International Journal of Engineering and Applied Sciences (IJEAS)
ISSN: 2394-3661, Volume-9, Issue-5, May 2022

# Single User TCP Downstream Throughput Models in IEEE802.11g WLAN

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*Abstract*—
Single User Models for predicting transmission control protocol (TCP) downstream throughput in IEEE 802.11g wireless local area networks (WLANs) was developed for different signal to noise ratio (SNR) categories. Single User (TCP) downstream throughput data corresponding to different SNRs were collected using Tamosoft throughput test over a wide range of environments namely: open corridors, free space and small offices in IEEE802.11g WLANs. SNR was computed from received signal strength indication and noise floor data collected using inSSIDer 2.1 software. Different types of quality of service (QoS) traffic that correspond to different wireless multimedia tags were transmitted in the network between a server and a client. Two types of single user TCP downstream throughput ($TCP_{down}T$) models that can predict $TCP_{down}T$ as a function of the SNR for different levels of signals were developed, validated and then compared with existing similar models. The first model was developed without data categorisation using SNR. The second model was developed by categorizing the field data into different signal categories (strong, grey and weak signals) which was then used to develop $TCP_{down}T$ models for each signal category.
The developed Single User Models for predicting transmission TCP downstream throughput in IEEE 802.11g WLANs were accepted as they passed the F tests. They also showed lower RMS errors after being compared with existing similar models. The models developed in this work provide IEEE 802.11g WLAN designers with a tool to estimate $TCP_{down}T$ based on SNR within reasonable accuracy on the network thereby enhancing easier network installation decision making.

*Index Terms*—**Throughput, WLANs, Signal to noise ratio, IEEE 802.11g.**

## I. Introduction

Today our lives activities are largely dependent on the internet [1, 2]. The ease and flexibility to access the internet using smart phones, computers and other internet enabled devices anywhere and anytime are now being provided by wireless local area networks (WLANs). Information access has become easier and more efficient [3].

In many organization and homes in Nigeria, IEEE 802.11b, IEEE 802.11g and IEEE802.11n WLANs are being used for sharing network resources both within the organizations and externally through connections with the internet. Transmission Control Protocol (TCP) provides mechanisms for reliable data communications. WLANs use TCP which makes up about 80% of internet traffic [4, 5] hence the need to develop tools that can predict the TCP performance of WLANs. To evaluate WLANs in real time is extremely challenging due to several issues such as varying interference scenarios, complexity in radio signal propagation, inherent inefficiencies in WLAN system mechanisms and protocols, etc.

Multiple communication data rates (which determine the throughput used for transmission) are specified in the physical layer of the IEEE802.11 standards. The multiple communication data rates change based on the signal quality (SNR) of the link [6].

The SNR is a major metric which determines the data link rate (DLR) selected by the WLAN for data transmission [6]. In WLANs, stations choose a data rate for transmission depending on the SNR sensed by the station and this action significantly influences the throughput behaviour [7]. This process is known as link adaptation.

In link adaptation, as SNR increases, stations use higher data rates to transmit their frames thereby having higher throughput closer to maximum channel capacity. Also as SNR decreases, stations use lower data rates for frame transmission thereby achieving lower throughput.

Round trip time (RTT) and Throughput are the two metrics considered most important for determining WLAN performance [8]. The ability to predict the RTT and throughput gives appreciable information about the WLAN performance. A minimum throughput must be obtained and a maximum RTT must not be exceeded if the WLAN is to be considered efficient in providing adequate coverage [9].

Throughput refers to the average data rate (in bits) that can be sent between one user and another in a network [10]. Downstream throughput describes the data speed sent from the server to the client and upstream throughput describes the data speed sent from the client to the server and. On the internet, Upstream is synonymous with uploads while downstream is synonymous with downloads. [11] presented findings that showed the need to study upstream and downstream throughputs separately as they show appreciable differences in throughput characteristics in a network.

Some models that were developed using cross layer modelling principles can predict throughput and RTT directly from SNR in an IEEE 802.11b WLAN within reasonable accuracy [6, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19]. These models developed by these authors required that some metrics like number of users, the type of protocol used, the type of data traffic and environment used for measurement should be specified for better accuracy.

