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Throughput and Range Performance Investigation for IEEE 802.11a, 802.11n and 802.11ac Technologies in an On-Campus Heterogeneous Network Environment

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***Abstract*—This paper presents an analysis and measurement results for an experimental study on throughput, range and efficiency performance of IEEE 802.11a, 802.11n and 802.11ac standards in an indoor environment on a typical University Campus. The investigation considers a number of key system features including PHY layers mainly, Multiple Input Multiple Output (MIMO), Multi-User Multiple Input Multiple Output (MU-MIMO), Channel Bonding and Short-Guard Interval (SGI) in the heterogeneous wireless network. The experiment is carried out for the IEEE 802.11ac standard along with the legacy protocols 802.11a/n in a heterogeneous environment which is typically deployed on Campus. The results compare the maximum throughput of IEEE 802.11 standard amendments, in terms of theoretical and experimental throughput over TCP and UDP protocols for different set of parameters and features to check their efficiency and range. To achieve this desired goal, different tests are proposed. The result of these tests will help to determine the capability of each protocol and their efficiency in a practical heterogeneous on-campus environment.**

Keywords— Multiple Input Multiple Output (MIMO), Multi-User Multiple Input Multiple Output (MU-MIMO), Short-Guard Interval (SGI), Time Difference of Arrival (TDOA) and Access Point (AP).

I. INTRODUCTION

The IEEE 802.11ac is also known as Gigabit Wi-Fi and represents more improved and scalable version extension to IEEE 802.11a and IEEE 802.11n with [1]. The IEEE 802.11ac standard incorporate many advanced features designed to improve Quality of Service (QoS) and user experience, including wider frequency channel (up to 160 MHz), MIMO (up to 8), Multi-User MIMO, higher spectral efficiency, high density modulation (up to 256-QAM) with channel bonding mechanism [2,3]. In enterprise network, however, the IEEE 802.11n is very much in use and it is serving this purpose very well but at lower efficiency as compared to IEEE 802.11ac. However, the IEEE 802.11ac claimed to achieve higher data throughput gains while being very energy efficient [2].

The deployment of wireless network in 2.4 GHz frequency band over the years has started to show limitations due to number of interference issues between neighboring devices which affects the performance of entire wireless network [4]. The emerging wireless technologies which operates in 5 GHz frequency spectrum has number of advantages over 2.4 GHz in terms of non-overlapping channels with wider channel bandwidth for gaining higher throughput.

According to [5], if there are two access points placed and operational in an indoor environment, one being 802.11n and other being 802.11ac then the signals transmitted by 802.11ac will overlap with the 802.11n resulting narrower channel width hence decrementing the network throughput. Another issue stated by [6], when an 802.11n and 802.11ac are deployed in an indoor environment the time difference of arrival (TDOA) of signal for 802.11ac decrement. However, using a wider bandwidth 802.11ac can improve the accuracy and stability of TDOA at low sound to noise ratio (SNR). Another interoperability issue stated by [7], that 802.11ac works only on 5 GHz band and 802.11n works on 2.4 GHz and 5 GHz band as there is no 80 and 160 MHz channel in 802.11n and it works on only 20 and 40 MHz. Hence, the backward compatibility should be evaluated with existing 802.11a/n devices in various practical scenarios to obtain a clear picture of the system performance in reality.

The purpose of this research is to test 802.11ac with the legacy protocol 802.11a/n for throughput, range and efficiency of typical heterogeneous wireless network deployed in a campus. The performance evaluation of IEEE 802.11ac devices has been widely explored over simulation platform, although there is not much experimental evaluation done in practical scenarios [8, 9].

The remainder of the paper is organised as follows: Section II, provides a brief discussion on details and problems of the IEEE 802.11 and their amendments in heterogeneous environment. Section III, describes the design and arrangement of the experiment. It includes the network diagram, list of equipment used and test cases for throughput and range test. The results are discussed in section IV. We conclude the work presented in this paper and future directions in section V.

