Upgrading 802.11 deployments: a critical examination of performance

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***Abstract*—The increased demand for communications and Internet access makes Wireless Local Area Networks (WLANs) one of the most popular solutions for network connectivity. In this paper, we examine the performance and the energy efficiency of WLANs in 2.4 GHz and 5 GHz and discuss paths for upgrading. Our results show that it is worth upgrading to the 5 GHz bands from the 2.4 GHz band for 802.11n, especially for applications that are sensitive to packet loss. We also show that it is little benefit in upgrading from 802.11n 5 GHz to its successor 802.11ac in terms of performance and energy efficiency. We consider overall performance as well as the energy efficiency of 802.11n 2.4 GHz, 802.11n 5 GHz and 802.11ac protocols, all with 40MHz channels, to give a typical 802.11 office scenario. It is clear that 802.11ac can achieve slightly higher throughput compared to 802.11 for flows of large packets. However, the comparatively small benefits of 802.11ac may not justify the cost of buying and deploying new equipment for the upgrade.**

I. Introduction

Although 5 GHz wireless LAN (WLAN) networks have been around for many years, they are not as popular as 2.4GHz wireless networks due to 5 GHz equipment having always been costly to buy compared to 2.4 GHz equipment. This is one of the main reasons that made 2.4 GHz networks an easy choice for many users and subsequently made 2.4 GHz networks more popular. However, after many years of deploying 2.4 GHz networks and the increasing number of users of these networks, their capacity limitations are beginning to show, especially in densely populated areas. Interference between neighbouring 2.4 GHz networks can reduce their performance [1]. Additionally, the 2.4 GHz band is used by many other home/office applications such as cordless phones and microwaves, which is another source of interference and affects performance [2], [3]. On the other hand, 5 GHz networks have several advantages over 2.4 GHz networks. 5 GHz networks have non-overlapping channels, unlike 2.4GHz channels, and more channels that can be combined for higher speeds [4], [5]. However, there are also some disadvantages. At the higher frequencies, 5 GHz signals may suffer from greater attenuation (e.g. from walls and people), and so have a lower range compared to 2.4 GHz networks. This can be mitigated by spatial diversity in the equipment, e.g. use of multiple- input multiple-output (MIMO).

Several IEEE 802.11 protocols have been recertified to operate in 2.4 GHz and 5 GHz networks. Some of these protocols operate in both bands and others operate on a single band. The IEEE 802.11n protocols can operate in both bands, while its successor, the IEEE 802.11ac protocol operates only in the 5 GHz bands. One of the main objectives of these two protocols is to provide significantly higher Basic Service Set (BSS) throughput for WLAN users, which should improve the user experience [6].

Considerable effort and time has been spent by the researches in studying the performance of the WLANs. In addition to considering performance, for ICT protocols, applications and devices, we need to consider their energy usage to reduce operational costs and carbon footprint, and to enable extended battery life of mobile devices.

In this paper, based on our on-going work, we focus on assessing and improving performance and energy efficiency at the client side of WLANs. Specifically, we have assessed 802.11n at 2.4 GHz and 5 GHz, and the new 802.11ac. We examine both performance and energy usage. Both 802.11n and 802.11ac offer a high throughput solution for WLANs by using wider channels (40MHz at least) compared to the 20MHz channels that have been used for 2.4GHz in the past.

A. Motivation and Approach

In this paper, we conduct an empirical study to find out the possible benefits by upgrading from 2.4 GHz to 5 GHz networks. A growing number of mobile and computer devices have the capability to use both of these bands. The 5 GHz bands have more non-overlapping channels compared to the 2.4 GHz band, so there should be a clear advantage to migrating from older 802.11 variants to newer ones. However, our experiments show that improved performance may not be so obvious in all cases.

Additionally, improving the user experience by increasing the throughput of the BSS has motivated the development of the new 802.11ac protocol. However, issues such as power consumption and packet loss need to be addressed and examined for any new protocol to find out if it meets the QoS requirements of the WLAN's applications, as well as its impact on energy usage.

In keeping with the methodology of our previous work [7]–[9], 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 consumer usage, so that our results are more likely to reflect real operational scenarios, rather than lab-specific, custom configurations.

- Make it possible to apply our methodology easily to other similar scenarios.
- Allow our results to be validated / reproduced easily.

B. Contribution and structure of this paper

This paper presents an empirical evaluation of performance and energy usage of 802.11 WLANs on 2.4 GHz and 5 GHz bands. Our test-bed configurations, settings and experimental environments have been chosen to represent a typical indoor office scenario. We show that by using 5 GHz bands instead of 2.4 GHz the performance and energy efficiency could improve especially for WLANs which support applications that are sensitive to packet loss, and for those users which require more than 140 Mbit/s data rate applications. However, our testbed scenario also shows that there is no considerable benefit to upgrade from 802.11n 5GHz to 802.11ac.

