Empirical Investigation on the Dependence of TCP Upstream Throughput on SNR in an IEEE802.11b WLAN System

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Abstract— **An empirical investigation on the dependence of TCP upstream throughput against signal to noise ratio (SNR) in an IEEE802.11b WLAN system was carried out in various environments and varieties of QoS traffic. The TCP upstream throughput ($TCP_{up}T$) was measured for various SNR observed. An Infrastructure based IEEE802.11b WLAN system having networked computers on which measurement software were installed, was set up consecutively in various environments (open corridor, small offices with block walls and plaster boards and free space). Empirical models describing the $TCP_{up}T$ against SNR for different signals ranges (all ranges of signals, strong signals only, grey signals only and weak signals only) were statistically generated and validated. Our results show a strong dependence of $TCP_{up}T$ on the received SNR which varied as the SNR values changed from high (strong signals) through low (grey signals) to very low (weak signals). Our models showed lower RMS errors when compared with other similar models. We observed RMS errors of 0.5431955Mbps, 0.447938789Mbps, 1.04536603Mbps and 0.4503096Mbps for all SNR model, strong signals model, Grey signals model and Weak signals model respectively. Our models will provide researchers and WLAN systems users with a tool to estimate $TCP_{up}T$ in a real network in various environments by monitoring the SNR.**

Keywords— ***TCP upstream throughput, Signal to noise ratio, empirical model, IEEE802.11b, WLANs***

I. INTRODUCTION

The need to access internet services in a fast and convenient way, anywhere and anytime has resulted in the ever growing demand for several wireless technologies and more bandwidth to access internet services [1]. Today transmission control protocol (TCP) accounts for over 80% of all the traffic in the Internet and there is no indication that its share will decline in the near future [2, 3]. Predicting the performance of TCP is therefore necessary for better understanding of modern systems which use TCP to access the internet. Several WLAN systems are based on the IEEE802.11 WLAN standard which allows different layers, a configuration that provides optimized functionality for wireless communication [4]. The physical layer of the IEEE802.11 standard specifies multiple communication data rates that vary depending on the quality of the current link which is typically measured by looking at the signal to noise ratio (SNR) which is the predominant metric for determining when to change the Data Link Rate (DLR) [5]. WLAN systems uses link adaptation where stations choose a data rate depending on underlying channel conditions which is predominantly the SNR sensed by the stations.

When the SNR available to a station increases, it uses higher data rates to transmit its frame, hence reaching closer to channel capacity. Thus, link adaptation in WLAN changes the throughput behaviour of WLAN significantly [6]. Most WLANs operate in indoor environments where there is no direct line of sight path between the transmitter and the receiver and where the presence of walls, office furniture and equipment, humans, etc. causes severe diffraction losses. Also, due to multiple reflections from various objects in the wireless physical channel, the electromagnetic waves travel along different paths of varying lengths with interactions between the waves leading to significant power fluctuations of the received signal due to fading which has significant impact on the SNR which determines the selected DLR. The DLR variations which are caused by channel condition variations have effects on both the average throughput attainable for a given average SNR and the variation in throughput observed [5].

Throughput (an important WLAN performance metric), is a measure of the average rate that data (in bits) can be sent between one user and another and is typically measured in kilobits per second (Kbps) or megabits per second (Mbps) [7]. Throughput is what the user sees after overheads. The throughput of the same network connection can vary greatly depending on the protocol used for transmission, the type of data traffic being sent as well as the quality (SNR) and data bandwidth of a network connection [7]. Throughput is an example of a transport layer performance parameter because it defines the actual rate obtained by the transport layer protocol such as TCP or UDP. Loss in performance of WLAN systems with respect to throughput obtained has been attributed to (i) the varying nature of the wireless channels resulting in incorrect reception of channel symbols at the physical layers,

(ii) packet loss probability due to packet collisions and inefficiency of error correction schemes or mechanisms for the received channel symbols and (iii) queuing process and buffer overflows at the IP layer [1, 8]. In TCP, losses trigger congestion control algorithm which reduces the sending rate and the retransmission of lost packets.