Throughput field data was collected at the transport layer while SNR data was collected at the physical layer assuming that all processes between the higher layer and the lower layer were taken into account even though they cannot be separately recognized or isolated [20, 21]. These models predicted throughput directly from the observed SNR within reasonable accuracy as presented by the authors. The models were developed using a combination of field data collected across different environments using different types of quality of service (QoS) traffic and users for IEEE 802.11b.

These models simplify the WLAN design process as they provide a tool that enables the WLAN designer to reliably predict the throughput and RTT to be experienced by a client in an IEEE 802.11b WLAN by monitoring only the SNR. The need to develop similar models for IEEE 802.11g WLANs was recommended.

In this paper, using cross layer modelling principles, we present single user throughput models which can predict the throughput from the SNR in an IEEE 802.11g WLANHighlight a section that you want to designate with a certain style, and then select the appropriate name on the style menu. The style will adjust your fonts and line spacing.

## II. Review Of Past Work

Several researchers have provided models for predicting TCP throughput based on SNR only with reasonable accuracy. [14] provided a detailed review of throughput models based on SNR observed which applied cross layer modelling and considered single and multiple users, upstream and downstream throughput etc. Models presented by [14] included those developed by [6, 10, 11, 12, 20, 21, 22]. All of these models directly predict throughput from the received signal for IEEE 802.11b WLANs. Models that predict throughput directly from the received signal for IEEE 802.11g WLANs were not presented in all of these works except in [6]. [6] developed four models for TCP throughput describing different fading conditions of an IEEE 802.11g WLAN. The models predicted throughput directly as a function of the received signal in dBm hence noise floor levels were not considered. The developed models are: One tap constant channel, One tap IEEE 802.11g Model A channel, Multi-Tap IEEE 802.11g Model B Channel and the Multi-Tap IEEE 802.11g Model C Channel. [6] developed model equations from the throughput data collected for each channel condition as a function of the received signal in dBm.

The first model called the one-tap constant channel model stands for an ideal channel hence it represents maximum throughput obtained. This ideal channel was used by [6] as a baseline for comparing the throughput measured with the other more realistic channels.

The throughput model for an IEEE 802.11g WLAN operating in a one tap constant channel developed by [6] is given by

$$one\ tap\ constant\ channel\ (p) = \begin{cases} 29.15\,, & p > -72.82 \\ 1.51p + 138.79, & -92.18 < p \leq -72.82\ \ (Mbps) \\ 0, & p \leq -92.18 \end{cases}$$

$p$ is the received signal value measured in dBm.

The second model called One Tap Rayleigh Fading Channel Model A represents a one-tap (one line of sight) Rayleigh fading channel. This channel is not very realistic in actual environments.

The throughput model for an IEEE 802.11g WLAN operating in a one tap Rayleigh fading channel (Model A) developed by [6] is given by

$$One\ tap\ Rayleigh\ fading\ channel\ (Model\ A = \begin{cases} 26.94, & p > -65.84 \\ 1.13p + 101.3, & -89.69 < p \leq -65.84 (Mbps) \\ 0, & p \leq -89.69 \end{cases}$$

The third model called Channel Model B is a multi-tap, two cluster multipath model which represents a residential indoor area. However note that two cluster is still very far from what we would have in a real scenario. The throughput model for an IEEE 802.11g WLAN which operates in the multi-tap IEEE Channel Model B fading channel developed by [6] is given by.

$$Multi\ tap\ IEEE\ channel\ (Model\ B) = \begin{cases} 26.61, & p > -65.49 \\ 1.12p + 99.92, & -89.27 < p \leq -65.49\ \ (Mbps) \\ 0, & p \leq -89.27 \end{cases}$$

The fourth model called Channel Model C stands for a slightly harsher channel than Channel Model B and A. It has a greater RMS delay spread and more taps. However the number of taps was still limited hence the multi path assumed is limited unlike what will be the case in a real life scenario.