We first present some related work in Section II covering WLANs channels (Section II-A) and WLANs performance and energy (Section II-B). We then present the methodology and metrics for our evaluation in Section III. In Section IV, we explain and discuss our result. We conclude with a summary in Section V.

II. Related Work and Background

A. WLAN channels and RF bandwidth

The Radio Frequency (RF) transmission characteristics of 802.11 radio are fully covered in the IEEE 802.11 standard, which includes the channelisation scheme as well as the spectrum radiation of the signal [1].

For the 2.4 GHz band, there are 11/13 channels for the Federal Communications Commission (FCC) / the European Telecommunications Standards Institute (ETSI) domains, respectively. A space of 5 MHz separates the channels but the frequency band used for each channel is 22 Mhz which mean 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 2.4 GHz band, which makes this band very crowded [10].

The 5 GHz bands consist of four sub-bands : UNII-1, UNII-2, UNII-2 Ext and UNII-3/ISM, with a total of 24 channels each of 20 MHz bandwidth available. The channels are non-overlapping, therefore each of them can serve be used without interference.

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 the consume the RF bandwidth of 8 of the 11/13 channels available.

IEEE 802.11ac also allows 80 MHz channels as well as 160 MHz channels (as a single block of 160 MHz or as 80 MHz + 80 MHz across the bands listed above), which are needed for the highest data rates. At the time of writing, equipment does exist that allows such capability, but it is not clear how widely these channels can be used in practise as they will interfere with neighbour cells that use similar RFC bandwidth. Also, UNII-2 and UNII-2 Ext have further restrictions of usage due to possible interference with radar.

For now, 20MHz is still widely used for 2.4GHz WLANs, and 20 MHz or 40 MHz channels appear to the be the most commonly used for 5GHz deployments.

B. WLANs performance and energy

Our own previous work in this area, established the use of the energy metric, E_A (see Section III-D) and the notion of the *energy envelope*, which gives the upper and lower bounds of the energy usage during the transmission of a flow [7]. Recently, we have investigated the energy usage of DCCP and UDP protocols over 802.11n WLAN at 5GHz [9]. The results show that DCCP can provide 10% to 40% greater energy efficiency than UDP. We have also investigated the possibility of application adaptation within the scope of this energy envelope [8] 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 [11]. Moreover, in [12] 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 2.4 GHz and 5 GHz bands.

Zeng *et al* [13] have examined 802.11ac and find that throughput and energy usage can be very variable, even though 802.11ac can achieve higher throughput overall. The authors also provide a comparison between 802.11n and 802.11ac protocols. However, this comparison is not a like-for-like comparison: the 802.11n experiments used 40 MHz channels while the 802.11ac experiments used 80 MHz channels.

Keranidis *et al* [14] have conducted an experimental comparison on energy efficiency for 802.11n WLAN. The study evaluated the energy consumption for the Network Interface Card (NIC) and not the total wireless node. Also, that study considered configuration optimisations to improve energy efficiency, while we consider default configurations that are likely to be employed by the majority of users.

Halpern *et al* [15] provide an empirical study of the power consumption of 802.11n WLAN. They conclude that using larger packets and higher date rate in transmission is more energy efficient than using a smaller packet size and lower data rate. Again, the authors draw this conclusion by measuring the energy consumption directly at the wireless NIC, whereas we consider the system as a whole.

Li *et al* [16] have examined the impact of the packet size to the energy consumption in heterogeneous wireless network environments. The study shows the importance of choosing the proper packet size in saving energy in a scenario composed of a body sensor network and WiFi network.

III. Experiment Design and Metrics

The aims of this paper are twofold:

- investigate the possibility of performance and energy efficiency improvement by upgrading to the 5 GHz band.

- investigate the possible benefits by upgrading to the latest 802.11ac protocol.

In our testbed experiments, we have used 'out-of-box' configurations, as we believe most users do not have the expertise or inclination to fine-tune their equipment. We used only standard, untuned WLAN radio-channel configurations and system parameters. Many WLAN NIC drivers permit various controls of the NIC hardware, but this is not easily accessible or comprehensible for adjustment and tuning by most users.

IEEE 802.11ac only operates in 5 GHz, but we compare this with IEEE 802.11n in both the 2.4GHz and 5GHz bands. IEEE 802.11n in the 2.4GHz band is very widely available for domestic and commercial use.

A. Overview

For each 802.11 protocol scenario, we generated UDP packet flows of various bit-rates and packet sizes, and measured power usage during the packet transmission. As shown in Fig. 1, the testbed consisted of a single client host, a host running a wireless access-point (AP) and experimental control units (only one shown in Fig. 1) for monitoring the WLAN environment, providing storage for measurement data, *ntp* [1] services and system configuration. The WLAN hosts were set up in a teaching lab in the University of St Andrews with a distance of $\sim$ 10 m between the antennae.

