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Environment Specific TCP Upstream Throughput Models in IEEE802.11b WLAN.

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ABSTRACT: This paper presents our study on environment based dependence of TCP Upstream Throughput ($TCP_{up}T$) on signal to noise ratio (SNR) for a single user in an IEEE 802.11b Wireless Local Area Network (WLAN). Small offices, open corridors and free space environments were studied using an infrastructure based network for different quality of service (QoS) traffic. Environment based Models that predict $TCP_{up}T$ directly from SNR for different signal categories were statistically generated, validated and compared with similar models that were earlier developed without considering specific environments. The first type of models developed in this work were developed from all data specifically collected from each environment while the second type of models were developed by first categorizing the data in each specific environment into different signal categories and then models were statistically generated for each signal category before combining them into one model equation. At the stated levels of significance and the different degrees of freedom, the developed models were accepted at 1% (for F test) and 0.5% (for T test). From the RMS errors computed, the specific environment based models developed in this work were more accurate (as they showed lower RMS errors compared with earlier similar models) in predicting $TCP_{up}T$ in IEEE 802.11b WLAN for a single user on the network. It was also observed that the second type of models were found to be more accurate having shown lower RMS errors.

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The internet has become an integral part of our everyday life (Mohammed, 2011). Smart phones, computers and other internet enabled devices can now use Wireless local area networks (WLANs) to access internet services in many homes and within organizations. This has made access to information easier and more efficient (Oghogho and Ezomo,2013). Throughput and the round trip time are the two most important metrics for determining the performance of WLANs (Geier, 2008a). Being able to predict and simulate the throughput in WLANs can help to determine the performance of such a network. A minimum throughput must be provided by a WLAN if it is to be considered to have provided sufficient coverage (Geier, 2008b).

Throughput measures the average data rate (in bits) that can be sent between one user and another in a network (Henty, 2001). Upstream and downstream throughputs are the speed of data sent from the Client to the WLAN radio and the speed of data sent from WLAN radio to the Client respectively. Oghogho,*et al,* (2018b) has shown that upstream and downstream throughput are appreciably different hence predicting them separately gives a more accurate result. Throughput has been found to be significantly accurate when predicted from Signal to noise ratio (SNR) only (Henty, 2001; Oghogho, 2018a). However other metrics like the number of users, the protocol used for transmission, the traffic type and the environment used for measurement appreciably influences the result.

Existing studies as reported in Oghogho *et al,* (2018a) presented models which were developed from a combination of field data collected across different environments. However, environment specific based models have been found to be more accurate than others which were developed without considering specific environments (Zia *et al,* 2016; Damaris *et al;* 2012). In this paper the author presents environment specific throughput models which were developed for better accuracy of throughput predictions in specific environments. Several researchers have provided models for predicting TCP throughput based on SNR only with reasonable accuracy. Oghogho, 2018a; 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 considered by Oghogho 2018a; included those developed by Henty

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(2001), Metreaud, (2006), Oghogho *et al,* (2014), Oghogho *et al* (2015a), Oghogho *et al* (2015b), Oghogho *et al,* (2017) and Oghogho *et al,* (2018b). All of these models directly predict throughput from the SNR computed without specific consideration for particular types of environments. The need to more accurately predict throughput specifically for the different environments (offices, open corridor and free space like open parks and airports) where WLANs are frequently used led to this work presented in this paper. The objective of this paper is to provide environment specific TCP upstream throughput models that more accurately predicts the TCP throughput of a single user for different SNR observed.

MATERIALS AND METHODS

The method used in Oghogho *et al,* (2014) and Oghogho *et al,* (2015a) was used in this work except that the models were developed for each specific environments (open corridor, small offices and free space) using only data collected in that environment. In this paper, open corridor, Small offices and free space are referred to as environment 1, environment 2 and environment 3 respectively. TCP upstream Throughput data were collected for a single user on an IEEE 802.11b WLAN. The data was sorted for different categories of signals (General, Strong, grey and weak) as described in Oghogho *et al,* (2014) and Oghogho*et al,* (2015a). However the sorting was done separately for each environment unlike what was the case in Oghogho *et al,* (2014) and Oghogho *et al,* (2015a). Single User TCP upstream throughput models for IEEE 802.11b WLAN were statistically generated from the data using statistical package for social sciences (SPSS). All signals in environment 1 are in the strong signal range hence environment 1 does not have the second model which combines equations developed for strong, grey and weak signals respectively into one general equation. However for uniformity, model 1 is retained as an attachment to the name of the only model developed in environment 1. Environment 2 consist of TCP upstream throughput data collected for all categories of signals (strong, grey and weak) hence two types of models were developed in environment 2. The first type of model was developed from the combined data in that environment while the second type of model was developed by first statistically generating model equations from data collected for each category of SNR and then combining the equations for the different signal categories to give one model equation for the entire SNR range. This was also done for environment 3. Validation data was collected from other environments different from where the Field data used for generating the model equations were collected. They were used to validate the models developed. Values of root mean square errors, F tests and T tests were used to further decide whether the models should be accepted or rejected.

