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EMPIRICAL OBSERVATION OF WIRELESS NETWORK PERFORMANCE FOR TRANSMISSION CONTROL PROTOCOL (TCP) UPSTREAM AND DOWNSTREAM FOR DIFFERENT USERS SCENARIOS

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Abstract— **The increase in demand for proper and fast access to network infrastructure around the University environment by staff, students, and visitors in the quest to carry out daily tasks or keeping up with trends/innovations around the globe is a daily experience resulting in some challenges. But these challenges are not unexpected. The access to network infrastructure around the environment encourages proper development. This paper presents an empirical observation of transmission control protocol upstream throughput ($TCP_{up}T$) and downstream throughput ($TCP_{down}T$) performance for an IEEE 802.11g wireless local area network (WLAN) installed at a corridor space of University of Nigeria, Nsukka campus. This work measured the TCP upstream and downstream throughput values for single, double, and multiple users (several Users) accessing an installed WLAN access point. The paper adopted basic WLAN system setup approach while observing the TCP performance in relation to SNR. Data collected for each environment were statistically analyzed, equations and results were also presented. The observed TCP throughput values vary as users increase thereby affecting the observed round-trip time (RTT). The generated equations were also used to predict TCP throughput which would aid network engineers in the deployment of IEEE 802.11g WLAN systems especially around the university environment. It is now clear that the generated model equations can be used for predicting the expected performance of IEEE 802.11g WLAN systems during deployment. This work gives WLAN engineers, researchers and users an apparatus to rapidly estimate the TCP upstream and downstream throughput, by monitoring the received SNR for IEEE 802.11g systems.**

Keywords— **TCP upstream and downstream Throughput, SNR, Empirical modeling, Single user, multiple users**

I. INTRODUCTION

Information and Communication Technology development around the globe is evolving and continually experiencing an increase in demand at various levels of operation and interactions. The growth in the use of internet of things (IoT) around the globe also demands a proper understanding of the operations and installations of the network infrastructure. Such knowledge as in this case, will enhance easy accessibility and create a good throughput experience**.** The increase in demand for proper and fast access to network infrastructure around the University environment by staff, students, and visitors in the quest of carrying out daily tasks or keeping up with trends and innovations around the world is a welcome development although faced with some challenges. To meet up with such demands, therefore, requires proper deployment of the network infrastructures within and around its environments. The provisioning of access to network infrastructure around the environment encourages proper development and the ability to compete and stay in tune with growth and development across the globe. Nowadays, the university environment is regarded as an epicenter of information and communication technology. Visitors or guests entering into the university environment expect a specific degree of wireless access speed and connectivity. It is one of the most requested demands and expectations, not just due to the sheer number of individuals getting into the University, but also due to the advancement in technology, the need for visibility, the ease required in accessing 24-hour digital libraries, and a recent increase in e-learning activities.

This work considers IEEE 802.11g WLAN system only as it is the dominant observed system around the university. Other IEEE 802.11 WLAN systems are also available and can be considered as they would provide actual users' data experience in the deployment of these devices thereby putting a check on the previous dominant pinging and RSSI values observed in deployment methods.

The use of IEEE 802.11 standard of wireless communication has found wide acceptance around the globe. Incidentally, the University of Nigeria, Nsukka also has a vast deployment of these infrastructure. In consideration of the accessibility of WLAN systems, the deployment of the access points also plays an important role among other things in determining the users' experience. It is observed that in the deployment of WLAN systems, real-time user experience is not often considered. Transmission Control Protocol (TCP) is a widely used transport protocol for transmitting data over the Internet. In a Wi-Fi system, TCP refers to the amount of data that can be transmitted per unit of time over the wireless network. TCP throughput, which defines how quickly data can be exchanged between devices, is a crucial parameter for assessing the effectiveness of a Wi-Fi system. A higher TCP throughput means that data can be transmitted at a faster rate, faster downstream and upstream rates. TCP throughput in a Wi-Fi system can be impacted by a number of variables, including network congestion, interference from other wireless networks, the distance between devices, and the strength of the wireless signal.

