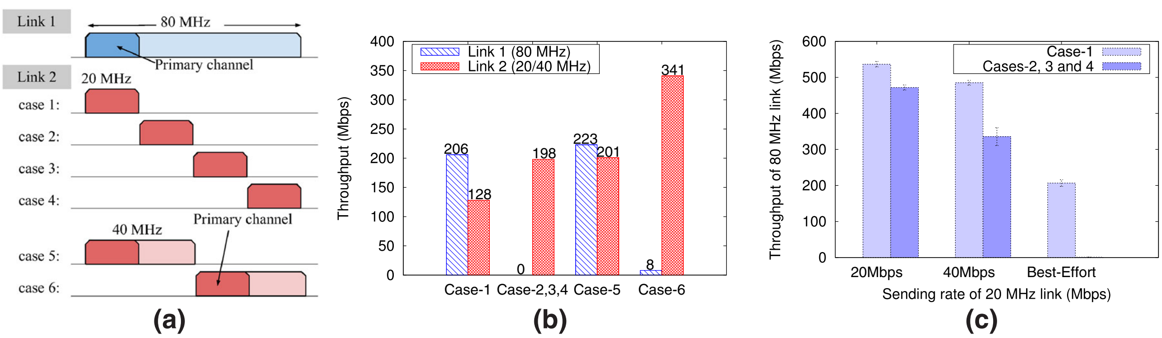


Figure 10. Link 1 is operating in 80-MHz fixed channel width and link 2 is operating on 40/20-MHz width. When link 2's primary channel is the same as that of link 1, both links share the medium proportionally (case 1 or 5). On the other hand, when link 2's primary channel falls within secondary channels of link 1, severe degradation of throughput is observed for link 1.

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 the primary channel performs sensing for distributed inter-frame space (DIFS) and backoff time; however, the secondary channels are only sensed for point inter-frame space (PIFS) 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 the primary channel sensing the medium for DIFS time. This is shown in Figure 11. The PIFS and DIFS are calculated as Equations 3 and 4 where aSIFSTime refers to a short inter-frame space (SIFS) duration. The backoff time is a random number selected from 0 to the current contention window size multiplied with the slot time (aSlotTime).

$$\text{PIFS} = \text{aSIFSTime} + \text{aSlotTime} \tag{3}$$

$$\text{DIFS} = \text{aSIFSTime} + (2 \times \text{aSlotTime}) \tag{4}$$

The main issue with the operation of Algorithm 1 is that when the secondary channel is sensed busy, instead of freezing the backoff counter of the primary channel, the transmission is aborted, and the cycle is re-initiated. Note that the freezing of backoff counter is indeed implemented for the primary channel but not for the secondary channels. This on top of smaller sensing time for secondary channel makes it very difficult for an 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: Because backoff timer of the 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 obtain useful medium access, which results into severe throughput reduction.

5.3. CCA thresholds

From [1], we know that the primary and secondary channels use different CCA mechanisms. The primary channel utilises 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 preamble and use that information to set the network allocation vector counter. However, the secondary channel implements a *reduced* CCA and does not set the network allocation vector counter.

Difference in CCA procedure and thresholds between primary and secondary channels is another reason of throughput degradation observed in Figure 10(b). Because 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 and energy detection.

Signal detection is used only when the detected channel activity is decodable (PLCP preamble detected), while the energy detection is used when the signal cannot be decoded. Furthermore, the signal detection thresholds for primary and secondary channels are different due to different CCA methods. We summarise the CCA thresholds used in 802.11ac in Table V. In the table, P-20 refers to the primary channel of 20 MHz, and similarly, S-20 refers to

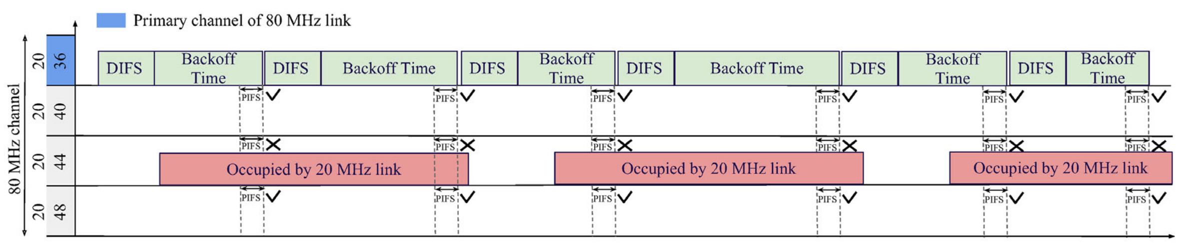


Figure 11. Different physical carrier sensing time and CCA methods in primary and secondary channels cause the 80-MHz link to continuously backoff.