The *iperf v2.0.5* tool [2] was used as a packet generator and for conducting the performance measurement of the experiments. A wrapper script executed *iperf* and extracted throughput and loss for individual UDP flows using the *iperf server report*. Power consumption was measured at the client using a commercial power meter [3].

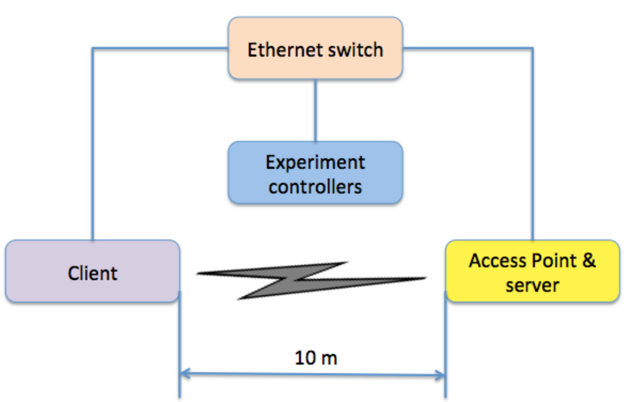

Fig. 1. Schematic of testbed showing physical connectivity. All experiments used 802.11n at 5/2.4GHz with 40MHz channels and 802.11ac at 5GHz with 40Mhz channel. The experiment controller uses Ethernet for control messages and shared file-system access to avoid control traffic interfering with test traffic on the WLAN. The separation between the antennas of the client and access point/server was $\sim 10 \pm 0.5$ m. Data packets generated by *iperf* were transferred across the WLAN.

[1]http://www.ntp.org/

[2]http://www.sourceforge/projects/iperf/

[3]http://www.i-sockets.com

B. Workloads: packet flow configuration

We have tested 802.11ac and 802.11n using 2.4GHz and 5GHz bands, all with 40 MHz channels. As stated earlier, although the new 802.11ac protocol can use 80MHz and 160 MHz channels, this would result in interference between neighbouring cells: 80MHz is the entire width of the UNII-1 and UNII-3 sub-bands. Therefore, using non-overlapping 40 MHz channels is the more common case currently, especially in deployments where there are neighbouring WLAN cells.

Additionally, we configured the UDP flows across a range of bit rates, with small and large packets, as shown in Table I. We chose an upper limit of 350Mbps data rate for a single flow, to cover a wide range of applications, and also based on our preliminary experimentation to baseline the testbed and discover its maximum throughput.

TABLE I
GENERIC UDP WORKLOAD.

Packet size in offered load	64; 1460 bytes
Offered load's bit rate	0.031; 0.049; 0.065; 0.25; 0.5; 0.639; 1; 2; 3; 4; 5; 6; 7; 8; 9; 10; 12; 14; 12; 14; 16; 18; 20; 22; 24; 26; 28; 30; 35; 40; 45; 50; 55; 60; 65; 70; 75; 80; 85; 90; 100; 125; 150; 175; 200; 225; 250; 275; 300; 325; 350 Mbps

Each packet size was combined with each bit-rate (120 combinations); 10 flows measured with each combination (1200 flows for each); each flow had a duration of 2 minutes. The experiments runs over three different WLANs scenarios giving a total of $\sim$120 hours of measurements.

Table I shows the data rates and packet sizes used in the experiments. The 64 byte packet is the smallest size for which we have observed that *iperf* is able to generate server reports, and very few applications will have packets smaller than this. The 1460 byte packet is chosen as that is a common MTU size used for Internet-wide communication (a known legacy of Ethernet), and we wished to avoid the effects of IP-level fragmentation.

C. Equipment

Our testbed was equipped with identical machines. The hardware specifications of the client and the server were: a Scan home-office PC (*V10* [4]) with an Intel ® Pentium ® Core i5 4440 3.1 GHz Quad Core CPU, 4 GB RAM, 1 TB HD. All machines used the same wireless LAN NIC hardware [5] based on the new QCA9880 Version 2 Atheros [6] chipset with 3×3 MIMO technology . Our power meter is an i-Sockets[7] instrumented, domestic, multi-way power extension.

Ubuntu 14.04 was used on each machine, a minimal server distribution, with the kernel 3.16.0-wl-ath+, and the latest ath10k driver [8]. For running the AP we have used the *hostapd*

[4]http://3xs.scan.co.uk/configurator/ready-to-ship-budget-value-amd-home-office-pc-v10a

[5]http://www.compex.com.sg/Datasheets/WLE900VX_Dsv1.0.1-140711-I.pdf

[6]http://www.atheros.com/

[7]http://www.i-sockets.com/

[8]https://github.com/kvalo/ath10k

[9] package version v2.3-devel. All nodes in the testbed ran in an isolated network. The system clocks of all the nodes where synchronised (using NTP [17]) before each individual experimental run. The linux utility *iwconfig*[10] was used to record the link quality and the signal level on the RF channel.

