Comparison of Theoretical and Practical Performances with 802.11n and 802.11ac Wireless Networking

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***Abstract*— This work explores the theoretical and practical performances of the two most recent IEEE standards, 802.11n and 802.11ac. Experiments were conducted to measure data rates to characterize performance effects of distance and interference between different channels. We conclude that the majority of test cases show 802.11ac achieved higher data rates than its predecessor, as expected. However, performance of 802.11ac decreased at a significantly faster rate with increasing distance from client to AP when compared to the decreasing performance experienced with 802.11n. Furthermore, 802.11n consistently achieved real data rates much closer to the theoretical data rate than did 802.11ac.**

Keywords*— *Wireless Networks, Network Monitoring, IEEE Standards, IEEE 802.11

I. Introduction

Transmission standards often state a theoretical data rate that is rarely achieved in practice.

The contemporary wireless standards, IEEE *802.11n* and *802.11ac*, promised data rates of up to 600Mbs and 6933Mbs respectively. This paper explores these two IEEE standards to discover their practical performance in an office-like environment. The theoretical capabilities and features of *802.11n* and *802.11ac* are also reviewed, and the data rates are tested using the lowest, mid and highest channel to compare the two standards' theoretical and practical performances.

Chen and Suzuki [1], Bejarano and Knightly [2], and Dianu et al. [3] have explored 802.11 amendment performances individually. The typical throughput of IEEE 802.11a/g is 25Mb/s with a physical-layer (PHY) data rate of 54Mb/s. The IEEE 802.11n standard was the first IEEE *802.11* amendment to introduce Multiple-Input-Multiple-Output (MIMO) by implementing spatial diversity. The *802.11n* standard aimed to achieve at least four times that of 802.11a/g with a capability of at least 100 Mb/s throughputs at the MAC layer.

A. Protocols and Features 802.11n

Innovative features which have been introduced with the new standards have included; Reduced Interframe Space (RIFS), Frame Aggregation, Transmit Beamforming (TxBF), Space Time Block Codes (STBC), Low Density Parity Check (LDPC), Modulation and Coding Schemes (MCS) index and Spatial Streams.

Reduced Interframe Space (RIFS) was a new feature to improve efficiency and performance. Kassner [4] explains that RIFS reduces the amount of wasted time required between Orthogonal frequency-division multiplexing (OFDM) transmissions. This feature is only available in deployments, where the R.F. environment is free from legacy devices.

Frame aggregation was implemented to the MAC layer as the primary method for increasing efficiency and providing a MAC layer throughput of at least 100Mb/s. Frame aggregation is the method of increasing the data portion's length within the frane in order to increase overall efficiency.

Transmit Beamforming (TxBF) is another new feature popularly employed in *802.11n*. TxBF can provide a better signal, greater Signal to Noise Ratio (SNR) and a higher throughput by concentrating the Access Point (AP) signal to a client's location.

STBC are orthogonal codes which can achieve full transmission diversity depending on the number of specified antennas [5]. STBC is a PHY layer implementation which improves link performance over MIMO with basic spatial-division multiplexing (SDM) by achieving the maximum diversity order for the number of MIMO streams. SDM transmits independent data streams via multiple transmit antennas to increase throughput. Whereas, STBC improves performance by utilising spatial transmit diversity at a given bit rate [6].

Low-Density Parity-Check (LDPC) is a forward error correcting code and an optional PHY specification which contributes to better performance. According to Gast[7], if LDPC is enabled, it can provide an additional antenna gain of 1-2dB and can also increase data rates.

The MCS index was created with the *802.11n* amendment to determine theoretical data rates of 802.11n devices. The standard introduced high-throughput orthogonal frequency division multiplexing (HT-OFDM) because of the use of additional parameters such as spatial streams, channel size, coding method, modulation technique, and guard interval. Prior to *802.11n*, standards which used OFDM had defined data rates between 6-54Mb/s depending on the type of modulation and coding techniques used [8].

MIMO implementation introduced the term "spatial streams". The amendment is capable of achieving up to 4x4 spatial streams which provides a theoretical throughput of 600Mb/s. As the infrastructure is limited to 2x2 spatial streams at the client side, theoretically, it should be able to achieve throughput of 300Mb/s in relation to its MCS index.

