Performance of TCP over 802.11ac based WLANs via Testbed Measurements

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***Abstract*—This paper presents measurement results collected from an IEEE 802.11ac based wireless test-bed to experimentally demonstrate how 802.11ac affects the throughput performance of a WLAN with different Transmission Control Protocol (TCP) variants implemented in Linux kernel. We compare the performance of 802.11ac with 802.11n for both single and multi-hop transmissions in a wireless mesh network (WMN). Our first observation is that the single-hop performance of 802.11ac outperforms 802.11n, however, as the number of transmission hops increases 802.11ac does not have a significant advantage over 802.11n. In addition, our measurement results show that the best throughput performance with the minimum standard deviation is achieved by TCP CUBIC and TCP BIC for multi-hop transmission. Lastly, we present the results on the behavior of congestion window (CW) with each TCP variant, and observe that the convergence time of the CW is smaller with 802.11ac for both single hop and multi-hop scenarios.**

***Index Terms*—802.11ac, TCP Congestion Control, test-bed, performance, congestion window**

I. Introduction

Today Internet and its applications have a great impact in our daily lives. Inherently, people use Internet at almost every place such homes, offices, airports, etc., where wireless local area networks (WLANs) are very popular, and commonly used. As the demand of WLANs for high data rates rapidly increases especially after the huge increase in the number of the internet users and applications, the new WLAN standards have been proposed regularly. Nowadays, although IEEE 802.11n based access points (APs) are commonly used, the new standard, namely the IEEE 802.11ac [1], has been approved in 2013, and many leading laptop and smart-phone manufacturers such as Samsung Galaxy S4 [2], Apple MacBook Air [3] have already started to use 802.11ac based chip-set for their Wi-Fi cards. Unlike 802.11n, 802.11ac, also known as very high throughput (VHT) amendment, can provide gigabit throughput in WLANs.

Many works [4-9] have already investigated the performance of 802.11ac from the point of view of MAC and PHY layers. In [4], the authors show that dynamic bandwidth allocation (i.e., 20, 40 or 80 MHz) outperforms the case where the bandwidth is allocated statically. Single user and multi-user multiple input multiple output (MIMO) with 802.11ac are investigated in [5] and [6], and the experimental performance of 802.11ac is presented in [9]. In [7] and [8], the energy consumption of 802.11 based AP is measured via experimental study. Although the works in [4-9] investigate the performance of 802.11ac in terms of MAC layer throughput and energy consumption, the interaction between MAC and higher layers such as TCP is not clear, and collecting and analyzing experimental data is a key element for a deep understanding of TCP over 802.11ac.

It is well-known that the main drawback of TCP for wireless communication is that TCP assumes that all errors are due to network congestion, rather than to packet loss [10]. When congestion occurs, TCP adjusts its congestion window (CW) size and retransmits the lost packets. In wireless networks, however, packet loss is mainly caused by high bit error rates over wireless links. Thus, the TCP window adjustment and retransmission mechanisms result in poor end-to-end performance for wireless transmission. There are many works which investigate the performance issue of TCP for 802.11 based WLANs. In [11] and [12], a performance analysis is developed for TCP over 802.11 WLANs. The authors in [13] present the performance of TCP for 802.11b networks, whereas the interaction between TCP and 802.11n is investigated in [14] without specifying a TCP variant. However, each TCP variant has its own characteristic such as the behavior of Congestion Window, which can directly affect the throughput of a transmitting station. Hence, unlike these works, we aim to experimentally investigate the interaction between TCP variants and IEEE layers, to understand how the increase in transmission rate by the improvements in IEEE MAC and PHY layers affect the features of TCP variants (i.e., the characteristic of the congestion window of a TCP variant).

Main contributions of this work are listed below:

- In our experimental study, we measure the performance of TCP variants implemented in Linux kernel with the version of 3.13.0.43. We observe that the performance of all TCP variants with 802.11ac increases significantly compared to 802.11n, except TCP Vegas which acts the main bottleneck. In all scenarios, the highest throughput

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is achieved with TCP Binary Increase Congestion Control (BIC) and TCP CUBIC. In addition, in multi-hop scenarios, the throughput performances of 802.11ac and 802.11n are close to each other.
- We also investigate the CW behavior of TCP variants, and our results show that the CW of a TCP variant with 802.11ac can reach to its maximum value within shorter duration of time compared to as that of 802.11n. Our results also help us to understand that TCP Vegas has the worst throughput performance.