In TCP measurement, consideration of SNR is crucial in view of optimizing Wi-Fi systems and ensuring that it operates optimally and efficiently. Again, observing TCP throughput in relation to SNR would aid network administrators in proper deployment and spotting possible issues and taking steps to address them. The TCP throughput values for different users account for most of the traffic experienced on the internet. Pinging and observed received signal strength indicator (RSSI) values have served as the dominant WLAN deployment information around the school environment. The tools, as good as they are, do not depict the real-time user's experience when accessing or connecting to the WLAN system. Due to the highly sensitive nature of wireless systems, some factors such as users' terrain orientation, buildings, and individual presence are expected to affect the WLAN system performance as can be observed in real-time users' access. This scenario, if observed in the deployment of WLAN systems around the environment, would enhance users' experience. This work, although referenced to University of Nigeria, is also implementable in any environment having IEEE802.11g WLAN system deployment in place.

The rest of the paper is as follows: Section 2 presents the related works, implementation in similar environments, weaknesses, and strengths. Section 3 describes the research methods used in this work, while section 4 shows the analysis and discussion of the simulation results. Finally, section 5 concludes the paper by showing the predicted models and the effect of TCP throughput.

II. RELATED WORKS

In view of the factors that can influence the performance of WLAN systems in the University environment such as the presence of elaborate trees that describe the actual physical features of such environments, there might be a need to deploy more access points. The effects of these obstructions, for example, trees, buildings, etc. on the distribution of the University WLAN system may be worrisome. The observations and measurements of the path loss and received signal strength variations as a function of distance have been done by [1] but the work did not consider TCP upstream and downstream performance with signal-to-noise ratio (SNR) in the deployment of WLAN systems.

The performance of IEEE 802.11 WLAN systems covering different aspects of performance and recommendations geared towards improving users' experience can be observed in [2]. Also, challenges that face the deployment of Wi-Fi in different aspects of the University in view of coverage, capacity limitations, density requirements, and security concerns have been studied by [3][4][5]. However, only [3] presented an enhanced network design for colleges. The work suggested designing and implementing a network with high quality, minimal expense, and better routing protocol using layer 3 device switches instead of layer 2 device switches. The work tends to handle load balancing and network security. It should be stated here that studying and investigating TCP upstream and downstream throughput depends on signal to noise ratio (SNR) for different user scenarios and its observed performance would aid in the proper deployment of WLAN systems [6].

The work done by [7], used NETSIM for simulation and analysis of LAN network performance implemented in CIT college campus network for realistic traffic scenarios and to study its performance metrics. In [8], empirical probability models for predicting TCP downstream throughput in WLAN system were presented. The paper contains information indicating the dependence of TCP downstream on SNR for various observed signal levels. The work aimed at developing models that would provide researchers and WLAN systems users the needed tool to estimate the TCP downstream throughput in a real network in various environments through monitoring and evaluation of the received SNR.

Papers on measuring and investigating TCP upstream dependence on SNR models that could predict TCP performance at various signal ranges and environments have been investigated. The investigations at real network time were done for IEEE 802.11b systems and the outcome indicates its importance as a tool in WLAN deployment as [developed in [8][9][10][11]. The work done in [12], used UDP traffic to measure 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. The paper used UDP traffic and did not consider TCP performance. [13] worked on Predicting throughput performance in IEEE 802.11 based wireless networks using directional antennas. The study suggests a model for predicting the throughput in IEEE 802.11 wireless networks using directional antennas for both indoor and outdoor environments. Using directional antennas can improve the performance of wireless networks by reducing interference and increasing signal strength but does not handle WLANs deployment considering SNR.

