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Measurement and modelling of TCP downstream throughput dependence on SNR in an IEEE802.11b WLAN system

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Abstract This paper presents our study on the dependence of TCP downstream throughput ($\text{TCP}_{\text{down}}\text{T}$) on signal to noise ratio (SNR) for multiple users in an IEEE 802.11b Wireless Local Area Network (WLAN) system. The study was carried out in small offices, open corridors and free space environments using an infrastructure based IEEE 802.11b WLAN while transmitting different quality of service (QoS) traffic all corresponding to different wireless multimedia tags. Models describing $\text{TCP}_{\text{down}}\text{T}$ against SNR for different signal categories were statistically generated and validated. Our findings show a large variation in the throughput behaviour of the IEEE 802.11b WLAN system for the different categories of signals. We observed RMS errors of 0.938012 Mbps, 1.047012 Mbps, 0.65833 Mbps and 0.452927 Mbps for the general (all SNR) model, strong signals model, grey signals model and weak signals model respectively which were much lower than that of similar models with which they were compared. Comparing our results with a previous work on TCP upstream throughput showed that it is more accurate to investigate upstream and downstream throughput separately. Our models enable network designers and installers to predict the $\text{TCP}_{\text{down}}\text{T}$ without the need to measure additional parameters other than the observed SNR which is already part of the normal network installation process.

1. Introduction

Today's global activities are increasingly and continuously being influenced by the Internet (Mohammed, 2011). Wireless Local Area Networks (WLANs) have become very useful for providing Internet services to many computers within organizations. The use of LANs, WLANs, Intercom systems, VoIP networks, etc. for communication within an organization and between two or more organizations has greatly helped to

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enhance efficiency and performance of these organizations at only the cost of installation and maintenance of these networks and systems (Oghogho and Ezomo, 2013; Oghogho et al., 2012). The most common architecture of WLANs used by most organizations is the infrastructure based network where one system is used as a server while others are used as clients. The server runs most or all of the application software and programmes while the client systems simply connect to the server through either an Ethernet (wired) interface or a wireless medium to access an application.

Transmission control protocol (TCP) used by WLANs constitutes about 80% of all the traffic on the Internet (Moltchanov, 2012; Loiseau et al., 2010). A good and well-designed network is basically evaluated by the throughput and round trip time (RTT) that the users experience for a given signal to noise ratio (SNR) received (Geier, 2008). Most WLAN implementations must support a minimum throughput before they can be said to provide adequate coverage (Geier, 2008). Predicting the performance of TCP throughput is therefore necessary for better understanding of the performance of WLANs.

From our experience on network design and installation, several network designers only focus on the received signal strength at different locations but do not have the time to deploy several client systems on the network so as to collect large volumes of throughput data at different locations on the network in order to determine the network performance for multiple users (Isiagbona and Obahiagbon, 2013). They however use Internet control message protocol (ICMP) for estimating the throughput. The throughput calculated by ICMP is a rough estimate of the actual value (Mitchell, 2014; Rouse, 2014). This is so because ICMP is a network layer protocol hence the throughput value it predicts is appreciably different from the throughput predicted at the transport layer due to additional overheads. The transport layer is closer to the application layer hence the throughput predicted at the transport layer is more representative of what the users will experience, hence the designed network can fall short of user's expectations after they are commissioned.

By not taking large volumes of throughput data at various locations on the network, the hidden node problem is therefore ignored and not considered in such instances. The hidden node problem occurs when a station attempts to access and use network resources (transmit its own data) because it cannot sense that another station with a weak signal (usually far away from the WLAN radio or the station attempting to transmit its data) is already transmitting its data hence packet collision will occur which degrades the throughput observed (Hung and Bensaou, 2011).

Network designers are constrained to continue to use pinging because available network throughput estimation tools such as Tamosoft throughput test, QCHECK, IxChariot, etc. require lots of time and network resources while available off network throughput models require lots of parameters to be specified (Padhye et al., 2000; Moltchanov, 2010; Gupta et al., 2011; Zhu et al., 2012; Wu et al., 2011; Detti et al., 2011; Loiseau et al., 2010; Ye and Abouzeid, 2010; Hung and Bensaou, 2011; Panda and Kumar, 2012; Tian and Tian, 2012).