The rest of this paper is structured as follows. In Section II, we provide an overview of the PHY and MAC layer enhancements with 802.11ac compared to 802.11n standard. In Section III, we describe the measurement setup used, including descriptions of the relevant equipment and software as well as the measurement environments. We then present and discuss the results from our measurement study in Section IV. We finally conclude the paper in Section V.

II. Background Information

In this section, a brief description of mechanisms that are used by 802.11 n/ac in order to achieve higher throughput is given. In 2009, IEEE ratified 802.11n standard, which offers faster data rates (up to 600 Mbps) compared to other 802.11 family members such 802.11a/b/g. 802.11n gained a major advance over 802.11a by introducing several major advances in the MAC and physical (PHY) layers. In PHY layer, orthogonal frequency division multiplexing (OFDM) is used as the transmission technique, and multiple input multiple output (MIMO) was the biggest innovation that comes along with 802.1n, which not only increases data throughput but also provides uplink and downlink reliability. 802.11n devices such as APs and clients are intended to operate at both 2.4 GHz and 5 GHz. Although the legacy devices which support IEEE 802.11 a/b/g standards make use of only 20 MHz bandwidth, IEEE 802.11n doubles the channel bandwidth from 20 MHz to 40 MHz. Moreover, this standard supports 64-quadrature amplitude modulation (QAM) with $5/6$ coding rate [15], [16]. In MAC layer, the most important innovation is the usage of aggregation, where multiple packets are aggregated and transmitted at the same time as single frame. By using aggregation, a significant amount of overhead is reduced compared to 802.11a standard.

IEEE 802.11ac standard, which has been approved in 2013, has focused on introducing improvements and new features in PHY and MAC layers to achieve Gbps data transmission rates. The standard allows using wider channel bandwidth. Specifically, instead of 40 MHz, 80 MHz channel bandwidth is defined. In addition, $80+80$ and 160 MHz bandwidths are kept optional for designers. This also implies that 802.11ac can operate only over 5 GHz, frequency band, which is also less crowded than 2.4 GHz, since the total available bandwidth in 2.4 GHz band is less than 80 MHz. The highest order modulation scheme is defined as 256-QAM with a coding rate of 5/6, whereas 8/9 coding rate is kept optional. In addition, the maximum number of spatial streams, which is 4 in IEEE 802.11n case, is increased to 8. Additionally, 802.11ac includes many of the improvements that were first introduced with 802.11n. For instance, 802.11n introduces three types of aggregation schemes, namely A-MSDU, A-MPDU and a two-level aggregation that combines both A-MSDU and A-MPDU. 802.11ac also uses these three aggregation schemes but enables larger frame sizes. After all of these innovations, 7 Gbps data rate at PHY layer is possible [16], [17]. For testing AP, the highest possible data rates according to hardware is calculated 3.47 Gbps for IEEE 802.11ac standard [16].

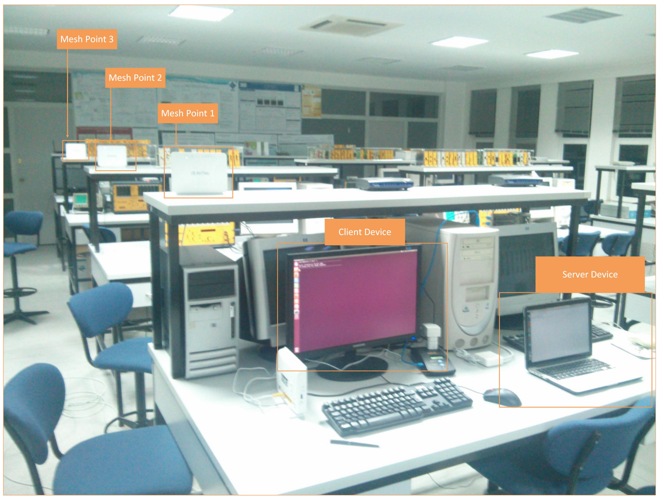

Fig. 1. Our test setup in Istanbul Technical University WCR Lab.

