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Empirical investigation on the dependence of TCP downstream throughput on SNR in an IEEE802.11b WLAN system

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Abstract The dependence of TCP downstream throughput ($TCP_{down}T$) on signal to noise ratio (SNR) in an IEEE802.11b WLAN system was investigated in various environments and varieties of QoS traffic. $TCP_{down}T$ 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 $TCP_{down}T$ against SNR for different signal ranges (all ranges of signals, strong signals only, grey signals only and weak signals only) were statistically generated and validated. As the SNR values changed from high (strong signals) through low (grey signals) to very low (weak signals), our results show a strong dependence of $TCP_{down}T$ on the received SNR. Our models showed lower RMS errors when compared with other similar models. We observed RMS errors of 0.6734791 Mbps, 0.472209 Mbps, 0.9111563 Mbps and 0.5764460 Mbps for general (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 the TCP downstream throughput in a real network in various environments by monitoring the received SNR.

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1. Introduction

Among several wireless technologies, the present increase in the popularity of wireless local area networks (WLANs) has resulted in the need for developing efficient and dependable performance prediction models for them. Engaging in real-time performance evaluation of WLANs is an extremely challenging task because of the unpredictable changes or

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variations in interference scenarios, the complexities in propagation and the inherent inefficiencies in the mechanisms and protocols used in WLAN systems. The physical layer of the IEEE802.11 standard specifies multiple communication data rates that vary depending on the quality of the current link (SNR observed) (Metreaud, 2006). Link adaptation in WLANs changes the throughput behaviour significantly (Mahmood et al., 2010). Link adaptation enables stations to use higher data rates to transmit their frames thus reaching close to maximum channel capacity as SNR increases. 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 (Metreaud, 2006). Several interference sources which operate in the same frequency band with WLANs also introduce several degrees of interference. Operating two or more WLANs in the same physical environment is also another source of interference which leads to losses.

The role of the internet in the daily life of people around the globe is continuously increasing (Mohammed, 2011). Transmission control protocol (TCP) accounts for over 80% of all the traffic in the Internet hence predicting the performance of TCP is therefore necessary for better understanding of modern systems which use TCP to access the internet (Moltchanov, 2012; Loiseau et al., 2010). In TCP, losses trigger congestion control algorithm which reduces the sending rate and begins the retransmission of lost packets. Causes of losses in TCP are presented in Moltchanov (2010), Detti et al. (2011) and Oghogho et al. (2015). Losses have significant impact on the throughput observed for a particular application. Since different layers have losses associated with them, cross-layer modelling principles 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 (Moltchanov, 2012). By varying some channel parameters (e.g. SNR) at a lower layer (e.g. physical layer) and monitoring a performance metric (e.g. throughput) at higher layers (e.g. transport layer), it is possible to have a model that gives an aggregate performance of the WLAN system. In this case, all processes involved between the lower layer and the higher layer where measurement is taken are implicitly taken into account regardless of whether they can or cannot be isolated or separately recognised.

Existing studies have shown that measurement based models, protocols and applications are more resilient to dynamic changes in network topology and traffic, and outperform the non-measurement based counterparts (Kolar et al., 2011). However the model will have to specify key parameters so as to have comparable results from the model when the throughput obtained are compared with real-time data in such networks and environments and that from other models.

In this paper, we discuss our empirical findings on the dependence of TCP downstream throughput (data speed in Mbps sent from WLAN radio to Client) measured at the transport layer against the received SNR varied at the physical layer by varying receiver position for a single user on the network. It was necessary to study downstream throughput because people often do more downloads than uploads.

1.1. Review of past work

Today, there are propagation models (Moltchanov et al., 2005; Heereman et al., 2011; Phaiboon et al., 2008; Mantilla et al., 2010), Protocol data units (PDU) error models (Khayam and Radha, 2003; Kong and Shwedyk, 1995; Wang and Moayeri, 1995; Kolar et al., 2011) and arrival models (Lombardo et al., 1998; Spaey and Blondia, 1998; Moltchanov et al., 2003; Loiseau et al., 2010; Dhomeja et al., 2011) all of which capture different aspects of the performance characteristics of WLANs. The RSSI, SNR, or PDU, bit or frame error models, though useful for design of transceivers, cannot be directly used in performance evaluation studies because they must be properly extended to higher layers which provide convenient characterisation of the dynamic nature of a wireless channel at the layer of interest (Moltchanov, 2010). Cross layer modelling (Lin et al., 2006; Bohge et al., 2007; Hung and Bensaou, 2011) was developed because of this since it allows us to numerically quantify the effect of various parameters of channel adaptation mechanisms on the performance provided to various applications. Ng et al. (2012) 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 hence we cannot directly compare our results with theirs.

