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TCP Throughput Efficiency Enhancement In IEEE 802.11n Network

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Abstract— **The new opportunities opened up by wireless technologies are also accompanied with new technical challenges. Principal among the challenges is the fact that wireless medium has limited bandwidth resources when compared with wired equivalent. The convenience brought about by the IEEE 802.11n protocol is also followed by the technical challenge of near average performance of the widely used transport control protocol (TCP) due to limited bandwidth resources of the wireless medium. IEEE 802.11n specifies standard for physical (PHY) and MAC layers of wireless local area networks (WLANs) which is based on the IEEE 802.11-2007 networking reference standard. This work is meant to enhance the efficiency of TCP in IEEE 802.11n network in order to improve per user bandwidth. ACK suppression in both downstream and upstream TCP flow is used to improve bandwidth. The network bandwidth of an IEEE 802.11n LAN is simulated under two access methods; request-to-send/clear-to-send (RTS/CTS) access method and the basic method. Results showed an improvement in throughput efficiency over 10 nodes, which demonstrate performance improvement of TCP ACK suppression as 50% in comparison with receiver policy of acknowledging every TCP data segment and approximately 20% when compared with receiver's policy of acknowledging every TCP data segment in the network. Simulation was conducted in Matlab R2012a.**

Keywords— IEEE 802.11n; Throughput; SNR; TCP

I. INTRODUCTION

The advancement in multimedia applications and the growth of the Internet has brought about the demand for high-speed digital communication systems. Sophisticated audio and video coding methods have reduced bit rate requirements for audio and video transmission. This in turn motivated the development of communication systems to achieve these requirements; brought technologies enabled high-quality audio and video transmission and introduced a number of new applications for businesses and residential consumers.

Current work investigates the problem of drastic fall in bandwidth with increasing distance. This paper focuses on improvement of bandwidth delivered over long distances using TCP throughput efficiency enhancement of IEEE 802.11n network. Most rural villages in developing world exist in clusters, with considerable distance between them ranging from 4-10km or even more [1]. Long distance from network backbone results in bandwidth attenuation, therefore extremely remote rural villages end up with relatively low bandwidth incapable of supporting basic network services such as email, and voice telephony.

In recent past, the most powerful set of specifications currently deployed is the IEEE 802.11g radio which operates on a bandwidth of 20 MHz and its Physical Layer (PHY) is based on a particular form of multicarrier transmission, namely, orthogonal frequency division multiplexing (OFDM) which enables these systems to achieve transmission rates of up to 54 Mbps. However, bandwidth intensive applications has made IEEE 802.11g data rate insufficient, and thus made way for a superior one. At present, a new standard IEEE 802.11n, is currently gaining ground because of its higher data rate. PHY channel extension to IEEE 802.11-2007 from 20 MHz to 40 MHz, the addition of Multiple Input Multiple Output (MIMO) features, and frame aggregation at the Media Access Control (MAC) layer gave birth to IEEE 802.11n in 2009 [2].

To alleviate the problem of drastic fall in bandwidth delivered over long distance, this work proposed TCP efficiency enhancement of IEEE 802.11n network. In meeting this goal, a simulation model of IEEE 802.11n was setup in Matlab to simulate different scenarios of network topology that represents the environment under investigation. Results obtained confirmed improvement in network bandwidth.

II. BACKGROUND

WLANs have evolved from an interesting idea to an essential and important technology that many individuals and businesses cannot live without today. The first Wi-Fi standards in the 802.11 series were produced in 1999 [3]. The next two standards produced by the IEEE were 802.11g, in 2003 and 802.11n in 2009. Each attempt is to improve on the performance of 802.11b and give it the performance achieved by 802.11a without raising the cost out of range of the consumer market. As users of network resources, we always ask for more; we need more speed and coverage. Under this circumstance, it then built up the foundation for the next

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generation WLAN, and therefore the development of the IEEE 802.11n amendment. Sample downstream (from the service provider to the consumer) and upstream (from the consumer to the service provider) bandwidth requirements are shown in Table 1.

