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# INVESTIGATION ON THE DEPENDENCE OF TCP UPSTREAM THROUGHPUT ON SNR FOR SINGLE AND MULTIPLE LINKS IN A WLAN SYSTEM

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## ABSTRACT

*An empirical investigation on the dependence of TCP upstream throughput ($TCP_{up}T$) against signal to noise ratio (SNR) in an IEEE802.11b WLAN system was carried out in various environments and varieties of QoS traffic using an Infrastructure based IEEE802.11b WLAN system set up consecutively in various environments (open corridor, small offices with block walls or plaster boards and free space). Empirical models describing the $TCP_{up}T$ against SNR for different signal ranges (all signals, strong signals, grey signals and weak signals) were developed and validated for both single and multiple users on the network. 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 they and other similar models were compared with validation data. We observed RMS errors of 0.5605471Mbps, 0.4479389Mbps, 1.04536603Mbps and 0.5813471Mbps for the General, Strong signals, Grey signals and Weak signals models respectively for the single user scenario. We also observed RMS errors of 1.3319396Mbps, 0.9457431Mbps, 0.8092979Mbps and 0.4220292Mbps for the multiple users scenario. An appreciable difference was observed between the throughput behavior for single and multiple users on the network showing the inefficiency of the distributed coordination function and Point coordination function used in WLANs as access mechanisms. Our models will provide researchers and WLAN systems users with a tool to estimate the TCP upstream throughput in a real network in various environments by monitoring the SNR.*

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



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**Contribution/ Originality**

This study has investigated and showed the dependence of TCP upstream throughput on SNR and originated new formulae for predicting TCP upstream throughput based on observed SNR by a Client on single and multiple IEEE802.11b WLANs.

## 1. INTRODUCTION

The ever growing demand for more bandwidth and wireless technologies to access internet services has resulted due to the need to access internet services in a fast and convenient way [1]. Transmission control protocol (TCP) presently accounts for over 80% of all the traffic in the Internet with no indication that this percentage will decline in the near future [2, 3]. In WLAN systems, the signal to noise ratio (SNR) is the predominant metric for determining when to change the Data Link Rate (DLR) [4]. WLAN systems use link adaptation where stations choose data rates depending on underlying channel conditions which is predominantly the SNR sensed by the station hence link adaptation has significant impact on the throughput behaviour of WLANs [5]. An important WLAN performance metric is the throughput which the user sees after overheads and is described as a measure of the average rate (usually in Kbps or Mbps) that data can be sent between one user and another [6]. 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, 7]. 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 [2]. In Cross layer modelling, a model applied at a lower layer can be replaced by a better one at a higher layer to obtain better results of the overall performance of the WLAN system since the mathematical models at each step of the cross-layer modelling, is independent of each other. According to Moltchanov [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. One way to overcome this challenge is to carry out extensive measurements of TCP throughput at the transport layer while varying the SNR at the physical layer, so as to generate 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 situation, all processes involved between the lower layer (e.g. physical layer) and the higher layer (e.g. transport layer) where measurements are taken are implicitly taken into account regardless of whether they can or cannot be isolated or separately recognised. In this paper, we discuss our empirical findings on the dependence of TCP upstream throughput measured at the transport



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layer of an IEEE802.11b WLAN system against the received SNR varied at the physical layer by varying receiver position for both single and multiple users on the network. According to Moltchanov, et al. [8] and Khanduri and Rattan [9] IEEE802.11b WLAN system still maintains its place as the technology that provides the largest range even though it is an old technology. In applications where range rather than high data speed or bandwidth is more important; IEEE802.11b is preferred above other newer technologies. Section 2 discusses related work to this study. Section 3 presents the method employed in the experimental set up, the data collection process and the method of analysis. Section 4 presents the results, 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 5 gives direction for future work and section 6 concludes the paper.

## 2. BRIEF REVIEW OF PAST WORK

Different aspects of the performance characteristics of WLANs are captured by several developed models. The path loss and SNR process of IEEE802.11 wireless channels at the physical layer are captured by propagation models [9-12]. Data link and network layers characteristic are captured by Protocol data units (PDU) error models which include symbol, bit and frame error models [13-16]. 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]. Cross layer modelling [17, 18] were developed to allow us 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 [5, 19] most of the approach has not used cross layer modelling principles by focussing on modelling the throughput measured at the transport layer while varying the SNR at the physical layer. Our work focuses on providing a tool that predicts the TCP upstream throughput in an IEEE802.11b WLAN System by simply observing the SNR only at the physical layer for both single and multiple users (saturation condition) on the network. Our method provides the uniqueness where the throughput is directly predicted by simply monitoring the SNR. Some researchers [4, 6, 19] have used our method in their work. Ng, et al. [19] 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. Authors in Henty [6], Metreaud [4] used our approach and worked on IEEE802.11b even though they did not investigate under a wide variety of traffic, physical environments and users as we did. We



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estimated their model parameters from our field data and compared them and our models with our validation data.

## 3. MATERIAL AND METHODS

The method used in this work was used by Oghogho, et al. [20]. However multiple links were also considered in this work as done in Oghogho, et al. [21]. The types of QoS traffic used and the description of the equipment used in the measurement test bed and how they were connected are as done in Oghogho, et al. [21]. For single user scenarios only one server and one client is used but for multiple user scenarios, the number of users on the network considered in this study was limited to seven. This choice was made due to the findings of Wu, et al. [22] where seven stations gave throughput values that was averagely the mid-point from two extremes (1 station and 16 stations respectively). The procedure for developing models was as done in Oghogho, et al. [20] except that models were also developed for multiple users. Henty [6] and Metreaud [4] models were used to compare models developed in this work. From our field measurements, we estimated the values of the variables specified by Henty [6] in the single user scenario. Metreaud [4] models were based on the received signal strength indication (RSSI) hence we estimated them directly using RSSI values throughout the entire signal range.