Most of the works as seen in [8][9][14][11], investigated TCP upstream and downstream throughput focusing on IEEE 802.11b WLAN system. The work presented in this paper followed the same research method used in [10][14][15] but focused on IEEE 802.11g WLAN system instead because it has a vast deployment in University of Nigeria Nsukka wireless network (Lionet). Authors in [16], modeled the performance evaluation of IEEE 802.11g under different channel conditions for small office and large open space and [17][18] investigated the received signal strength of IEEE 802.11n. As seen in [17], the paper addresses the challenges faced by network engineers in IEEE 802.11n access points deployment. It carried out RSSI measurement and evaluation in solving the difficulties encountered while generating high data rates and quality of service of the system. The approach has some limitations in that it did not cover users experience as high data rates and quality of service can be affected by usage. The study did not also consider IEEE 802.11g system. Papers [19][20], considered the optimal deployment of various IEEE 802.11 standards which remains vital for maximum user experience. [19] proposes an optimal deployment strategy for IEEE 802.11ac wireless networks in high-speed railway systems. The authors used simulations to evaluate the performance of the strategy and compared it with other deployment strategies. In [20], the authors examined the benefits and challenges of integrating 5G and IEEE 802.11ax (Wi-Fi 6) and propose a hybrid approach for optimal deployment. [21] examined the performance of the IEEE 802.11b standard (also known as Wi-Fi 7) for next-generation Wi-Fi networks. Here, the author paid particular attention on impact of various factors, such as, channel bandwidth, multi-user MIMO, and spatial reuse on the performance of the standard using simulations. but did not consider its deployment strategy. [22] Reviewed techniques, technologies, and challenges in WiFi-based indoor positioning, and compares the performance of different approaches. Discussion was on the impact of various factors on the accuracy and reliability of WiFi-based indoor positioning, such as multipath, interference, and environmental factors and suggested various ways of improving deployment such as positioning accuracy, reducing power consumption, and enhancing privacy and security. The paper did not however, provide approach for positioning accuracy and decision on TCP throughput with SNR in achieving deployment accuracy. [23] provides approach to optimization policy in the deployment of wireless local area networks (WLANs) in indoor environments. The study presents a mathematical model for optimal WLAN deployment for an indoor environment which takes into account various factors such as user density, network capacity, signal propagation, and interference. The authors also proposed two-stage approaches for optimal WLAN deployment. Firstly, the optimal placement of access points (APs) and secondly, the optimal channel allocation for each access point. Thereafter, the approach was evaluated using simulations and real-world experiments. Both [22][23] did not consider TCP throughput in relation to SNR.

[24] Viewed the need for line-of-sight communication and the substantial attenuation of millimeter-wave signals as two of the primary deployment difficulties for 802.11ad. To address these issues and enhance the performance of 802.11ad in both indoor and outdoor settings, the authors via simulations and experiments suggested system deployment using directional antennas, multiple access points, and beamforming methods. As noted earlier in [13], TCP throughput dependence on SNR should be considered for determining real-time user expected experience. And this is the direction this study is trying to unveil. It is also very imperative in wireless systems such as IEEE 802.11 standard.

The implementation and deployment of various IEEE 802.11 WLAN system standard exists in various levels and fields, using various techniques based on certain conditions as frequency band, bandwidth, modulation and maximum data rates, etc. These varying standards of TCP throughput if evaluated in real time scenarios will meet design expectations in the deployment of this system.

III. RESEARCH METHODS

In this paper, the TCP upstream and downstream throughputs were investigated and measured in an open corridor environment of Electronic Engineering Department, University of Nigeria, Nsukka Campus. The area is encompassed with nearby buildings, trees, students and staff, in consideration of real time experience while accessing WLAN systems. Data collection was done in both active and less active moments in the environment and the users facing different directions away from the access points. Also, different users' scenarios are considered while collecting data (closely clustered and distant users) basically for multiple users' case. The measurement consists of observed TCP throughput single user and multiple user experiences when accessing an IEEE 802.11g WLAN system from a vendor EnGenius Technologies (EnGenius ENS202EXT). The wireless access point was placed in such a location above any direct physical interference and obstructions on the terrain. When monitored, the network connection displayed a typical WLAN connection consisting of the access point, the server, and the wirelessly connected user/users. The access point referred to here as mentioned above was set to operate on IEEE 802.11g standard and a server connected to the access point using an Ethernet cable while the users connected wirelessly. Internet protocol version 4 (IPv4) was selected and restrictions were set based on the required users for each measurement. The various quality of service (QoS) traffic used and throughput field test, together with setup are as discussed in [9][11][12][14][25][26], while received signal strength indicator (RSSI) were measured in dBm using in SSIDer software. The dependence of TCP upstream and downstream throughput on SNR observed in real time network for IEEE 802.11g WLAN system was measured The TCP upstream and downstream throughput real time field data collected and the signal to noise ratio (SNR) was used to statistically analyze and develop models. These models can be verified by empirical methods but the scientific application readily available for such purpose is the 'Statistical package for Social Sciences' (SPSS) as done in [15]. Fig. 1 shows different users at different points WLAN basic connection.