To the best of the Authors knowledge, most of the previous approach (Mahmood et al., 2010; Ng et al., 2012) has not focused on modelling the $TCP_{down}T$ measured at the transport layer while varying the SNR at the physical layer. This work involves cross layer modelling. Although we do not proceed to extend the modelling process layer by layer consecutively, measurements are taken at the physical layer and transport layer while 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. In some related work, Oghogho et al. (2014a) modelled TCP upstream throughput as a function of SNR for a single link, Oghogho et al. (2015) modelled TCP upstream throughput as a function of SNR for both single and multiple links while Oghogho et al. (2014a) provided empirical probability models for predicting the probability of TCP downstream throughput falling into specified ranges for strong, grey and weak signals. Neither of these works provided empirical models for predicting TCP downstream throughput as functions of SNR only.

Henty (2001) and Metreaud (2006) used our approach and worked on IEEE802.11b even though they did not investigate under a wide variety of traffic, did not differentiate between TCP upstream and downstream throughput and did not consider many physical environments as we did. We estimated their model parameters from our Field data and proceeded to compare their results with ours.

Section 2 presents the method employed giving details of experimental set up, the data collection process and the method of analysis. Section 3 presents the models developed from the field data along with their discussion. Our models are also compared with other models and measurements taken in different real-environments. Section 4 gives direction for future work and Section 5 concludes the work.

Table 1 Specifications of laptop computers used for measurement.

Computer name/use	Processor	Operating system	Installed measurement software	Network card	RAM size
Laptop1/ single server	Celeron® dual-core CPU T3300 @ 2.00 GHz 2.00 GHz	32 bit operating system	1. inSSIDer 2.1 2.Tamosoft throughput test	1. Atheros AR8152 PCI-E fast ethernet controller (NDIS 6.2) 2. Atheros AR9285 wireless network adapter	2.00 GB
Laptop2/ single client	Pentium® dual core CPU T4500 @ 2.30 GHz	32 bit operating system	1. inSSIDer 2.1 2. Tamosoft throughput test	1. Microsoft virtual miniport adapter #2 2. Ralink RT 3090 802.11 b/g/n Wifi adapter 3. Realtek PCle FE family controller	2.00 GB

2. Research methodology

In this paper, the dependence of the throughput for TCP downstream obtained in IEEE802.11b WLAN system from a vendor (Ubiquiti Networks) on the SNR was studied in various real life environments (Corridor, Small Offices, and Free space). The method used by Oghogho et al. (2015) was used except that TCP downstream throughput was being monitored and measured. The types of QoS traffic used in this research are presented in Oghogho et al. (2014b). The specifications of the Laptop computers used in this research are shown in Table 1.

We categorised the collected $TCP_{down}T$ 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 $TCP_{down}T$ as dependent variables and SNR as independent variable. From all data collected (and not from the average values) we statistically developed one model which relates $TCP_{down}T$ with SNR in each category: (i) all signals considered (ii) strong signals (SNR > 25 dB) (iii) grey signals (25 dB > SNR > 18 dB) and (iv) weak signals (SNR < 19 dB) 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. The measurement test bed is shown in Fig. 1.

3. Results and discussion

In this section the results obtained are presented along with the models developed accompanied by the discussion of the results using graphs and tables.

3.1. Statistical description of variables

Table 2 shows the statistical parameters for $TCP_{down}T$ for different cases of SNR in a single user scenario both for our original and validation data.