## 4. RESULTS AND DISCUSSION

The Single user $TCP_{up}T$ statistical parameters values for different cases of SNR both for our field and validation data are as presented in Oghogho, et al. [20]. $TCP_{up}T$ varies considerably over the entire range of SNR from strong signals through grey signals to weak signals as seen from the observed variance (3.288) and standard deviation (1.81327Mbps). Also the variance (2.378) and standard deviation (1.54209Mbps) for the $TCP_{up}T$ obtained for all grey signals only were also high. This can be explained as resulting from the error control mechanism which adjusts the transmission rate to reduce errors in packet transmission as signal becomes weak. However the variance and Standard deviation obtained for strong signals (0.415 and 0.64389Mbps) and weak signals (0.457 and 0.67621Mbps) were much lower indicating that $TCP_{up}T$ does not vary significantly.

We also observed a highly skewed distribution for the $TCP_{up}T$ obtained for all SNR (-1.601), strong signals only (-2.332), and weak signals only (1.079). Grey signals only showed a low positive skewness (0.461) which can be due to the bimodal distribution noticed in this range of SNR. Grey signals showed multiple mode occurring at class intervals (0-1) Mbps and (2-3) Mbps. The graphs of Standard deviation, Standard errors and Average values of $TCP_{up}T$ observed for the field data against SNR in the single user scenario are as presented in Oghogho, et al. [20]. The average $TCP_{up}T$ observed for the entire strong signal range is appreciably constant and high (>5Mbps). The Authors in Oghogho, et al. [20] also pointed out a sharp momentary drop in the average value of $TCP_{up}T$ observed at the transition from Strong to Grey signals (SNR=24dB).



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Table 1 shows the multiple users $TCP_{up}T$ statistical parameters for different cases of SNR. From Table 1, it can be seen that the variance (3.568) and standard deviation (1.8888Mbps) for the $TCP_{up}T$ obtained for all values of SNR considered are high implying that $TCP_{up}T$ varies considerably over the entire range of SNR from strong signals, through grey signals to weak signals for multiple users on the network.

**Table-1.** Multiple Users $TCP_{up}T$ statistical parameters for different cases of SNR.

| **Statistical Parameter** | **ALL RSSI (SNR) considered (63dB≥ $SNR \geq 13dB$)** | | **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) | 1844 | 550 | 1451 | 444 |
| Mean | 2.510255 | 2.5992 | 2.991923 | 3.0136 |
| Std. Error of Mean | 0.043985 | 0.09065 | 0.0465907 | 0.10119 |
| Median | 2.15 | 2.1600 | 2.77 | 2.6000 |
| Mode | 0.28 | 0.61 | 1.86 | 0.52*, 2.3*, 2.55*, 3.88* |
| Std. Deviation | 1.8888 | 2.12603 | 1.7747314 | 2.13221 |
| Variance | 3.568 | 4.520 | 3.15 | 4.546 |
| Coefficient of dispersion | 0.752434 | 0.817956 | 0.593174 | 0.941350 |
| Skewness | 0.439 | 0.857 | 0.205 | 0.647 |
| Kurtosis | -0.930 | -0.074 | -0.934 | -0.344 |
| Range | 8.35 | 10.20 | 8.32 | 10.19 |
| Statistical Parameter | Grey signal (25dB>SNR≥19dB) | | Weak Signal (SNR<19dB) | |
| | $TCP_{up}T$ Field data | $TCP_{up}T$ Validation data | $TCP_{up}T$ Field data | $TCP_{up}T$ Validation data |
| N (Sample Size) | 362 | 40 | 32 | 66 |
| Mean | 0.7517 | 1.2167 | 0.487813 | 0.6494 |
| Std. Error of Mean | 0.05627 | 0.18109 | 0.1146521 | 0.05445 |
| Median | 0.36 | 0.8500 | 0.24 | 0.5900 |
| Mode | 0.26 | 0.35*, 1.36* | 0.23 | 0.31*, 0.33* |
| Std. Deviation | 1.07056 | 1.14534 | 0.6485703 | 0.44235 |
| Variance | 1.146 | 1.312 | 0.421 | 0.196 |
| Coefficient of dispersion | 1.424185 | 0.941350 | 0.995675 | 0.681167 |
| Skewness | 3.368 | 1.436 | 2.701 | 1.661 |
| Kurtosis | 13.652 | 2.204 | 8.355 | 4.089 |
| Range | 7.74 | 5.05 | 3.07 | 2.36 |

*Multiple mode exist

The variance (3.15) and standard deviation (1.7747314Mbps) for strong signals only was high for multiple users unlike what was the case for single user scenario. This result shows that depending on the traffic conditions, the selected data rate varies largely over the entire range of strong signals for multiple users. Also, other causes of losses such as buffer overflows come into



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play with multiple users on the network since the data traffic and queuing is high. The variance (1.146) and standard deviation (1.07056Mbps) for the $TCP_{up}T$ obtained for all grey signals only in the multiple user scenarios are also averagely high. For multiple users, $TCP_{up}T$ does not show any bi modal distribution as observed for grey signals in the single user scenario. Also, $TCP_{up}T$ shows a high probability (0.79558011) of having a $TCP_{up}T$ value in the class interval of 0-0.999Mbps and shows a low $TCP_{up}T$ mean (0.7517Mbps) observed for grey signals for multiple users on the network unlike the case of single user. The variance (0.421) and Standard deviation (0.6485703Mbps) obtained for weak signals were low indicating that the transmission rate selected for weak signals under multiple user scenarios is appreciably constant and always low. This is also supported by the low mean (0.487813Mbps), median (0.24Mbps), mode (0.23Mbps) and range (3.07Mbps) observed. The distribution shows high positive skewness for weak and grey signals indicating a higher probability of having a $TCP_{up}T$ towards the 0-0.999 (Mbps) class interval in the multiple users scenario. Positive skewness was low for all signals (0.439) and strong signals only (0.205) showing that no $TCP_{up}T$ class interval dominates under such signal conditions. Fig. 1 shows the field data Standard deviation, Standard error and Average values of $TCP_{up}T$ against SNR in the multiple users scenario while Figure 2a and Figure 2b show graphs of Average and Standard deviations respectively of $TCP_{up}T$ for both single and multiple users scenarios plotted together.