Table V. 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, clear channel assessment; SD, signal detection; ED, energy detection.

the secondary channel of 20 MHz. Also, signal detection-th denotes the signal detection threshold, while ED-th denotes the energy detection threshold.

CCA in cases 1 and 5: In cases 1 and 5, because the primary channel is overlapped, link 1 can detect 20-MHz or 40-MHz signal of link 2, and similarly, link 2 can detect link 1's signal (beacons on the primary channel). This way, both links use signal detection thresholds for CCA, which results in nearly fair Carrier Sense Multiple Access (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 cannot 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 that the CCA threshold for link 2 in cases 2, 3 and 4 is −62 dBm, which is different with what Park said (−82 dBm) in [2]. The reason for this is that 20-MHz link cannot decode 80-MHz Physical Protocol Data Unit from the secondary channel as there are not beacons.

Additionally, when the received interference power at each 20-MHz channel 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 backoff and has 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 is gradually increasing from 0 to 400 Mbps, but the throughput of 20-MHz link decreases only a little. This way, in out experiments, the significant backoff issue (as presented in [2]) does not happen. We attribute this to the difference between simulation and real-world experiments.

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

6. DYNAMIC CHANNEL WIDTH ACCESS

6.1. Enhanced RTS/CTS protocol

We consider an example as shown in Figure 12 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 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 (Figure 12). When the client receives the four 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 carried out.

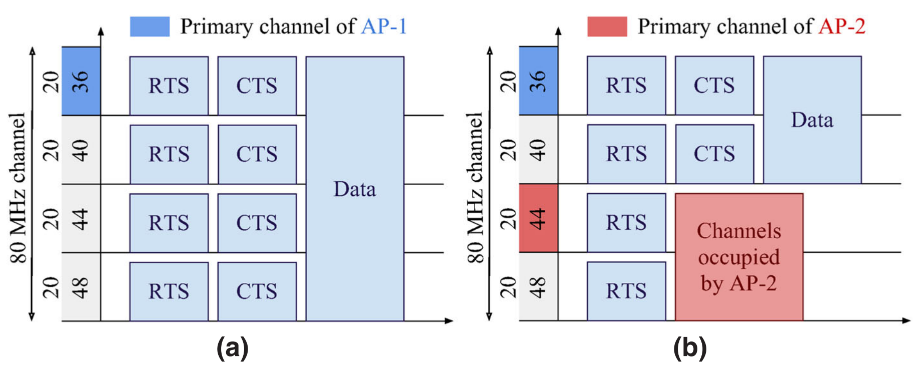


Figure 12. E-RTS/CTS protocol.

Now let us consider the cases where there is some activity on secondary channels. For example, 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 two 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 Figure 12.

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.

6.2. Sharing or dividing 80 MHz

To test the E-RTS/CTS protocol, we experiment with setup of Figure 9. We fix the channel widths for both links to be 80 MHz, and their primary channels to be the same.

We now send data at a maximum possible rate on both links. Figure 13(a) shows how RTS/CTS messages are exchanged to use the 80-MHz channel. Because the primary channel is the same, both links use the 80-MHz channel in a time-divided manner. The average throughput of the links is shown in case 1 of Figure 13(b).

To study the impact of selecting different primary channels, we assigned different primary channels for both links. Here, there are two possibilities where links can share the 80-MHz channel in a 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 a time-divided manner. The results of average throughput are given in case 2 of Figure 13(b).

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 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 the throughput of two 40-MHz links sums 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 the best of their capacity. In such case, choosing non-adjacent channels or in fact utilising a larger channel width in a time-divided manner is a better option.