II. RELATED WORK

The practical and theoretical throughput of IEEE 802.11a are 25Mb/s and physical-layer (PHY) data rate are 54Mb/s respectively [10]. The IEEE 802.11n standard introduced the

MIMO by implementing spatial diversity, which enables it to achieve at least four times more throughput than legacy protocols [11].

The measurement-based evaluation of IEEE 802.11n (2.4 and 5 GHz) and 802.11ac (5GHz) with channel bandwidth of 20, 40, 80 MHz are performed by [12]. This settings (802.11n 2.4 GHz model: 20Mhz, 802.11n 5.0 GHz model: 40MHz, 802.11ac: 80MHz) are used in a client server setup for different types of IPv4 UDP traffic with varying packet size from 128 B to 512 KB, concluding that IEEE 802.11ac provides higher throughput than IEEE 802.11n. We have to consider the traffic generator (Server) is usually outside of the WLAN.

The performance study conducted by [13], on analysing the impact of utilizing wider channel width on energy efficiency and interference, which are the main foundation of IEEE 802.11ac. In Client server environment they fix the location of the client on one end of the parking lot and move the AP away from the client by creating a downlink (AP to client) using Iperf UDP flow which sends data at maximum possible data rate. All experiments in this paper were repeated 10 times and average values are reported and each run of experiment involves running Iperf for anywhere between 3 to 10 minute. It is noted that the wider channel provides substantial improvement in throughput but at the cost of higher power consumption. The author also noted that the increasing the number of spatial streams is more energy efficient than using a wider channel to achieve the same performance increase in throughput. However, the number of streams supported by the adapter is very limited and vendor specific, where most of them only supports one or two spatial streams and channel width of only 80 MHz is used with 802.11ac for the experiment.

Another performance and energy efficiency study conducted by [14], on IEEE 802.11n and 802.11ac in 2.4 GHz and 5 GHz frequency spectrum to discuss the migration strategy from legacy protocols (IEEE 802.11a/n) in an enterprise network environment to the IEEE 802.11ac. The results of performance and energy efficiency in 2.4 GHz and 5 GHz frequency spectrum with channel width of 40 MHz using UDP traffic shows that, it is worth upgrading to 5 GHz from 2.4 GHz as there are more number of non-overlapping channels available, lesser interference and provides higher throughput. Also, 10%-30% and 8% improvement is achieved in energy efficiency and throughput respectively, concluding that modest increase in throughput contributes to the noticeable improvement in quality of service (QoS).

It can be seen from the work above, the authors provide valuable information with number of thorough studies however, this studies are not much focused on the performance of IEEE 802.11 protocols in a subjective point of view considering the behavior of both TCP and UDP protocols in terms of their theoretical data rate, range, signal strength, practical data rate and efficiency in performance while operating in a heterogeneous wireless network environment. Thus, our contribution is to build a test bed and set of tests to determine the capability of each protocol (IEEE 802.11a/n/ac) and their efficiency in a heterogeneous environment with off-the-shelf equipment and indoor heterogeneous environment.

III. TEST-BED SETUP AND EQUIPMENTS LISTS

In order to investigate the performance in terms of data throughput of wired and wireless network we have created the test-bed described in Fig. 1. In the proposed test-bed, we have used off-the-shelf equipment and they are configured on required settings (refer table 1 and 2).