Cross-layer modelling principles consisting of three basic steps (Wireless channel modelling, Cross-layer extension of the wireless channel of interest to the layer of interest and Performance evaluation at the layer of interest) have been suggested to provide the practical methodology to evaluate the effects of wireless channel characteristics, channel adaptation mechanisms and buffering process at the IP layer on the throughput of TCP connections sharing a wireless bottleneck [2]. These mathematical models at each step of the cross-layer modelling, is independent of each other hence a model applied at one layer can be replaced by a better one at another higher layer to obtain better results of the overall performance of the WLAN system. The cross layer modelling of the aggregate performance of the WLAN system is difficult when approached analytically. According to [1], each wireless application is characterised by its own traffic and environmental (or propagation) characteristics as well as its own protocols and their parameters hence; the performance that a given application achieves is a complex function of the properties and interactions between these components which are often difficult and complicated to analytically model. Carrying out extensive measurements by measuring TCP throughput at the transport layer while varying the SNR at the physical layer, will help to provide data that will aggregately provide sufficient information of the WLAN system performance over an aggregate of different layers in various real life environments. In this case, all processes involved between the lower layer (e.g. physical layer) and the higher layer (e.g. transport layer) where measurement is taken are implicitly taken into account regardless of whether they can or cannot be isolated or separately recognised. SNR can be varied at the physical layer by varying distance of the Client system from WLAN system or radio. In this paper, we discuss our empirical findings on the dependence of TCP upstream throughput (data speed in Mbps sent from Client to WLAN radio) measured at the transport layer against the received SNR varied at the physical layer by varying receiver position in an IEEE802.11b WLAN system. Although IEEE802.11 WLAN system is an Old technology, it still provides the largest range possible which makes it useful for applications where range rather than data speed is more important [9].

Section 2 discusses related work to this study. Section 3 presents the method employed giving details of experimental set up, the data collection process and the method of analysis. Section 4 and 5 presents the models developed from the field data along with their discussion. Our models are also compared with other models and validation measurements taken in different real-environments by estimating the RMS errors. Section 6 gives direction for future work, section 7 concludes the work.

II. REVIEW OF PAST WORK

Several models have been developed which capture different aspects of the performance characteristics of WLANs. Propagation models [10, 11, 12] captured the path loss and SNR process of IEEE802.11 wireless channels at the physical layer. Another set of models are Protocol data units (PDU) error models which include symbol, bit and frame error models [13, 14]. The RSSI, SNR, or PDU, bit or frame error models, already mentioned though useful for design of transceivers, cannot be directly used in performance evaluation studies hence they must be properly extended to higher layers which provide convenient characterization of the dynamic nature of a wireless channel at the layer of interest [1]. This has led to the development of cross layer modelling[15, 16, 17] which allows us to numerically quantify the effect of various parameters of channel adaptation mechanisms on the performance provided to various applications. To the best of the Authors knowledge, although numerous works has been done in estimating the throughput performance of WLANs [6, 18] most of the approach has not focused on modelling the throughput measured at the transport layer while varying the SNR at the physical layer.

In this paper, we do not focus on PDU, bits and frame errors neither on the arrival of particles to describe the traffic characteristics of a source at the IP layer but on the characterisation of the dependence of $TCP_{up}T$ (data sent from a Client to WLAN radio) measured at the transport layer on SNR varied at the Physical layer. All processes and mechanisms in the layers in between these two extreme layers are implicitly taken into account regardless of whether they can or cannot be isolated or separately recognised. Some researchers [7, 5, 18] have used our method in their work. [18] measured uplink and downlink signal strength from a Network Interface Card while monitoring the Packet error rate at the data link layer and the throughput at the transport layer. Their work however used UDP traffic and was based on IEEE802.11n WLAN system and they proceeded to incorporate link layer measurements into an analytical (Markov) model to obtain improved throughput and PER prediction hence we cannot directly compare our results with theirs. Authors in [5, 7] used our approach and worked on IEEE802.11b even though they did not investigate under a wide variety of traffic and physical environments as we did. We estimated their model parameters from our field data and compared them with our models.