D. Performance Metrics

We used some directly observed measurements and also some derived metrics in order to evaluate performance and energy usage. The following metrics are consider in our study:

- *Power consumption:* We measured power consumption on the client side at 30 second intervals which is then used to find the energy usage of the client. The Effective Application-specific energy-usage E_A has been used [7] as defined in the following:

$$E_A = \frac{\text{mean power used during transmission of flow}}{\text{mean throughput of flow}}$$

with smaller values of E_A being better. E_A has units Joules/Mega-bit (J/Mb):

$$\frac{\text{power in Watts}}{\text{throughput in Mbps}} = \frac{J/s}{Mb/s} = J/Mb$$

and the lower the value of E_A, the better in terms of energy usage. To generate values for E_A, for each individual flow, we use the following measurements:

$$E_A = \frac{P_A - P_I}{T_A} \tag{1}$$

P_A Mean power consumption measured during the transmission of flow [Watts].

P_I Mean power consumption measured for an idling node [Watts].

T_A Mean throughput measured (using *iperf*) during flow transmission [Mbps].

- *Performance:* Throughput and loss, as recorded by *iperf*'s server reports, on the client for each flow.
- *link Quality and signal strength:* The mean value of the link quality and the signal strength for the WLAN RF channel during the experiments, as reported by the WLAN NIC driver.

Table II summarises the observables measured during the experiments and the metrics derived from the observations.

TABLE II
OBSERVABLES AND DERIVED METRICS FOR THE EXPERIMENTS

Observable / metric	Units	Comment
Power	Watts	power meter at the client
Energy E_A efficiency	J/Mb	As defined in [7]
Performance	throughput - Mbps loss - %	*iperf* server reports
Link Quality	%	from *iwconfig*
Signal Strength	dBm	from *iwconfig*

IV. Results and Discussion

In this section we provides the analysis and discussion of the results obtained from our experiments. Firstly, in subsection IV-A, we answer the question, “Is it worth to move to the 5 GHz band?”. Secondly, in subsection IV-B, we address another important question, “Is it worth upgrading to IEEE 802.11ac?”. In all the Figures int this section, we plot the mean point of the runs, and plot standard error bars (95% confidence), but in the majority of the experiments, only very small error bars were calculated, so they may not always be easily visible even though they have been plotted.

[9]http://hostap.epitest.fi/hostapd/

[10]http://www.linuxcommand.org/man_pages/iwconfig8.html

A. 802.11n 2.4 GHz vs 802.11n 5 GHz

We consider the throughput and packet loss of IEEE 802.11n in both 2.4 GHz and 5 GHz bands. Firstly, we consider flow-level performance in terms of throughput and loss. The throughput results are given in Figures 2a and 2b and the loss results are given in Figures 3a and 3b. The key finding is: *IEEE 802.11n performs better at 5 GHz band than at 2.4 GHz band for both small and large packets flows, with the same 40MHz channel width used in each band.* This is discussed in subsection IV-A1. Energy usage is discussed in subsection IV-A2. Figures 4a and 4b provide upper and lower bound for what energy efficiencies might be possible for 802.11n at both bands. The key finding is: *Although it is hard to determine which network band is more energy efficient for low rate traffic loads; it is clear that for high traffic load, the 5 GHz band is more energy efficient for both small and large packets sizes.*

1) Performance: Performance is one of the key issues that affect the Quality of Experience (QoE) of the WLAN users. Figures 2a and 2b shows the throughput for experiments and Figures 3a and 3b shows the loss. It is clear that for the large packets, 802.11n has better throughput at 5 GHz bands than that at 2.4 GHz. The maximum throughput that 802.11n can achieve at 2.4 GHz is $\sim$ 140Mbit/s, while at 5 GHz 802.11n can achieve $\sim$ 285 Mbit/s. Also for small packets flows, 802.11n performs better in terms of throughput at 5 GHz bands under heavy traffic load scenarios. The maximum throughput for 802.11n at 2.4 GHz is $\sim$ 33.7Mbit/s while at 5 GHz 802.11n can achieve 35.4 Mbit/s at most. So, for throughput 802.11n performs better at 5 GHz than at 2.4 GHz.

From the figures 2a and 2b, it is clear that 802.11n performs better at 5 GHz in terms of throughput for large and small packets flows compared to 2.4 GHz. At 5 GHz, the throughput of 802.11n is 100% and 5% better for large and small packets flows, respectively, compared to throughput of 802.11n at 2.4 GHz.