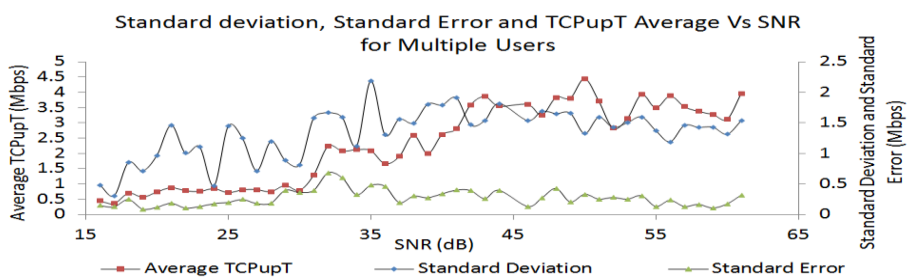

**Fig-1.** Standard deviation, Standard error and Average $TCP_{up}T$ values Vs. SNR for Multiple users

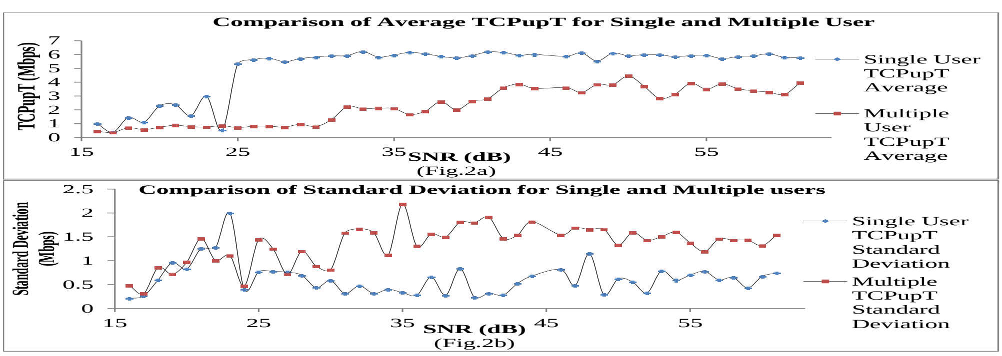

**Fig-2.** Comparison of $TCP_{up}T$ Graphs for Single and Multiple users on the network

From the graph of Figure 1, it can be seen that the average $TCP_{up}T$ observed for the entire strong signal range varies considerably for SNR> 30dB. However below 30dB (even in the weak and grey ranges) the average $TCP_{up}T$ is fairly constant for multiple users. Also the standard



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deviation is appreciably high for strong, grey and weak signal ranges. However, strong signals show the highest standard deviation over a wider range. At the transition from strong to grey signals (SNR=24dB) there is no drop in average $TCP_{up}T$ as was the case for single user scenario observed by Oghogho, et al. [20]. It is obvious that the Distributed coordination function (DCF) and Point Coordination function (PCF) used by WLANs to control Client access to the network are largely inefficient. Also multiple users show higher deviations of $TCP_{up}T$ throughout over the entire SNR ranges considered.

### 4.3. Development of Throughput Models

For single users on the network, equations 1, 2, 3 and 4 show our different model equations for general (all SNR) model, strong signal model, Grey signal model and Weak signal model respectively which were developed from all instantaneous field data collected [20]. C, $C_1$ and $C_2$ are constants while $a_1$, $a_2$ and $a_3$ are coefficients of the different models.

(General) $TCP_{up}T = f(SNR) = \begin{cases} C_1 & SNR > 38dB \\ a_1\mathrm{SNR} + a_2SNR^2 + a_3SNR^3 & 39dB > SNR > 16dB \\ |a_1\mathrm{SNR} + a_2SNR^2 + a_3SNR^3 - C_2| & 17dB > SNR \end{cases}$ ……1

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

(Grey) $TCP_{up} = f(SNR) = a_1SNR$ ……3

(Weak) $TCP_{up} = f(SNR) = \begin{cases} a_1SNR^2 + a_2SNR^3, 19dB > SNR > 11dB \\ 0 \quad ,SNR \le 11dB \end{cases}$ ……4

For multiple users on the network, equations 5, 6, 7 and 8 show our different model equations for general (all SNR) model, strong signal model, Grey signal model and Weak signal model respectively which were statistically generated using all instantaneous field data collected.

$TCP_{up}T = f(SNR) = C * SNR^{a_1}$ ……5

$TCP_{up}T = f(SNR) = {a_1}^{SNR}$ ……6

$TCP_{up}T = f(SNR) = e^{(a_1/_{SNR})}$ ……7

$TCP_{up}T = f(SNR) = e^{(a_1/_{SNR})}$ ……8

The parameters of our models and the F-distribution test results carried out are shown in Table 2 and Table 3 for single and multiple users respectively. 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. We defined the following hypothesis to carry out the test:

**Null hypothesis;** $H_{01}$ **and** $H_{02}$ = Proposed $TCP_{up}T$ model does not fit the data well and the slope of the regression line does not differ significantly from zero for single and multiple users respectively on the network.

**Alternative hypothesis;** $H_{11}$ **and** $H_{12}$ = Proposed $TCP_{up}T$ model fits the data well and the slope of the regression line differs significantly from zero for single and multiple users respectively on the network implying that $TCP_{down}T$ is significantly dependent on SNR.



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**Table-2.** Parameters of Our models and F-Test Results for Single User [20]

| 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 | 1.109 | 0.000% | 0.000% | $F_{0.0\%,3,1882}$=17661 | 6.63 | $H_{01}$ rejected and model is accepted at 1% level of significance |
| 2 | Strong signals model | 0.991 | 0.147 | 0.000% | 0.000% | $F_{0.0\%,1,1505}$ =158888.1 | 6.63 | $H_{01}$ rejected and model is accepted at 1% level of significance |
| 3 | Grey signals only model | 0.683 | 1.518 | 0.000% | 0.000% | $F_{0.0\%,1,315}$ =678.998 | 6.63 | $H_{01}$ rejected and model is accepted at 1% level of significance |
| 4 | Weak signal only model | 0.756 | 0.499 | 0.000% | 0.000% | $F_{0.0\%,2,61}$=94.731 | 7.08 | $H_{01}$ rejected and model is accepted at 1% level of significance |