III. RESEARCH METHOD

An infrastructure based IEEE802.11b WLAN system from a vendor (Ubiquiti Networks) having networked computers on which measurement software (tamosoft throughput test and inSSIDer 2.1) were installed, was set up in the various environments (Corridor, Small Offices, and Free space) consecutively. Antenna polarization of the WLAN radio was selected as horizontal and Internet Protocol Version4 (IPV4) was selected for all sets of measurements in all the chosen environments. A Server and a Client supported by the software (tamosoft throughput test) installed in the Computers were used to send different Quality of service (QoS) traffic which corresponds to different Wireless Multimedia Extension (WME) over the network through the WLAN radios. The inSSIDer 2.1 software was used to measure the received signal strength indication (RSSI) in dBm, and to monitor interfering access points so as to make the decision of which channel to use for measurement. The noise floor level was observed by logging into the WLAN radio from either the client or server computer. We measured $TCP_{up}T$ (using Tamosoft throughput Test software) for each RSSI or SNR observed at a particular time in a particular position. Several positions spaced far apart were chosen for measurement in each environment. At each position, three close sub positions (about 0.7m apart) were used to take measurements so as to have a wider spread of RSSI values for which data is collected. At each sub position, three measurements of all the variables studied were taken with the Client Computer facing North, East, South and West, consecutively. We categorised the collected $TCP_{up}T$ data for all types of QoS traffic in all environments into four categories using the received SNR. Using SPSS and Microsoft excel we ran regressions to develop models for $TCP_{up}T$ as dependent variables. From all data collected (and not from the average values) we statistically developed one model which relates $TCP_{up}T$ with SNR in each category: (i) All signals considered, (ii) Strong signals (SNR>25dB), (iii) Grey signals (25dB>SNR>18dB) and (iv) weak signals (SNR<19dB) and compared them with the validation data collected in different environments from where we initially gathered data. RMS errors for our model and other models were compared for the different signal ranges to evaluate their performance.

IV. STATISTICAL DESCRIPTION OF VARIABLES

Table I shows the statistical parameters for $TCP_{up}T$ for different cases of SNR both for our original and validation data. Fig.1. shows the plot of the Average, Standard deviations and Standard Error of the means observed in $TCP_{up}T$ for the different SNR values respectively. The ranges of the different SNR values are also shown in the table headings. From Table1, it can be seen that the standard deviation (1.81327Mbps) obtained for all values of SNR considered is high. This implies that $TCP_{up}T$ varies considerably over the entire range of RSSI from strong signals through grey signals to weak signals. Also the standard deviation (1.54209Mbps) obtained for all grey signals only were also high. This was found to be so even though the range of SNR (6dB) is small for all grey signals. This happens because the error control mechanism adjusts the transmission rate to lower values so as to reduce errors in packet transmission as signal becomes weak. The variation occurs as the selected transmission rate fluctuates between higher, medium and lower values of transmission rates thus resulting in high, medium and low $TCP_{up}T$ values observed.

Grey signals also showed a bimodal distribution occurring at class intervals (0-1) Mbps and (2-3) Mbps. However the Standard deviation obtained for strong signals (0.64389Mbps) and weak signals (0.67621Mbps) were much lower indicating that TCPupT does not vary significantly under such conditions of SNR, a useful result that shows that TCPupT does not vary considerable even though the SNR range (39dB) for strong signals is large. The results implies that the transmission rate selected for strong signals is appreciably constant and always high while that selected for weak signals is also approximately constant and always low.