Since Network designers presently proceed with WLAN design by measuring received signal strength indication (RSSI) at different positions, can throughput be modelled as functions of SNR only within reasonable accuracy? This will provide a handy tool to WLAN designers without necessarily increasing the parameters they must measure and specify during WLAN design and installation. According to Mahmood et al. (2010), link adaptation process where an increase in the SNR sensed by a station prompts it to use higher data rates for frame transmission changes the throughput behaviour of WLANs appreciably. It therefore follows that by applying cross layer modelling principles (Moltchanov, 2012), the possibility of modelling throughput as a function of SNR only with reasonable accuracy exists. This paper presents our research findings towards providing this tool.

2. Review of past work

To tackle the challenge of providing models for predicting TCP throughput based on observed SNR some researches have applied cross layer modelling principles. Henty (2001) provided models for predicting TCP throughput for single and two users as functions of the received SNR. However their models did not differentiate between upstream and downstream throughput and were limited to two users which does not adequately represent a saturation condition where each client always has a packet to transmit (Wu et al., 2011). Metreaud (2006) also provided throughput models based on received SNR but used UDP traffic. The Author did not also differentiate between upstream and downstream throughput and the models were also limited to a single user on the network. Ikponmwosa et al. (2014) modelled TCP upstream throughput based on observed SNR for a single user while Oghogho et al. (2015a) provided models for predicting TCP upstream throughput as a function of SNR both for single and multiple users. These two models were limited to upstream throughput hence they cannot be applied for predicting TCP downstream throughput with reasonable accuracy as was confirmed in this paper.

Oghogho et al. (2014) provided empirical probability models which predict the probability of having a TCP downstream throughput value depending on the category of signal strength (strong, grey or weak) but do not predict the TCP downstream throughput value for a SNR observed. Oghogho et al. (2015b) developed models for predicting TCP downstream throughput based on observed SNR for a single user on the network. Their model developed for a single user is limited in adequately describing and predicting multiple users' experience in real life scenarios where each client usually has a packet to transmit (saturation condition). None of these works provided multiple users empirical models for predicting TCP downstream throughput as functions of SNR only. This paper fills this gap.

3. Research method

The method used by Oghogho et al. (2015a) was used in this work except that multiple users are considered and TCP downstream throughput is measured and monitored instead of TCP upstream throughput. The number of users is limited to seven due to the findings of Wu et al. (2011) where seven stations (indicating a saturation condition where each client always has a packet to transmit), gave throughput values that were averagely the mid-point from two extremes (1 station and 16 stations).

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4. Results and discussion

The field data description and the developed models' accompanied discussion are presented in this section using graphs and tables.

4.1. Statistical description of variables

Table 1 shows the statistical parameters of TCP$_{\text{down}}$T data for different cases of SNR. The statistics were generated from collected field data using statistical packages for social sciences (SPSS). The collected data were grouped into four different categories using the SNR. The first category contained all SNR considered, the second category consist of strong signals only ($\text{SNR} \geqslant 25$ dB), the third category consist of grey signals only ($25\text{ dB} > \text{SNR} > 18$ dB) while the fourth category consist of weak signals ($\text{SNR} < 19$ dB).

From Table 1, it can be seen that the TCP$_{\text{down}}$T variance (2.54) and standard deviation (1.59385 Mbps) obtained for all values of SNR considered are high. This implies that TCP$_{\text{down}}$T varies considerably over the entire range of SNR from strong signals, through grey signals to weak signals for multiple users on the network. It was also observed that TCP$_{\text{down}}$T variance (2.205) and standard deviation (1.48491 Mbps) observed for strong signals only was high and not much different from that obtained for all signals. This is a large deviation from the results obtained by Oghogho et al. (2015b) for a single user on the network where the variation of TCP$_{\text{down}}$T was much lower for strong signals.