**Table-3.** Parameters of Our models and F-Test Results for Multiple Users

| 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 | 0.551 | 0.794 | 0.000% | 0.000% | $F_{0.0\%,1,1842}$ 2257.678 | 6.63 | $H_{02}$ rejected and model is accepted at 1% level of significance |
| 2 | Strong signals model | 0.547 | 0.824 | 0.000% | 0.000% | $F_{0.0\%,1,1450}$ =1753.197 | 6.63 | $H_{02}$ rejected and model is accepted at 1% level of significance |
| 3 | Grey signals only model | 0.42 | 1.047 | 0.000% | 0.000% | $F_{0.0\%,1,361}$=261.270 | 6.63 | $H_{02}$ rejected and model is accepted at 1% level of significance |
| 4 | Weak signal only model | 0.612 | 1.051 | 0.000% | 0.000% | $F_{0.0\%,1,31}$=48.969 | 7.56 | $H_{02}$ rejected and model is accepted at 1% level of significance |

From the decision and remarks columns in Table 2 and 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 at the respective degrees of freedom for both single and multiple users scenarios.

**Table-4.** Comparison of Our $TCP_{up}T$ Models with other Models using RMS errors in the single user scenario [20].

| **RMS errors observed for All SNR** | | | | | | |
|---|---|---|---|---|---|---|
| **Model description** | **General model for all SNR** | **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) | 0.5605471 | 1.8514437 | 1.7344925 | 1.8226758 | 2.4099217 | 1.4127219 |
| **RMS errors Observed for Strong signals** | | | | | | |
| Model description | Strong signals model | 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) | 0.4479389 | 0.6074643 | 0.5928823 | 0.5511798 | 0.6148696 | 0.5191729 |
| **RMS Errors observed for Grey signals** | | | | | | |
| Model description | Grey signals model | 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) | 1.04536603 | 3.7286058 | 3.7095765 | 3.7656603 | 3.7381242 | 3.7381242 |
| **RMS Errors observed for Weak signals** | | | | | | |
| Model description | Weak signals model | Metreaud Multi tap Model C | Metreaud Multi tap model B | Metreaud One tap model A | Metreaud One tap Constant Channel | Henty Exponential Model (single User) |
| RMS error (Mbps) | 0.5813471 | 3.9950067 | 4.3964423 | 6.7716979 | 6.7716979 | 0.7272674 |



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Table4 shows the RMS errors for our model and other models when they were compared with validation data for single user respectively. It can be seen that our models performed better than the other models in all cases considered. In the single user scenario, 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 5 shows comparison of our General model with models developed for specific SNR category. From Table 5, it can be seen that it is better to develop models by categorizing the data into different SNR categories. This is implied from the fact that strong signal models and weak signal models developed from the categorized data showed lower RMS errors than the General all SNR model in the single user scenario. However the General model performed better than the grey signal model where large variations are observed.

**Table-5.** Comparison of RMS Errors for Our Different Models in the Single User Scenario [20].

| | | |
|---|---|---|
| **Model A** | **All SNR or General models in the single User scenario** | |
| | Instantaneous General TCPUPT Model | |
| RMS error (Mbps) | 0.5605471 | |
| **Model B** | **Strong signals only in the Single User scenario** | |
| | Strong signal model | Instantaneous All SNR (General) Model but limited to Strong signal range |
| RMS error (Mbps) | 0.4479389 | 0.49908182 |
| **Model C** | **Grey signals only in the Single User scenario** | |
| | Grey signal model | Instantaneous All SNR (General) Model but limited to Grey signal range |
| RMS error (Mbps) | 1.04536603 | 0.9609165 |
| **Model D** | **Weak signals only in the Single User scenario** | |
| | Weak signal model | Instantaneous All SNR (General) Model but limited to weak signal range |
| RMS error (Mbps) | 0.5813471 | 0.6681608 |

**Table-6.** Comparison of Our $TCP_{up}T$ Models with other Models using RMS errors in the multiple users scenario.

| | | | |
|---|---|---|---|
| **RMS errors observed for All SNR** | | | |
| Model description | General model for all SNR | Henty's Model for WaveLAN | Henty's Model for 3Com |
| RMS error (Mbps) | 1.3319396 | 2.769778 | 2.3538621 |
| RMS errors Observed for Strong signals | | | |
| Model description | Strong signals model | Henty's Model for WaveLAN | Henty's Model for 3Com |
| RMS error (Mbps) | 0.9457431 | 2.882439 | 2.49952579 |
| RMS Errors observed for Grey signals | | | |
| Model description | Grey signals model | Henty's Model for WaveLAN | Henty's Model for 3Com |
| RMS error (Mbps) | 0.8092979 | 3.118858 | 2.4046998 |
| RMS Errors observed for Weak signals | | | |
| Model description | Weak signals model | Henty's Model for WaveLAN | Henty's Model for 3Com |
| RMS error (Mbps) | 0.4220292 | 2.39028 | 1.7125527 |



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Table 6 shows the comparison of our models (Strong, Grey and Weak models) for the different ranges of signals developed for $TCP_{up}T$ with models developed by Henty [6] in the multiple users scenario.

Our models performed better in all cases considered. The high RMS errors observed for Henty's models as shown in Table 6 indicates that models developed from data collected for two users on the network does not appropriately predict the throughput observed under saturation conditions (e.g. 7 users). Table 7 shows the comparison of our models for the different ranges of signals (Strong, Grey and Weak models) developed for $TCP_{up}T$ with the General (all SNR) model in the multiple users scenarios.