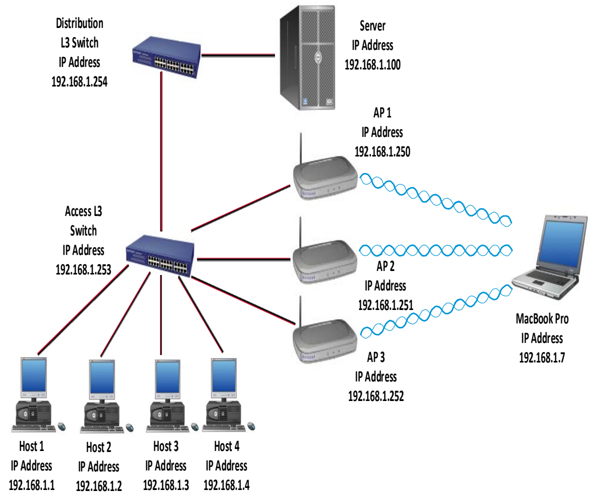

Fig 1. Network Diagram for Experiment

For the test bed setup two Cisco 3560 switches with 12-fibre gigabit Ethernet and 2-copper gigabit ports are used at distribution and access layer respectively. The speeds of 1000 Mbps of gigabit Ethernet on these switches provides the bandwidth to meet new and evolving network demands by alleviating bottlenecks and boost performance. The Cisco Catalyst 3560 switches deliver extremely high-performance for hardware-based IP routing. Also, Cisco Fast Ether Channel technology on these switches enhances fault tolerance and offers high-speed aggregated bandwidth between switches and to routers including individual servers. The Layer 2 traceroute functionality of these switches eases troubleshooting by identifying the physical path that a packet takes from source to destination. The IP traffic generator used on a server which acts as a host connected to the 1 gigabit port on distribution switch. Also, the Fibre optic port provides the downlink from the distribution switch to access the layer switch as both 802.11n and 802.11ac supports the data rates up to 600 Mbps and 1300 Mbps and all connections terminates at access layer. Thus facilitates the requirements of our experiments.

Three wireless access points are used for the setup, two Cisco AIR-AP-1242AG-E-K9 used for testing 802.11a and 802.11n respectively. This access points are equipped with 2X3 MIMO with two spatial streams operating on 20 and 40 MHz channels, providing data rates up to 300 Mbps with beamforming features. Also, these access points support the 1000BASE-T interfaces which supports gigabit Ethernet technology. The Asus RT-AC66U access point was used to test 802.11ac as it works on dual-band 2.4 and 5 GHz to achieve super-fast data rates by using 3X3 MIMO and multiple streams, providing data rates of 450 to 1300 Mbps for 802.11n and 802.11ac respectively.

Jperf (Software tool) is used to measure the throughput and performance of network by varying parameters. The host machine used as client and server with the configuration of Windows 7 Service Pack 1 64- bit with AMD Athlon dual core processors is running at 2.20 GHz with 8 GB RAM to provide sufficient computational resources. Each hosts consist of two network adapters to connect the wireless infrastructure and an on-board network card to connect the wired network. For the throughput and range test of wireless protocols, a Mac Book Pro with 2.5 GHz Intel i5 processor with 4GB of RAM is used with external wireless adapters like, Cisco-Linksys WUSB600N and ASUS dual band USB-AC56 which facilitates the wireless network connectivity as these network adapters offers simultaneous multiple streams operation based on IEEE 802.11 amendments [15]. The Cisco-Linksys WUSB600N supports dual band and have two omnidirectional internal antennas which facilitates beamforming and MIMO functionality while ASUS USB-AC56 also operate in dual band with two internal and one external antennas to facilitates the MU-MIMO. A software tool Wi-Fi scanner is used on the Mac Book for gathering transmission information including signal strength, noise, SNR and data rates.

A. Throughput Test

The advertised/theoretical data rates and practical throughput are compared by varying the number of hosts transmitting the continuous streams of data to and from the server. The host sends a continuous stream of data to the server for a fixed period of time and the throughput output is recorded. Since the link is not saturated by only a single stream of data, multiple streams of data are sent simultaneously to the server by multiple hosts. The result of the tests shows the maximum practical throughput generated by each protocol being tested. 10 runs are recorded to get more accurate results by taking their average and every test is performed on TCP and UDP

Table 1 summarises the throughput test cases which are setup with different features including frequency spectrum, channel bonding and short guard interval.