RESULTS AND DISCUSSIONS

The field data description, the developed models and the accompanied discussions are presented in this section using graphs and tables. Table 1 shows the statistical parameters of $TCP_{up}T$ data collected for different SNR in all the environments. Fig. 1 shows averages of single user $TCP_{up}T$ field data plotted against SNR for all signal ranges in the three environments considered. All signals for which throughput was measured in environment 1 (open corridor) were in the strong signal range (≥25dBm) hence only strong signals data were collected for this environment. However Single user TCP upstream throughput data were collected for strong, grey and weak signals in environments 2 and 3. Environment is represented as " Env" in the Tables. From Table 1, it can be observed that the standard deviation (0.6387616 Mbps) and range (3.9Mbps) computed for the $TCP_{up}T$ obtained for all values of SNR considered were low in environment 1. This implies that $TCP_{up}T$ does not vary considerably in this environment for a single user on the network.

Table 1: Statistical Parameters of $TCP_{up}T$ Field Data in all Environments

Statistical Parameters	All SNR $TCP_{up}T$ (Mbps)			Strong signals $TCP_{up}T$ (Mbps)			Grey signals $TCP_{up}T$ (Mbps)		Weak signals $TCP_{up}T$ (Mbps)	
	Env 1	**Env. 2**	**Env 3**	**Env 1**	**Env.2**	**Env 3**	**Env. 2**	**Env 3**	**Env. 2**	**Env 3**
Sample Size (N)	648	728	593	648	426	432	204	113	98	48
Mean (Mbps)	5.879	4.399	4.543	5.8798	5.827	5.981	2.978	0.8104	1.1504	0.391
Std. Error of Mean	0.025	0.074	0.100	0.0250	0.033	0.029	0.088	0.08219	0.0819	0.046
Median (Mbps)	6.065	5.500	5.860	6.0650	6.00	6.145	2.735	0.4900	0.8600	0.320
Mode (Mbps)	6.160	6.23	6.27	6.1600	6.23	6.27	2.61	*0.17, 0.41	*0.63, 0.87, 1.91	0.11
Std. Deviation (Mbps)	0.638	1.9969	2.446	0.6387	0.681	0.604	1.259	0.87372	0.8116	0.321
Variance	0.408	3.988	5.985	0.408	0.464	0.365	1.587	0.763	0.659	0.104
Skewness	-2.363	-0.661	-0.983	-2.363	-1.97	-2.793	0.547	1.870	1.671	1.015
Std. Error of Skewness	0.096	0.091	0.100	0.096	0.118	0.117	0.170	0.227	0.244	0.343
Kurtosis	6.643	-1.050	-0.862	6.643	4.286	9.700	-0.027	3.428	4.719	0.168
Std. Error of Kurtosis	0.192	0.181	0.200	0.192	0.236	0.234	0.339	0.451	0.483	0.674
Range (Mbps)	3.900	6.8300	6.70	3.900	3.78	3.68	5.83	4.40	5.06	1.18

High negative skewness (-2.363) was observed for $TCP_{up}T$. This means that the distributions of $TCP_{up}T$ for single user have longer tails towards the left of its mean (5.879846Mbps). Multi modal distribution was absent for $TCP_{up}T$ single user in environment 1. Since all $TCP_{up}T$ data collected in environment 1 (open corridor) were in the strong signal range, environment 1 does not have $TCP_{up}T$ data for grey and weak signals.