TABLE I. BUSINESS APPLICATIONS WITH UPSTREAM/DOWNSTREAM DATA RATES [4]

S/N	Application	Downstream Data rate (kb/s)	Upstream Data rate (kb/s)
1	Voice Telephony	16 - 61	16 – 61
2	Facsimile	9 - 128	9 – 128
3	Internet	14 - 3000	14 – 384
4	Intranet	64 – 3000	64 – 1500
5	E-commerce	28 -384	28 – 384
6	Home Office	128 - 6000	64 – 1500
7	LAN Interconnection	384 - 10000	384 – 10000
8	Electronic Mail	9 - 128	9 – 64
9	Videophone	128 - 1500	128 – 1500
10	Database Access	14 - 384	9
11	Software Download	384 - 3000	9

802.11n is much more than just a new radio for 802.11 standards. In addition to providing higher bit rates (as was done in 802.11a, b, and g), 802.11n makes dramatic changes to the basic frame format that is used by 802.11 devices to communicate with each other.

III. RELATED WORK

Wi-Fi technology remains the only practicable solution in rural connectivity initiatives. While cost is an important advantage for using these set of wireless radios, another benefit is the ease of deployment. Our interest in this work is on IEEE 802.11n wireless technology standard with considerable data rate. To the best of our knowledge, only few research works has gone into the adaptation of 802.11n to rural connectivity projects, rather 802.11a, b and g are more common.

Large body of work investigated fair scheduling algorithms in wireless networks [5], [6]. These algorithms were derived from the Weighted Fair Queuing (WFQ) algorithm in [7] and its variants such as Self-Clocked Fair Queuing [8] or Start-Time Fair Queuing for the context of wireless networks.

Bianchi [8] proposed a model that applies to both the RTS/CTS method and the basic access method. It computes the saturation throughput performance in the presence of a finite number of terminals based on the approximation that the collision probability of a packet is independent of the back-off stage of the station, or the number of retransmission times due to collisions. The saturated throughput S is expressed as in (1).

$$S_T = \frac{PsE[P]}{E[\Phi] + PsTs + (1 + Ps)Tc} \qquad (1)$$

where E [P] is the average packet length, PS is the probability of a transmission being successful, TS is the average time the channel is sensed busy due to a successful transmission, TC is the average time the channel is sensed busy due to collision, and E[Φ] is the average number of consecutive idle slots between two consecutive transmissions on the channel. Time values are measured in slots, the unit specified in IEEE 802.11 standard.

In [9], an original theoretical model that casts SNR to the saturated throughput of WLAN was introduced. This work relates the wireless bandwidth to the signal strength by (2).

$$\mathrm{S}(t) \xleftrightarrow{\eta[.]} \mathrm{PER}(t) \xleftrightarrow{P[.]} \mathrm{BER}(t) \xleftrightarrow{Q[.]} \mathrm{SNR}(t) \qquad (2)$$

This is simplified further in (3).

$$\mathrm{S}(t) = f[\mathrm{SNR(t)}] \qquad (3)$$

Where $f[.] = \eta[P[Q[.]]]$, *PER(t)*, *BER(t)* and *SNR(t)* denote the saturated throughput, packet error rate, bit error rate and signal-to-noise-ratio as a function of time, t, respectively.

$\eta[.]$, P[.] and Q[.] are operators or functions that relates the two neighbours in the above model. This paper will follow this model and in particular extend it to IEEE 802.11n WLAN.

The motivation for this work is that we need a transparent solution that can interact with TCP and IEEE 802.11n networks. In the course of review on this topic it was discovered that investigation work on IEEE 802.11n by the research community is still at the surface level. However, there are lots of opportunities in the future. The rest of this paper is organized as follows: Section IV discusses the simulation model and processes, and quantifies the overhead of TCP acknowledgment packets over IEEE 802.11n protocol. Section V presents results of the simulation. Section VI concludes this paper.