TABLE I. STATISTICAL PARAMETER VALUES OF TCPUPT FOR DIFFERENT CASES OF RECEIVED SIGNAL STRENGTH

Statistical Parameter	ALL RSSI (SNR) considered (63dB $\geq SNR \geq 13dB$)		Strong Signal (SNR ≥ 25dB)	
	$TCP_{up}T$ Field data	$TCP_{up}T$ Validation data	$TCP_{up}T$ Field data	$TCP_{up}T$ Validation data
N (Sample Size)	1885	762	1506	568
Mean	5.1038	4.7366	5.8942	5.6502
Std. Error of Mean	0.04176	0.06978	0.01659	0.03585
Median	5.8800	5.6100	6.0700	5.8550
Mode	6.20	6.18* and 6.23*	6.20	6.18* and 6.23*
Std. Deviation	1.81327	1.92635	0.64389	0.85452
Variance	3.288	3.711	0.415	0.730
Coefficient of dispersion	0.35528	0.40670	0.109241	0.1512371
Skewness	-1.601	-1.219	-2.332	-2.198
Kurtosis	1.257	0.034	6.406	5.874
Range	6.84	6.54	4.05	5.75
Statistical Parameter	Grey signal (25dB>SNR≥19dB)		Weak Signal (SNR<19dB)	
	$TCP_{up}T$ Field data	$TCP_{up}T$ Validation data	TCP_{Up} Throughput Original data	TCPupT Validation data
N (Sample Size)	316	98	63	96
Mean	2.2078	3.1284	0.736	0.9726
Std. Error of Mean	0.08675	0.16686	0.08519	0.07943
Median	2.31	3.2900	0.47	0.7100
Mode	0.17*, 0.41*, 2.61*	0.79	0.11	0.63* and 0.64*
Std. Deviation	1.54209	1.65186	0.67621	0.77826
Variance	2.378	2.729	0.457	0.606
Coefficient of dispersion	0.6985	0.528021	0.91876	0.8001851
Skewness	0.461	-0.139	1.079	2.367
Kurtosis	-0.474	-1.236	0.282	8.021
Range	6.24	5.50	2.4	5.06

*Multiple mode exist

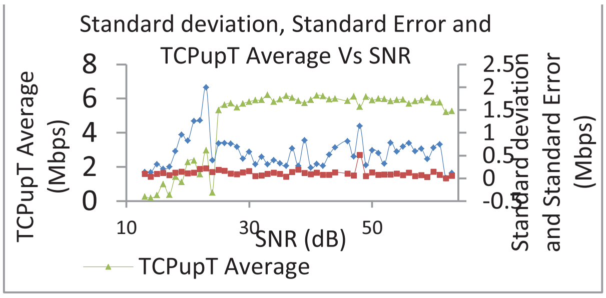

Fig. 1. Graph of Standarad deviation, Standard error and Average values of TCPupT against SNR.

The coefficient of dispersion is lowest for strong signals (0.109241) even though this range covers the largest range (39dB) of all RSSI values considered.

V. DEVELOPMENT OF THROUGHPUT MODELS

Equations 1, 2, 3 and 4 show our different model equations for general model (all SNR), strong signal model, Grey signal model and Weak signal model respectively.

(General) $TCP_{up}T = f(SNR) =$

$$\begin{cases} C_1, & SNR > 38dB \\ a_1\mathrm{SNR} + a_2SNR^2 + a_3SNR^3, & 39dB > SNR > 16dB \\ |a_1\mathrm{SNR} + a_2SNR^2 + a_3SNR^3 - C_2|, & 17dB > SNR \end{cases} \quad \ldots\ldots\ldots\ldots 1$$

(Strong) $TCP_{up}T = f(SNR) = SNR^{a_1}$ ……………………….2

(Grey) $TCP_{up}T = f(SNR) = a_1\mathrm{SNR}$ ………………………..3

(Weak) $TCP_{up}T = f(SNR) =$

$$\begin{cases} a_1SNR^2 + a_2SNR^3, & 19dB > SNR > 11dB \\ 0 & ,SNR \le 11dB \end{cases} \quad \ldots\ldots\ldots\ldots 4$$

The parameters of the model are shown in Table II. Table III shows the RMS errors for our model and other models when they were compared with validation data. Table IV shows comparison of RMS errors of our different models

TABLE II. PARAMETERS OF OUR MODELS.

S/N	Model Description	R^2 value	SE of the estimate (Mbps)	F value	Level of significance of the model	Level of significance of the model coefficients
1	General model	0.958	1.109	$F_{0.0\%,3,1882}$ =17661	0.000%	0.000%
2	Strong signals model	0.991	0.147	$F_{0.0\%,1,1505}$ =158888.1	0.000%	0.000%
3	Grey signals model	0.683	1.518	$F_{0.0\%, 1, 315}$ =678.998	0.000%	0.000%
4	Weak signals model	0.756	0.499	$F_{0.0\%, 2, 61}$ =94.731	0.000%	0.000%

TABLE III. RMS ERROR VALUES WITH RESPECT TO VALIDATION DATA FOR OUR MODELS AND OTHER MODELS.