**Table-7.** Comparison of RMS errors for our different models for $TCP_{up}T$ for different signal ranges in the Multiple users.

| | | |
|---|---|---|
| **Model A** | **All SNR or General models in the Multiple User scenario** | |
| | General TCPUPT Model | |
| RMS error (Mbps) | 1.3319396 | |
| **Model B** | **Strong signals only in the Multiple User scenario** | |
| | Strong signal model | Instantaneous All SNR (General) Model but limited to Strong signal range |
| RMS error (Mbps) | 0.9457431 | 1.479604 |
| **Model C** | **Grey signals only in the Multiple User scenario** | |
| | Grey signal model | Instantaneous All SNR (General) Model but limited to Grey signal range |
| RMS error (Mbps) | 0.8092979 | 0.789909 |
| **Model D** | **Weak signals only in the Multiple User scenario** | |
| | Weak signal model | Instantaneous All SNR (General) Model but limited to weak signal range |
| RMS error (Mbps) | 0.4220292 | 0.457789 |

For multiple user scenarios, it can be seen from Table 7 that the General model (which was developed from data involving all SNR) also performed better than the model developed from Grey signals as was the case for single user scenario. This implies that it is better to use the developed General models to estimate $TCP_{up}T$ in Grey signal range both for single and multiple users on the network. However the model for strong and weak signals performed better than the general models as they show lower RMS error values for both single and multiple users. Figure 3 and Figure 4 show the various graphs of $TCP_{up}T$ models and the validation data for different SNR ranges for single and multiple users respectively. Our models performed better than that of Henty [6] and Metreaud [4]. However all models performed well in the strong signal range for a single user on the network. We also plotted graphs of $TCP_{up}T$ instanteneous and mean values for selected SNR values as shown in Figure 5 and Figure 6 for single and multiple users respectively. The graphs show the variations of $TCP_{up}T$ about the respective mean values for different SNR considered. For single user scenario, it can be observed that the variation of $TCP_{up}T$ about the means were higher for SNR values of 60dB, 57dB, 53dB and 46dB compared with 43dB, 36dB and 32dB where they were lower. However the variation became higher again as signal became weaker from 28dB through the grey signal range. Also grey signals showed a very large variation of $TCP_{up}T$ about the mean and this trend began to decrease as the signal became weak (<18dB) for single users. We also observed a drop in the $TCP_{up}T$ mean value at SNR of 24dB which is the transition from strong to Grey signals for a single user.


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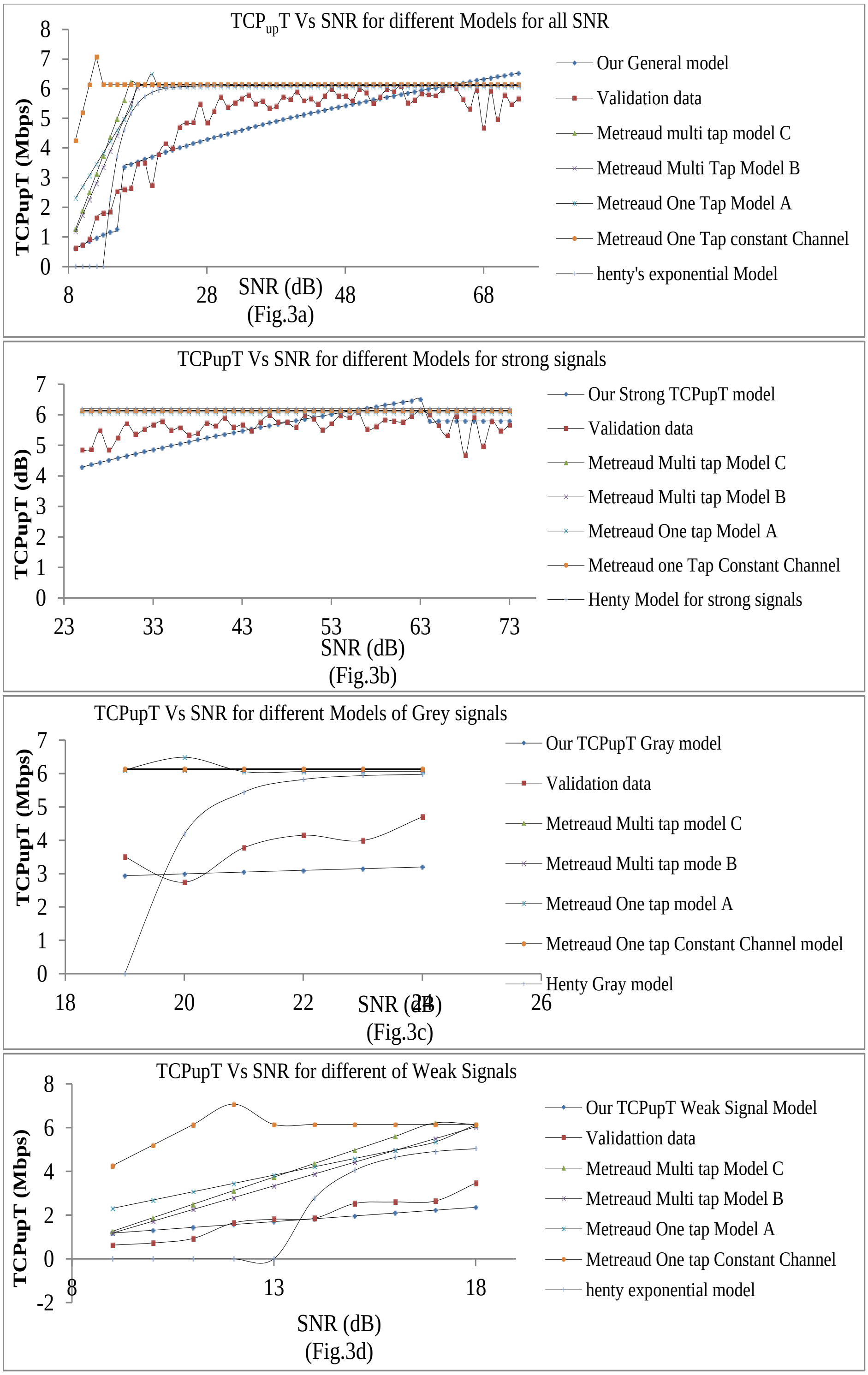