From Table 2, it can be seen that the standard deviation (1.33735 Mbps) observed for all values of SNR considered are high. This implies that $TCP_{down}T$ varies considerably over the entire range of SNR from strong signals, through grey signals to weak signals. The Standard deviation obtained for strong signals (0.60438 Mbps) is much lower than that of grey and weak signals indicating that the $TCP_{down}T$ does not vary significantly for strong signals. This implies that the transmission rate selected for strong signals is appreciably constant and always high. The standard deviation (1.37022 Mbps) observed for all grey signals only was high. This was found to be so even though the range of SNR (6 dB) is small for all grey signals. The large variation results from the error control mechanism which adjusts the transmission rate to reduce errors in packet transmission as signal moves from strong through grey to weak. For grey signals, selected transmission rate fluctuates more frequently between higher, medium and lower values thus resulting in a wider range and variation of $TCP_{down}T$ values when compared with that observed for strong signals only.

The standard deviation for weak signals (1.51961 Mbps) was also found to be high. This implies that for $TCP_{down}T$, when signal becomes weak, selected data rates for transmission of packets also fluctuate more frequently compared to when the signal was strong. This could be due to packet queuing and delay becoming an issue at the WLAN radio buffer thus appreciably influencing the triggering of the error control mechanisms which changes the selected data rate more rapidly thus resulting in higher variations in $TCP_{down}T$. If traffic

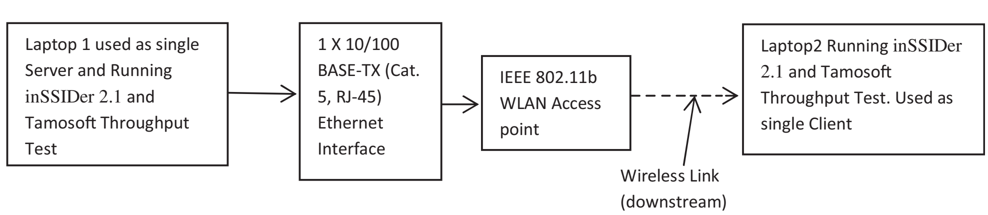

Figure 1 Measurement test-bed setup.

Table 2 Statistical parameter values of $TCP_{down}T$ validation data compared with original data for different cases of received signal strength (Oghogho et al., 2014b).

Statistical parameter	$TCP_{Down}T$ for all RSSI values SNR values (63 dB to 11 dB)		$TCP_{Down}T$ for all strong signals (SNR $\geqslant$ 25 dB)		$TCP_{Down}T$ for all grey signals SNR values (25 dB > SNR > 18 dB)		$TCP_{Down}T$ all weak signals (SNR < 19dB)	
	$TCP_{down}T$	$TCP_{down}T$ validation data	$TCP_{down}T$	$TCP_{down}T$ validation data	$TCP_{down}T$	$TCP_{down}T$ validation data	$TCP_{down}T$	$TCP_{down}T$ validation data
N (sample size)	1885	762	1506	568	316	98	63	95
Mean	5.2323	4.9748	5.7489	5.5910	3.3915	4.0413	2.1143	2.2459
Std. error of mean	0.03080	0.05257	0.01557	0.03018	0.07708	0.11572	0.19145	0.13923
Median	5.85	5.7050	5.94	5.8900	3.2750	4.3500	1.91	2.1000
Mode	6.03	5.92[a] and 6.08[a]	6.03	5.92[a] and 6.08[a]	2.76[a], 3.2[a] and 4.89[a]	5.01	0.36[a], 0.54[a], 0.56[a], 1.15[a], 2.56[a], 3.1[a]	3.73[a], 1.87[a], 0.77[a], 0.74[a], 0.67[a], 0.39[a]
Std. deviation	1.33735	1.45124	0.60438	0.71916	1.37022	1.14553	1.51961	1.35703
Variance	1.788	2.106	0.365	0.517	1.878	1.312	2.309	1.842
Coefficient of dispersion	0.2556	0.2917	0.1051	0.1286	0.4041	0.2835	0.7187	0.7187
Range	10	7.13	7.65	6.18	9.19	5.14	7.47	4.85

[a] Multiple mode exist in different or the same class intervals.

conditions are favourable a higher data rate is selected for transmission but if traffic condition becomes more congested a lower data rate is selected. Hence the larger bandwidth capacity available at the WLAN radio downlink buffer still permits higher transmission rates at intervals even when signal has become weak depending on traffic conditions. The coefficient of dispersion is lowest for strong signals (0.1051 Mbps) even though strong signals cover the largest range (39 dB) of all SNR values considered. This also confirms that the $TCP_{down}T$ varies least if the signal is strong.