IV. TCP THROUGHPUT IMPROVEMENT IN 802.11N NETWORK

The approach used in this work is based on the understanding that TCP acknowledgment packets (ACK packets) can be spared to save precious bandwidth resource on a wireless link. Although these TCP ACK packets are small; they incur a large overhead at the link layer because the RTS/CTS handshake at the link layer has to be completed for the transmission of each IP packet. Furthermore, the IEEE 802.11n standard specifies that the RTS and CTS frames be transmitted at the base rate. Thus, the higher the rate the wireless link is operated at, the larger the overhead of the RTS/CTS handshake for a transmission of an IP packet is on the wireless link. The rest of this section is organized as follows: Simulation process is covered in section IV-A, overhead observed for TCP ACK packets is quantified in section IV-B, section IV-C presents the design synopsis specific to the TCP throughput measurement of the simulation.

A. Simulation Models and Processes

A simulation model of the IEEE 802.11n standard was implemented using MATLAB/SIMULINK and used to improve throughput of an IEEE 802.11n network through ACK suppression in both upstream and downstream TCP flow. The simulation was performed in Matlab R2012a. The MIMO-OFDM system simulations was performed with data rates from 6.5 to 540Mbps using 2 transmit and 2 receiver antenna. The undoubted advantage of the presented solution is that the simulations were carried out on radio frequency so that simulation results could be directly related to measurements of real systems. Fig. 1 shows part of the simulation model with SNR from the various ports in the multi-port switch. Bandwidth value is at 130 Mbps as shown in Fig. 1, but could reach 540 Mbps for 40 MHz channel, and 270 Mbps for the 20 MHz channel.

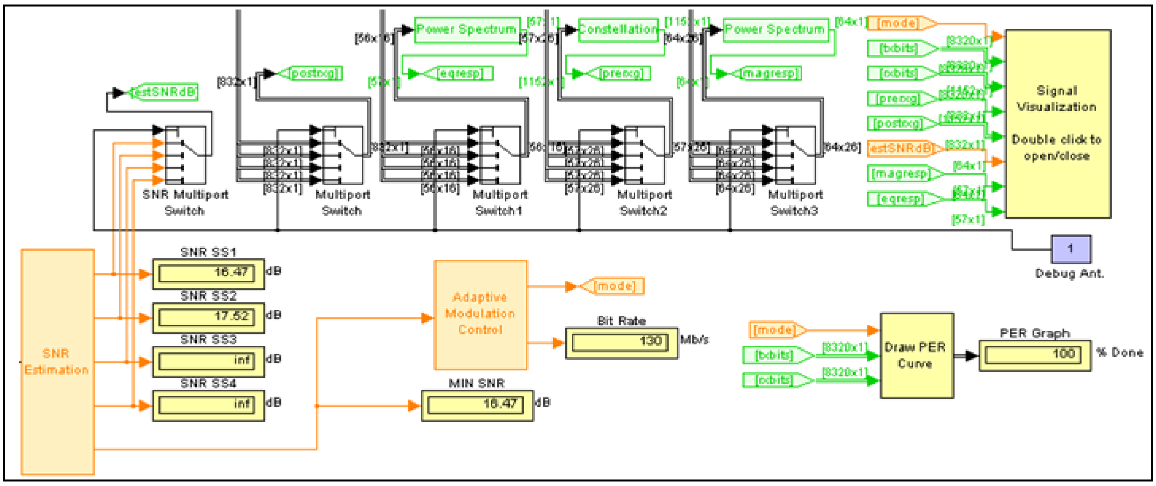


Fig. 1. Part of Matlab/Simulink model of IEEE 802.11n standard

The system architecture shown in Fig. 2 represents the overall architecture. To remove the overhead caused by TCP ACK packets on wireless links, this relies exclusively on the WLAN access point to act as a proxy for the wireless stations. The access point buffers TCP data packets for wireless stations. Also, for upstream TCP flows when wireless stations are TCP senders, the access point suppresses TCP ACK packets from fixed hosts in the Internet. For downstream TCP flows when wireless stations are TCP receivers, the access point generates TCP ACK packets for the wireless stations and passes on the packets to fixed hosts on the Internet.