III. Test Setup

In our experiments, we aim to understand the performance of all TCP variants when 802.11ac is employed by considering both single and multi-hop transmissions. All of the experiments have been performed at Istanbul Technical University Wireless Communication Research Laboratory as shown in Figure 1.

A. Used Tools

1) Iperf: Iperf is an open source, client-server based throughput measurement tool [18]. We use iperf to generate TCP traffic required for our tests.

2) tcpprobe: Tcpprobe module can be found in any Linux operating system [19]. It is used to monitor the status of the CW and the slow start threshold from Linux kernel.

3) bash: Bash is a UNIX shell which can be found any Linux based operating system. The shell script allows us to change the TCP parameters online and also to automatize our tests.

B. Test properties

We evaluate 11 different TCP variants, which are implemented in 13.04 Ubuntu with the kernel version of 3.13.0-43 generic. These TCP variants are as follows; TCP BIC, TCP CUBIC, TCP HighSpeed, TCP HTCP, TCP Hybla, TCP Illinois, TCP Scalable, TCP Vegas, TCP Veno, TCP Westwood and TCP YeAH.

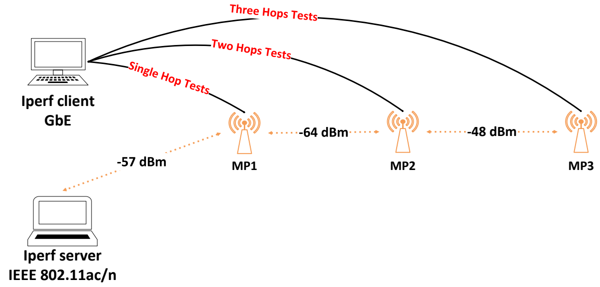

Fig. 2. Iperf server (MacBook Air) is connected to MP1. Iperf client, which generates TCP traffic, is connected to each MPs with gigabit Ethernet. MP2 is placed between MP1 and MP3. The distance between MP1 and MP2 is 235 cm and the distance between iperf server and MP1 is 118 cm. There is no transmission link between MP1 and MP3.

Our test setup is given in Figure 2. In our tests, there are three wireless mesh points, which are denoted as MP1, MP2 and MP3, respectively. Each mesh point is Air5760 router [8], which uses Broadcom BCM4360 chipset and can support 80 MHz channel bandwidth, up to 256 QAM and 3x3 MIMO. As a user terminal (i.e., iperf server in Figure 2), we use MacBook Pro with Mac OS X 10.10.1 operating system and the capability of 802.11ac standard. The user terminal is connected to MP1 with 802.11ac. In order to see the effect of multi-hop transmission, we employ a static routing algorithm where MP3 is connected MP2 and MP2 is connected to MP1. There is no direct connection between MP3 and MP1, hence, MP3 first should transmit to MP2 to reach the user terminal.

C. 802.11ac experiments with multiple nodes

We measure the performance of all the TCP variants over 802.11ac by considering single-hop, two-hop and three-hop transmission. All tests are performed over 5 GHz frequency band where the channel bandwidth is set to 80 MHz channel bandwidth with the full transmit power for a duration of 200 seconds.

First, we measure the performance of TCP variants for single hop transmission. To do that, we connect our iperf client to MP1 via gigabit Ethernet to generate downlink traffic from MP1 to the MacBook Pro. We then establish a wireless connection between MacBook Pro to MP1. For two-hop transmission, we connect our iperf client to MP2 via gigabit Ethernet cable, and the wireless connection between MP2 and MP1, and MP1 and MacBook Pro is established. Similarly, for three-hop transmission, the iperf client is connected to MP3, and we make sure that wireless connections between MP3 and MP2, MP2 and MP1, MP1 and the MacBook Pro are established. For 802.11n tests, we configure MPs to operate with 802.11n mode, and set the channel bandwidth to 40 MHz.

