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Introducing IEEE 802.11ac into existing WLAN deployment scenarios

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***Abstract*—In mature wireless LAN (WLAN) deployments, we show that introducing 802.11ac could have little benefit compared to existing 802.11n deployments. Using a testbed with common characteristics for an existing WLAN deployment (such as an office environment), we compare throughput for 802.11ac and 802.11n (in both 5GHz and 2.4GHz bands). We find that 802.11ac has lower throughput than for 802.11n for our testbed configuration. We also provide an evaluation of energy usage for 802.11ac and 802.11n.**

I. Introduction

Worldwide, the number of mobile internet users will be around 2.5 billion at the end of year 2015, which will represent 83.6% of the Internet users around the world [1]. IEEE 802.11 Wireless Local Area Networks (WLANs) provide a cheap and convenient connectivity solutions for many of these users. Also, WLANs are used even when mobile devices are not in use, as setting up a wireless network is quick and convenient compared to wired networks. However, with the increase in the number of users, and the growing needs of higher data rate applications (e.g. video streaming), there is a an ever-present need to improve WLAN performance.

Many existing deployments of WLAN are based on either mature 2.4GHz IEEE 802.11 configurations (802.11g and 802.11n), or mixed configurations of both 2.4GHz (802.11g and 802.11n) and 5GHz (802.11n). The latest IEEE 802.11 variant, IEEE 802.11ac, is now being introduced. Existing, mature WLAN deployments are often based on a 20MHz channel usage, with network planning and access point (AP) placement from 2.4GHz WLAN designs. In the 2.4GHz band, a 20MHz channel width allows three non-overlapping channels. 802.11n on 2.4GHz also allows a 40MHz channel, but it is not possible to have two non- overlapping 20MHz channels in the 2.4GHz band. The 5GHz band has scope for greater radio frequency (RF) bandwidth overall and wider RF channels. 5GHz 802.11n and 802.11ac WLAN variants can support a 20MHz channel, but have been designed to allow the use of channel widths of 40MHz (802.11n and 802.11ac), 80MHz (802.11ac) and 160MHz (802.11ac), in order to provide improved throughput. However, even though such wide channels are desirable for increased throughput, we argue that such channels may not always be easily usable in real deployments.

A. Motivation and Approach

We use a common deployment configuration for our testbed WLAN configuration. We test throughput with the Transmission Control Protocol (TCP) which is the most widely used transport protocol on the Internet. TCP supports different types of application such as email, WWW access and video streaming. In this paper we conduct an empirical study using the two 5GHz 802.11 WLANs variants – 802.11n and 802.11ac – with TCP traffic. For 802.11n we conduct the experiments in the 2.4GHz band also, for comparison, and we also present results using 100baseT, again for comparison. We use a 20MHz channel only, and justify this choice in Section II-B.

In keeping with the methodology of our previous work [2]–[4], our approach is empirical, based on measurements of performance and energy usage of real systems. We use off-the-shelf equipment, opensource software, and consumer devices wherever possible. Our intentions are:

- To examine systems that are typical of normal usage, so that our results reflect real operational scenarios, rather than lab-specific, optimised configurations.
- Make it possible to apply our methodology easily to other similar scenarios, to allow comparisons.
- Allow our results to be validated / reproduced easily.

B. Contribution and structure of this paper

We examine the performance of WLAN at the client. Specifically, we have assessed 802.11n (at both 2.4GHz and 5GHz), and 802.11ac, all using a 20MHz channels width. We take the position that the 20MHz channel width remains a common choice for configuration, due to the nature of network planning for WLANs. We evaluate performance using TCP flows, and we also examine energy usage of the 802.11 variants.

In Section II we provide background information and a rationale for our deployment scenario. In Section III we explain our methodology and describe our testbed. We discuss our results in Sections IV and V, including our analyses of 802.11 deployment choices for the future. We conclude with a short summary in Section VI.