The observed high variation of TCP$_{\text{down}}$T for multiple users' scenarios when the signal is strong can be explained to have occurred because: (i) There is higher probability of collision of transmitted packets due to increased users who are all attempting to transmit packets simultaneously at high data rates (because the signal is strong) and (ii) There is a higher probability of packet queuing and delays at the buffer located at the WLAN radio or access point due to multiple users on the network. The limit of the capacity of the WLAN access point will constrain the packets to queue and be delayed over longer periods and sometimes retransmission occurs if the packets are lost thus causing further queuing, delays and higher probability of packet loss. The data rate used for data transmission by the system for multiple users therefore varies largely over the entire range of strong signals depending on the conditions just described. When conditions are favourable, a higher data rate is selected and when conditions become poorer, a lower data rate is selected. The large variation of TCP$_{\text{down}}$T indicates that the probability of conditions remaining favourable or poor over a large time interval is low, hence data rate selection fluctuate largely when signal is strong.

TCP$_{\text{down}}$T does not show multiple mode distributions in the strong and grey signal ranges but a multimodal distribution which is spread across different class intervals was observed for weak signals. The variance (3.304) and standard deviation (1.81778 Mbps) obtained for grey signals were also high. This trend was also observed for weak signals but the deviation observed for weak signals was slightly lower than that of grey signals. A positively skewed distribution was observed for the TCP$_{\text{down}}$T obtained for grey signals (1.051) and weak signals (1.493). The observed skewed distribution implies that TCP$_{\text{down}}$T showed a longer tail towards the right of the observed mean of 1.8242 Mbps for grey signals and a longer tail towards the right of the observed mean of 1.4034 Mbps for weak signals. Skewness was positive and low for all signals (0.246) and strong signals only (0.094) showing that no TCP$_{\text{down}}$T class interval dominates under such signal conditions. Weak signals showed a positive kurtosis (1.036) implying a peaked distribution near the mean unlike the negative kurtosis observed for strong (−1.007) and grey (−0.123) signals. Fig. 1 shows the graph of standard deviation, standard errors and average values of TCP$_{\text{down}}$T observed for the field data against SNR.

From the graph of Fig. 1, it can be seen that the average TCP$_{\text{down}}$T observed for the entire signal range varies considerably for the entire range of SNR (from strong through grey to

Table 1 Statistical parameters of TCP$_{\text{down}}$T field data.

Statistical parameter	All SNR values (63 dB to 11 dB)	Strong signals ($\text{SNR} \geqslant 25$ dB)	Grey signals ($25\text{ dB} > \text{SNR} > 18$ dB)	Weak signals ($\text{SNR} < 19$ dB)
	Field data	Field data	Field data	Field data
N (sample size)	1813	1447	334	32
Mean	2.5025	2.6833	1.8242	1.4034
Std. error of mean	0.03743	0.03904	0.09946	0.27455
Median	2.38	2.6900	1.0100	0.79
Mode	0.12*, 4.13	4.13	0.16	0.14*, 0.28, 0.29, 0.57, 1.86, 4.30
Std. deviation	1.59385	1.48491	1.81778	1.55312
Variance	2.54	2.205	3.304	2.412
Coefficient of dispersion	0.63690	0.55339	0.99648	1.10668
Skewness	0.246	0.094	1.051	1.493
Std. error of skewness	0.057	0.064	0.133	0.414
Kurtosis	−1.008	−1.007	−0.123	1.036
Std. error of kurtosis	0.115	0.129	0.266	0.809
Range	7.16	7.16	6.68	5.12

* Multiple modes exist.

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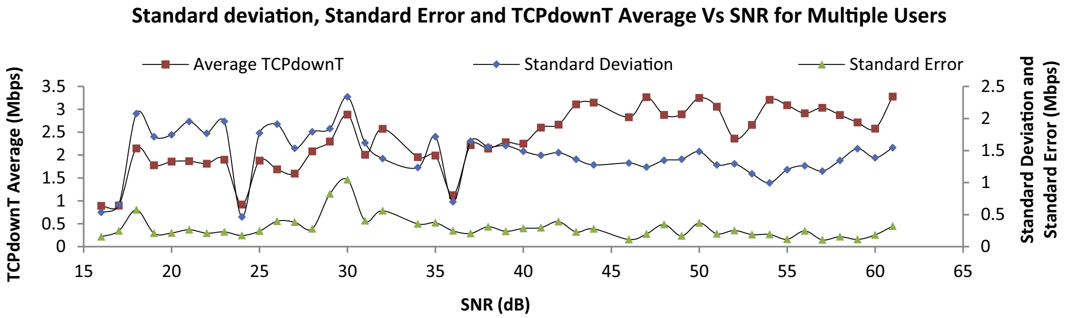