IV. EXPERIMENTS

We first present the results for TCP CUBIC since most of Linux operating systems use TCP CUBIC as the default TCP variant. The throughput performance of TCP CUBIC

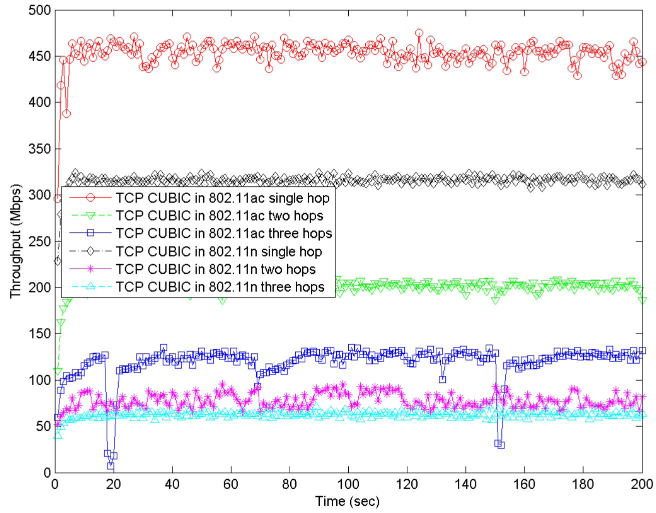

Fig. 3. TCP CUBIC throughput with 802.11ac and 802.11n, and single, two and three hops transmission during 200 seconds.

with 802.11ac and 802.11n with using one-hop, two-hop and three-hop transmission is shown in Figure 3, where each point shows the average iperf throughput measured within 1 second. As seen in Figure 3, as the number of hops increases, the performance of both 802.11ac and 802.11n decreases. However, for 802.11ac there is a significant performance degradation when the number of hops increases from two-hop to three-hop. On the other hand, the performance of 802.11n with two-hop and three-hop are very similar. Next, we present the performance of 802.11n and 802.11ac with different TCP variants in multi-hop transmission. We represent BI, CU, HI, HT, HY, IL, SC, VG, VN, WW, YE for TCP BIC, TCP CUBIC, TCP HighSpeed, TCP HTCP, TCP Hybla, TCP Illinois, TCP Scalable, TCP Vegas, TCP Veno, TCP Westwood and TCP YeAH, respectively.

A. Performance of TCP Variants with 802.11ac

Figure 4 depicts the average throughput performance of all TCP variants with one-hop, two-hop and three-hop transmission when the MPs and the client are configured to 802.11ac mode. TCP BIC, TCP CUBIC, HTCP and TCP Illinois have similar performance in terms of average throughput as shown in Figure 4. Also, we note that these TCP variants have the highest performance. On the other hand, as the number of hop increases, the average throughput achieved by all TCP variants decreases significantly. For instance, the throughput achieved by TCP BIC with two hop is 55 % lower than the throughput achieved with single hop throughput. Also, the throughput performance of TCP BIC with three-hop is 37 % worse than that of two hop performance.

We observe that TCP BIC has the lowest standard deviation which is equal to 9.25 Mbps with single hop. Three highest standard deviation of the TCP variations are TCP Veno, TCP YeAH and Scalable TCP. Standard deviation of the TCP Veno

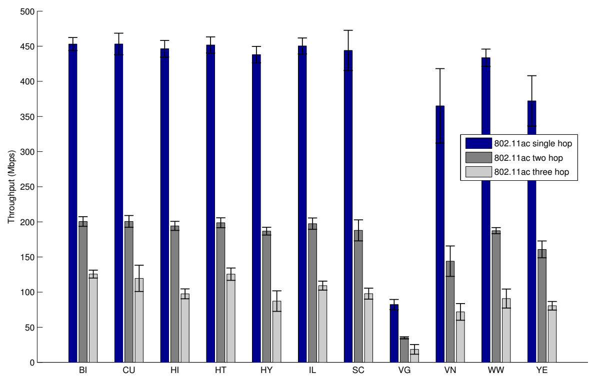

Fig. 4. Average throughput and standard deviation with different TCP variants for 802.11ac in multi-hop transmission.