The throughput model for an IEEE 802.11g WLAN which operates in the multi-tap IEEE Channel Model C fading channel developed by [6] is given by:

$$Multi\ tap\ IEEE\ channel\ (Model\ C) = \begin{cases} 26.71, & p > -66.33 \\ 1.16p + 103.79 & -89.32 < p \leq -66.33\ \ (Mbps) \\ 0, & p \leq -89.32 \end{cases}$$

The models presented by [6] has some limitations. The number of taps were restricted hence the number of paths (multi path) the signal is estimated to pass through is limited unlike that of real life radio signal data where the number of paths is very large. Also the models were presented using signal strength in dBm and not SNR in dB hence the effect of the noise floor level was assumed negligible which is not always the case. [6] did not also consider models specifically for different signal levels (strong, grey and weak signals). In this work these three draw backs were taken into consideration hence the signal was not considered for a limited number of paths as different real life scenarios was used in gathering the data. The SNR in dB was used to develop the models instead of the signal strength in dBm to ensure that the effect of the noise floor is considered. Also models were developed considering the different levels of signals.

## III. Research Method

The method used in [11, 12, 20] was used in this work. However in this work the models were developed using data collected in an IEEE 802.11g WLAN instead of IEEE 802.11b WLAN. The procedures were detailed in these past work hence are omitted here. The QoS traffic types used in this work corresponds to different wireless multimedia tags as are described in [23]. Single user TCP downstream throughput field data was collected using Tamosoft throughput test on an IEEE 802.11g WLAN. SNR was computed from the Received signal strength indication measured in dBm and the noise floor level in measured in dBm. The received signal strength was measured using inSSIDer 2.1 software in dBm and the noise floor level was monitored as a parameter displayed in the WLAN radio in dBm. The inSSIDer 2.1 was also used for monitoring interfering access points and wireless devices to avoid taking measurements using channels with substantial interference. Data was sorted using SNR thereby providing data categories for All SNR (General), Strong signals (SNR ≥25dB), grey signals (25dB>SNR>18dB) and weak signals ($SNR < 19dB$) as described in [11, 12, 20]. Single User

TCP downstream throughput models for IEEE 802.11g WLAN were statistically generated from the data using statistical package for social sciences (SPSS). TCP downstream throughput ($TCP_{down}T$) models that can predict $TCP_{down}T$ as a function of the SNR for different levels of signals were developed, validated with field data and then compared with existing similar models developed for IEEE 802.11g WLAN. The first model was developed without data categorisation using SNR. The other models were developed by categorizing the data into different signal categories (strong, grey and weak signals) and then used to develop $TCP_{down}T$ models for each signal category. Computed values of root mean square errors and F tests were used to check if the developed models should be accepted or rejected.

## IV. Results and Discussion

Table I shows the statistical parameters of $TCP_{down}T$ field data for all categories of SNR considered. Statistical packages for social sciences (SPSS) was used to generate the statistics presented in Table I from collected field data. As done in [20], the collected field data were grouped into four classes of SNR. All SNR range made up the first data group. The second data group consist of $TCP_{down}T$ for strong signals only (SNR ≥25dB), the third data group consist of $TCP_{down}T$ for grey signals only (25dB>SNR>18dB) while the fourth data group consist of $TCP_{down}T$ for weak signals only ($SNR < 19dB$).

As presented in Table I, $TCP_{down}T$ variance (62.122) and standard deviation (SD) (7.8817Mbps) computed for the combined data for all SNR range are high. This implies that $TCP_{down}T$ varies considerably from weak, through grey to strong signals. However this variation reduces if only strong signals are considered. This is evidenced in the reduced variance (36.033) and SD (6.0028Mbps) of $TCP_{down}T$ strong signals data compared with that of all signals data as shown in Table 1.

From Table I, it can be seen that multi modal distribution is absent for $TCP_{down}T$ in the grey and strong signal ranges but present for weak signals which is spread across two class intervals. The variance (6.903) and SD (2.6273Mbps) obtained for grey signals were appreciably low compared with strong signals. Weak signals showed the lowest variance (2.069) and SD (1.4385) hence the variation of $TCP_{down}T$ for weak signals is lower compared with strong and grey signals.