II. Related Work and Background

Our context is planned, office and site deployments of WLANs, rather than ad hoc or domestic deployments of WLANs. However, we comment on domestic deployments in Section II-B. In considering planned deployments, we present our background work in three parts: (i) the structure of existing WLAN deployments today; (ii) RF channel options in WLANs; (iii) previous work related to performance analyses of 802.11n and 802.11ac.

A. Structure of existing WLAN deployments

Planned WLAN deployments for offices and sites/campuses are based around the placement of access points (APs) to provide radio coverage across a confined geographical area. Ideally, the radio coverage is complete in that area, e.g. office, site, or campus. This may require placement of APs at intervals, e.g. every ∼10m, to ensure good coverage and support a given population of users. This means that after an initial planning phase, structured cabling (e.g. CAT5e or CAT6 Ethernet cable), and power is installed at the sites chosen for AP placement. Today, it is also possible to use power over Ethernet (PoE) for power provision, but increases the cost of equipment, and relies on appropriate structured cabling being in place.

In such a planned environment, the initial capital costs (CAPEX) for cabling (Ethernet and power) can be significant, but might be amortised with other building costs for new buildings. For older buildings, such a cost could be a significant outlay. Additionally, after the initial instalment of structured cabling, unless spare capacity (cabling) was planned and installed, it may not be possible to change AP locations or introduce new AP sites easily or at low cost.

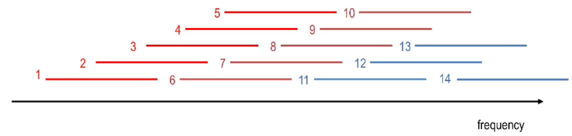
So, when upgrading WLAN equipment, there may be a trade-off in costs between introducing new 802.11 variants and infrastructure costs. In many cases, to maximise expenditure on new 802.11 equipment, it may be desirable to reuse existing AP sites. Hence, it is often the case that, in the first instance at least, new 802.11 AP deployments are based on old WLAN network plans, reusing AP sites.

B. RF channel options in WLANs

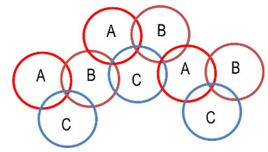
The Radio Frequency (RF) transmission characteristics of 802.11 radio are described in the IEEE 802.11 standard, which includes the channelisation scheme as well as the spectrum radiation of the signal [5]. There is a well-known problem of RF channel allocation in the 2.4GHz band, depicted in Figure 1. Channels 12-14 are not available in all regions. This means that there are sometimes only three non-overlapping channels (Figure 1a) (each channel is 22MHz). So, a WLAN deployment plan is based on this (or similar) repeating, three-channel pattern (Figure 1b). If four cells are available, then an alternative simple cell plan is also possible (Figure 1c).

For the 2.4GHz band, there are 11 channels for the Federal Communications Commission (FCC) and 13 channels for the European Telecommunications Standards Institute (ETSI) domains. A space of 5MHz separates the channels but the frequency band used for each channel is 22MHz which means any neighbouring channels overlap and interfere with each other. To avoid interference, in the US, the channels 1, 6 and 11 are typically used, while channels 1, 5, 9 and 13 are recommended for use in the rest of the world. Most WLAN devices can operate on the 2.4GHz band, which makes this band very crowded [6].

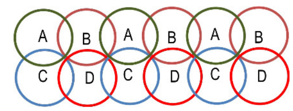
IEEE 802.11n at 2.4GHz and 5GHz allows the use of 40MHz channels. For 2.4GHz, 40MHz channels are difficult to use in practice, as they consume the RF bandwidth of 8 of the channels available.



(a) 2.4GHz channels (12, 13 and 14 not always usable).



(b) A 3-channel cell plan



(c) A 4-channel cell plan

Fig. 1. WLAN channel usage for planned networks.