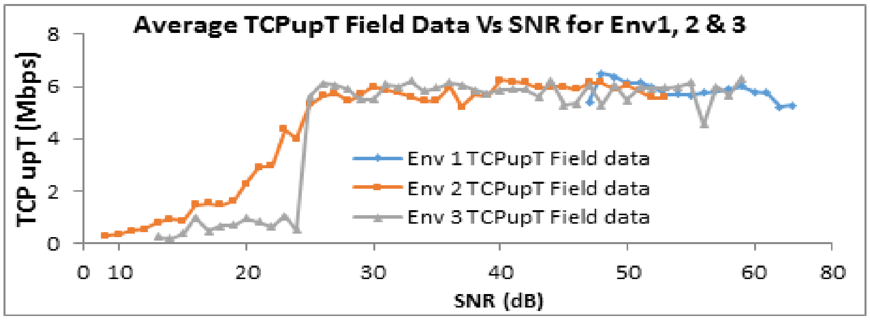

Fig. 1 Averages of Single User $TCP_{up}T$ Field data VsSNR

In environment 2, the standard deviation (1.9969Mbps) and range (6.8300Mbps) for $TCP_{up}T$ data collected for all SNR were relatively high compared to that of environment 1. This implies that $TCP_{up}T$ varies considerably in environment 2 than in environment 1 for a single user on the network over the entire range of signals. This difference in standard deviation observed between environment 1 and environment 2 is because in environment 1, $TCP_{up}T$ data could be collected for only strong signals while in environment 2, $TCP_{up}T$ data was collected for strong, grey and weak signals. For strong signals in environment 2, it was observed from Table 1 that the standard deviation (0.68137Mbps) and range (3.78Mbps) computed for the $TCP_{up}T$ data for single user were low. This is very comparable with what was observed in environment 1 where all signals are in the strong range. This implies that $TCP_{up}T$ does not vary considerably in environment 2 for a single user on the network when the signal is strong. Negatively skewed distribution (-1.976) was observed for $TCP_{up}T$ strong signal data in environment 2 as was also observed in environment 1. This means that $TCP_{up}T$ field data distribution has a longer tail towards the left of its observed mean of (5.8278Mbps) for strong signals. The observed range (3.78Mbps) for strong signal data only was appreciably lower than what was the case for all SNR data (6.8300Mbps) in environment 2. This is so because when the signal is strong, higher data rates are selected for data transmission but as signal degrades lower data rates are selected thereby increasing the $TCP_{up}T$ range observed for all SNR (strong through grey to weak signals) compared with strong signals only. For grey signals single user data in environment 2, it can be seen from Table 1, that the standard deviation (1.25988Mbps) and range (5.83Mbps) for the $TCP_{up}T$ single user data are high. This implies that when there is a single user on the network, $TCP_{up}T$ vary considerable for grey signals. Low positively skewed distribution (0.547) was observed for $TCP_{up}T$ data for grey signal in this environment. From the observed Kurtosis (-0.027), $TCP_{up}T$ single user distribution has a flat peak and light tail for grey signals in environment 2. For Weak signals single user data in environment 2, it can be seen from Table 1 that the standard deviation (0.81162Mbps) for $TCP_{up}T$ is low for weak signals. This implies that when there is a single user on the network, $TCP_{up}T$ does not vary considerably for weak signals in environment 2. High positively skewed distribution (1.671) was observed for $TCP_{up}T$ weak signal data. The observed Kurtosis (4.719) shows that $TCP_{up}T$ single user distribution has a sharp peak and heavy tails compared with normal distribution for weak signals. For All SNR single user $TCP_{up}T$ data in environment 3, it can be seen from Table 1 that the standard deviation (2.44640Mbps) and range (6.7Mbps) obtained for the entire range of signals considered are higher unlike what was the case for environment 1. The standard deviation was also higher than that of environment 2. This implies that $TCP_{up}T$ vary considerably in free space environment for a single user on the network over the entire range of signals than in small offices and open corridor environments. This difference can be explained as follows. The grey and weak signal values (which usually introduce large variations into measured $TCP_{up}T$ values are observed at greater distances from the WLAN radio in free space than what is the case for small offices. The differences in distances (which provide the same value of SNR in the different environments) and the obstacles in the small offices environments introduce the slight variations in standard deviations observed. Since there is a single user on the network, the WLAN radio, server and clients are still able to use high data link rates at random even when signal has become grey or weak thus allowing the possibility of large variations for single user based on differences in the different environments. An obvious reason for the difference in standard deviation and range between $TCP_{up}T$ data for environment 3 and environment 1 occurs because data were collected for only strong signals in environment 1 while in environment 3, $TCP_{up}T$ data were collected for strong, grey and weak signals. Negatively skewed distribution (-0.983) was observed for All SNR $TCP_{up}T$ data in environment 3 for a single user on the network. From the observed Kurtosis (-0.862), the $TCP_{up}T$ distribution has a flat peak and light tails for all SNR in environment 3 for single user. For strong signals single user $TCP_{up}T$ data in environment 3, it can be seen from Table 1 that the standard deviation (0.60427Mbps) and range (3.68Mbps) obtained were low. This is very comparable with what was observed in environment 1 and environment 2 for strong signals. This implies that $TCP_{up}T$ does not also vary considerably in environment 3 for a single user on the network when the signal is strong. Negatively skewed distribution (-2.793) was observed for $TCP_{up}T$ strong signal data in environment 3. From the observed Kurtosis (9.700) for $TCP_{up}T$ single user data the distribution will have narrow peaks for strong signals in environment 3.