Fig. 2 shows plot of the standard deviations, Standard Error of the means of $TCP_{down}T$ and the average $TCP_{down}T$ values observed for the different SNR values. The graph shows the high standard deviation observed for $TCP_{down}T$ in the Grey signal range. The largely constant $TCP_{down}T$ average values observed for the entire strong signal range confirm the high and appreciably constant data rate selected for transmission of data when signal is strong. The average $TCP_{down}T$ values observed dropped considerably for SNR greater than 61 dB.

3.2. Development of throughput models

Eqs. (1)–(4) show our different model equations for General model (all SNR), Strong signal model, Grey signal model and Weak signal model, respectively. C_1, C_2 and C_3 are constants:

$$(\text{General})TCP_{down}T = f(SNR) = \begin{cases} SNR^{a_1} & SNR > 15\,dB \\ SNR^{a1} - C_1 & 16\,dB > SNR > 8\,dB \\ 0 & SNR < 9\,dB \end{cases} \tag{1}$$

$$(\text{Strong})TCP_{down}T = f(SNR) = \begin{cases} C_2 & SNR > 64\,dB \\ C_3 & 64\,dB > SNR > 56\,dB \\ SNR^{a_1} & 57\,dB > SNR > 24\,dB \end{cases} \tag{2}$$

$$(\text{Grey})TCP_{down}T = f(SNR) = SNR^{a_1} \tag{3}$$

$$(\text{Weak})TCP_{down}T = f(SNR) = \begin{cases} a_1 SNR & SNR \geqslant 7\,dB \\ 0 & SNR < 7\,dB \end{cases} \tag{4}$$

The parameters of our models and the F-distribution test results carried out are shown in Table 3. The model performances for the respective degrees of freedoms were evaluated by comparing the F values obtained for the developed models with F-values obtained from F Tables.

The F distribution test was used to determine the performance of the models so as to know if they are to be accepted or rejected at the stated level of significance and degrees of freedom.

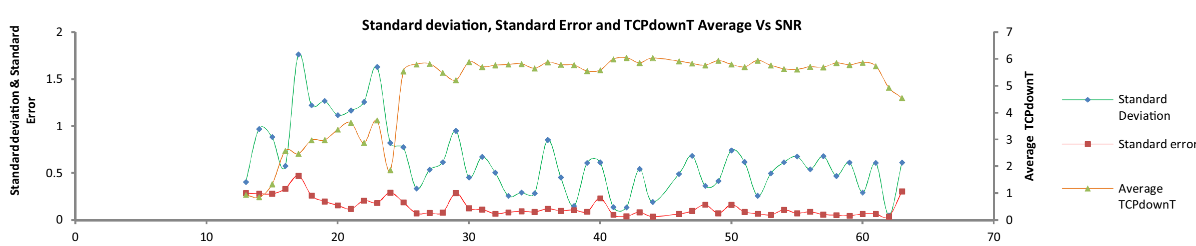

Figure 2 Standard deviation, standard error and average $TCP_{down}T$ values Vs. SNR.

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Table 3 Parameters of our models and *F*-test results.

S/N	Model description	R^2 value	SE of the estimate (Mbps)	Level of significance of the model (%)	Level of significance of the model coefficients (%)	*F* value obtained from regression model	*F* value from *F* Table	Decision/remarks
1	All SNR General model	0.958	0.338	0.000	0.000	$F_{0.0\%,\ 1,\ 1884} = 43041.166$	6.63	H_0 rejected and model is accepted at 1% level of significance
2	Strong signals model	0.991	0.169	0.000	0.000	$F_{0.0\%,\ 1,1506} = 159760.6$	6.63	H_0 rejected and model is accepted at 1% level of significance
3	Grey signals only model	0.834	0.499	0.000	0.000	$F_{0.0\%,\ 1,315} = 1585.447$	6.63	H_0 rejected and model is accepted at 1% level of significance
4	Weak signal only model	0.683	1.475	0.000	0.000	$F_{0.0\%,1,62} = 133.290$	7.08	H_0 rejected and model is accepted at 1% level of significance

To carry out the test, we defined the following hypothesis:

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

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

From the decision and remarks column in Table 3, 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 and degrees of freedom.