For loss, Figures 3a and 3b illustrate a comparison between 802.11n 2.4 GHz and 802.11n 5 GHz, respectively. It is clear from Figure 3b that 802.11n 5 GHz has virtually observed loss for small and large packets flows. However, 802.11n at 2.4 GHz reports no loss for large packets flows, but $\sim$3%

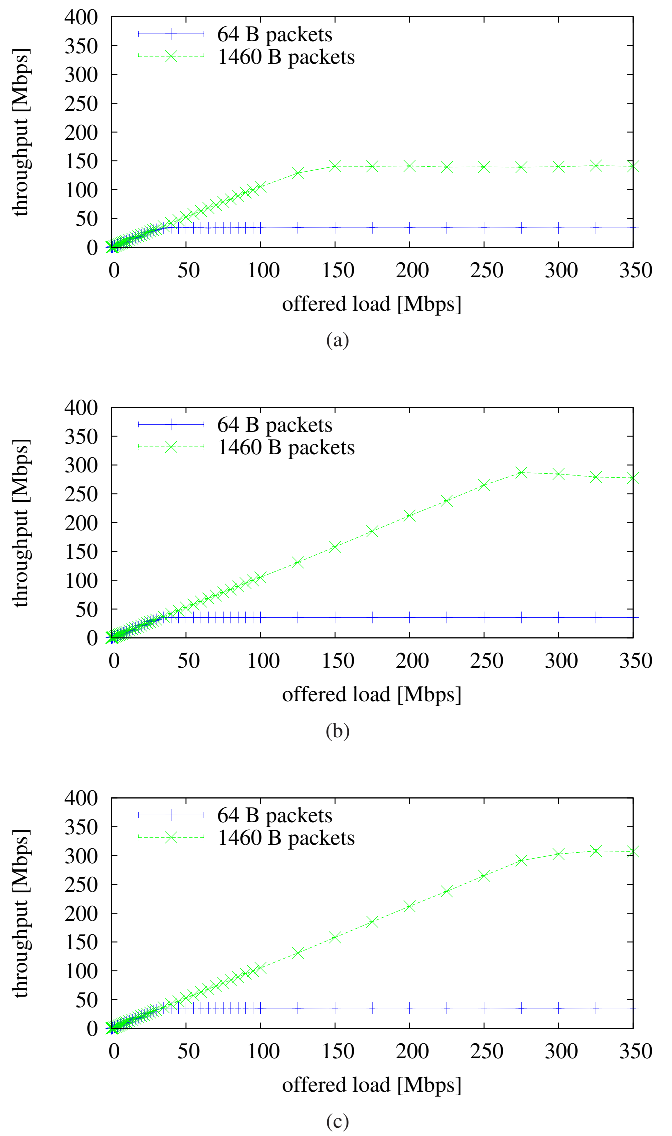

Fig. 2. Throughput of 802.11n 2.4 GHz (a), 802.11n 5GHz (b) and 802.11ac (c)

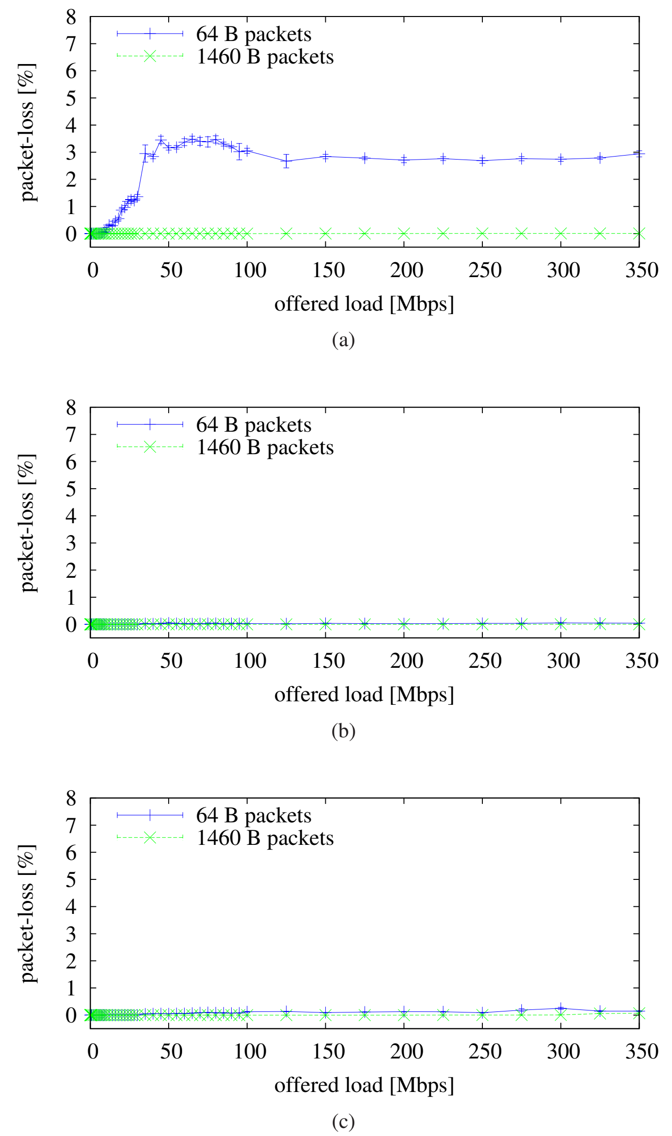

Fig. 3. Packet loss of 802.11n 2.4 Ghz (a), 802.11n 5GHz (b) and 802.11ac (c)

loss for small packets flows after traffic load exceeds ∼35 Mbit/s. Although the measured loss is low, the packet loss could impact real-time applications: Brosh et al [18] have previously reported that for real-time VoIP, the loss rate should be less than 2% to achieve an acceptable quality for the end user.