Figure 1 Graph of standard deviation, standard errors and average values of $TCP_{down}T$ observed for the field data against SNR.

weak range) as already discussed. The variation is however low between 54 dB and 60 dB and between 18 dB and 23 dB. Also, the standard deviation is appreciably high for strong, grey and weak signal ranges. However, some signal ranges namely: (i) between 25 dB and 35 dB (strong signals), (ii) between 23 dB and 19 dB (grey signals) and (iii) 18 dB only (weak signals) show the highest standard deviation observed.

4.2. Development of throughput models

Eqs. (1)–(4) show our different model equations statistically generated from field data using SPSS. Models were respectively developed for all SNR considered (general model), Strong signals, grey signals and weak signals. The models were developed using the TCP downstream throughput instantaneous field data values measured for each SNR category. a_1 and a_2 are the model coefficients which were obtained from the field data using SPSS. The equations predict the TCP downstream throughput as a function of SNR only. Eq. (1) can be used to predict TCP downstream throughput for any value of SNR observed. Eqs. (2)–(4) are used to predict TCP downstream throughput for strong, grey and weak signals respectively.

$$(\mathrm{General})\mathrm{TCP_{down}}T = f(\mathrm{SNR}) = a_1\mathrm{SNR} + a_2\mathrm{SNR}^2 \quad \mathrm{SNR} > 9\ \mathrm{dB} \tag{1}$$

$$(\mathrm{Strong})\mathrm{TCP_{down}}T = f(\mathrm{SNR}) = a_1\mathrm{SNR} + a_2\mathrm{SNR}^2 \quad \mathrm{SNR} > 24\ \mathrm{dB} \tag{2}$$

$$(\mathrm{Grey})\mathrm{TCP_{down}}T = f(\mathrm{SNR}) = a_1\ln(\mathrm{SNR}) \quad 18\mathrm{dB} < \mathrm{SNR} < 25\ \mathrm{dB} \tag{3}$$

$$(\mathrm{Weak})\mathrm{TCP_{down}}T = f(\mathrm{SNR})a_1\mathrm{SNR} \qquad \mathrm{SNR} < 19\ \mathrm{dB} \tag{4}$$

The model parameters and the *F*-distribution test results are shown in Table 2. We evaluated the performances of the models by comparing *F* values obtained for the developed models with *F*-values obtained from *F* Tables. The following hypotheses were defined as the following:

Null hypothesis; H_0 = Proposed $TCP_{down}T$ model does not fit the data well and the slope of the regression line does not differ significantly from zero for multiple users on the network. (This means that $TCP_{down}T$ is not significantly dependent on SNR).

Alternative hypothesis; H_I = Proposed $TCP_{down}T$ model fits the data well and the slope of the regression line differs significantly from zero for multiple users on the network. (This means that $TCP_{down}T$ is significantly dependent on SNR).

From the decision and remark column in Table 2, it can be seen that H_0 was rejected (implying that H_1 should be accepted) and all the models were accepted at 1% level of significance at the respective degrees of freedom.

Table 3 shows Root mean square (RMS) errors obtained for the $TCP_{down}T$ all SNR (general), strong signal, grey signal and weak signal models compared with multiple users' TCP upstream throughput ($TCP_{up}T$) model developed by Oghogho et al. (2015a) and Henty's models.

The RMS errors were estimated with respect to TCP downstream throughput validation data. The large RMS errors observed for Henty's model for WaveLAN and Henty's model for 3Com clearly shows that two users are not representative of a saturation condition. It can be seen that the $TCP_{down}T$ model developed in this work performed better than $TCP_{up}T$ model developed by Oghogho et al. (2015a). This implies that there is better accuracy of prediction if we study upstream separately from downstream throughput. From Table 3 the $TCP_{down}T$ general model when applied in a specific signal category or range performed better than the strong signals only and weak signals only models. The grey signals only model performed better than the general model when both models were used to estimate $TCP_{down}T$ throughput in the grey signal range.