From our field measurements, we estimated the values of the variables specified by Henty (2001) in the single user scenario as shown in Table 4.

To reduce the errors in Henty's model and improve its accuracy, we used the aggregate maximum throughput as $T_{\max}$ instead of the actual maximum observed throughput. Metreaud (2006) models were based on the received signal strength indication (RSSI) hence Metreaud's model $\mathrm{TCP_{down}T}$ values were estimated directly using RSSI values throughout the entire signal range.

Table 5 shows the RMS errors for our model and other models when they were compared with validation data. It can be seen from Table 5 that our models performed better than Metreaud and Henty's models in all categories considered as they show lower RMS errors. However all the models show low RMS error for Strong signals.

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.

Table 6 shows the comparison of our models (Strong, Grey and Weak models) for the different ranges of signals developed for $\mathrm{TCP_{down}T}$ with the General (all SNR) model.

From Table 6, it is clear that the General model (which was developed from data involving all SNR) performed better than models developed from Grey signals only due to lower values of RMS errors observed when the General model is used to estimate $\mathrm{TCP_{down}T}$ in Grey range. However the model for Strong and Weak signals only performed better than the general model since they show lower RMS error values. Fig. 3 shows the various graphs of $\mathrm{TCP_{down}T}$ models for different SNR ranges. It can be seen from Fig. 3 that our models follow the validation data more closely than the other models for all SNR categories considered.

We also plotted graphs of $\mathrm{TCP_{down}T}$ instantaneous and mean values for selected SNR values as shown in Fig. 4. The graphs show the variations of $\mathrm{TCP_{down}T}$ about the respective mean values for different SNR considered. Grey signals showed a very large variation of $\mathrm{TCP_{down}T}$ about the mean. We observed a drop in the $\mathrm{TCP_{down}T}$ mean value at SNR of 24 dB which is the transition from Strong to Grey signals. This trend was also evident in Fig. 2 for the average $\mathrm{TCP_{down}T}$ series. From Fig. 4(a–o), it can be seen that when signals are strong (SNR > 24 dB), $\mathrm{TCP_{down}T}$ has average values approximately equal to the mean value of 5.7489 Mbps. A sharp drop in mean value was observed at the transition from

Table 4 Henty's exponential model parameter estimated from our field data.

Throughput type	Parameter	All signals	Strong signals	Grey signals	Weak signals
$\mathrm{TCP_{down}T}$	T_{max}	6.1 Mbps	6.2 Mbps	5.99 Mbps	5.15 Mbps
	$\propto$ (slope)	0.4692308	2.84	1.198	0.7683333
	$\mathrm{SNR_0}$	13 dB	[a]	19	13 dB

$T_{\max}$ = maximum throughput observed; $\propto$ = slope of the exponential curve; $\mathrm{SNR_0}$ = SNR where throughput = 0 dB.
[a] Throughput never falls to zero for strong signals, hence throughput was estimated without considering SNRo.

Table 5 RMS error values with respect to validation data.

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	Metreaud one tap model A	Metreaud one tap constant channel	Henty exponential model
RMS error (Mbps)	0.6734791	1.270154	1.1553061	1.2361709	1.8673939	1.0362001898141
RMS errors observed for strong signals						
Model description	Our strong signal model	Error for Metreaud multi tap model C	Metreaud multi tap model B	Metreaud one tap model A	Metreaud one tap constant channel	Henty exponential model
RMS error (Mbps)	0.472209	0.621029	0.604214	0.555038	0.629506	0.67252025849117
RMS errors observed for grey signals						
Model description	Our grey signal model	Error for Metreaud multi tap model C	Metreaud multi tap model B	Metreaud one tap model A	Metreaud one tap constant channel	Henty exponential model
RMS error (Mbps)	0.911156	2.405285	2.385927	2.443087	2.414967	2.05678759457031
RMS errors observed for weak signals						
Model description	Our weak signal model	Error for Metreaud multi tap model C	Metreaud multi tap model B	Metreaud one tap model A	Metreaud one tap constant channel	Henty exponential model
RMS error (Mbps)	0.576446	2.735511	2.248387	2.377786	3.70645	1.73884188554618

Table 6 Comparison of RMS errors for our different $TCP_{down}T$ models.