B. *Modulation Types*

There are two modulation types using 20 MHz and 40 MHz channels. Unlike previous 802.11 amendments, where only an available channel width of 20MHz is attainable, the *.n* amendment introduced a larger channel width of 40MHz. Two 20MHz channels are combined in order to provide the 40MHz channel width, potentially doubling the data rate. Increasing the bandwidth has a relatively low cost and as a result, has become an important feature of the 802.11n standard. Most *802.11n* devices now support 40MHz bandwidth channels, but it is optional due to interoperability of *802.11a/b/g* legacy devices which use 20MHz channels.

Table 1: Capabilities of *802.11n* hardware and *802.11n* IEEE specification (amended from Cisco 2015)

	802.11n	802.11n IEEE Specification
Frequency Band:	Dual Band 2.4 & 5GHz	Dual Band 2.4 & 5GHz
No. of Spatial Streams:	3x3	4x4
Channel Width:	20 / 40 MHz	20 / 40 MHz
Max Modulation Scheme:	64-QAM	64-QAM
Max PHY Rate:	450 Mb/s	600 Mb/s
Max MAC Throughput:	293 Mb/s	390 Mb/s
Beamforming Support:	Vendor Specific	Vendor Specific
MIMO Support:	Yes(SU-MIMO)	Yes (SU-MIMO)

C. *Technical Specification of 802.11ac*

The majority of the *802.11ac* amendments propose significant efficiency enhancements to those introduced in 802.11n. An improvement to the MAC layer supports new physical layer features which provide considerably higher throughput and data rates. The increase in frame sizes within the amendment has contributed to increasing data rates and throughput.

Although RIFS reduces the amount of time between frame transmissions in *802.11n*, it is more efficient to aggregate frames instead. RIFS transmits two frames separately resulting in two full headers and Physical Layer Convergence Protocol (PLCP) frames being transmitted. In *802.11ac*, a single Aggregated MAC Protocol Data Unit (A-MPDU) transmits two frames at once, increasing efficiency.

Frame Size and Aggregation Frame size has had several improvements in *802.11ac*. Frame sizes have increased and each frame is now transmitted individually as an A-MPDU, even if it only contains a single frame. It may seem inefficient to transmit A-MPDU which only has a single frame. However, rather than sending a large number of bytes in a PLCP header which is then transmitted at the lowest possible data rate, 802.11ac moves the length indication to the MPDU which is then transmitted as part of the high data rate payload [7]. Ultimately, the most significant enhancement to frame size is Physical Layer Service Data Unit (PSDU) PLCP payload size which was increased from 0.06 MB to 4.45 MB.

The available spectrum is used by *802.11ac* more efficiently by determining channel bandwidth on a frame-by-frame basis. Primary and secondary channels are introduced which help divide airtime between channels so that the same frequency space can be used by multiple networks. Each channel bandwidth, such as 20MHz, 40MHz, 80MHz, and 160MHz has one primary channel which transmits data at its native bandwidth. The evolution of wider channels in *802.11ac* built upon *802.11n* which combines two channels together for transmission.

A single method for beamforming was introduced by *802.11ac*. Null Data Packet (NDP) sounding reduces complexity by preventing the proprietary issues with *802.11n*. Another major change to beamforming is multi-user MIMO (MU-MIMO). MU-MIMO was introduced in the second wave of hardware and is a technique which enables simultaneous transmission to multiple clients.

The data rate of *802.11ac* is improved by a better modulation scheme. Previously, 64-QAM restricted potential data rates. Building on its predecessor, *802.11ac* uses a better modulation type, with data rates four times higher that of 64-QAM.

Table 2: Comparison of Wave 1 and 2 of *802.11ac* hardware and the IEEE *802.11ac* Specification (amended from Cisco 2015)

	Wave 1	Wave 2	802.11ac IEEE Specification
Frequency Band:	5GHz	5GHz	5GHz
No. of Spatial Streams:	3x3	3x4	8x8
Channel Width:	20 / 40 / 80 MHz	20 / 40 / 80 / 80-80 / 160 MHz	20 / 40 / 80 / 80-80 / 160 MHz
Max Modulation Scheme:	256-QAM	256-QAM	256-QAM / 1024-QAM (Quantenna 2015)
Max PHY Rate:	1.3 Gb/s	2.5 – 3.47 Gb/s (Cisco 2015)	6.9 Gb/s
Max MAC Throughput:	845 Mb/s	1.52 – 2.26 Gb/s (Cisco 2015)	4.49 Gb/s
Beamforming Support:	Vendor Specific	Yes	Yes
SU/MU MIMO Support:	SU-MIMO	MU-MIMO	MU-MIMO

II. EXPERIMENTAL DESIGN

Dianu et al. [3] have measured *802.11ac* and arrived at a similar expectation of practical performance and an indication of an array of variables to use for the experiment. Chen and Suzuki [1] have carried out experiments using MIMO in *802.11n* over different channels and MCS numbers, similarly. Our experiment extended this work with additional variables that had not previously been considered.