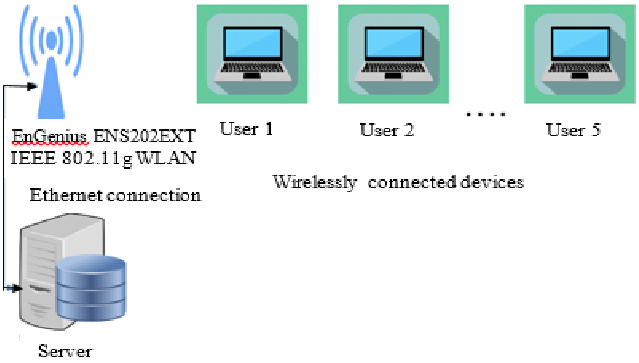


Fig. 1. WLAN basic connection with different users

VI. RESULTS AND DISCUSSION

A. Scenario Description

The results for the statistical analysis gotten from the real data collected are shown in Tables 1 and 2. The developed models are obtained by running a regression analysis of the results to determine the level of significance and freedom. Regression analysis being a statistical analysis used to establish the relationship between the dependent variable and independent variables. The goal was to find the best description or relationship between the variables. Also, linear regression was carried out using SPSS to observe the relationship and strength between the dependent and independent variables. Finally, the F-Table results are presented for each user's experience.

Tables 1 and 2 show each user's experience for different observed SNR. The tables developed are required for proper analysis and understanding of the transmission control protocol upstream throughput (TCPupT) and downstream dependence throughput (TCPdownT) on SNR. The tables also show the model summary, analysis of variance (ANOVA), and coefficient summary. The model Equations (1), (2), (3), (4), (5), and (6) for all user considerations are provided for verification for tables. The equation for each user consideration for both upstream and downstream are based on the model that best explains the dependence of TCP throughput on SNR. This explains the observed difference in model equations. For all equations, the variable 'a' represents the model coefficient for SNR

Table-1 Users $TCP_{up}T$ model parameters for all SNR

	Single User	**Double User**	**Multiple User**
General model			
R(coefficient of correlation)	0.957	0.981	0.967
Rsquare(coefficient of determination or goodness of fit)	0.915	0.962	0.935
Adjusted R square	0.915	0.962	0.935
Standard error of estimate	0.792	0.518	1.415
Anova			
DF(degree of freedom)	1	1	2
F(F- Test or F distribution)	7214.734	1628.726	2925.238
Sig(level of significance)	0.000	0.000	0.000
Model Coefficient			
a(model coefficients)	1.059	0.15	0.830
Standard error	0.001	0.001	0.023
T-test	1476.928	127.510	78.611
Sig	0.000	0.000	0.000

Single user equation, $TCP_{up}T = f(SNR) = a^{SNR}$ (1)

Double user equation, $TCP_{up}T = f(SNR) = e^{a(SNR)}$ (2)

Multiple user equation, $TCP_{up}T = f(SNR) = SNR^{a}$ (3)

Table-2 Users $TCP_{down}T$ model parameters for all SNR

	Single User	Double User	Multiple User
General model			
R(coefficient of correlation)	0.964	0.987	0.939
R square(coefficient of determination or goodness of fit)	0.936	0.975	0.882
Adjusted R square	0.936	0.975	0.882
Standard error of estimate	0.682	0.446	0.729
Anova			
DF(degree of freedom)	1	1	1
F(F- Test or F distribution)	9754.547	2495.236	2930.297
Sig(level of significance)	0.000	0.000	0.000
Model Coefficient			
a(model coefficients)	0.058	0.760	0.530
Standard error	0.001	0.001	0.023
T-test	98.765	157.985	67.631
Sig	0.000	0.000	0.000

Single user equation, $TCP_{down}T = f(SNR) = e^{a(SNR)}$ (4)

Multiple user equation, $TCP_{down}T = f(SNR) = SNR^{a}$

Double user equation, $TCP_{down}T = f(SNR) = SNR^{a}$ (5)