When moving to 5GHz, there are more channels available, as shown in Table I. Each channel is 20MHz. The 5GHz band has several sub-bands. UNII-1 is widely available, globally, as is UNII-3, but the latter may not be supported so widely in equipment, especially cheaper or low-end client devices. The UNII-2 and UNII-2-Ext sub-bands require the use of Dynamic Frequency Selection (DFS) algorithms for avoiding radar systems (e.g. weather radar). So, UNII-2 and UNII-2-Ext sub-bands might not be so widely available for use, as well as not being implemented in some equipment. Hence, for many systems, it may be that only UNII-1 is available for use. So, using a 20MHz channel from the UNII-1 band will allow a WLAN cell plan with a similar layout to that for 3-cell plan (Figure 1b) or a 4-cell plan (Figure 1c).

TABLE I
5GHz WLAN BANDS, EACH CHANNEL IS 20MHz

5GHz sub-band	Channel numbers
UNII-1	36, 40, 44, 48
UNII-2	52, 56, 60, 64
UNII-2-Ext	100, 104, 108, 112, 116, 120 124, 128, 132, 136, 140
UNII-3	149, 153, 157, 161, 165

UNII - Unlicensed National Information Infrastructure

Of course, if UNII-3 is available, then it is possible to have four 40MHz channels, in a 4-cell plan (Figure 1c), which would offer greater throughput. Deek *et al* have previously examined the use of a 40MHz channel, and find some constraints on its use also [7]. Moving to an 80MHz channel would allow only a 2-cell plan, and using a 160MHZ channel (as 80MHz UNII-1 + 80MHz UNII-3) would only allow a single cell.

For our experiments, we have taken the position that a 20MHz channel is likely to remain in use for some time with 5GHz WLANs, for both 802.11n and 802.11ac.

C. WLAN performance and energy usage

Our own previous work in this area, established the use of the energy metric, E_A (see Section III-C) and the notion of the *energy envelope*, which gives the upper and lower bounds of the energy usage during the transmission of a flow

[2]. We have also investigated the possibility of application adaptation within the scope of this energy envelope [3] to trade of performance against energy usage. Also, we have found that the generic 802.11 power save mode (PSM) has little effect during system usage [8]. In [9] we address the problem of the interference impact of WLAN by investigating the impact of low Received Signal Strength Indication (RSSI) on WLAN performance. These studies all include measurements in both the 2.4GHz and 5GHz bands. We have also examined the energy usage of the Datagram Congestion Control protocol (DCCP) and User Datagram Protocol (UDP) at different packet sizes and data rates over 802.11n WLAN at 5GHz [4]. The results show DCCP can provide ∼10% to ∼40% greater energy efficiency than the UDP.

Zeng *et al* [10] have evaluated 802.11ac performance. They observed that throughput and energy usage was very variable, but that 802.11ac can achieve higher throughput overall when using wide RF channels (40MHz and greater). The authors provided a comparison between 802.11n and 802.11ac protocols, but the 802.11n experiments used 40MHz channels while the 802.11ac experiments used 80MHz channels.

Keranidis *et al* [11] have considered an experimental comparison of energy efficiency for 802.11n. However, they evaluated the energy consumption for the Network Interface Card (NIC) only, while in this paper and our previous work, we consider the impact on the client system as a whole, as that will be the real impact observed by users. Additionally, their study used optimisations to system configuration to improve energy efficiency, whilst we take the position that users normally adopt default configurations.

Halpern *et al* [12] provided an empirical study of the power consumption of 802.11n WLAN but again only considered the NIC. Their study concluded that the use of larger packets and higher date rate in transmission is more energy efficient than using a smaller packet size and lower data rates.

Li *et al* [13] also examined the impact of packet size on energy consumption in heterogeneous wireless network environments, with similar observations: larger packet sizes and higher data rates give better energy efficiency.