Negatively skewed distributions were observed for all SNR $TCP_{down}T$ field data (-0.682) and strong signals field data (-1.203). This implies that for all signals and strong signals, $TCP_{down}T$ field data showed a longer tail towards the left of the observed mean of 17.013Mbps and 19.529Mbps respectively.

Positively skewed distributions were observed for grey (0.411) and weak (0.391) signals $TCP_{down}T$ field data. This implies that for grey and weak signals, $TCP_{down}T$ field data showed a longer tail towards the right of the observed mean of 4.819Mbps and 3.582Mbps respectively.

Only strong signals showed a positive kurtosis (0.392) hence near the mean, a peaked distribution exists unlike the negative kurtosis observed for all SNR (-1.049), grey (-0.552) and weak (-0.710) signals $TCP_{down}T$ field data.

The graph of SD and $TCP_{down}T$ average observed for the field data plotted against SNR is shown in Figure 1. From the graph of Figure 1, it can be seen that $TCP_{down}T$ observed increased linearly until a SNR of 42dB after which it was averagely constant despite increasing SNR. The standard deviation was also observed to increase fairly linearly with SNR until the SNR of 42dB was crossed after which the standard deviation dropped appreciably.

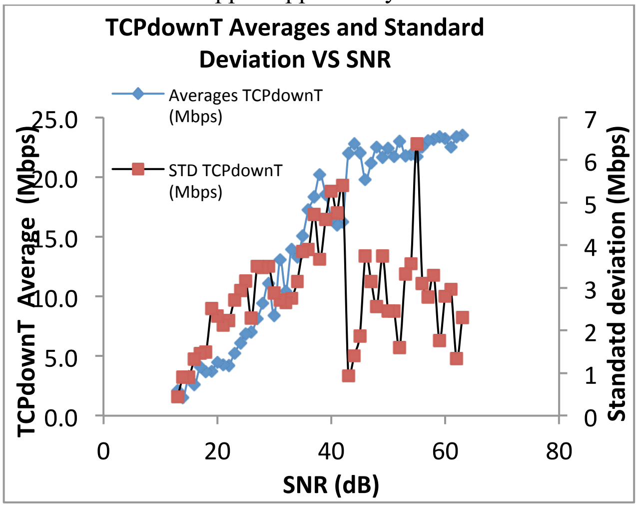


Fig. 1: Graph of SD, and $TCP_{down}T$ field data Averages against SNR.

## V. Development Of Throughput Models

Equations 1-4 show the model equations which were generated statistically by SPSS using categorized field data. The models developed were for all SNR (General Model), weak, grey and strong signals. The constants and coefficients of the models are represented by $c$ and $a_1$ respectively in the respective equations. Their numeric values differ for each equation.

For a single user on the IEEE802.11g WLAN, the model equations directly predict the $TCP_{down}T$ as a function of SNR. Equation 1 covers the entire SNR range as it was developed using the total field data collected. Equation 2, 3 and 4 can respectively predict Single user $TCP_{down}T$ for strong, grey and weak signals.

$$(General)TCP_{down}T = f(SNR) = \begin{cases} 23(Mbps), & SNR>58dB \\ e^{(c+\frac{a_1}{SNR})}(Mbps), & 12dB<SNR\leq 58dB \\ 1\ (Mbps), & 9dB<SNR\leq 12dB \\ 0\ (Mbps), & SNR\leq 9dB \end{cases}$$

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$$(Strong)TCP_{down}T = f(SNR) = \begin{cases} 23\ (Mbps), & SNR > 59dB \\ e^{(c+\frac{a_1}{SNR})}\ (Mbps), & 24dB<SNR\leq 59dB \end{cases}$$ …