From the observed model parameters, an R value of (0.957, 0.981, and 0.967) for $TCP_{up}T$ and values (0.964, 0.987,0.939) for $TCP_{down}T$ indicates a high degree of correlation. The R^2 value indicates how much of the total variation in the dependent variable ($TCP_{up}T$) and ($TCP_{down}T$) can be explained by the independent variable (SNR). The obtained R^2 values of: (0.915, 0.962, and 0.935) for ($TCP_{up}T$) and ($TCP_{down}T$) R^2 values of (0.936, 0.975, 0.882) which is referred to as the coefficient of determination shows that the independent variable SNR explains (91.5, 96.2, 93.5) % of the dependent variable $TCP_{up}T$ and (93.6, 97.5, 88.2) % for $TCP_{down}T$. Different standard error estimates were also observed for different user scenarios. The ANOVA readings in table 1 predict how well the regression equation fits the data. The table shows that the regression model predicts the dependent variable significantly well. All users had a significance value of 0.000% > 0.05 indicating that the independent variables statistically significantly predict the dependent variable. Table 1 also gives ‘f’ values of (7214.734, 1628.726, 2925.238) and degree of freedom of 1.0 for single and double users while 2 .0 degree of freedom for multiple users. Table 2 gives ‘f’ values of (9754.547, 2495.236, and 2930.297), and degree of freedom of 1.0 for all users. All the coefficients of the models for each table were also significant at 0.000%.

B. F-table value Hypothesis

The F distribution was used to determine the various degree of freedom and significance of the data. The F distribution test presented in tables 3 and 4 was utilized in determining the models’ performance to know whether they are to be accepted or rejected at the stated significance level and degree of freedom. For the F test, the following hypotheses are defined;

Null Hypothesis

The proposed $TCP_{up}T$ and $TCP_{down}T$ models do not fit the data well and the slope of the regression line does not differ significantly from zero for a user on the network. (This means that TCP values are not significantly dependent on SNR for a user on the network).

Alternative hypothesis

The proposed $TCP_{up}T$ and $TCP_{down}T$ model fits the data well and the slope of the regression line differs significantly from zero for a user on the network. (This means that TCP values are significantly dependent on SNR for a user on the network)

Table-3 F-table value Hypothesis for $TCP_{up}T$

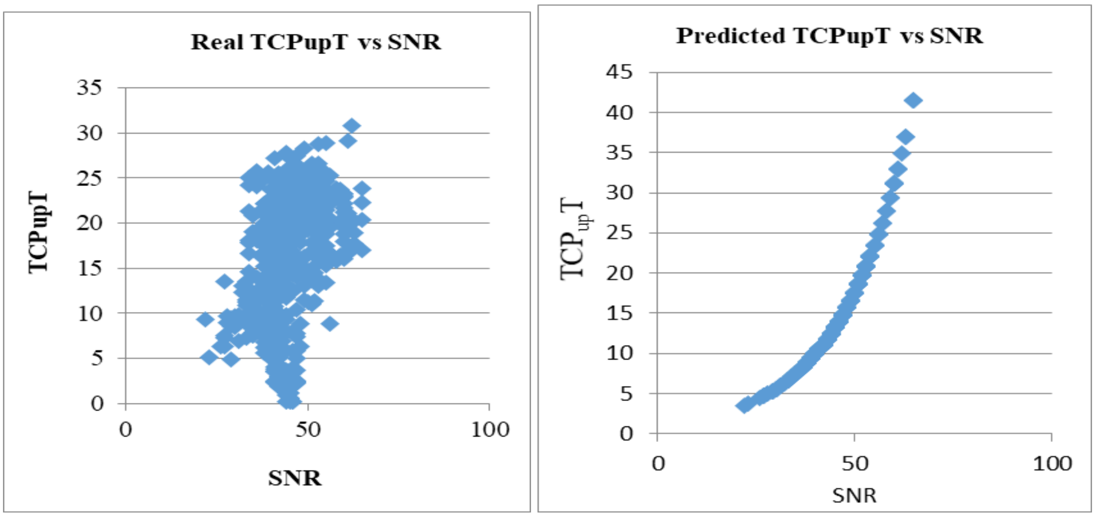
Single User Model			
Variable	Model F value for general SNR	F values from F Table	Remark
$TCP_{up}T$	$F_{0.05,1,668}$ =7214.734	3.84	null is rejected and both models are accepted at 5 % level of Significance
Double User Model			
$TCP_{up}T$	$F_{0.05,1,645}$ = 1628.40	3.84	null is rejected and both models are accepted at 5 % level of Significance
Multiply Users Model			
$TCP_{up}T$	$F_{0.05,3,614}$ = 2925.238	2.60	null is rejected and both models are accepted at 5 % level of Significance