**Fig-3.** TCP$_{up}$T Models compared with Validation data for different ranges of signals for single user scenario



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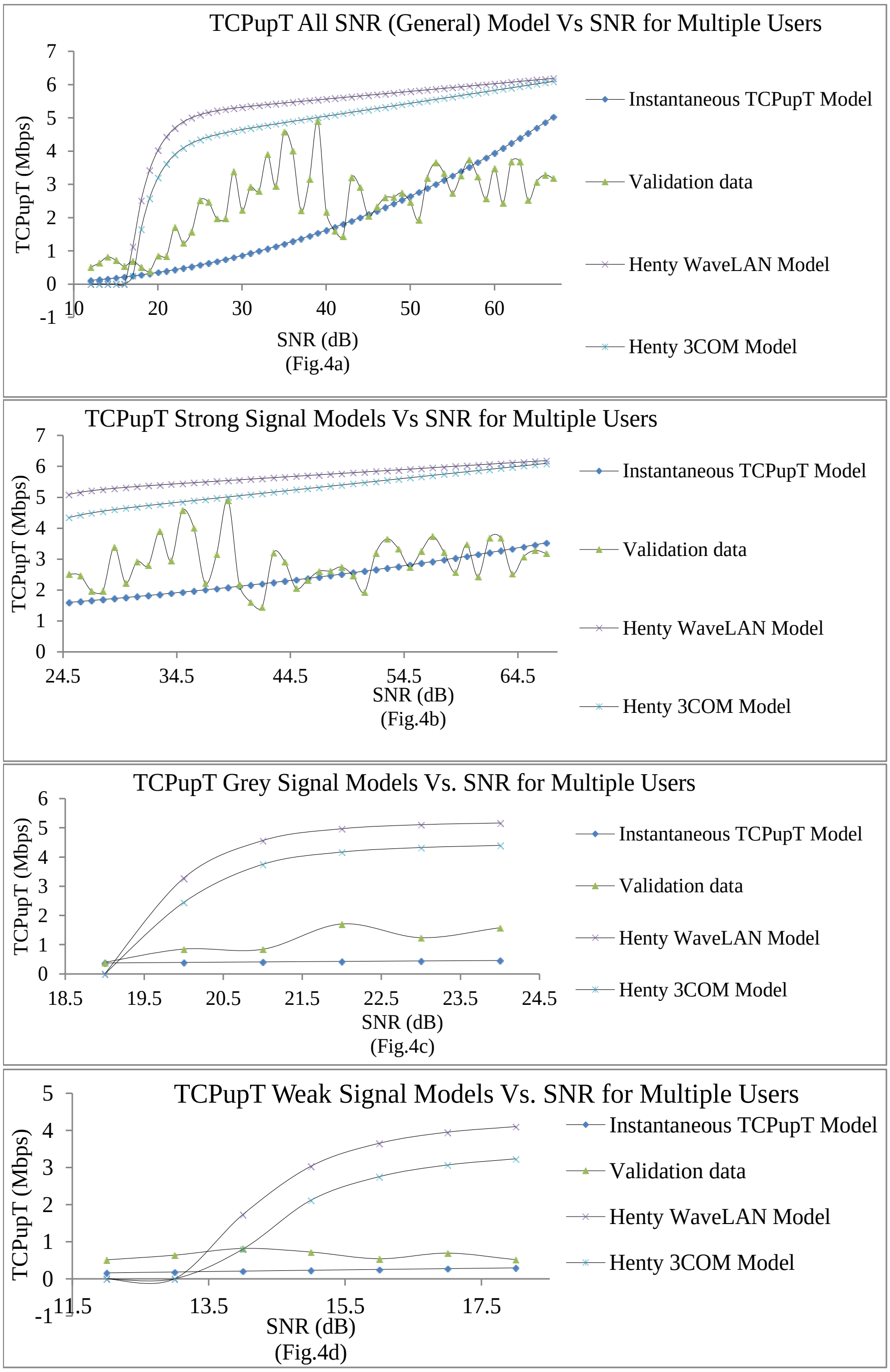


**Fig-4.** TCP$_{up}$T Models compared with Validation data for different ranges of signals for multiple user scenario



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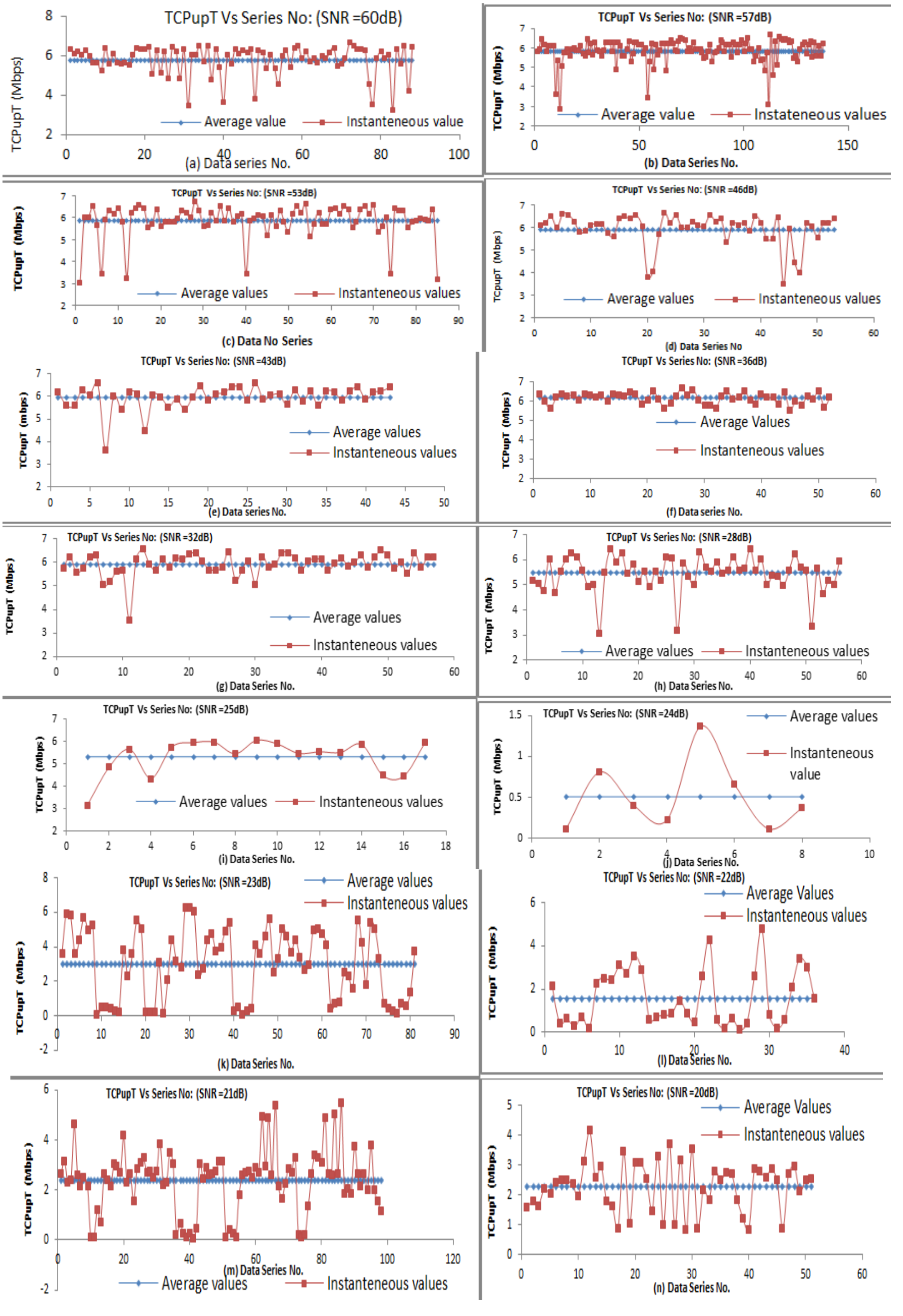