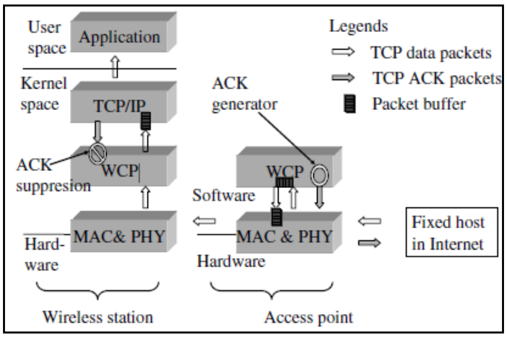


Fig. 2. Overall system architecture

A new component called Wireless Coordination Protocol (WCP) was introduced, that sits between the IP and the MAC layer at the access point and the wireless stations. The technique used assumes that WCP can intercept and suppress outgoing TCP ACK packets from the IP layer when necessary. In particular, we assume that WCP will be informed by the MAC layer about the successful or failed transmission of a TCP data packet. This assumption is necessary for the access point to generate TCP ACK packets for fixed hosts on the Internet.

The simulation topology used for the simulation process follows that shown in Fig. 3. The simulation topology models a telecentre scenario where N wireless stations are connected to an 802.11n access point. The wireless network is 802.11n with a base rate of 6.5 Mbps and a channel data rate of 540 Mbps.

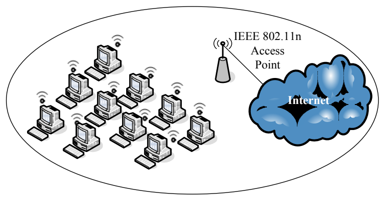


Fig. 3. Simulation Topology

The TCP segment size is set to 1460 bytes. The access point is connected to the Internet via a bandwidth of at least 130-Mbps uplink with a one-way propagation delay of 20 milliseconds. All experiments ran for 30 minutes but results of the first 10 minutes were discarded to eliminate any start-up error. The numbers of TCP upstream and downstream flows were varied in the simulation and the results is as shown in Fig. 4 and 5.

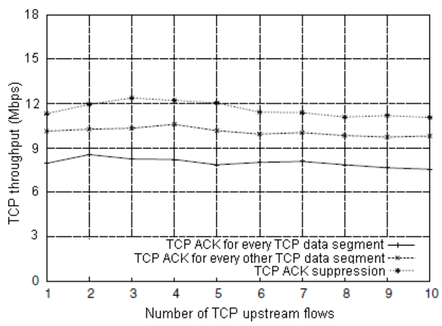


Fig. 4. Total TCP throughput as function of no. of upstream flow

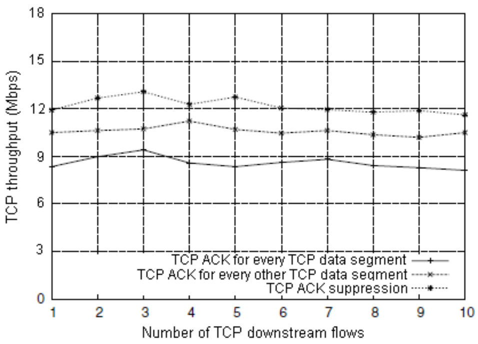


Fig. 5. Total TCP throughput as function of no. of downstream flow

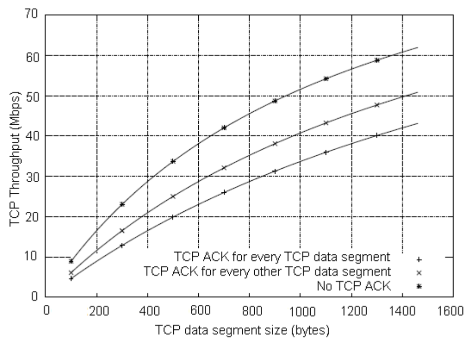


Fig. 6. TCP throughput as function of TCP segment size

B. Quantifying TCP Overhead for ACK Packets

Let *basic_Rate* and *channel_Rate* be the basic and channel data rate; *rts*, *cts*, and M_{ack} be the sizes of the RTS, CTS, and ACK frame; ***rifs*** (Reduced Interframe Space) and ***difs*** (Distributed Coordination Function Interframe Space) be the RIFS and DIFS interval in the IEEE 802.11n protocol. Additional, let Htcp and Hmac be the header sizes of a TCP segment and a MAC frame (including preamble). The transmission time for a TCP data segment of size ***s*** is computed as follows:

$$T_{data} = difs + 3 * rifs + \frac{rts + cts}{basic\_rate} + \frac{s + H_{tcp} + H_{mac} + M_{ack}}{channel\_Rate} \tag{4}$$