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$$(Grey)TCP_{down}T = f(SNR)$$

$$= a_1^{SNR} \quad \text{(Mbps)}, \quad 18dB<SNR<25dB$$ ......3

Table 1: Statistical Parameters of $TCP_{down}T$Field data
*multiple mode exists

| Statistical Parameter | All SNR (63dB to 11dB) | Strong Signals (SNR ≥25dB) | Grey Signals (25dB>SNR>18dB) | Weak Signals (SNR < 19$dB$) |
|---|---|---|---|---|
| N (Sample Size) | 1907 | 1584 | 290 | 34 |
| Mean | 17.013 | 19.529 | 4.819 | 3.582 |
| Std. Error of Mean | 0.1805 | 0.1508 | 0.1543 | 0.2467 |
| Median | 21.000 | 22.610 | 4.495 | 3.490 |
| Mode | 23.7 | 23.7 | 4.8 | 1.52*, 2.48* |
| Std. Deviation | 7.8817 | 6.0028 | 2.6273 | 1.4385 |
| Variance | 62.122 | 36.033 | 6.903 | 2.069 |
| Skewness | -0.682 | -1.203 | 0.411 | 0.391 |
| Std. Error of Skewness | 0.056 | 0.061 | 0.143 | 0.403 |
| Kurtosis | -1.049 | 0.392 | -0.552 | -0.710 |
| Std. Error of Kurtosis | 0.112 | 0.123 | 0.285 | 0.788 |
| Range | 37.8 | 36.4 | 11.1 | 5.4 |

$$(Weak)TCP_{down}T \quad = f(SNR) = \begin{cases} a_1{}^{SNR\ (Mbps)}, & 13dB \leq SNR < 19dB \\ 1\ (Mbps), & 9dB < SNR < 13dB \\ 0 (Mbps), & SNR \leq 9dB \end{cases}$$
......................................................................4

Parameters of the model and the F distribution test results are presented in Table 2. The models were evaluated for performance by comparing their F values with F-values obtained from F-Table. The hypothesis defined were as follows:

**Null hypothesis ($H_0$):** This means the proposed $TCP_{down}T$ model does not properly fit the data. Thus the conclusion is that if a single user is in an IEEE 802.11g WLAN, $TCP_{down}T$ is not significantly dependent on SNR.

**Alternative hypothesis ($H_1$):** This means the Proposed $TCP_{down}T$ model properly fits the data. Thus the conclusion is that if a single user is in an IEEE 802.11g WLAN, $TCP_{down}T$ is significantly dependent on SNR.

As seen in Table II, $H_0$ was rejected thus $H_1$ is accepted. At 1% level of significance and the stated degrees of freedom the models developed in this work were all accepted.

Table III shows the root mean square (RMS) errors computed for the respective models by comparing them with the validation field data averages. RMS errors for [6] models for IEEE 802.11g were also computed so that comparison can be made.

The RMS errors of the models were estimated with respect to $TCP_{down}T$ field data. It can be observed that the strong and weak signal models showed lower RMS errors compared with the general model. This justified the need to categorize the data before developing the models. However in the grey signal range (which is the transition region from strong to weak signals), the general model (RMS error = 0.487Mbps) performed slightly better than the grey signal model (RMS error =0.966Mbps) by showing a slightly lower RMS error.

Table III also shows that our models performed better than [6] models obviously because of the reasons we stated earlier. [6] models restricted the number of paths the signal is estimated to pass through unlike what is the case for real life throughput data where the number of paths is very large. Also [6] models were presented using signal strength in dBm not using SNR in dB hence the effect of the noise floor level was assumed negligible. [6] did not also consider models specifically for different signal levels

Fig. 2-5 show the respective graphs of developed $TCP_{down}T$ models for all SNR, Strong signals, Grey signals and weak signals plotted against SNR along with $TCP_{down}T$ Field data averages, and [6] models. The models developed in this work can be seen from Fig. 2-5 to follow the validation data more nearly compared with [6] models hence they are better for $TCP_{down}T$ prediction.

## VI. Limitation of Study

In this work, the dependence of $TCP_{down}T$ on SNR for a single user on the IEEE 802.11g WLAN has been investigated. Models were developed to aid WLAN users and researchers to estimate $TCP_{down}T$ as a function of SNR. However in many real networks there are multiple user hence it is very necessary that this work be carried out for multiple users on the network. Since throughput and RTT are both very important metrics in determining WLAN performance, RTT models should also be considered.