Table-4 F-table value Hypothesis for $TCP_{down}T$

Single User Model			
Variable	Model F value for general SNR	F values from F Table	Remark
$TCP_{down}T$	$F_{0.05,1,668}$ = 9754.547	3.84	null is rejected and both models are accepted at 5 % level of Significance
Double User Model			
$TCP_{down}T$	$F_{0.05,1,645}$ = 2495.234	3.84	null is rejected and both models are accepted at 5 % level of Significance
Multiply Users Model			
$TCP_{down}T$	$F_{0.05,3,614}$ = 2930.297	3.84	null is rejected and both models are accepted at 5 % level of Significance

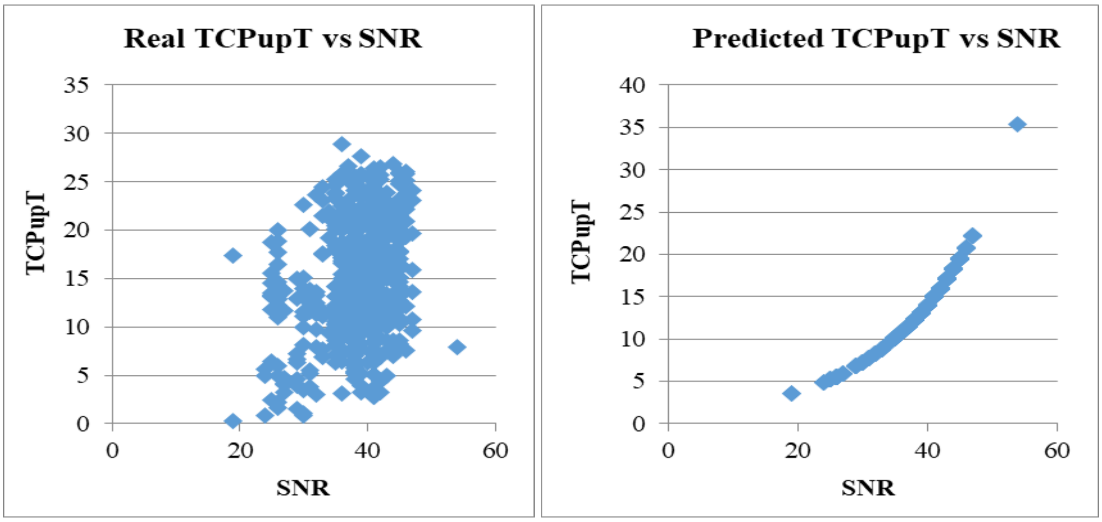
C. F-table value Hypothesis

All models are accepted at 0.05 level of significance and degree of freedom. The null hypothesis was rejected and the alternative hypothesis accepted. Figures 2, 3, 4, 5,6 and 7 are graphical representations of the real data and predicted values from the model, and a graph of TCP against SNR. Figures 2(a), 3(a), 4(a), 5(a), 6(a) and 7(a) are showing the TCP against the SNR real time data collected while the predicted or generated values from the modal equations are shown in figures 2(b), 3(b), 4(b), 5(b), 6(b) and 7(b), respectively. From all predicted graph representations, noticeable little variations (above and below) from the real data value graphs are evident. From the graphs in both (a) and (b), it could be noticed that there are data saturations at various values and a wide spread of data values for different users' experiences. For the single and double users' scenarios, TCP values are stronger between the values 10-25 and there was a noticeable drop in values for a sixth user scenario.