Likewise, the transmission for a TCP ACK packet is computed as follows:

$$T_{ack} = difs + 3 * rifs + \frac{rts + cts}{basic\_rate} + \frac{H_{tcp} + H_{mac} + M_{ack}}{channel\_Rate} \tag{5}$$

If n is the average number of TCP ACKs generated by a TCP receiver of a TCP data segment and if all TCP ACKs are suppressed, $n = 0$. If a TCP receiver sends a TCP ACK for *every other* TCP data segment, $n = 0.5$. If a TCP receiver sends a TCP ACK for every TCP data segment, $n = 1$. The throughput of a long-lived TCP flow is computed as follows:

$$Throughput_{TCP} = \frac{s}{T_{data} + n * T_{ack}} \tag{6}$$

Fig. 6 depicts the throughput of a long-lived TCP flow over an 802.11n 40MHz channel with 5 GHz radio as a function of the TCP data segment size s. The following typical setting of an 802.11n network: *basic_Rate* = 6.5 Mbps, *channel_Rate* = 540 Mbps for 40MHz channel, *rifs* = 16 μs, *difs* = 50 μs, *rts* = 44 bytes, *cts* = 40 bytes, *Hmac* = 40 bytes, and *Htcp* = 40 bytes were used in the simulation. As expected, TCP throughput increases with the TCP data segment size since the overhead (RTS/CTS and protocol overhead) is made better. Further, as can be seen in Fig. 6, TCP throughput can be improved by approximately 50% if TCP ACKs are suppressed.

C. Design Synopsis for TCP Throughput

This section presents a technique to remove TCP ACK overhead packets by influencing the layer coordination between TCP and MAC in 802.11n wireless networks. The technique exploits the reality that the IEEE 802.11n protocol which came from IEEE 802.11 de facto standard, have an already implemented, a semi-reliable transmission with each data frame encapsulating an IP packet transmitted on the wireless medium and is succeeded by an ACK frame that acknowledges the successful transmission of the data frame. Fig. 2 is the design structure for the TCP throughput. We note that transmissions provided by the IEEE 802.11n protocol are semi-reliable because retransmissions for *RTS* and a *reduced* data frame are performed up to *ShortRetryLimit* times and for a long data frame up to *LongRetryLimit* times. After that, the data frame is dropped and higher layer is notified of the failed transmission. *ShortRetryLimit* and *LongRetryLimit* are configurable parameters with default values of 4 and 7 respectively.

As shown in Fig. 7a, the access point accumulates TCP data packets originating from fixed hosts on the Internet in a packet buffer and subsequently transmits these packets to wireless stations. When a TCP data packet is successfully transmitted across the wireless link, the access point removes the TCP data packet from its internal buffer, generates a TCP ACK packet for the TCP data packet, and sends the TCP ACK packet to the fixed host. Outgoing TCP ACK packets at the wireless stations are intercepted and suppressed by the Wireless Coordination Protocol (WCP) layer shown in Fig. 2. If notified of any failed transmission of a TCP data packet, WCP at the access point passes down that TCP data packet to the MAC layer again and initiates a retransmission. In Fig. 7b, the access point caches TCP data packets originating from wireless stations in a packet buffer and forwards them to fixed hosts on the Internet. WCP at the access point performs the following tasks for upstream TCP flows: (a) it intercepts and suppresses TCP ACK packets from fixed hosts in the Internet to save bandwidth resource of the wireless link. (b) Since TCP data packets may be lost in the Internet, WCP at the access point has to detect (and drop) duplicate TCP ACKs from fixed hosts in the Internet, and retransmits the lost TCP data packets. (c) WCP at the access point will need to maintain a congestion window that dictates the maximum number of TCP data packets allowed for an upstream TCP flow to avoid causing congestion in the Internet.