In term of performance, it is clear that it is worth moving to the 5 GHz band, as it provides 100% throughput improvement and no loss compared to 2.4 GHz. However, for non-heavy users of WLANs (i.e where usage does not exceed ∼140 Mbit/s) and where the ∼3% loss is acceptable, then there is little benefit upgrading to 5 GHz, especially if that would require additional capital costs for access point and terminal/user devices, as well as the cost of deploying the new access points.

It should be noted, however, that we have performed experiments with a 40MHz channel at 2.4GHz. This is widely supported by equipment, but may not be feasible for deployment: 40MHz uses the RF capacity of 8 of 11 or 13 5 MHz channels available. This may not be suitable for densely populated domestic or office environments. In such circumstances, considerations should be made for migration to 5 GHz, but then there is still the question of whether to consider 802.11n or 802.11ac, which we address later.

2) Energy Efficiency: Figures 4a and 4b show the energy usage of 802.11n 2.4 GHz and 802.11n 5 GHz using different packet size flows and under different traffic loads, which allow us to define an *energy envelope* for 802.11n for both bands. As reported in our previous studies [7], [8], it is clearly that packet size and the data rates have a dramatic affect on the energy usage of the WLANs. For both packet sizes we see that

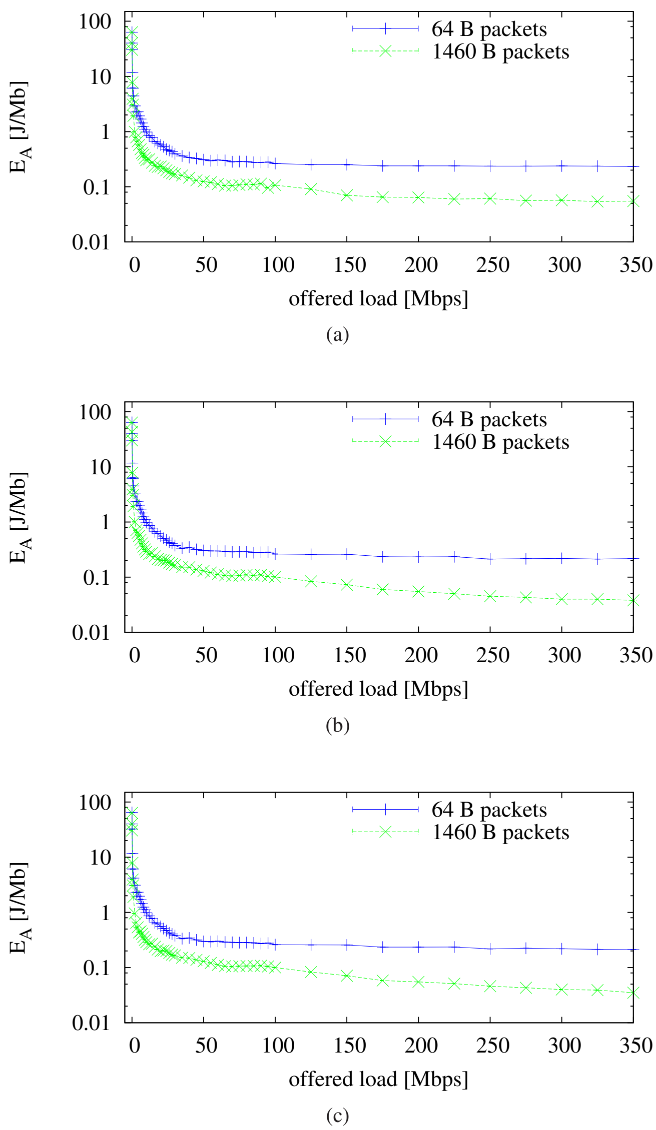

Fig. 4. E_A of 802.11n 2.4 Ghz (a), 802.11n 5GHz (b) and 802.11ac (c)

802.11n has same general trend for energy efficiency in both bands. However, above ∼140 Mbit/s load, 802.11n 5 GHz is able to achieve greater throughput which makes it upto ∼10% and ∼30% more energy efficient than 802.11n 2.4 GHz for small packet and large packet flows, respectively. Therefore, there may be little advantage in terms of energy efficiency between 2.4 GHz and 5 GHz from the client side, as most of applications have data rates well below ∼140 Mbit/s.