Figs. 2–5 show the graphs of $TCP_{down}T$ developed in this work (All SNR (general) model, strong signal model, grey signal model and weak signal model) respectively plotted against SNR along with $TCP_{down}T$ validation data average, Oghogho et al. (2015a) $TCP_{up}T$ models, Henty's WaveLAN model and 3Com model.

Our models can be seen to follow the validation data more closely than the other models implying better prediction of the TCP downstream performance of the system. As earlier mentioned, Henty's models show appreciable deviation from the validation data because they were developed from two users on the network. Although Oghogho et al. (2015a) models are less accurate compared with that developed in this work for predicting $TCP_{down}T$, they show appreciable accuracy when the signal is strong as can be seen in Fig. 3.

5. Future research direction

This work focused on investigating the dependence of TCP downstream throughput on SNR for multiple users on the network by developing models that will enable researchers and

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Table 2 Parameters of developed model.

Serial number	Model description	R^2 value	Standard error of the estimate	Level of significance of the model (%)	Level of significance of the model coefficient (%)	*F* value obtained from regression model	*F* value from *F* table	Decision or remark
1	All SNR general model	0.736	1.524	0.000	0.000	$F_{0.01,2,1811} = 2527.621$	4.61	H_o is rejected and model is accepted at 1% level of significance
2	Strong signals model	0.778	1.447	0.000	0.000	$F_{0.01,2,1445} = 2527.990$	4.61	H_o is rejected and model is accepted at 1% level of significance
3	Grey signals model	0.502	1.818	0.000	0.000	$F_{0.01,1,333} = 335.847$	6.63	H_o is rejected and model is accepted at 1% level of significance
4	Weak signals model	0.475	1.527	0.000	0.000	$F_{0.01,1,31} = 28.066$	7.56	H_o is rejected and model is accepted at 1% level of significance

Table 3 RMS error values for our $\text{TCP}_{\text{down}}\text{T}$ models and other models for multiple users.

RMS errors observed for all SNR observed					
Model description	Developed general model for all SNR	Oghogho et al. (2015a) general TCP upstream throughput model	Henty's model for WaveLAN	Henty's model for 3Com	
RMS error (Mbps)	0.938012	1.656648	2.946084	2.522817	
RMS errors observed for strong signals					
Model description	Developed strong signals model	General model but limited to strong signals	Oghogho et al. (2015a) strong signal TCP upstream throughput model	Henty's model for WaveLAN	Henty's model for 3Com
RMS error (Mbps)	1.047012	1.009797	1.115592	3.017467	2.653041
RMS errors observed for grey signals					
Model description	Developed grey signals model	General model but limited to grey signals	Oghogho et al. (2015a) grey signal TCP upstream throughput model	Henty's model for WaveLAN	Henty's model for 3Com
RMS error (Mbps)	0.65833	0.754645	1.850687	2.949298	2.160277
RMS errors observed for weak signals					
Model description	Developed weak signals model	General model but limited to weak signals	Oghogho et al. (2015a) weak signal TCP upstream throughput model	Henty's model for WaveLAN	Henty's model for 3Com
RMS error (Mbps)	0.452927	0.407932	1.043520	2.368461	1.797761

*RMS error is estimated for all the models using TCP downstream throughput validation data.

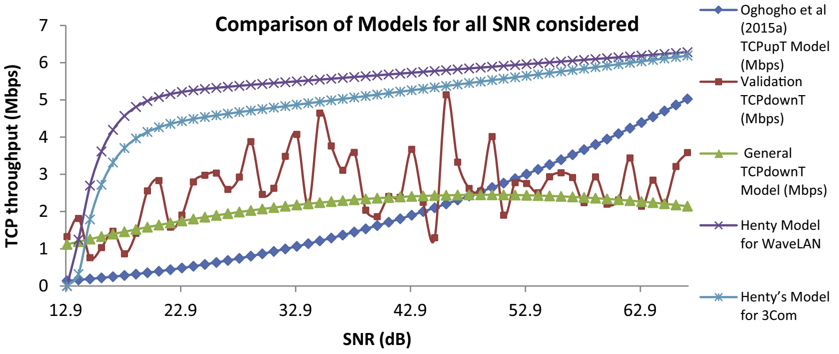

Figure 2 $\text{TCP}_{\text{down}}\text{T}$ model values vs. SNR for all signals considered.