TABLE 1: TEST CASES USED FOR PRACTICAL THROUGHPUT ANALYSIS

Test	Test Cases
1	Wired
2	802.11a 5GHz 20MHz
3	802.11n 5GHz 20 MHz, 1 Stream and SGI=ON
4	802.11n 5GHz 20 MHz, 2 Streams and SGI=ON
5	802.11n 5GHz 40 MHz, 1 Streams and SGI=ON
6	802.11n 5GHz 40 MHz, 2 Streams and SGI=ON
7	802.11ac 5GHz 20 MHz, 3 Streams and SGI=ON
8	802.11ac 5GHz 40 MHz, 3 Streams and SGI=ON
9	802.11ac 5GHz 80 MHz, 3 Streams and SGI=ON

B. Range test

Here, the test will determine data rates performance against different distance in an indoor environment in campus test. The outcome of this test will become a practical reference for the design proposal for 802.11ac to co-exist with 802.11a/n. For this test a long corridor 60 meters has been used and a Mac Book Pro for connecting the access points along with external USB network adapter, see Fig. 2. At one end of the corridor the access points are conFig.d as in Table 2. The distance resolution is 5m, i.e. the corridor is segmented into 5m segment each, where the measurements are taken. To get the comprehensive investigation, the measurements are both taken walking towards and away from the access points. The tests were performed for 10 runs to get the precise readings.

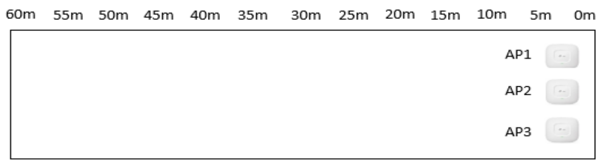

Fig. 2: Corridor where range was tested

TABLE 2: TEST CASES USED FOR RANGE TEST

Test	Test Cases
1	802.11a 5GHz 20 MHz Channel width
2	802.11n 5GHz 20 MHz Channel width, 1 stream
3	802.11n 5GHz 20 MHz Channel width, 2 streams
4	802.11n 5GHz 40 MHz Channel width, 1 stream
5	802.11n 5GHz 40 MHz Channel width, 2 streams
6	802.11ac 5GHz 20 MHz Channel width, 3 streams
7	802.11ac 5GHz 40 MHz Channel width, 3 streams
8	802.11ac 5GHz 80 MHz Channel width, 3 streams

IV. RESULTS

A test is designed to test the throughputs of all undertest protocols (IEEE 802.11a/n/ac) as mentioned above. All the outcomes obtained from the experiment are summarised in Table 3.

In the case of 802.11a the performance degrades as the new hosts are added. The maximum throughput recorded by 802.11a on TCP is 23.25 Mbps and on UDP is 26.61 Mbps. The 802.11n performance is evaluated with 20 MHz and 40 MHz channel bandwidth with one and two streams. The maximum throughput achieved on 802.11n 20 MHz single stream is 52.64 Mbps, while with multiple stream it is 91.79 Mbps. This denotes that the two streams performs better and gives the maximum throughput. Although, it is noticed that the throughput did not doubled up with two streams transmitting simultaneously, due to collision in transmission detected and the delay in re-transmission is interrupted by random back off time.

On the other hand the throughput achieved on 802.11n 40 MHz channel bandwidth is almost double the throughput of 802.11n with 20 MHz channel bandwidth; the maximum throughput achieved on 802.11n 40 MHz single stream and multiple stream is 94.41 Mbps and 144.2 Mbps respectively. The same results are observed with 802.11n 5GHz frequency with 20/40 MHz channel bandwidth using UDP. It can be clearly concluded that the channel bonding feature in 802.11n increases the performance.

The 802.11ac test on a 20 MHz channel bandwidth shows decrement in the throughput after four hosts transmitting simultaneously. However, with the channel bonding (i.e., 40 MHz and 80 MHz) feature the throughput increases with new host is added onto the network and this nature is observed on both TCP and UDP. The maximum throughput achieved with 4 hosts transmitting simultaneously using 80 MHz channel bandwidth on TCP is 217.38 Mbps and on UDP is 223.54 Mbps. It can also be seen that for a 40 MHz channel bandwidth the 802.11ac with 4 hosts transmitting simultaneously generates the throughput of 170.1 Mbps on TCP, while 802.11ac with 80 MHz bandwidth with 4 hosts transmitting simultaneously and generate the throughput of 217.38.