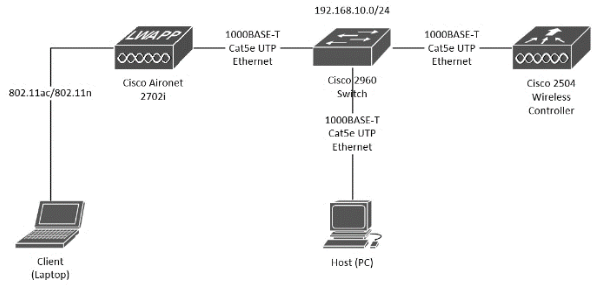

Fig 1: Physical network diagram of the proposed experimental infrastructure.

In summary, the tests record practical data rates of both standards at distances starting at zero metres up to twenty five metres in five metre increments. Tests for the lowest, mid and highest channel number were recorded and then formed into average data rate.

The frequency band used for the experiment was 5GHz. Other variables under consideration are Received Signal Strength Indicator (RSSI), dBm, datagram size, and transport protocol. RSSI will provide an indication of signal strength at the client. Similarly, dBm is power received at the client from the transmitting antennas at the AP. The exact frequency of communication is recorded. Datagram size was recorded in bytes as the size of each datagram being generated as traffic. The transport protocol employs User Datagram protocol (UDP) for which WireShark [9] will be used to inspect network data. Analysis rows such as errors/packet loss, highest, lowest and average data rate will be recorded for evaluation purposes.

WirelessMon will be used to gather and record the data for each test case. The result is a radar representing signal strength from which graphs can be exported that contain data rates. There are several parameters within the graph which can be selected such as RSSI, dBm, received data rate, sent data rate, and total data rate, all of which are of concern. Also present in graphs are fields for channel usage, wireless devices within the environment, number of antennas and transmit power. The WirelessMon software was the primary tool for gathering the data and AdapterWatch [10] will be used in parallel for verification.

A. *Experimental set up*

Changes, made to infrastructure configuration from the original design, are now described.

It was originally planned to record data rates at distances from five to thirty metres in five metre increments. However, the laboratory used allowed distances of up to fifteen meters only. This resulted in potentially measuring longer distances outside in open space. This is not a true representation of typical office environments. Instead, data rates were recorded up to twenty five metres by moving the client to the adjacent room, which better represents a typical office environment at distances from twenty to twenty five metres. Fig 2 shows the floor plan of the two rooms and the physical infrastructure.

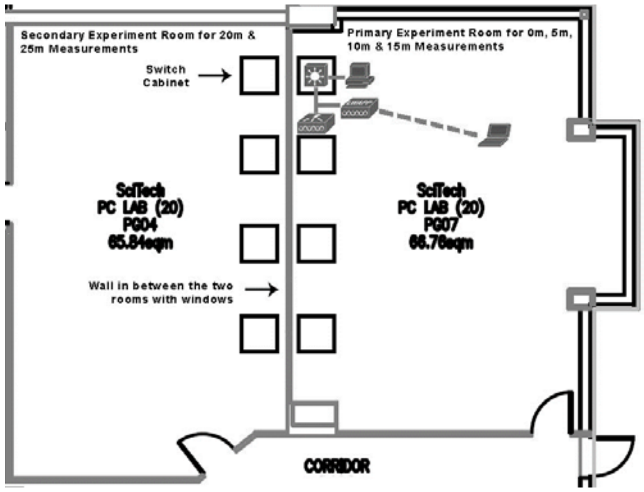

Fig 2: Floor plan of the laboratory infrastructure

III. Findings

Three hundred and twenty results sets of the two standards practical performance were measured. Space only permits a summary of the results to be described.

A. *Average 802.11n Data Rate Over Each Channel*

Distances from twenty to twenty five metres where data rates were measured through a wall, data rate performance significantly drops over the mid and low channels. However, on the highest channel (136) data rates increased through the wall showing better performance at distances and through obstacles than its lower channels. Interestingly, the highest average data rate recorded (164Mb/s) was at ten meters on channel 36 which had the highest number of APs (21) operating over the same channel, representing the highest potential interference.