6.3. 80-MHz channel interference pattern

In order to further understand the difference between 40-MHz and 80-MHz interference ranges, we setup two 802.11ac links (similar to Figure 9). We then increase the distance between the two links and observe how the throughput is affected on both links. The measurements are presented in Figure 14. As we expect, when both links operate at 80 MHz, their mutual interferences reduce 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 complicate the interference management as there will be more neighbouring cells for each AP.

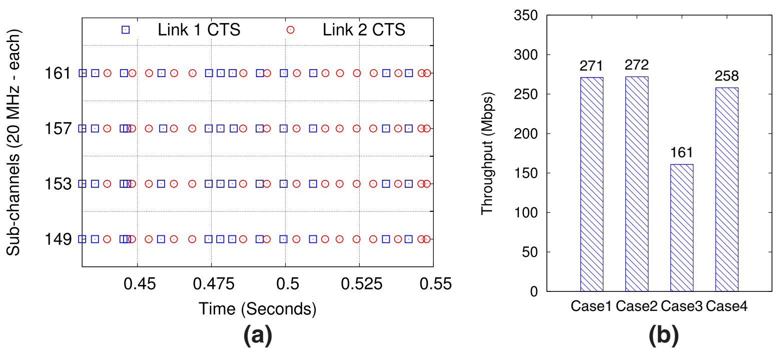


Figure 13. (a) RTS-CTS packets captured by sniffer (b) throughput comparison of four cases where two links (case 1): share 80 MHz with the same primary channel, (case 2): share 80 MHz with different primary channels, (case 3): divide 80 MHz into adjacent 40-MHz channels, (case 4): divide 80 MHz into non-adjacent 40-MHz channels.

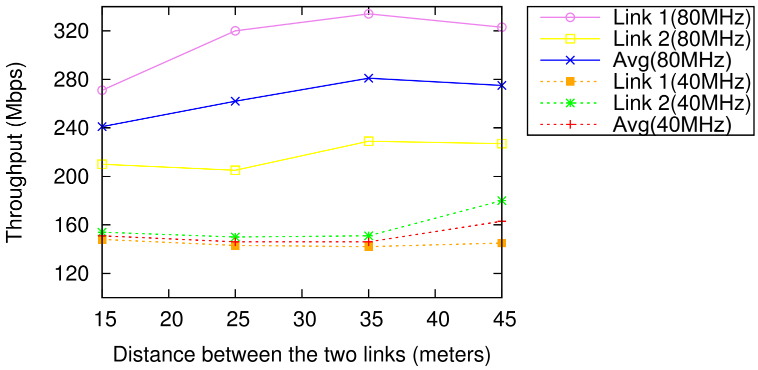


Figure 14. Two 802.11ac links—comparison of interference pattern between two cases: case 1, when both links operate on 80 MHz and case 2, when both links operate on 40 MHz.

7. RELATED WORK

802.11n is the most prevalent standard used in current WLANs. Compared with other WLAN standards (802.11a/b/g), 802.11n introduced MIMO and frame aggregation as new features for throughput enhancement. Many previous research studies [22–25] provide an overview of these features of 802.11n. A detailed experimental evaluation of 802.11n is provided in [26]. It was observed that the throughput of an 802.11n link degrades severely in the presence of an 802.11g link. Our observation about the degradation of 802.11ac link performance is largely due to heterogeneous channel widths as we have discussed. The work of Pelechrinis et al. [27] characterises 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. [28] use regression analysis based on the testbed data to show that how these new features work independently to optimise the overall performance. The work in [29] studies the mobile devices performance using WLAN with interference. But, all aforementioned testbed works are based on 802.11n and they did not 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 obtain 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 characterisation, Carcia-Saavedra et al. [14] present a new energy consumption model to measure the per-frame energy cost with higher accuracy and confidence. Halperin et al. [15] investigate the power consumption of 802.11 NICs and mainly focus on the effect of MIMO on energy cost. Other recent work [30–32] discuss the energy efficiency design for different kinds of wireless techniques. 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.

8. CONCLUSIONS

In this paper, we presented a performance characterisation of 802.11ac standard. We identified what is the impact of utilising 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 SS is more energy efficient compared with increasing the channel width in achieving the same percentage increase in throughput. Also, our interference characterisation 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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