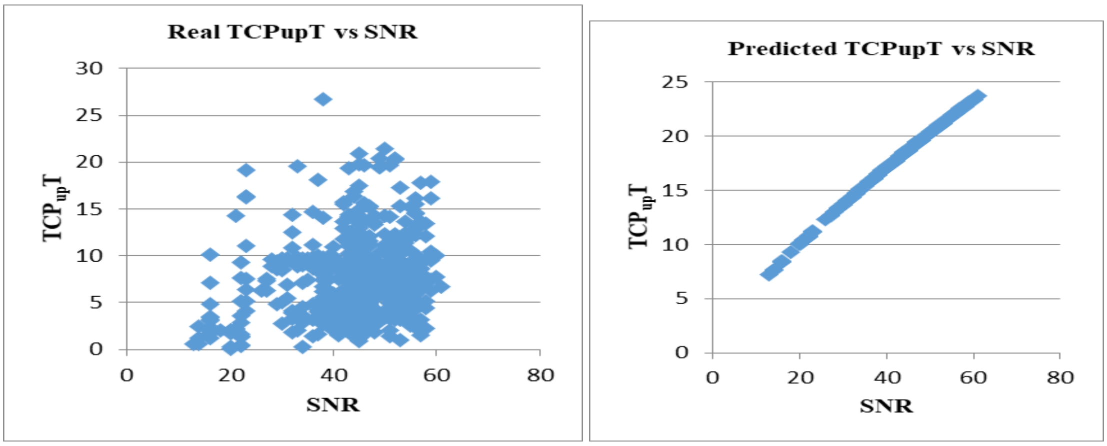
(a) **(b)**

Fig. 2. $TCP_{up}T$ single user real time data and modal predicted data



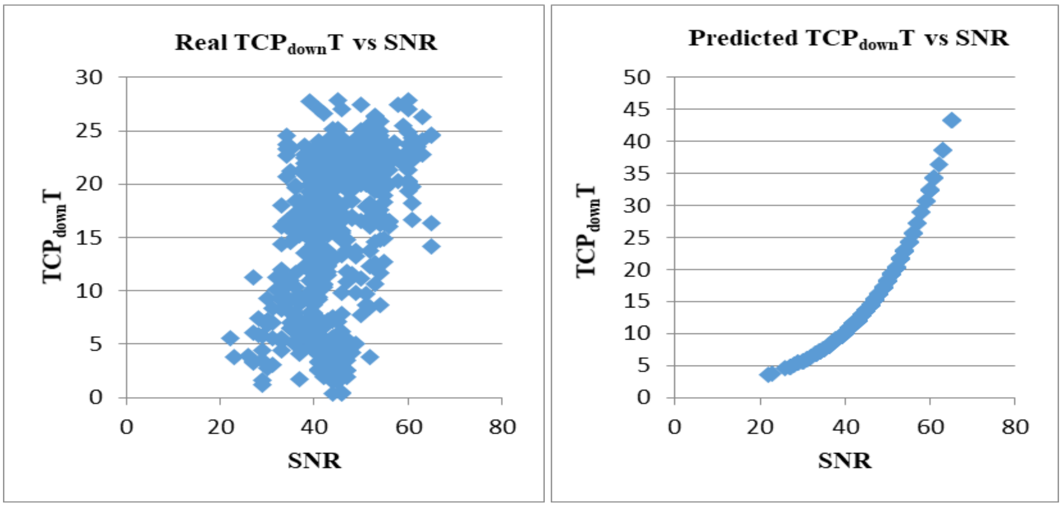
(a) (b)

Fig. 3. $TCP_{up}T$ double users real time data and modal predicted data



(a) (b)

Fig. 4. $TCP_{up}T$ multiple users' real data and predicted modal value



(a) (b)

Fig. 5. $TCP_{down}T$ single user real time data and modal predicted data

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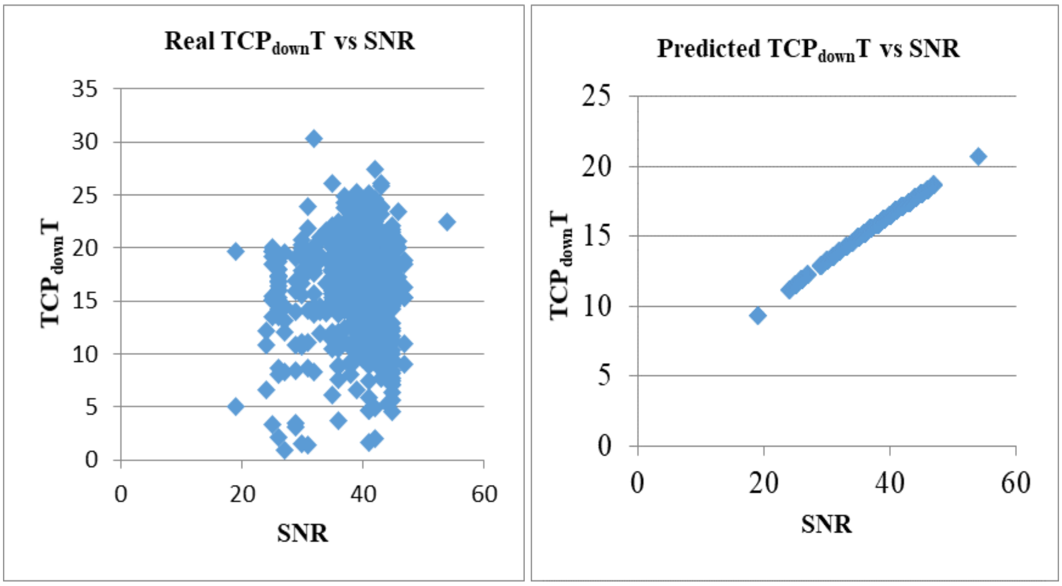