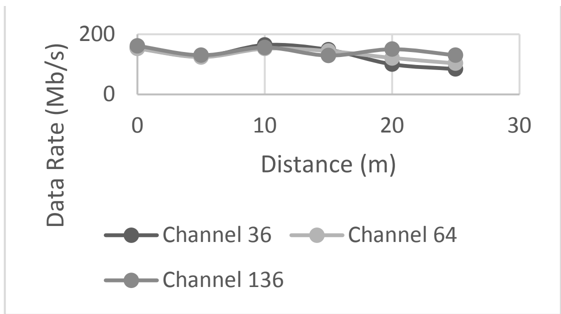

Fig 1: *802.11n* average data rate over the lowest (Ch 36), mid (Ch 64), and highest (Ch 136) channels

B. *Highest 802.11n Data Rate Over Each Channel*

The average data rates recorded over the lowest, mid and highest channel in *802.11ac* can be seen in Fig 4. The highest average data rate recorded was 282Mb/s over the highest. Dissimilar from *802.11n* average data rate, the mid channel over *802.11ac* which had interference performed better at longer distances than the highest channel which had no interference. Average data rates recorded over channel 64 appear rather inconsistent compared to channels 36 and 112 which may be due to interfering APs transmitting at the same time.

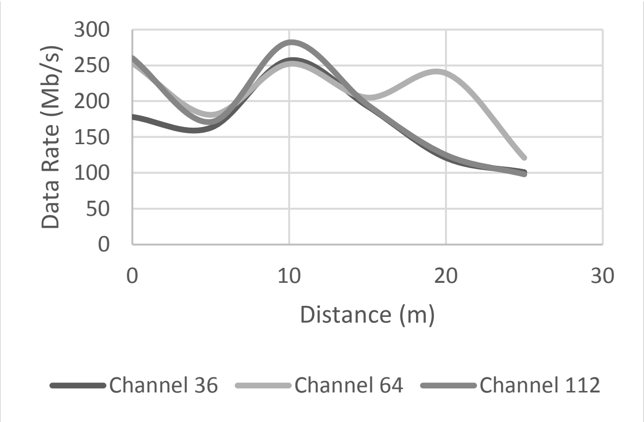

Fig 2: *802.11ac* average data rate over the lowest (Ch 36), mid (Ch 64), and highest (Ch 112) channels

C: Comparing 802.11n and 802.11ac Average Data Rates Over the Lowest Channel

Fig 5 represents the comparison between *802.11n* and *802.11ac* average data rate over the mid channel. *802.11n* has an extremely similar trend to its lower channel average which can be seen in Fig 7. However, 802.11ac's average varies considerably with spikes of data rates increasing and decreasing at each distance. This could be down to interfering APs transmitting simultaneously over the mid channel as 16 APs were present in the wireless environment. 802.11ac recorded the highest data rate at 253Mb/s whereas 802.11n recorded 152Mb/s at zero and ten meters. Both highest data rates recorded were similar to the lower channel results in Fig 7. A continuous pattern which emerges is the decrease in data rate with 802.11ac over longer distances where 802.11n was only 18Mb/s less at the same distance.

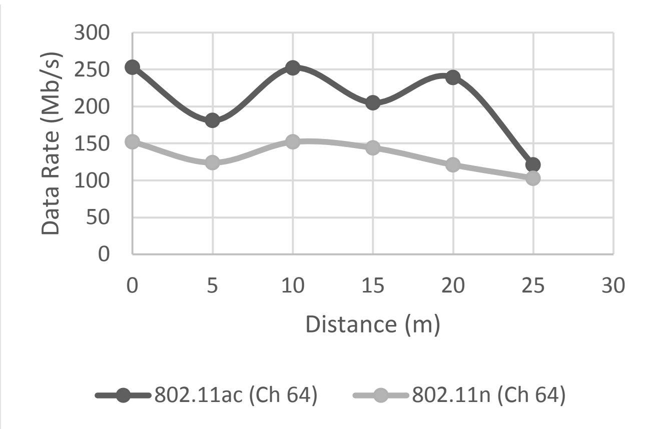

Fig 3: A comparison of the average data rates recorded at the mid channel over both *802.11n* and *802.11ac*

C. Comparing 802.11n and 802.11ac Average Data Rates Over the Highest Channel

A graph containing the comparison between 802.11n and 802.11ac's average data rate over the highest channel can be seen in Fig 6. 802.11n's performance doesn't show the same consistency shown in Fig 5. Instead, the data rate appears to fluctuate regardless of the distance or obstacles within the environment and shows the highest data rates recorded at further distances shown in in Fig 5. 802.11ac maintains inconsistency in performance beginning with a spike until data rates eventually decrease below 802.11n's data rates. 802.11ac managed to achieve 282Mb/s at ten meters whilst 802.11n achieved 161Mb/s at zero meters. Non-interference over the highest channel may be the reason why 802.11n managed to maintain data rates at the furthest distance and also why 802.11ac achieved its highest average.