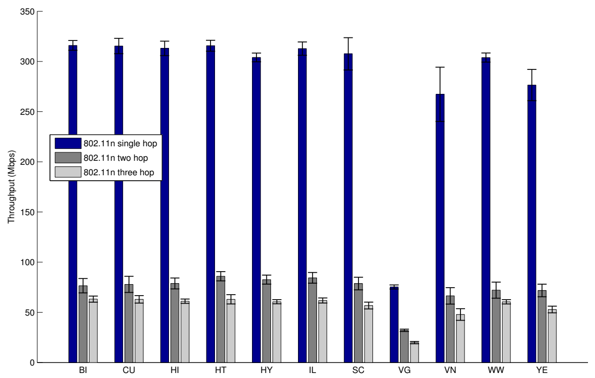

Fig. 5. Average throughput and standard deviation with different TCP variants for 802.11n in multi-hop transmission.

is 52.97 Mbps, TCP Westwood is 35.81 Mbps and Scalable TCP is 28.66 Mbps. By using 2 and 3 hops WMN, the highest standard deviations is observed in TCP Veno.

B. Performance of TCP Variants with 802.11n

The average throughput performance of all TCP variants with one-hop, two-hop and three-hop transmission when the MPs and the client are configured to 802.11n mode is shown in Figure 5. Similar to the case where we use 802.11ac mode, TCP BIC, TCP CUBIC, HTCP and TCP Illinois have the highest performance with similar statistics (e.g., about 315 Mbps). When we increase the number of hops, as expected, the average throughput achieved by all TCP variants decreases significantly. For instance, the throughput achieved by TCP BIC with two hop is 75 % lower than the throughput achieved with single hop throughput.

For single hop transmission with 802.11n, the lowest standard deviation is achieved with TCP BIC and TCP Hybla, which are measured as 4.87 and 4.33 Mbps, respectively. Moreover, the highest standard deviations are with TCP Veno, TCP Scalable and TCP YeAH, which are equal to 27.04 Mbps,

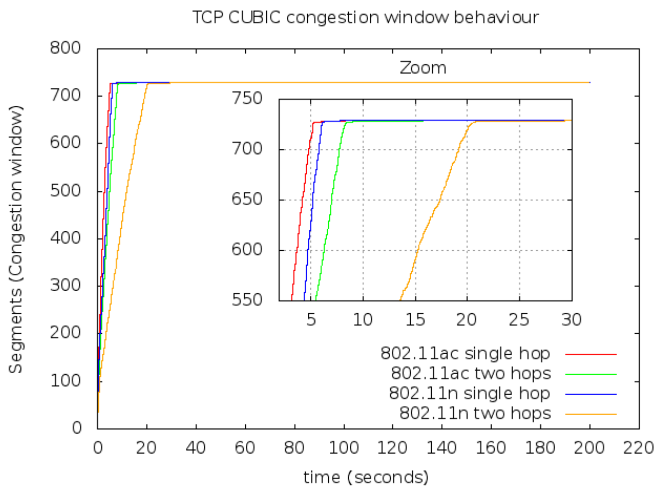

Fig. 6. The behavior of CW of TCP CUBIC with 802.11ac/n for single hop and two hops.

16.10 Mbps and 15.55 Mbps, respectively. The standard deviation of TCP Veno with two-hop is eqaul to 8.17 Mbps whereas the standard deviation of the TCP Veno with three hops is 5.78 Mbps. TCP Veno has the lowest standard deviation with two and three-hop.

C. Impact of 802.11 on TCP Congestion Window

Here, we present the results on the impact of 802.11ac and 802.11n on different TCP variants with different number of transmission hops. Figure 6 depicts the variation in the CW of TCP CUBIC when 802.11ac and 802.11n are used with singe-hop and two-hop. Since there is no other transmission in our environment the CW converges to a fixed point (i.e., 700 bytes) after a time. However, the convergence time of TCP CUBIC with 802.11ac is less than as that of 802.11n. Moreover, as the number of hops increases, the convergence time increases for both 802.11ac and 802.11n as well, but the negative effect of transmission hops on the convergence time is more significant with 802.11n.