RMS errors observed for All SNR			
Model description	***Our general model for all SNR***	***Error for Metreaud Multi tap Model C***	***Metreaud Multi tap model B***
RMS error (Mbps)	0.5431955	1.851443724	1.734492517
Model description	***Metreaud One tap model A***	***Metreaud One tap Constant Channel***	***Henty Exponential Model (single User)***
RMS error (Mbps)	1.82267584	2.40992165	1.412721882
RMS errors Observed for Strong signals			
Model description	***Our Strong signal model***	***Error for Metreaud Multi tap Model C***	***Metreaud Multi tap model B***
RMS error (Mbps)	0.447938789	0.607464282	0.59288230
Model description	***Metreaud One tap model A***	***Metreaud One tap Constant Channel***	***Henty Exponential Model (single User)***
RMS error (Mbps)	0.55117975	0.61486956	0.519172932
RMS Errors observed for Grey signals			
Model description	***Our Grey signal model***	***Error for Metreaud Multi tap Model C***	***Metreaud Multi tap model B***
RMS error (Mbps)	1.04536603	3.7286058	3.7095765
Model description	***Metreaud One tap model A***	***Metreaud One tap Constant Channel***	***Henty Exponential Model (single User)***
RMS error (Mbps)	3.7656603	3.7381242	2.2700362
RMS Errors observed for Weak signals			
Model description	***Our Weak signals model***	***Error for Metreaud Multi tap Model C***	***Metreaud Multi tap model B***
RMS error (Mbps)	0.4503096	3.4830047	3.0945189
Model description	***Metreaud One tap model A***	***Metreaud One tap Constant Channel***	***Henty Exponential Model (single User)***
RMS error (Mbps)	3.4054695	5.2453346	0.563339

TABLE IV. COMPARISON OF RMS ERRORS FOR OUR DIFFERENT MODELS FOR TCPUPT.

<table>
<tr><td rowspan="2">Model description</td><td>General model</td><td colspan="4">Strong signals only</td></tr>
<tr><td>General model only</td><td>Strong signal model</td><td colspan="3">General model but limited to Strong Signal range</td></tr>
<tr><td>RMS error (Mbps)</td><td>0.5431955</td><td>0.447938789</td><td colspan="3">0.473524853</td></tr>
<tr><td rowspan="2">Model description</td><td colspan="2">Grey signals only</td><td colspan="3">Weak signals only</td></tr>
<tr><td>Grey signals only model</td><td>General model limited to Grey Signal range</td><td colspan="2">Weak signals only model</td><td>General model limited to Weak Signal range</td></tr>
<tr><td>RMS error (Mbps)</td><td>1.04536603</td><td>0.959322</td><td colspan="2">0.4503096</td><td>0.516733</td></tr>
</table>

Our models performed better (show lower RMS errors) in all cases considered. The very high RMS error observed for Metreaud's models for grey and Weak signal ranges are so because the authors used UDP traffic in their experiments and also developed their models from isolated test beds which are completely free from interference and are not representative of real life scenarios.

VI. FUTURE RESEARCH DIRECTION

This work focused on developing models that will enable researchers and WLAN users to quickly estimate $TCP_{up}T$ for various observed values of SNR when there is a single user on the network. This work opens the door for several other researches which are necessary to fully describe the dependence of TCPupT on SNR. There is the need to extend the research to IEEE802.11g/n/e WLAN systems, TCP downstream throughput and also to multiple users on the network which is usually the case in a real network. Also, additional means of predicting the throughput obtained under different conditions using probability and Round trip time (RTT) models need to be considered. It is also necessary that models specifically developed for specific traffic types (Voice or audio, video, control, etc.) corresponding to different WMM tags and specific environments be considered. WLAN systems from other vendors can also be used to repeat this research and the results compared with what was obtained here. Most of these concerns are already being considered by us in our on-going research.

VII. CONCLUSION

In this paper, we discussed our empirical findings on the dependence of TCPupT measured at the transport layer against the received SNR varied at the physical layer. We studied the dependence of TCPupT on SNR over a wide range of signals (Strong, Grey and Weak). Our models estimate the throughput with low RMS errors observed when they were compared with data from other environments. Our models showing lower RMS errors also performed better than other similar models considered. This study provides researchers and WLAN systems users with a tool to quickly estimate TCPupT in a real IEEE802.11b WLAN in various environments by monitoring SNR.