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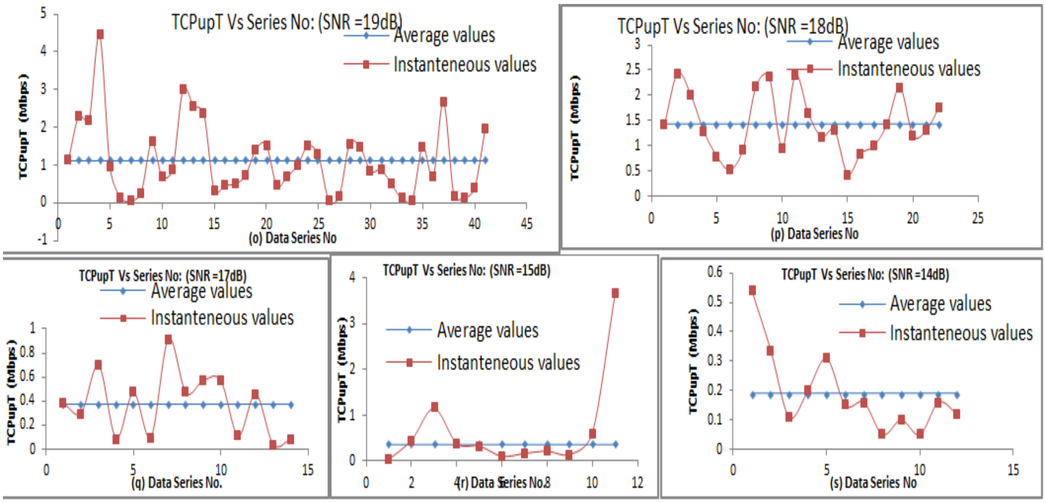
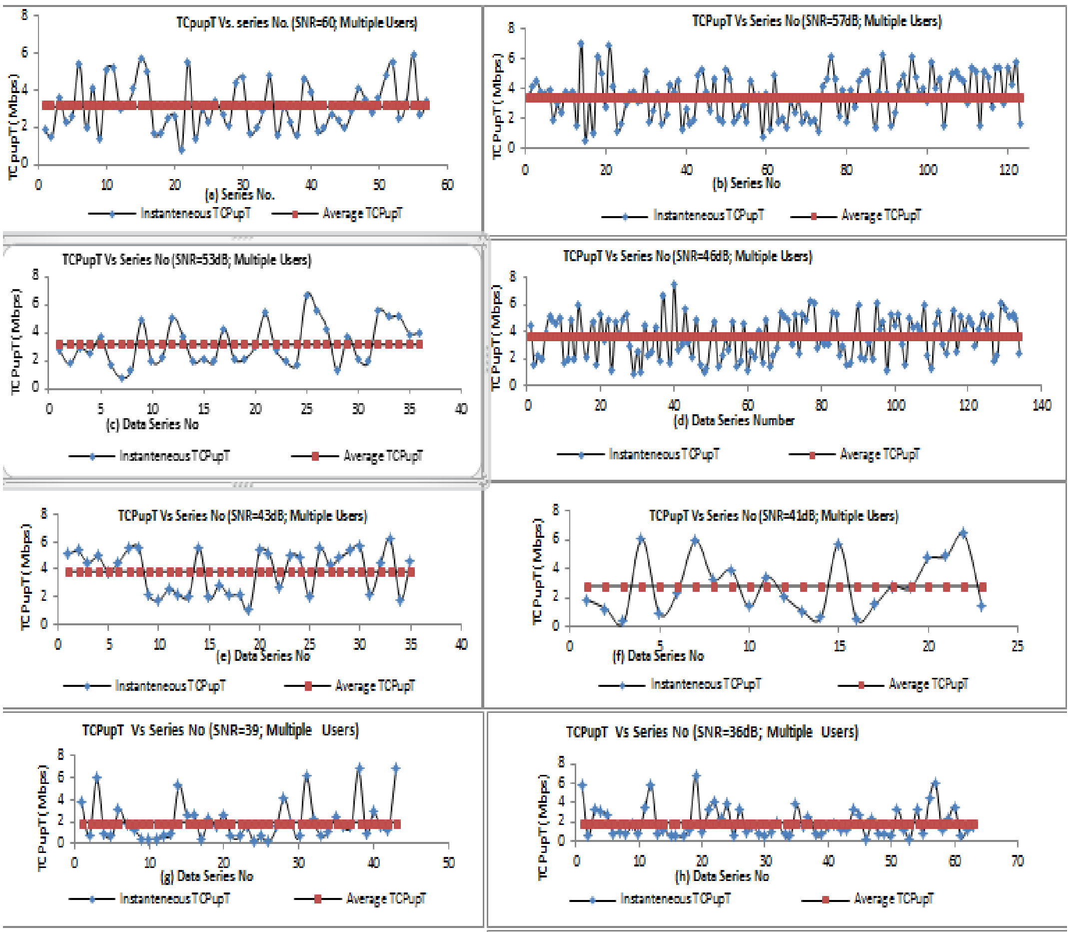