It is observed that increase in number of host results in throughput loss and this affects the performance of the network. It has been documented that multiple streams generate higher throughput than single stream. The channel bonding almost doubles the throughput when compared to the similar number of streams used for all other variations of 802.11n and 802.11ac. UDP outruns TCP for throughput.

TABLE 3: COMPARISONS OF AVERAGES AGAINST THE NUMBER OF HOSTS FOR TCP AND UDP (TEST CASES ARE DESCRIBED IN TABLE 3)

	TCP				UDP			
Test Case/ Host	1 Host	2 Hosts	3 Hosts	4 Hosts	1 Host	2 Hosts	3 Hosts	4 Hosts
1	687.8	850.8	855	837.5	131.5	244.5	421.9	532.1
2	23.2	20.7	19.5	18.17	25.83	26.33	26.61	22.81
3	44.2	50.0	52.6	44.0	59.22	61.33	61.39	60.73
4	67.7	75.1	90.9	91.7	113.9	114.5	112.8	113.6
5	74.7	91.4	94.09	94.41	116.5	117.	117.5	117.1
6	114.7	122.8	134.9	144.2	180.6	196.7	192.8	188.5
7	76.1	93.4	104.2	96.27	108.2	111.9	114.6	108.0
8	106.8	145.5	160.8	170.1	125.5	201.5	209.1	215.5
9	110.4	175.2	189.3	217.3	117.6	199.2	215.9	223.5

A. *Efficiency of Protocols*

This section analyses the results from the previous sections and the efficiency of protocols are tested. Every protocol offers different data rates, hence to compare all the protocols data rate, throughput and efficiency on the same scale, we calculate Efficiency (E) as follows:

$$E=(T_{10}/D_R)\times 100 \quad (1)$$

where, T_{10} is the average throughput obtained from 10 runs, and D_R is the maximum data rate offered by that protocol.

B. *TCP and UDP Protocol Efficicency*

The Fig. 3 shows that the efficiency of TCP on the protocols tested. The wired network is full duplex and the wireless network is half duplex. However, the wireless network is susceptible to collision detection, hence the efficiency of the wireless network decreases as new hosts are connected.

The 802.11a with one host shows the efficiency of 43.055% while more number of hosts added, it drops to 33.648%. However in case of 802.11n and 802.11ac, the throughput increases as new hosts are added till certain limit. The 802.11n and 802.11ac behaves like wired network in terms of throughput and efficiency because it has a feature called MIMO and MU-MIMO respectively. This new feature introduced in wireless network protocols has improved their throughput and range capacity. The 802.11n in 5GHz spectrum with 20 MHz channel bandwidth and one stream shows the efficiency 35.09%, while with streams the efficiency is 30.59%. Since the 5GHz band is fairly empty as compared to 2.4GHz the efficiency of the 802.11n in 5GHz should be better.

Multiple streams of data transmitted should improve the efficiency than single stream, but in the test it is observed that the efficiency is worst with multiple streams as compared to single stream. Similarly, in case of 802.11n in 5GHz with 40 MHz channel bandwidth the efficiency on one stream and two streams is 62.94% and 48.06% respectively. Since the channel bonding feature with multiple streams makes the 802.11n works on full potential and not using the complete spectrum, which results in 1 stream performs better than 2 streams.

The 802.11ac in 5GHz spectrum with 20 MHz channel width with three streams shows an efficiency of 12.03%, whilst other variants 40 MHz and 80 MHz show 19.64% and 25.10% efficiency respectively. In the case of 802.11ac with 20 MHz, the one host efficiency is 8.79% and increasing linearly till the three hosts delivering 12.03%. The data rates achieved by the 802.11ac and all their variants are better than 802.11n but in terms of efficiency the 802.11ac fails to keep up with 802.11n protocol.

The Fig. 4 shows UDP efficiency of the 802.11a is 49.27%. With UDP all wireless protocols and their variations show better efficiency than TCP. The 802.11n in 5GHz spectrum with 20 MHz channel width with one stream, shows the maximum efficiency of 40.48% along with two streams it shows 37.96%. It can be seen here that one-stream system performs better than two-stream system. The same phenomenon is observed with 802.11n with channel bonding feature, the maximum efficiency recorded with one stream is 78.38%, while with two streams it is 65.52%. It is also noted that the 802.11n gives best throughput with channel bonding and multiple spatial streams but not utilizing the spectrum completely.