In this paper, we have examined energy usage of TCP for the client systems as whole for 802.11n (2.4Ghz and 5GHz) as well as 802.11ac.

III. EXPERIMENT DESIGN AND METRICS

We measured performance and energy usage of TCP flows transmitted over the 802.11n (2.4GHz and 5GHz) and 802.11ac, in a modern, open-plan office environment. We used opensource software, off-the-shelf hardware and default configurations for all systems, unless otherwise detailed below.

A. Overview

Our testbed (Figure 2) consisted of a single client system, with another host operating as both a wireless access-point (AP) and as a server. Both hosts were set up in a teaching lab in the University of St Andrews with a distance of ∼ 10 m between the antennae. *iperf v2.0.2* [1] was used in server mode to receive traffic flows. The energy usage of the client was measured by using a commercial power meter. This measurement regime was executed with four network configurations: 802.11n at 2.4GHz, 802.11n at 5GHz, 802.11ac, and 100baseT. The 802.11 configurations all used a 20MHz channel, and the 100baseT configuration was for comparison. Each TCP *iperf* measurement was a 100MB transfer, and was performed 30 times for each of the four network configurations we used (120 measurements in total).

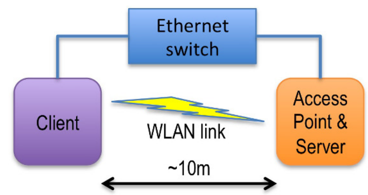


Fig. 2. Schematic of testbed showing physical connectivity. All experiments used 802.11n at 2.4GHz and 5GHz and 802.11ac at 5GHz with 20MHz channels. The experiments used Ethernet for a control channel and file-system. Only test-traffic traversed the WLAN link. The antennas of the client and access point/server were ∼ 10 ± 0.5 m apart. TCP flows generated by *iperf v2.0.2* were transferred across the WLAN link.

B. Equipment

Our testbed was equipped with identical machines. The hardware specifications of the client and the server were: a Scan home-office PC (*V10* [2]) with an Intel ® Core i5 4440 3.1GHz Quad Core CPU, 4GB RAM, 1TB HD. All machines used the same wireless LAN NIC hardware [3] based on the QCA9880 Version 2 Atheros [4] chipset, with 3×3 MIMO technology. Our power meter was an i-Sockets[5] instrumented, domestic, multi-way power extension.

Ubuntu 14.04 was used on each host, a minimal server distribution, with the Linux kernel version 3.16.0-wl-ath+, and the latest ath10k driver [6]. For implementing the AP, we used the *hostapd* [7] package version v2.3-devel. All nodes in the testbed were connected via a local ethernet network which was also used for controlling the experiment: only test traffic traversed the WLAN link. The Linux utility *iwconfig*[8] was used to record the link quality and the signal level of the RF channel.

C. Performance Metrics

From *iperf* we had for TCP the end-to-end datarate, r. The energy metric used, E_A, had units micro-Joules per bit ($\mu J/b$) (Eqn. 1), which is numerically equal to Joules per megabit.

[1]http://www.erg.abdn.ac.uk/∼gerrit/dccp/apps/
[2]http://3xs.scan.co.uk/configurator/ready-to-ship-budget-value-amd-home-office-pc-v10a
[3]http://www.compex.com.sg/Datasheets/WLE900VX_Dsv1.0.1-140711-I.pdf
[4]http://www.atheros.com/
[5]http://www.i-sockets.com/
[6]https://github.com/kvalo/ath10k
[7]http://hostap.epitest.fi/hostapd/
[8]http://www.linuxcommand.org/man_pages/iwconfig8.html

For each flow, we measured the mean power usage over the duration of the flow (P_F), and subtracted the idle power (P_I) measured for the client (36W), then divided by the throughput (r). Lower values of E_A are better.

$$E_A = \frac{P_F - P_I}{r} \quad (1)$$

TABLE II
MAIN METRICS FOR EVALUATION

Metric	Description	Units	Comment
E_A	energy usage of flow	μJ/b	Eqn. 1
r	TCP throughput	Mbps	from *iperf*

IV. RESULTS

Our measurements are summarised in Figure 3. As variability in performance can be high in each graph we show:

- All 30 measurements summarised as a standard boxplot (minimum whisker, 25th-percentile, median, 75th-percentile, maximum whisker).
- Offset to the right of the boxplot, for each set of 30 measurements, we plot a point for the mean value, with a whisker showing the 95th-percentile and 99th-percentile.