Fig. 6. $TCP_{down}T$ double users real time data and modal predicted data

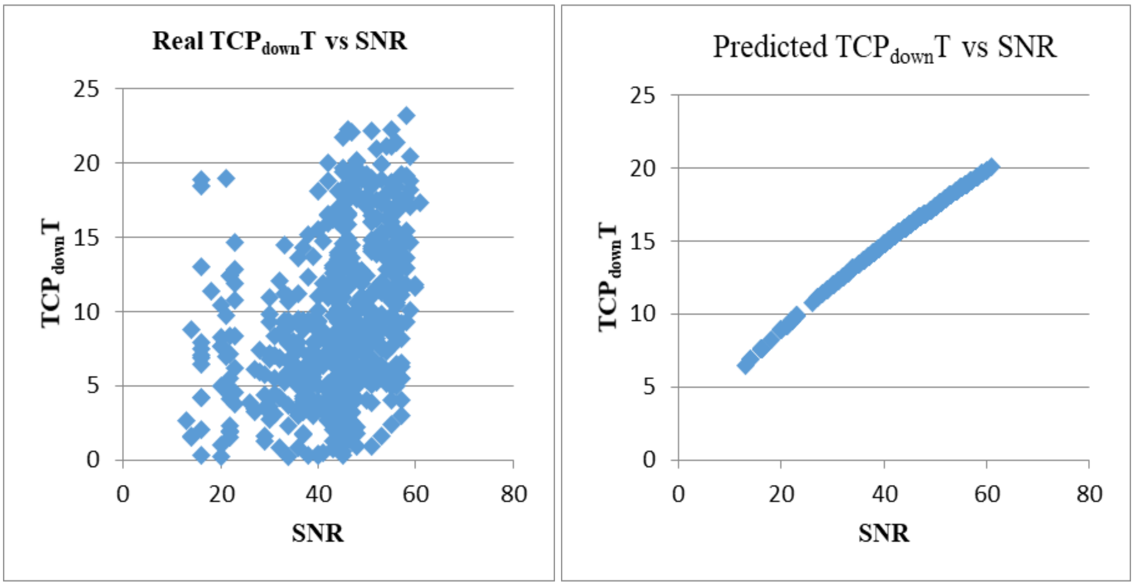

Fig. 7. $TCP_{down}T$ multiple users' real data and predicted modal value

V. CONCLUSION

The importance of proper deployment of any IEEE 802.11 standard cannot be over-emphasized. In essence, it makes for proper users' accessibility, throughput and quality of service. Therefore, considering TCP throughput in view of users not just ping and determining the RSSI would make the process more user inclusive and friendly.

This paper has investigated the dependence of TCP upstream and downstream against the received SNR for different user connections. The real time data collected models were generated and performance evaluated. The generated model equations were used for generating predicted data and its relationship depicted in graphs. It is now clear that the generated model equations can be used for predicting the expected performance of IEEE 802.11g WLAN systems during deployment.

This work gives WLAN engineers, researchers and users an apparatus to rapidly estimate the TCP upstream and downstream throughput, by monitoring the received SNR for IEEE 802.11g systems. Other models can be developed for other protocols like User Datagram Protocol considering various IEEE 802.11 WLAN standards. Overall, the paper makes a significant contribution to the subject of WLAN design, deployment and optimization and would be useful for both researchers and professionals working in the wireless networking industry.

This paper presented the dependence of TCP upstream and downstream throughput on SNR for IEEE 802.11g WLAN systems. Further work can be done by other researchers in this area to investigate the reliability, accessibility and speed of performance for a WLAN system. It is a highly accepted technology and performance is of key importance coupled with the rapid population growth around the world today. Model research simulations on IEEE 802.11(n/e/ac) systems, considering various environments and models for high throughput are also possible and could be investigated. Finally, throughput models' evaluation of round-trip time for this system and other WLAN system vendors can be used to repeat this research and results compared.

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