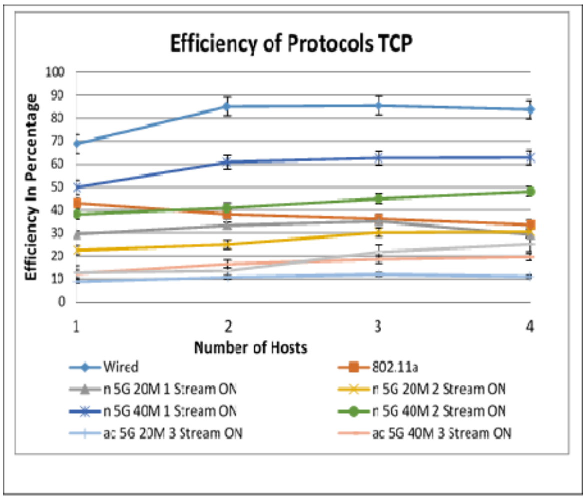

Fig 3. Efficiency of TCP Protocols

The 802.11ac in 5GHz spectrum with 20 MHz channel bandwidth with three streams shows the maximum efficiency of 13.24%, while the other variants 40 MHz and 80 MHz shows 24.88% and 25.81% respectively. The 802.11ac and all variants give maximum throughput but they show less efficiency than any variant of the 802.11n. UDP outruns TCP in terms of throughput and efficiency but it is not as reliable as TCP. It is also noted that, the single stream is more efficient than the multiple streams but multiple streams give a better throughput, as MIMO and MU-MIMO functionality in 802.11n and 802.11ac transmit the signal from transmitter to receiver using multiple paths resulting in reaching the receiver at same time. The 802.11n with channel bonding has a better efficiency than all the variants of the 802.11ac.

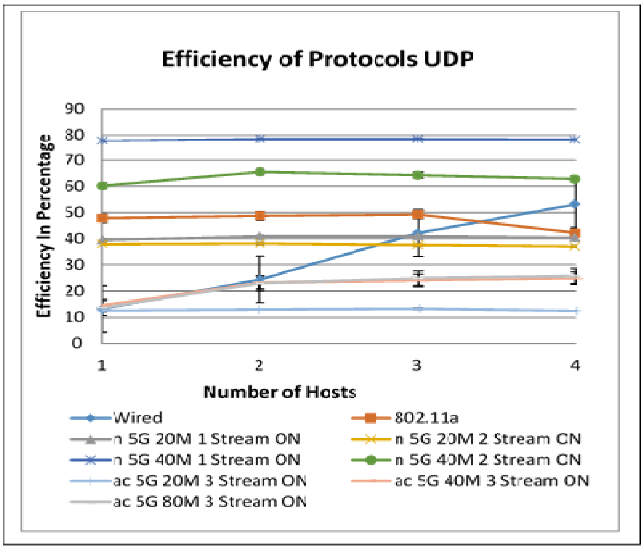

Fig. 4. Efficiency of UDP Protocols

The range test is comprised of the data from all the previous tests. The comparison is made with data rate to the distance checking the strength of the signal is shown in a Fig. 1.8 below. From the graph above it can be seen that 802.11a gives the maximum data rate in the range of 5 meters and as the host move away from the access point the data rate drops. After certain point the host is unable to connect to the access point. The 802.11a losses the connectivity to the host at 40 meters and after that the host in not able to connect to the access point.