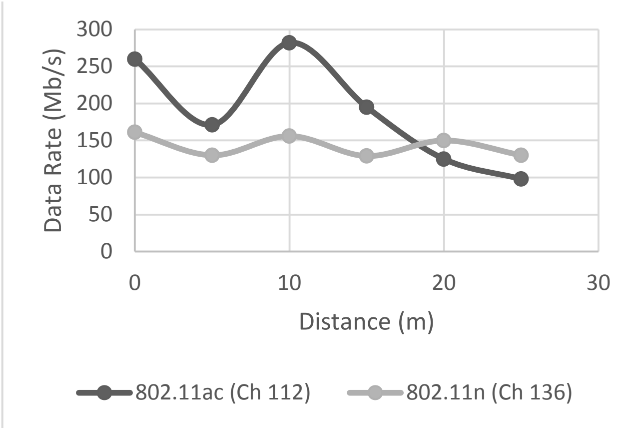

Fig 4: A comparison of the average data rates recorded at the highest channel over both 802.11n and 802.11ac (Personal Collection)

D. Comparing Combined 802.11n and 802.11ac Average Data Rates Over All Channels

With the average data rate of the lowest, mid, and highest channels over 802.11n and 802.11ac compared and analysed, Fig 7 presents a combined average data rate over all three of the channels. *IEEE 802.11n* retained its performance with the highest data rates recorded at zero and ten metres which then steadily decreased as the distance increased. *802.11ac* maintained its highest data rate at ten metres but then rapidly decreased to an average extremely close to 802.11n. The highest total average data rate was 264Mb/s for 802.11ac and 157Mb/s for 802.11n. The lowest however were nearly identical with 802.11ac recorded at 107Mb/s and 802.11n at 106Mb/s. This leads onto the conclusion that 802.11ac appears rather volatile to its surroundings with a huge impact on performance over further distances compared to 802.11n.

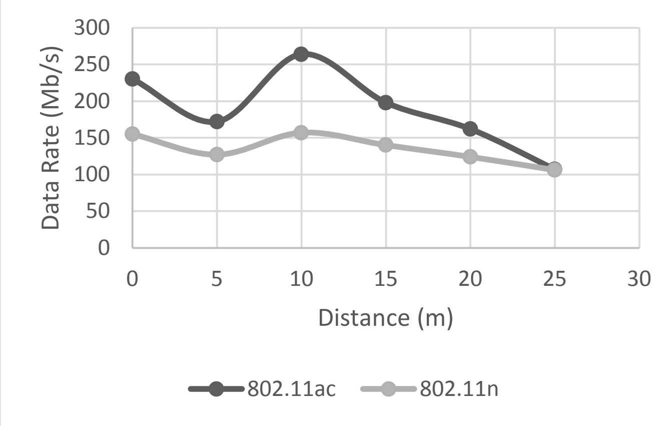

Fig 5: A comparison of the average data rates recorded over the lowest, mid, and highest channels combined for both 802.11n and *802.11ac* (Personal Collection)

E. Highest 802.11n and 802.11ac Data Rate Over All Channels For Each Distance

Fig 8 shows the comparison *of 802.11n* and *802.11ac's* practical performance against their corresponding theoretical performance. Results in Fig 8 respectably support previous analysis within this chapter with evidence showing *802.11n's* consistency over 802.11ac. *802.11n* achieved on average 44.9% of its theoretical performance as opposed to *802.11ac's* practical average performance of 21.7% of its theoretical performance. This trend continued for the highest data rates recorded with *802.11n* achieving 84.4% of its theoretical performance compared to *802.11ac's* 47%. *802.11n* also accomplished better performance with the lowest data rates recorded at 8.8% whereas *802.11ac* provided an average of just 2.6%.