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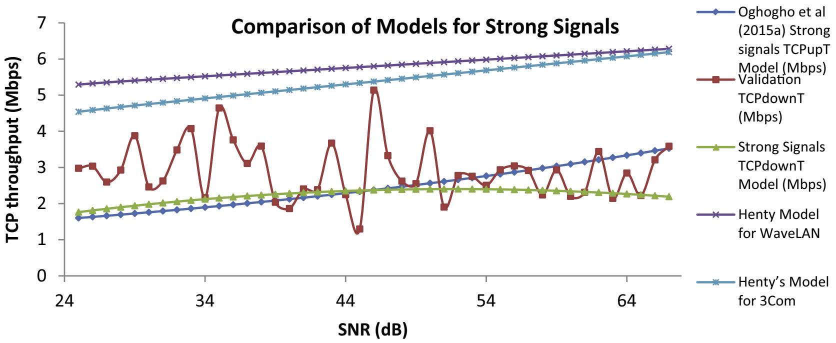

Figure 3 $TCP_{down}T$ strong signal model values vs. SNR.

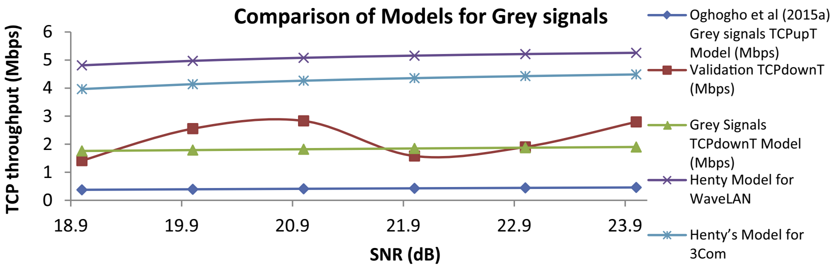

Figure 4 $TCP_{down}T$ grey signal models vs. SNR.

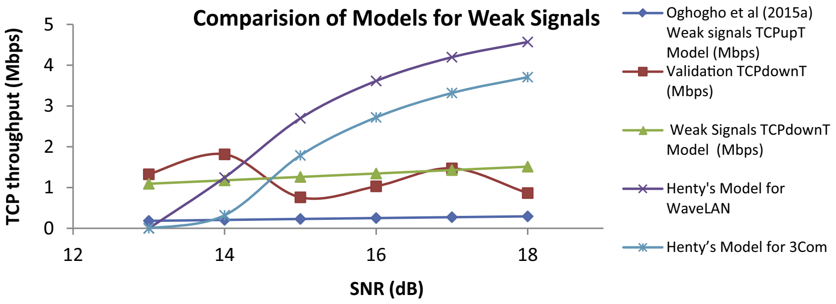

Figure 5 $TCP_{down}T$ weak signal model values vs. SNR for multiple users.

WLAN users to estimate TCP downstream throughput for various observed values of SNR. Round trip time (RTT) models and models specifically developed for specific traffic types (voice or audio, video, control, etc.) corresponding to different WMM tags and specific environments should also be considered. It may also be necessary to develop models from WLAN systems from other vendors and the results compared with what was obtained here.

6. Conclusion

This paper presented our empirical findings on the dependence of TCP downstream throughput measured at the transport layer against the received SNR varied at the physical layer by varying receiver position for multiple (7) users on the network. This study was carried out over a wide range of signals and QoS traffic. Our models passed the *F* tests and performed better than other similar models considered when the RMS errors were compared. Comparison of our TCP downstream throughput models with TCP upstream throughput models developed by Oghogho et al. (2015b) shows that it is more accurate to study upstream and downstream throughput separately. Our models provide network designers with a tool to estimate TCP downstream throughput as a function of SNR within reasonable accuracy hence their network decision making is simplified without increasing the parameters they need to measure and monitor during network installation.

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