Model description	Our general model for all signals (all SNR)	Strong signals only for single user		Grey signals only for single user		Weak signals only for single user	
		Strong signal only model	General (All SNR) model but limited to strong signal range	Greys signals only model	General (All SNR) model but limited to grey signal range	Weak signals only model	General (All SNR) model but limited to weak signal range
RMS error (Mbps)	0.6734791	0.472209	0.6948140	0.9111563	0.5000727	0.5764460	0.6577478

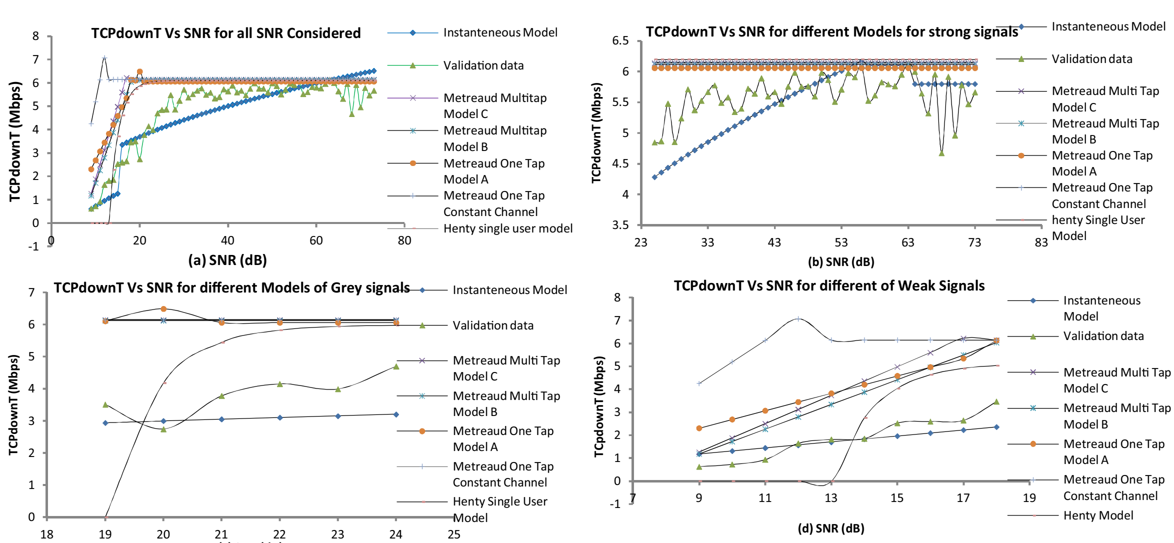

Figure 3 $TCP_{down}T$ models compared with validation data for different ranges of signals.