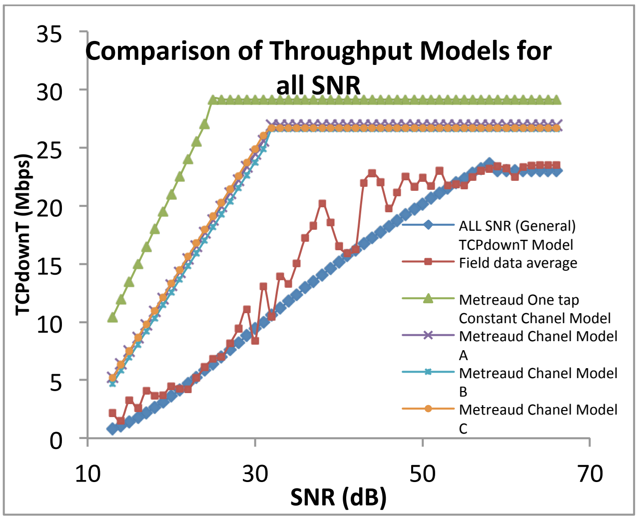


Fig. 2: $TCP_{down}T$ Models Values Vs. SNR for all Signals

Table II: Parameters of the developed models

| 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 | Model for All SNR (General) | 0.738 | 0.395 | 0.000 | 0.000 | $F_{0.01,1,1905}$ =5365.109 | 6.63 | $H_o$ is rejected. level of significance =1%. Model is accepted |
| 2 | Model for Strong Signals | 0.623 | 0.281 | 0.000 | 0.000 | $F_{0.01,1,1582}$ =2610.627 | 6.63 | $H_o$ is rejected. level of significance =1%. Model is accepted |
| 3 | Model for Grey Signals | 0.782 | 0.728 | 0.000 | 0.000 | $F_{0.01,1,289}$ =1035.881 | 6.63 | $H_o$ is rejected. level of significance =1%. Model is accepted |
| 4 | Model for Weak Signals | 0.898 | 0.409 | 0.000 | 0.000 | $F_{0.01,1,33}$ =291.770 | 6.63 | $H_o$ is rejected. level of significance =1%. Model is accepted |