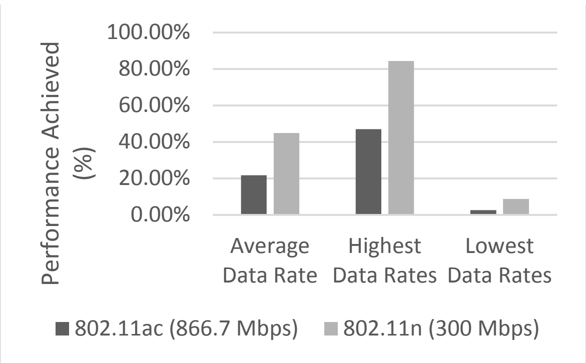

Fig 6: Comparison of 802.11n and 802.11ac practical performance against their theoretical performance.

IV. Summary

In terms of performance, *802.11n* outperformed *802.11ac* in relation to theoretical speeds. *802.11n* was also the closest to achieving its theoretical speed with 288Mb/s whereas *802.11ac* was far from its theoretical speed of 866.7Mb/s with 510Mb/s. However at closer distances, higher practical speeds were attained with *802.11ac* than *802.11n*. Data rates of *802.11ac* dropped significantly at further distances when compared to *802.11n*. The fluctuation in performance of *802.11ac* could be due to the deployment of other APs within the R.F. environment. As *802.11ac* requires an 80MHz channel to achieve maximum performance, made up of two 40MHz channels, both channels have to be available in order to transmit maximum data rate over the 80MHz channel. APs within the environment may have been operating over one 40MHz channel instead. The limiting of 802.11ac to one 40 MHz channel had a significant impact on performance and is likely to be the explanation for the poor performance. However, as the experiment replicates a typical office environment, there are likely to be other APs operating in the wireless environment in practice, hence the scenario is realistic.

Packet loss was significantly higher over *802.11ac* than *802.11n* with the highest percentage of packet loss recorded at the nearest distance (0.097%). This could also support the theory of interference with *802.11ac* due to other *802.11n* APs within the environment. Furthermore, *802.11n* continued to present consistency with minimal packet loss at the closest distance (0.002%) which as expected, increased with distance.

Although *802.11ac* achieved some of the highest data rates recorded throughout the experiment, it rarely showed consistency, performing on average at 21.7% of its full potential. *802.11ac* also had significantly higher packet loss than *802.11n* with longer distances and obstacles having a serious impact on *802.ac* performance. On average, *802.11n* performed better that of *802.11ac*, achieving 44.9% of its full potential with a consistently lower error rate.

Both standards did not achieve their full potential when averaged. However, *802.11ac* was more volatile and susceptible to distance, obstacles and interference. It did not present a significant increase to performance over 802.11n within an office environment over distances. The *802.11ac* specification however, suggests otherwise.

V. Conclusions and Further Work

The review showed that work by Dianu et al. [3] explored the performance of *802.11ac* in an indoor environment. Bejarano and Knightly [2] covered channelization and MIMO issues. Gauntlett [11] provided an insight to Modulation and Coding Scheme Values. Several software programs were evaluated to determine good test cases. Wireshark and WirelessMon were chosen for monitoring purposes. An office environment like experimental scenario was designed and used to collect data about the practical capability of *802.11ac*. It was found that there are a vast range of parameter settings configurable within the Cisco wireless controller. In order to carry out each test case in a feasible time, variables were chosen that optimised data rate. The laboratory used to carry out the experiment was limited in size to fifteen meters. It would have been better to perform the experiment in a laboratory of twenty five meters to avoid transmitting through the wall, which had a noticeable impact on data rate. Ideally, the project should have been repeated in an RF anechoic chamber.

Graphs containing data rates for each standard, at each distance, over each channel have been analysed to compare to the highest, lowest and the mean data rates. Additionally more detailed graphs could be created from screen shots of data taken at each distance showing the number of interfering APs present at each distance. The AP implemented for the experiment was a Wave 1 Cisco Aironet 2702i. Ideally, the experiment would have benefited from a Wave 2 Cisco Aironet AP such as the Cisco Aironet 2800i. This would be able to demonstrate a greater *802.11ac* performance with theoretical data rates of up to 2.6Gb/s rather than Wave 1’s 866.7 Mb/s. Another improvement would be to test the impact of interference from *802.11n* signals on *802.11ac* when transmitting simultaneously. The findings showed inconsistencies with *802.11ac* which were may be caused *802.11n* transmissions. Whereas *802.11n* proved to be consistent, providing evidence that there was likely to be little interference. By implementing an additional AP that performs *802.11n* transmission alongside *802.11ac*, the experiment would then provide data about signals interfering with *802.11ac* performance.

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