B. 802.11n vs 802.11ac

The main aim of developing the IEEE 802.11ac protocol was to provide significantly higher throughput for WLAN users. This subsection:

- provides performance and energy efficiency measurements for the new IEEE 802.11ac protocols

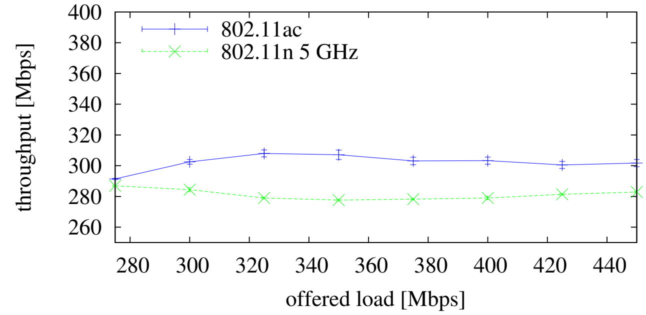

Fig. 5. Throughput of 802.11ac and 802.11n for large packet flows under high data rate.

- compares IEEE 802.11ac with its predecessor, IEEE 802.11n.

In the previous subsection we considered throughput, packet loss and energy efficiency in our analysis. The throughput and loss measurements of 802.11ac are given in Figures 2c and 3c. *The key finding is: 802.11ac can achieve higher throughput with almost no packet loss compared to 802.11n.* However, by comparing the 802.11ac performance results with the 802.11n 5GHz performance results in Figures 2b and 3b, subsection IV-B1 provides a fuller discussion on this. For energy usage and efficiency, subsection IV-B2 shows the energy envelopes of 802.11ac and the energy saving possibility. This is followed by an energy efficiency comparison between the 802.11ac and 802.11n at 5 GHz.

1) Performance: Figure 2c shows the throughput of 802.11ac protocol 40 MHz channels. The maximum throughput that 802.11ac can achieve for flows of small packets (64 byte packet size) is ∼ 35 Mbit/s. For the flows of large packets (1460 byte packet size), 802.11ac can achieve up to ∼ 310 Mbit/s. On the other hand, Figure 3c shows that 802.11ac has almost no packet loss for both small and large packet flows. However, to answer the question, "Is it worth upgrading to IEEE 802.11ac?", taking into account the extra cost of buying a new equipment, we compare performance between 802.11ac and 802.11n at 5 GHz. Figures 3c and 3b show that there is no difference in throughput between 802.11ac and 802.11n 5 GHz for flows of small packet size. Both achieve similar throughput up to ∼ 35 Mbit/s. *Therefore, if the use of the WLANs is mainly to support applications that use small packet sizes, such as VoIP, there is no benefit in upgrading to 802.11ac.*

For flows of large packets, 802.11ac has better throughput only at very high data rates, greater than ∼285 Mbit/s. To investigate this, Figure 5 compares the throughput between 802.11ac and 802.11n 5GHz at high data rate. The Figure shows that in the best case, 802.11ac achieves up to ∼ 8% btter throughput than 802.11n. As a result 802.11ac, can perform better than 802.11n 5 GHz only for flows of large packet at very high data rates (∼ 285 Mbit/s). *So, if 802.11n at 5GHz is already available, there may be little benfit from migrating to 802.11ac.* Again, this is particularly so if upgrading to

802.11ac requires capital expenditure on access points and terminal/user devices, and associated deployment costs.

2) Energy Efficiency: Figure 4c shows the energy efficiency envelope of 802.11ac using a 40 MHz channel. Similar to other variants of the 802.11 family reported in our previous works [7], [8], the packet size and application data rate play a key role in energy efficiency. However, by comparing with 802.11n 5 GHz in Figure 4b, *it is clear there is no benefit in upgrading to 802.11ac protocol in terms of energy efficiency*.

C. Moving to IEE 802.11ac

From our measurements, we see that, at this point in time, the potential of the higher data rates of 802.11ac is going to require the availability of the very high throughput (VHT) channels that are currently defined, but not yet available commercially. The key technology that will make a difference here is:

- *MU-MIMO.* The use of beam-forming technologies will allow multi- user MIMO (MU-MIMO) systems in access points to permit multiple users to transmit and receive simultaneously. While this may not improve the overall benefit to individual users dramatically compared to our measurements here (we have used a single client system), it will improve the throughput of the WLAN cell overall.
- *Additional spatial streams.* 802.11ac allows the use of up to 8 spatial streams, with upto 433Mbps per stream under ideal conditions. This requires additional antenna. Additional antenna would also be required to allow MU-MIMO functionality.