**Fig-5.** TCP$_{up}$T variation about the mean for different SNR observed for single user scenario.



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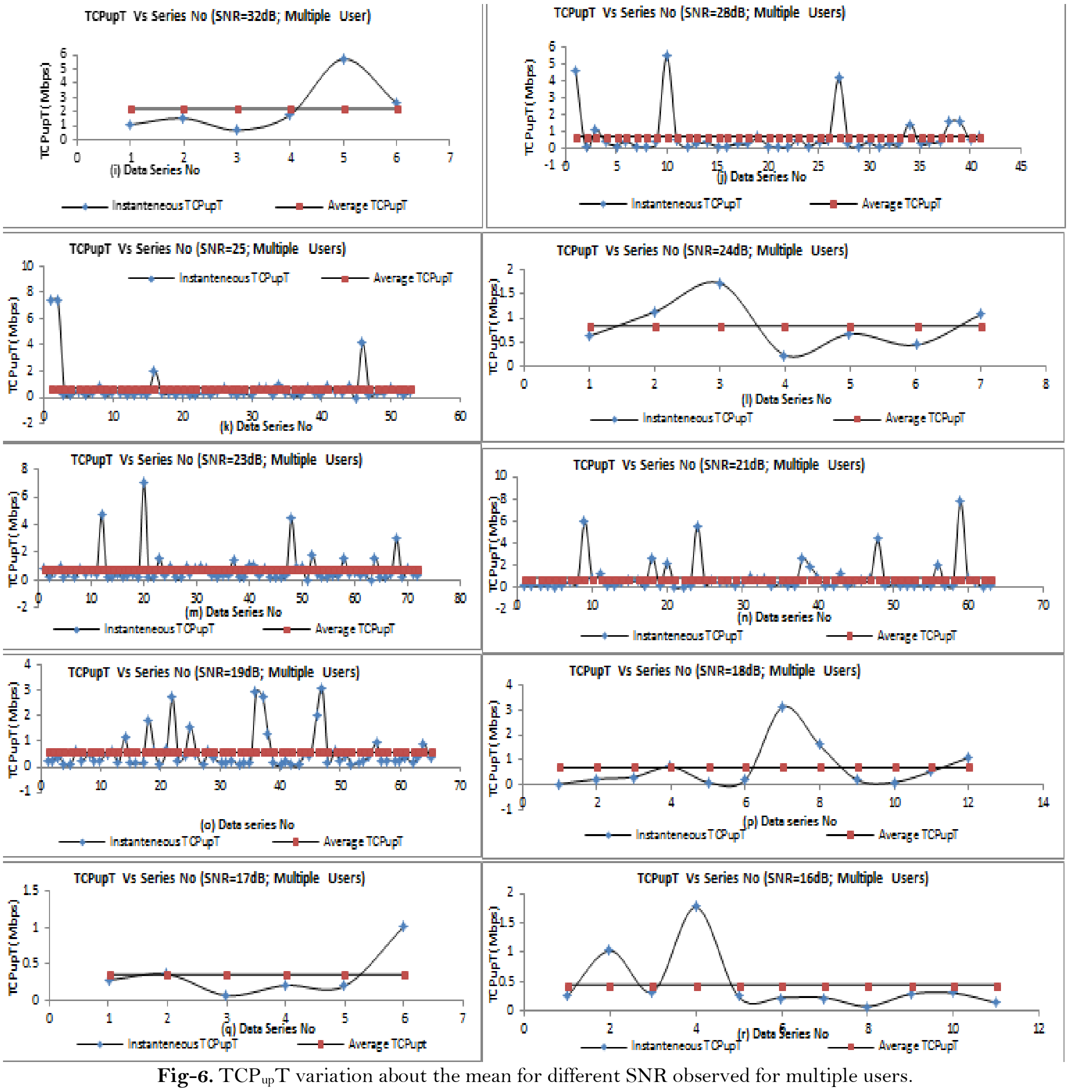


**Fig-6.** $TCP_{up}T$ variation about the mean for different SNR observed for multiple users.

The mean $TCP_{up}T$ value dropped from 5.33Mbps at a SNR of 25dB to 0.51Mbps at a SNR of 24dB. This drop in mean $TCP_{up}T$ value observed improved again (2.975Mbps for SNR of 23dB) 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 $TCP_{up}T$ average values which is more evident in Fig 5(r) for the SNR of 15dB. In Figure 5 (k, l and m), it can be seen that $TCP_{up}T$ values stay low for a series group and then becomes high for another series group. This implies that the selected data rate remains low for a short interval and then goes high after which it goes low again for a single user on the network in the grey signal range.

For multiple users on the network, strong signals showed a large variation about the mean values as can be seen in Figure 6. This observation is in line with the high standard deviation observed for strong signals in the multiple user scenario shown in Table 1 and Fig.1. However, the variation about the mean was greatly reduced for grey and weak signals when compared with



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strong signals. The large drop in average $TCP_{up}T$ observed for single users at SNR=24dB was absent for multiple users.

## 5. FUTURE RESEARCH DIRECTION

This work focused on developing models that will enable researchers and WLAN users to quickly estimate TCP upstream throughput 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 TCP throughput on SNR. There is the need to extend the research to TCP downstream throughput. 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 environments and traffic types (Voice or audio, video, control, etc.) corresponding to different WMM tags 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.

## 6. CONCLUSION

In this paper, we discussed our empirical findings on the dependence of $TCP_{up}T$ measured at the transport layer against the received SNR varied at the physical layer by varying receiver position in different environments under varieties of QoS traffic. We studied the dependence of TCP upstream throughput on SNR over a wide range of signals (Strong, Grey and Weak). Our models (for each signal range and a general model for all signal ranges considered) estimate the throughput with low RMS errors observed when they were compared with data from other environments. Our models showing lower RMS errors performed better than other similar models considered. The large difference between the throughput observed for single and multiple users on the network shows the inefficiency in DCF and PCF access mechanisms used for WLANs. This study will provide researchers and WLAN systems users with a tool to quickly estimate or simulate the $TCP_{up}T$ in a real network in various environments by monitoring SNR.

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