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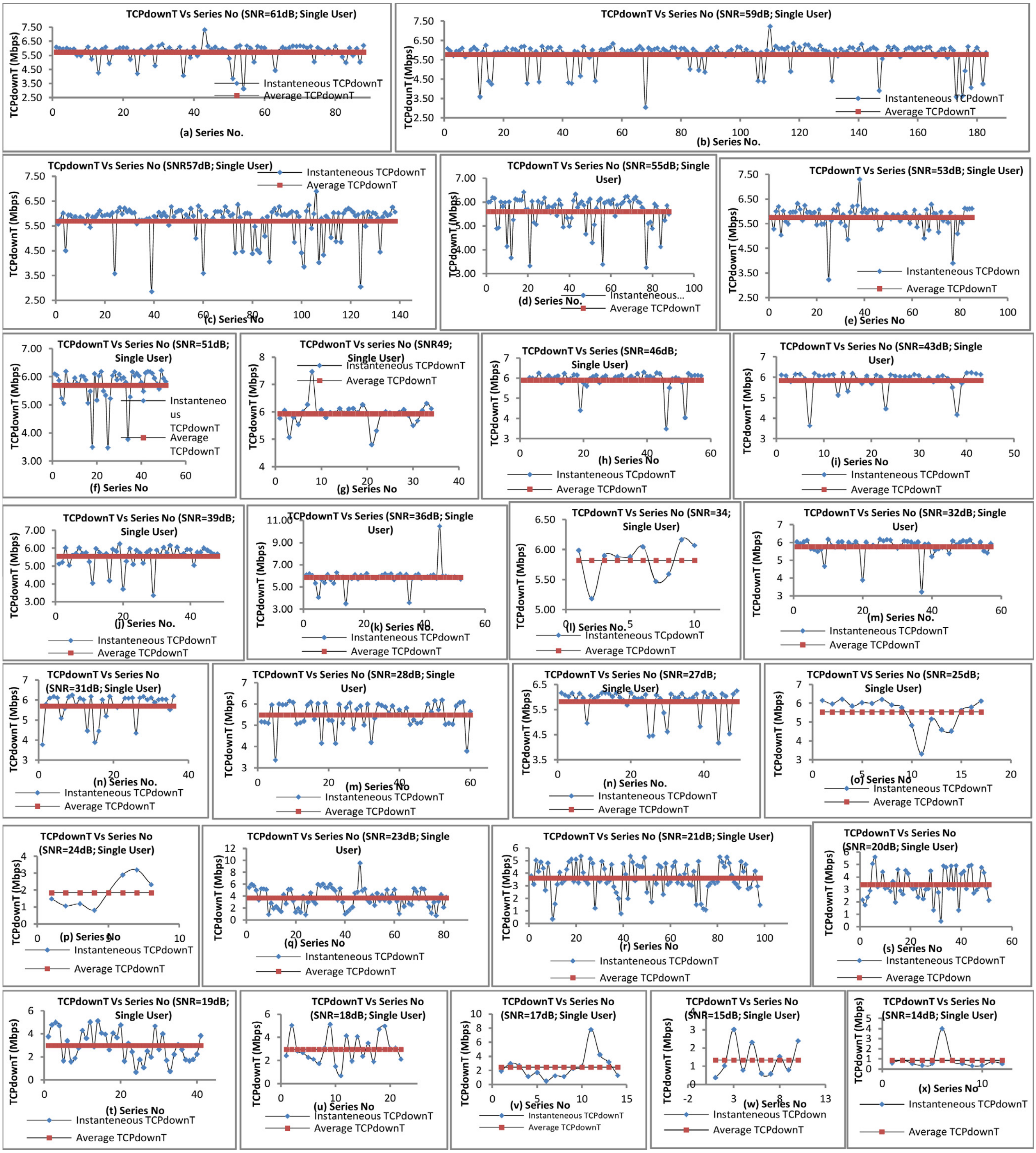

Figure 4 $TCP_{down}T$ variation about the mean for different SNR observed.

strong signal to grey signals. The mean $TCP_{down}T$ value dropped from 5.54 Mbps at a SNR of 25 dB to 1.86 Mbps at a SNR of 24 dB. This drop in mean $TCP_{down}T$ value observed improved again (3.71 Mbps for SNR of 23 dB) as we progressed into the grey signal range. The mean values dropped again as the signals entered the weak range. Weak signals showed isolated cases of high $TCP_{down}T$ average values. The large variation of $TCP_{down}T$ about the mean for grey and weak signals can be seen in Fig. 4(p–w). This was also observed in Table 2 where grey and weak signals showed standard deviations of 1.37022 Mbps and 1.51961 Mbps, respectively which were far higher than the standard deviation (0.60438 Mbps) observed for strong signals. From the findings on the dependence of $TCP_{down}T$ on the SNR, there is the need to ensure during installation that all WLAN clients and access points on a network are located such that they receive a SNR > 24 dB for efficient performance of the network.

4. Future research direction

This work focused on investigating the dependence of TCP downstream throughput on SNR and developing models that will enable researchers and WLAN users to estimate TCP downstream throughput for various observed values of SNR when there is a single user on the network. To fully describe the dependence of TCP throughput on SNR, we need to consider additional means of predicting the throughput obtained under different conditions such as probability and Round trip time (RTT) models and extend the research to multiple users on the network which is usually the case in a real network. 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 should also be considered. WLAN systems from other vendors need to 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.

5. Conclusion

In this paper, we discussed 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. We studied the dependence of TCP downstream throughput 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 validation data from other environments. Our models showing lower RMS errors also performed better than other similar models considered. This work provides a tool needed by researchers and network Engineers to estimate the TCP downstream throughput for different SNR observed in a network. From the findings there is the need to ensure that during installation all WLAN clients and access points on a network are located such that they receive a SNR > 24 dB for efficient TCP downstream performance of the network.

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