Note that both of the items above would require new hardware, and so a capital cost. The benefits listed above would be visible to some extent through access point only upgrades, as some more modern terminal/user devices may be upgradeable using firmware updates. However, such upgrades would depend on vendors providing suitable support for existing products, rather than expecting users to make new purchases.

If an existing 2.4 GHz deployment is to be upgraded to 5 GHz, then it is worth looking at equipment that is firmware upgradeable, else there may be additional costs for further hardware upgrades and deployment costs when migrating to 802.11ac.

Overall, for those sites with an existing 5GHz 802.11n capability, it is worth waiting for the full 802.11ac capability to mature before upgrading.

D. Limitations of our experiments

Our testbed presents a “best case” scenario, with a single client system, no contention within the cell from other users, and no neighbouring WLAN cells. While this is a somewhat sanitised environment, the value of our experiments is to provide an upper limit of what is achievable in terms of performance. Real deployments will have additional complications, e.g. building construction, additional, neighbouring WLAN deployments, highly heterogeneous equipment etc.

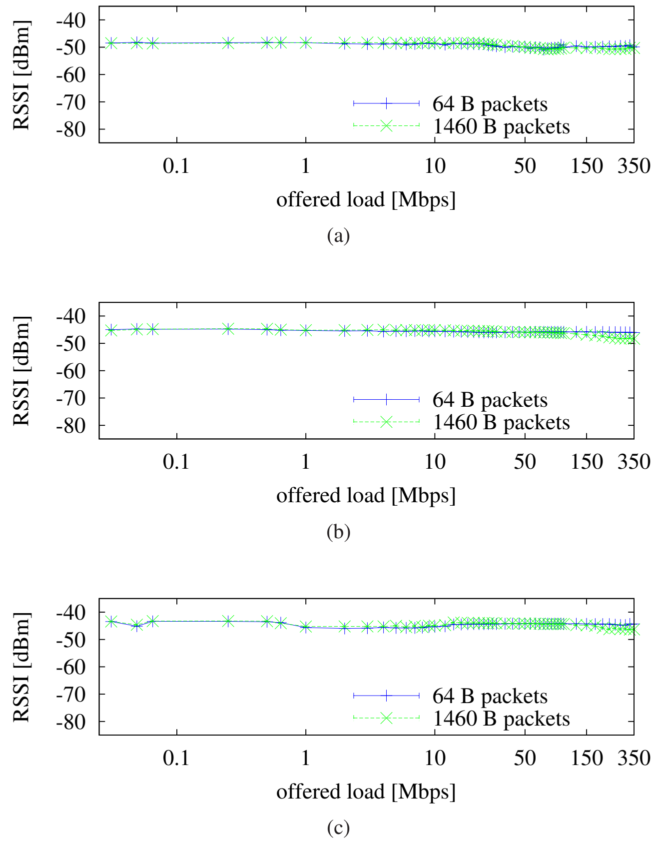

Fig. 6. Signal strength of 802.11n 2.4 GHz (a), 802.11n 5GHz (b) and 802.11ac (c)

Our experience shows that energy efficiency measurements, especially will vary greatly depending on both hardware and software components and their configuration. However, our energy measurements provide a useful indication as to the trends and profiles that can be expected when considering systems and technology in relation to each other.

Also, our experiments consider network-level measurements, and the impact on applications and users, especially on quality of experience (QoE) for users, would required further investigation with separate experiments.

E. Signal Strength and Link Quality

This subsection shows the signal strength and the link quality for our experiments. As shown in Figure 6 the signal strength for the three scenarios is $\sim -48dBm$ for 802.11n 2.4 GHz and $\sim -40dBm$ for 802.11n 5 GHz and 802.11ac (larger value is better and $-35dBm$ presents $\%100$ link quality. This signal strength can provides very good indications of the link quality during the experiments. According the above figures and the iwconfig reports, during the experiments the link quality were above $\%88$ for 802.11n 2.4 GHz and $\%92$ for 802.11n 5 GHz and 802.11ac. So, in our experiments, the WLAN RF transmission was never cause any problem to the results.

V. Conclusion

We have conducted an empirical evaluation of the performance and energy usage of WLANs using 2.4 GHz and 5 GHz with two latest variants of the IEE 802.11 family, 802.11n and 802.11ac, with a 40MHz channel. We have assessed the energy efficiency and the network level flow performance by considering throughput and packet loss using UDP.

From the our experiments, we find that it is worth upgrade from the 2.4 GHz bands to the 5 GHz bands which have more non-overlapping channels. In particular, this recommendation is highly advised for packet loss sensitive real time applications, or if the use of the WLAN is likely exceed $\sim$140 Mbit/s.

We also provide an empirical study and performance evaluation for the latest 802.11ac protocol. By comparing the results with 802.11n at 5 GHz, we find the 802.11ac can achieve 8% more throughput for flows of large packets under our testbed conditions. However, it is unlikely that this modest increase in throughput will contribute to noticeable improvements in the QoE for the end users.

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