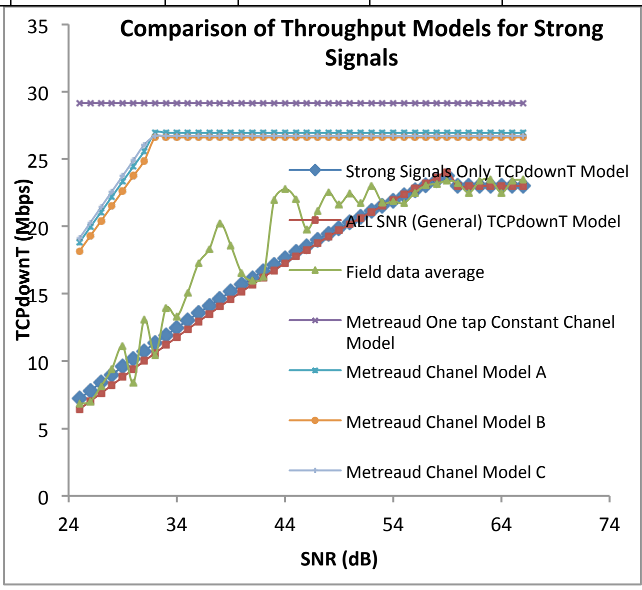


Fig. 3: $TCP_{down}T$ Strong Signal Models Values Vs. SNR

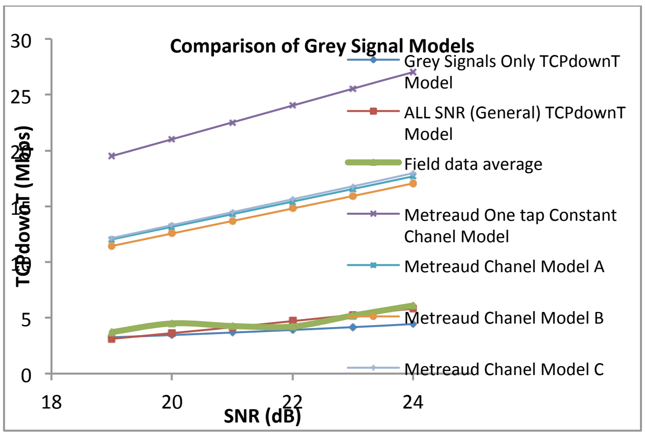


Fig. 4: $TCP_{down}T$ Grey Signal Models Vs. SNR

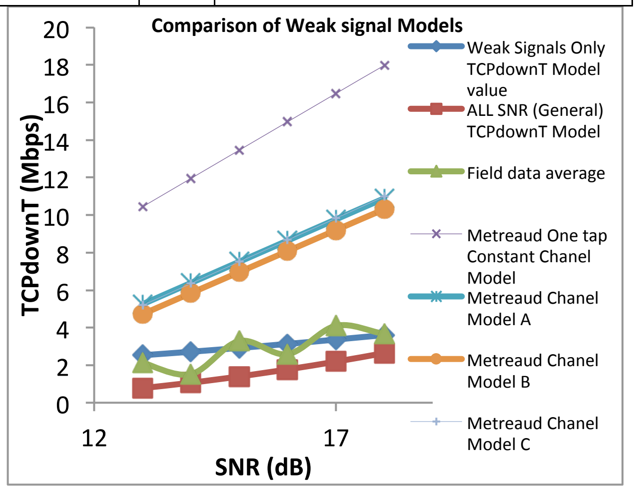


Fig. 5: $TCP_{down}T$ Weak Signal Models Values Vs. SNR.

## VII. Conclusion

This paper presented $TCP_{down}T$ models developed by measuring $TCP_{down}T$ in various environments. $TCP_{down}T$ is measured at the transport layer while the received SNR is varied at the physical layer by varying the position and direction of the client for a single user on the IEEE802.11g WLAN. Different types of QoS traffic that corresponds to different wireless multimedia tags were sent in the network. The developed models passed the F tests and showed lower RMS errors compared with [6] models. The models developed in this work provide IEEE 802.11g WLAN users and Installers with a tool to estimate reasonably estimate the $TCP_{down}T$ based on SNR computed from the received signal strength indication and the noise floor level. This will enhance easier network decision making during network installation.

Table III: RMS errors for comparison of models

| RMS ERRORS (ALL SNR ) | | | | | |
|---|---|---|---|---|---|
| **Model** | **General (All SNR)** | **Metreaud One tap Constant Channel Model** | **Metreaud Channel Model A** | **Metreaud Channel Model B** | **Metreaud Channel Model C** |
| **RMS error (Mbps)** | 2.235 | 13.062 | 8.709 | 8.285 | 8.710 |

| RMS ERRORS (STRONG SIGNALS) | | | | | | |
|---|---|---|---|---|---|---|
| **Model** | **Strong signals** | **General model** | **Metreaud One tap Constant Channel Model** | **Metreaud Channel Model A** | **Metreaud Channel Model B** | **Metreaud Channel Model C** |
| **RMS error (Mbps)** | 2.210 | 2.563 | 12.203 | 8.862 | 8.475 | 8.825 |

| RMS ERRORS (GREY SIGNALS) | | | | | | |
|---|---|---|---|---|---|---|
| **Model** | **Grey signals** | **General model** | **Metreaud One tap Constant Channel Model** | **Metreaud Channel Model A** | **Metreaud Channel Model B** | **Metreaud Channel Model C** |
| **RMS error (Mbps)** | 0.966 | 0.487 | 18.707 | 10.270 | 9.658 | 10.470 |

| RMS ERRORS (WEAK SIGNALS) | | | | | | |
|---|---|---|---|---|---|---|
| **Model** | **Weak signals** | **General model** | **Metreaud One tap Constant Channel Model** | **Metreaud Channel Model A** | **Metreaud Channel Model B** | **Metreaud Channel Model C** |
| **RMS error (Mbps)** | 0.6525 | 1.351 | 11.498 | 5.360 | 4.820 | 5.387 |

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