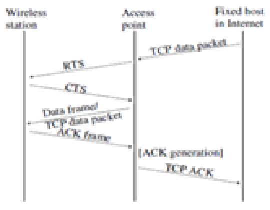


Fig. 7. (a)

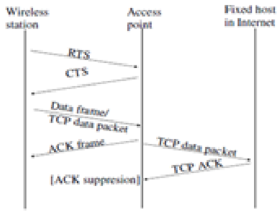


Fig. 7. (b)

V. SIMULATION RESULTS

The simulation was conducted in Matlab R2012a to quantify the effects of ACK suppression on both upstream and downstream data flow in TCP data packets. When TCP ACKs are suppressed an improvement in bandwidth is observed. The simulation topology is shown in Fig. 3 and models a scenario where N wireless stations are placed within the coverage distance of an access point. The wireless network under consideration is 802.11n with a base rate of 6.5 Mbps and a channel data rate of up to 540 Mbps or slightly higher. The TCP segment size is set to 1460 bytes. The numbers of upstream and downstream TCP flows were varied; the results are shown in Fig. 4 and 5. Fig. 8a and 8b are the packet error rate (PER) plot and simulation screenshot for the PER simulation.

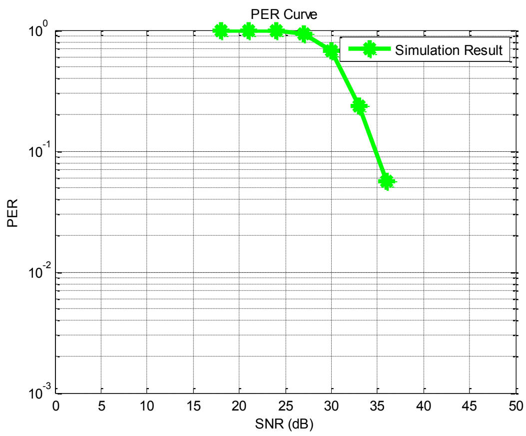
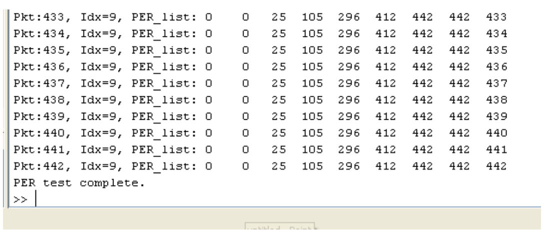


Fig. 8. (a) PER plot as function of SNR



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Pkt:433, Idx=9, PER_list: 0    0   25  105  296  412  442  442  433
Pkt:434, Idx=9, PER_list: 0    0   25  105  296  412  442  442  434
Pkt:435, Idx=9, PER_list: 0    0   25  105  296  412  442  442  435
Pkt:436, Idx=9, PER_list: 0    0   25  105  296  412  442  442  436
Pkt:437, Idx=9, PER_list: 0    0   25  105  296  412  442  442  437
Pkt:438, Idx=9, PER_list: 0    0   25  105  296  412  442  442  438
Pkt:439, Idx=9, PER_list: 0    0   25  105  296  412  442  442  439
Pkt:440, Idx=9, PER_list: 0    0   25  105  296  412  442  442  440
Pkt:441, Idx=9, PER_list: 0    0   25  105  296  412  442  442  441
Pkt:442, Idx=9, PER_list: 0    0   25  105  296  412  442  442  442
PER test complete.
>>
```

Fig. 8 (b) Screenshot of PER simulation

VI. CONCLUSION

MIMO-OFDM system simulations was performed using IEEE 802.11n standard, with data rate range between 6.5Mbps (base rate) to 540Mbps (channel data rate). Simulation results confirm performance improvement on bandwidth as a result of TCP ACK suppression for both uplink and downlink data flow. Results showed an improvement in throughput efficiency over 10 nodes, which demonstrate performance improvement of TCP ACK suppression up to 50% in comparison with receiver policy of acknowledging every TCP data segment and approximately 20% when compared with receiver's policy of acknowledging every TCP data segment in the network.

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