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REFERENCES

[1] D. Moltchanov, "Performance models for wireless channels" Computer Science Review 4(2010) pp153 – 184, 2010.

[2] D. Moltchanov, "A study of TCP performance in wireless environment using fixed-point approximation" Computer Networks 56 (2012) 1263–1285, 2012.

[3] P. Loiseau, P. Gonçalves, J. Barral,. and V. P. Primet, "Modeling TCP throughput: An elaborated large-deviations-based model and its empirical validation" Performance Evaluation Vol. 67 pp1030–1043, 2010.

[4] D. D. Lachhman, A. Shazia, A. S. Asad and A. M. Yasir, "Performance Analysis of WLAN Standards for Video Conferencing Applications" International Journal of Wireless & Mobile Networks (IJWMN) Vol. 3, No6. pp 59-70, 2011.

[5] L. T. Metreaud, "An RF-Isolated Real-Time Multipath Test bed for Performance Analysis of WLANS" Masters of Science in Electrical and Computer Engineering Thesis. Worcester Polytechnic Institute. pp1-123, 2006.

[6] M.H. Mahmood, C. Chang, D. Jung, Z. Mao, H. Lim, and H. Lee, "Throughput behavior of link adaptive 802.11 DCF with MUD capable access node" Int. J. Electron. Commun. (AEU) Vol.64 (2010) 1031 – 1041, 2010.

[7] B.E Henty, "Throughput Measurements and Empirical Prediction Models for IEEE 802.11b Wireless LAN (WLAN) Installations" Masters of Science in Electrical Engineering Thesis, Virginia Polytechnic Institute and State University, 2001. Retrieved 21/08/12 at http://scholar.lib.vt.edu/theses/available/etd-08142001-172523/unrestricted/hentythesis.pdf

[8] A. Detti , N. Blefari-Melazzi, I. Habib and A. Ordine "Per-station throughput fairness in a WLAN hot-spot with TCP traffic" Computer Networks Vol. 55 pp1820–1833, 2011.

[9] R. Khanduri, S. S. Rattan "Performance Comparison Analysis Between IEEE802.11a/b/g/n Standards" International Journal of Computer Applications. Vol 78 No1, pp13-20, 2013.

[10] F. Heereman, W. Joseph, E. Tanghe, D. Plets, L. Verloock. and L. Martens "Path loss model and prediction of range, power and throughput for 802.11n in large conference rooms" Int.J.Electron.Commun.(AEÜ) Vol.66 pp561–568, 2011.

[11] S. Phaiboon, P. Phokharatkul, S. Somkuarnpanit "New upper and lower bounds line of sight path loss model for mobile propagation in buildings" AEU International Journal of Electronics and Communications Vol.62(3) pp207–215, 2008.

[12] E. E. Mantilla, C. R. Reyes and B.G. Ramos "IEEE 802.11 b and g WLAN Propagation Model using Power Density Measurements at ESPOL". World Academy of Science, Engineering & Technology.Vol70 93-96, 2010.

[13] S. Khayam, H. Radha, "Markov based modeling of wireless local area networks" ACM MSWiM. San Diego, US, September, 2003, pp. 100-107.

[14] V. Kolar, S. Razak., P. Mähönen. and N. B. Abu-Ghazaleh "Link quality analysis and measurement in wireless mesh networks". Ad Hoc Networks 9 (2011) 1430–1447, 2011.

[15] X. Lin, N. Shroff, R. Srikant, "A tutorial on cross-layer optimization in wireless networks" IEEE JSAC 24 (8), 2006.

[16] M. Bohge, J. Gross, A. Wolisz, M. Meyer, "Dynamic resource allocation in OFDM systems: an overview of cross-layer optimization principles and techniques" IEEE Netw. 21 (1) pp 53-59, 2007.

[17] K. Hung., B. Bensaou "Throughput optimization in wireless local networks with inter-AP interference via a joint-association control, rate control, and contention resolution" In press Ad Hoc Netw., doi: 10.1016/j.a dhoc.2 011.08.004, 2011.

[18] B. Ng, Y.F. Tan, S. W. Tan, S.W. Lee, "Throughput and PER estimates harnessing link layer measurements for indoor 802.11n WLAN" Computer Standards & Interfaces Vol.34 (2012) 135– 145, 2012.