This gives a complete picture of the metrics we have observed: throughput and energy, E_A from Eqn. 1 (Section III-C). During the measurement period, we have recorded the link quality and signal strength and have observed them to be relatively stable as shown in Figure 4.

A. Comparison of 802.11 variants

In Figure 3a we see the throughput measurements for our experiments.

Key observation: 802.11n outperforms 802.11ac. There is a clear difference between the throughput of 802.11n (both at 2.4GHz and 5GHz) and 802.11ac. If we compare median and mean values, 802.11n provides ∼5% - ∼17% greater throughput than 802.11ac.

So, where a mature 802.11n deployment exists, there may be little benefit from upgrading to 802.11ac at this time.

B. Comparison of energy usage

We consider now Figure 3b. Here, we see the values for E_A from Eqn. (1) as energy per bit. If we consider only the mean and median values then 802.11ac has marginally better energy performance than 802.11n. However, if we consider the range of variability of the values, then there is no real difference in energy usage between the variants.

C. Comparison with 100baseT

The measurements for 100baseT were for comparison only, as 100baseT is still widely used in office environments, still being cheaper in terms of infrastructure equipment costs Gigabit Ethernet (1000baseT). It is clear that both 802.11n variants and 802.11ac outperform 100baseT in all cases. It should be noted, however, that this is with the use of a 3×3 MIMO configuration. Our previous studies have observed lower throughput from the more common 2×2 MIMO configurations, e.g. [4], [7].

D. Signal Strength and Link Quality

The signal strength and the link quality for our experiments is shown in Figure 4a. The signal strength for the three wireless scenarios is, ∼-48 dBm for 802.11n 2.4 GHz, and ∼-40 dBm for both 802.11n 5 GHz and 802.11ac (smaller values are better and -35 dBm was the best signal strength value observed). Additionally Figure 4b shows the link quality as reported by the driver via *iwconfig*. According to the figure, during the experiments, the link quality had median values of ∼62 for 802.11n 2.4 GHz and ∼69 for both 802.11n 5 GHz and 802.11ac. The maximum link quality is 70. So, in our experiments, the WLAN RF transmission all showed variability, and more so variable for 2.4GHz.

E. Limitations of our experiments

In our experiments, we have used a best-case scenario: a single client, in a single cell with no contention from other clients and no interfering neighbour cells. So, performance will be lower in use of deployed systems.

We have considered planned office deployments, but much WLAN usage is in domestic environments, where planning does not exist: individual households configure their systems independently of neighbours. In such scenarios, users rely on auto-detection mechanisms in their equipment to both detect the best channel to use and to select RF channel width.

V. DISCUSSION

Our results show an unexpected finding: 802.11n at 5GHz outperforms 802.11ac in our testbed configuration. We present here some reasons why this is so, and also present our position on the conditions under which 802.11ac will really be beneficial for wider-spread deployment. We focus on this in our discussion.