As we mentioned previously, TCP Vegas and Veno have the worst throughput performance. The results depicted on Figure 7 confirm that the worst performance is due to the TCP variant instead of MAC and PHY. As shown in Figure 7, the CW (around 25 Bytes) is very low with TCP Vegas. That is to say, there is very small amount of data being transmitted from TCP to MAC layer. We observe that TCP Veno converges to a fixed point logarithmically. Note that the the rate of convergence with TCP CUBIC is linear. The best performance in terms of CW is achieved with 802.11ac with single-hop, and as the number of hops increases, the CW behavior of TCP Veno with 802.11ac and 802.11n becomes similar.

Main findings of this work are listed below:

- As the number of transmission hops increases, the achieved average throughput with both 802.11ac and 802.11n decreases. Interestingly, the amount of decrease is much more higher with 802.11n, with which the

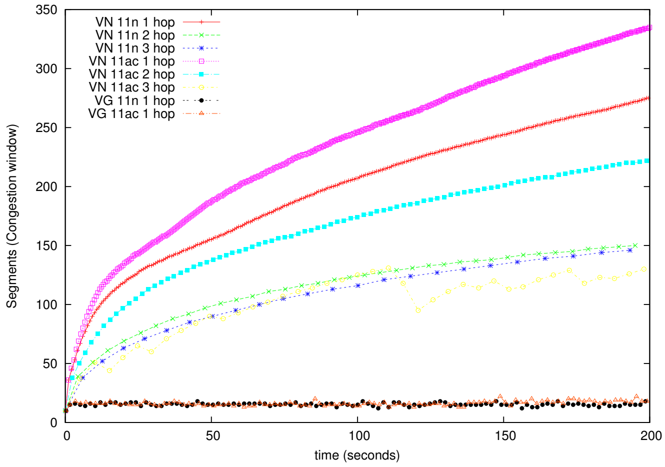

Fig. 7. The CW behavior of TCP Vegas and TCP Veno for 802.11ac and 802.11n networks.

amount of decrease can be up to 75 % when we switch from one-hop to two-hop. One can conclude that 802.11ac is more robust to multi-hop transmission. However, the most of the improvements cannot be reflected to higher layers in multi-hop transmission.

- Although TCP CUBIC is the default TCP variant in many Linux operating systems, we observe that TCP BIC has also very good performance in terms of average throughput and standard deviation. TCP BIC also has lowest standard deviation with multi-hop transmission.
- As consistent with previous research results, TCP Vegas has the lowest throughput performance. The amount of the improvement with 802.11ac is insignificant when we use TCP Vegas. In addition, the amount of throughput improvement with 802.11ac for TCP Veno is not much compared to other TCP variants. However, we note that the throughput of TCP Veno is much higher than the throughput of TCP Vegas.
- The convergence time of CW of a TCP variant is much smaller with 802.11ac, which may be considered as one of the direct effects of MAC layer on TCP variants. Due to the delay and packet loss the convergence time of CW of a TCP variant become larger in multi-hop scenarios.

V. Conclusion

In this paper, we present experimental results for the performance characterization of TCP variants implemented in Linux operating systems by considering IEEE 802.11ac/n standards. We first provide the results for TCP CUBIC, which is usually the default TCP variant in Linux operating systems, and achieves the maximum throughput for 802.11ac and 802.11n. However, we also observe that TCP BIC has very close performance to that of TCP CUBIC. We also observe that since as the number of transmission hops increases the throughput decreases significantly, the improvements in IEEE MAC and PHY layers become less significant, and to achieve a better performance in multi-hop networks additional improvements are needed at MAC and upper layers. One can also conclude that the expected gain achieved after MAC and PHY improvements may not be observed in practice due the characteristic of TCP variants (i.e., TCP Vegas). Lastly, the behavior of the convergence of a TCP variant strongly depends on the number of hops and the capability of MAC and PHY layers.

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