Fig. 5 depicts the data rate results from all tests. The comparison is made with data rate to the distance checking the strength of the signal. From the graph above it can be seen that 802.11a gives the maximum data rate in the range of 5 meters and as the host move away from the access point the data rate drops. After certain point the host is unable to connect to the access point. The 802.11a losses the connectivity to the host at 40 meters and after that the host in not able to connect to the access point. With 802.11ac tested it is observed that it can reach to far distance than any other protocols tested in this experiment. The comparison made between 802.11n with channel bonding and one stream to 802.11ac without channel bonding. It is noted that the data rate offered by both protocols are good for a long distance but 802.11n loses the connectivity to the host at 60 meters while 802.11ac remain connected even after 60 meters. The 802.11ac with channel bonding outperforms every other protocol tested as the range and signal strength of it in close and long range is higher than any variant of 802.11n.

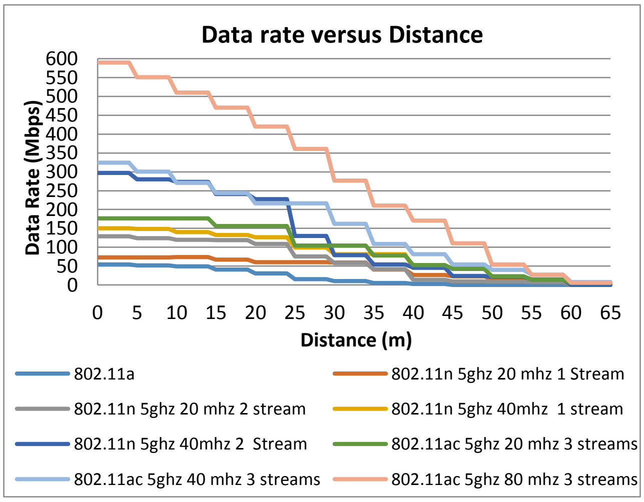

Fig. 5. Data rate vs Distance

V. CONCLUSION AND FUTURE WORK

Throughput and efficiency tests have been extensively carried out under different conditions in the University campus. Multiple configuration and settings have been considered throughout the experiments to obtain a full picture of system performance in a real condition. The MU-MIMO functionality in access point and adapters, with potentially multiple antennas, transmit and/or receiver independent data streams simultaneously to and from multiple stations. The 802.11n the access point transmit multiple data streams to single clients but in 802.11ac the access point can transmit multiple data stream to multiple clients [16]. The clients received the higher data rate using MU-MIMO as compared to MIMO because in MU-MIMO the packets can be transmitted using maximum data rate per clients [9]. The multiple spatial streams i.e., 8 supported by IEEE 802.11ac helps distribution of data streams to multiple clients/stations hence improving the efficiency of MU-MIMO [17].

The IEEE 802.11ac and supported network devices and adapters defines a protocol similar to "explicit compressed feedback" which is used in IEEE 802.11n for beamforming [18]. This unique transmit beamforming method in IEEE 802.11ac can be used to enable both SU-MIMO and MU-MIMO [19]. This beamforming technique used in IEEE 802.11ac is called as "Sounding" and it directs the beam former precisely towards the receiver. The beamforming allows the data streams to be sent to single or multiple users. Results obtained from the throughput test has shown that the theoretical throughputs are never achieved during this experiment due to delay incurred by reflection, scattering, diffraction/refraction of transmitting and receiving signal. On the other tests on TCP and UDP, the advertised throughputs of protocols have been never reached; TCP performance was 50% and UDP as 65% compared to the actual advertised data rate of the protocol due to UDP operate without overhead for setting up the connection and acknowledgement. Also, UDP is a best effort delivery protocol which makes it faster than TCP. Applying a short guard interval (i.e.400ns) to SGI=ON setting will boost the data rate by 8-12%.

The increment in the throughput of the 802.11n and the 802.11ac with new features like, short guard interval, channel bonding, MIMO and MU-MIMO have helped the wireless networks to achieve data rate and throughput close to the wired networks. In future, it is worthy to study the wireless protocols operating in 5 GHz frequency spectrum for evaluating their signal strength, and exploring the compatibility with each other. It would be interesting to see how hand-off takes place between these protocols at different criteria in an indoor and outdoor environment and the comparison can be made in terms of range and compatibility with legacy protocols. Another research area would be to test these protocols in terms of power consumption due to multiple antennas, the effect of channel bonding and multiple spatial streams.

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