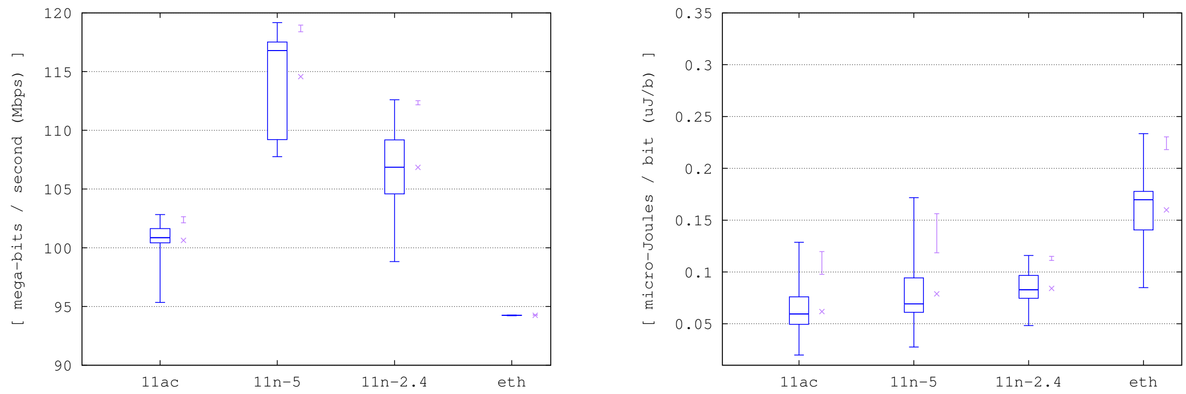
The new features of 802.11ac compared to 802.11n are:

- New modulation and coding schemes, including up to 256QAM.
- Wider channels (80MHz and 160MHz).
- More spatial streams – upto 8×8 MIMO – and multi-user MIMO using beam-forming techniques.

We discuss each of these in turn.

A. New modulation and coding schemes

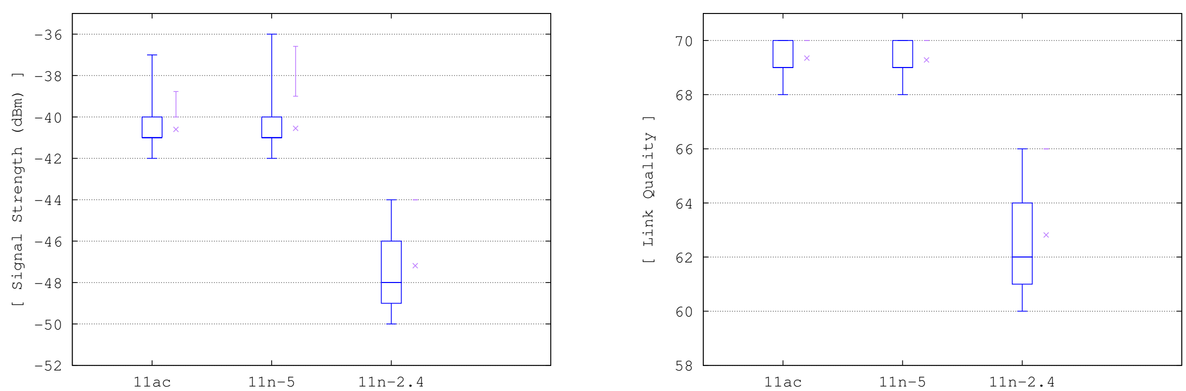
The modulation and coding schemes (MCS), especially for the higher rates, rely on high-density QAM, e.g. 256QAM. However, such schemes typically require good SNR and short distances from AP to client, especially 256QAM. From Figure 4a, we see that while signal strength for 802.11ac and 802.11n for our testbed environment was comparable: (i) it was too low for the higher QAM rates; and (ii) it was to variable to sustain the use of higher QAM rates even if they could be selected. To use 256QAM, signal strength of ∼-32dBm is required, but we measure a maximum of ∼-36dBm and a median of ∼-41dBm for both 11ac and 11n-5GHz. The 95th percentile and 99th



(a) Throughput, TCP at client

(b) Energy usage, TCP at client

Fig. 3. Client-side measurements with a CUBIC server: Throughput and E_A for TCP flows. To the right of each boxplot, we show the mean and a whisker marking the 95th and 99th percentiles.



(a) Signal Strength at client

(b) Link Quality at client

Fig. 4. Signal Strength and Link Quality as reported by the WLAN driver via *iwconfig*. The maximum value of Link Quality reported by the driver is 70. To the right of each boxplot, we show the mean and a whisker marking the 95th and 99th percentiles.

percentile for 11n-5GHz is ∼1-2dBm better than for 802.11ac, which is enough in our testbed for 802.11n to have better performance.

B. Wider channels

802.11ac allows wider channels, and certainly using 80MHz channels or 160MHz channels, 802.11ac outperforms 802.11n. However, as we argue in Section II-B, it is unlikely that these wide channels would be used in existing deployments of planned networks which have been designed to have neighbouring cells that do not overlap in RF usage.

It is only possible to have two non-overlapping 80MHz cells in UNII-1 and UNII-3. UNII-2 and UNII-2-Ext offer greater possibilities, but are subject to constraints due to DFS and lack of wide geographic support. A 160MHz channel would use up the whole of UNII-1 or UNII-3.

Meanwhile, in unplanned networks, such as domestic (home user) scenarios, equipment is designed to provide ease of use. Home equipment is often configured to switch to smaller channel-widths automatically when interfering signals are detected, e.g. from a neighbour's home equipment. So, as 5GHz becomes more widely deployed, the wider channels will become less usable, with a 20MHz channel being the minimal configuration possible.

C. More spatial streams and MU-MIMO

At the time of writing, 802.11ac equipment is mainly 'Phase 1' (aka 'First Wave') equipment: 2×2 or 3×3 MIMO, with some access points having 4×4 capability, and no multi-user MIMO (MU-MIMO) capability. The 'Phase 2' (aka 'Second Wave') is now becoming available and will feature;

- *More spatial streams.* Upto 8×8 MIMO is permitted by the 802.11ac standards, but it is not yet clear how this will manifest itself in real usage.
- *Multi-user MIMO.* With beam-forming technology as well as additional spatial streams, multiple clients will be able to transmit simultaneously, improving throughput for a population of clients in the same cell.

Of course, this will require further equipment changes, and it is unlikely, especially in domestic scenarios, that existing equipment could be upgraded: new APs will be required to support such features. It is possible that MU-MIMO beam-forming features could benefit a population of existing clients without upgrade. For example, an AP with MU-MIMO could offer simultaneous access to more than one client simultaneously using beam-forming at the AP only, increasing the overall throughput of the AP and improving WLAN access for clients, even though individual channel speeds might not be greater than for 802.11n-5GHz.

Of course, for Phase 2 features to be fully effective, client devices may also have to be upgraded or changed. Some smaller devices, such as smartphones and tablets, may not be able to exploit fully the Phase 2 features, if their form factors do not allow for multi-antenna capabilities. Client devices may be subject to greater constraints than infrastructure equipment, e.g. issues such as size and power constraints for portable devices when additional antennas or spatial streams are used. The additional costs for upgrades for an existing client base could be high, as they outnumber infrastructure devices by an order of magnitude or more in office environments. Additionally, for consumer devices, users can be very sensitive to prices.

Overall, the real benefits of 802.11ac Phase 1 might not be seen so readily compared to mature 802.11n-5GHz deployments. Also, Phase 2 802.11ac features that could yield greater capacity might require both infrastructure and client upgrades or changes before benefits are truly visible.

VI. Conclusion

We have conducted experiments to determine the performance of 802.11ac in comparison to 802.11n in an office scenario, using a 20MHz channel, as might be required for a existing (legacy) deployment scenario, such as a planned office environment. We find that in our testbed, 802.11n outperforms 802.11ac. We find little difference in energy usage across the variants. We conclude that the Phase 2 802.11ac functionality (additional spatial streams and MU-MIMO), may offer the real benefits of 802.11ac.

Acknowledgements

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