For grey signals single user data in environment 3, it can be seen from Table 1 that the standard deviation (0.87372Mbps) and range (4.40Mbps) for $TCP_{up}T$ were appreciably low for grey signals. This is a big deviation from what was observed in environment 2 where the standard deviation and range for $TCP_{up}T$ were high for grey signals. This is so because for single user, the WLAN client selects lower data rates more consistently when signal has become grey thus resulting in low $TCP_{up}T$ variation. There is a greater probability that the WLAN system continuously selects lower data rates for transmission in environment 3 (free space) compared with environment 2 (small offices) when signal is in the grey range. Note that in environment 3, grey signals occur when Client is very far from the WLAN radio unlike what is the case in environment 2 where the obstructions inside the building allows grey signals to be measured at distances not too far away from the WLAN radio. Positively skewed distribution (1.870) was observed for $TCP_{up}T$ data in environment 3 for grey signals. From the observed Kurtosis (3.428), $TCP_{up}T$, has an arrow peak and heavy tails for grey signals in environment 3 for a single user on the network.

For weak signals single user data in environment 3, it can be seen from Table 1 that the standard deviation (0.32188Mbps) and range (1.18Mbps) for $TCP_{up}T$ (0.32188Mbps) were low for weak signals. This implies that when there is a single user on the network, $TCP_{up}T$ does not vary considerably, a trend that was also observed in environment 2. However for single user, the deviations observed for $TCP_{up}T$ in environment 3 is slightly lower than that of environment 2 for weak signals. $TCP_{up}T$ does not vary considerably for weak signals in this environment because when the signal has become weak for a single user, the WLAN Client which sends upstream data consistently uses low data rates for transmission hence the variation is low. Positively skewed distribution (1.015) was observed for $TCP_{up}T$ data for weak signals in environment 3 for a single user. From the observed Kurtosis (0.168) for $TCP_{up}T$, the distribution has a narrow peak and heavy tails for weak signals in environment 3. Environment 1 is an open corridor environment. All signals in environment 1 are in the strong signal range, hence environment 1 does not have the second model which combines equations for strong, grey and weak signals. However for uniformity, model 1 is retained as an attachment to the name of the only model developed in environment 1. Key parameters of all the developed models in this paper are available in Table 2. The model equations developed allows the network designer, or the WLAN user to estimate the TCP upstream throughput directly from SNR values computed from received signal strength indication (RSSI) measured on site. Equation 1 shows the developed model equation for Environment 1 Single User TCP Upstream Throughput Model 1 ($Env_1SU\ TCP_{up}T\ \ Model_1$). a_1 is the coefficient of the model.

$$Env_1SU\ TCP_{up}T\ \ Model_1 = f(SNR) = \begin{cases} SNR^{a_1} - 0.6Mbps & SNR > 64dB \\ SNR^{a_1} & SNR < 65dB \end{cases} \quad \text{............1}$$

Environment 2 is made up of small offices. Equation 2 shows the developed model equation for Environment 2 Single User TCP Upstream Throughput Model 1($Env_2SU\ TCP_{up}T\ \ Model_1$). $a_1$is the coefficient of the model.

$$Env_2\ SU\ TCP_{up}T\ \ Model_1 = f(SNR) = \begin{cases} 6.07Mbps & SNR > 41dB \\ a_1^{SNR} & 42dB > SNR > 18dB \\ a_1^{SNR} - 1Mbps & SNR < 19dB \end{cases} \quad \text{....2}$$

Equation 3 shows the developed model equation for Environment 2 Single User TCP Upstream Throughput Model 2 ($Env_2SU\ TCP_{up}T\ \ Model_2$).

$Env_2SU\ TCP_{up}T\ \ Model_2$ is a combination of $TCP_{up}T$ single user models developed in the strong, grey and weak signal ranges with parameters presented in Table 2.

$$Env_2\ SU\ TCP_{up}T\ \ Model_2 = f(SNR) = \begin{cases} 6.15Mbps & SNR>41dB \\ SNR^{a_1} & 42dB>SNR>24dB \\ a_2^{SNR} & 25dB>SNR>18dB \\ a_3 * SNR & SNR<19dB \end{cases} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 3$$

Environment 3 is a free space environment. Table 2 shows parameters of Environment 3 single user $TCP_{up}T$ model 1 ($Env_3SU\ TCP_{up}T\ \ Model_1$). Equation 4 shows the developed model equation for $Env_3SU\ TCP_{up}T\ \ Model_1$. a_1, a_2 are coefficients and C is a constant of the equation.

$$Env_3\ \ SU\ TCP_{up}T\ Model_1 = f(SNR) = \begin{cases} 5.6Mbps & SNR>61 \\ a_1SNR + a_2SNR^2 + (C-1)Mbps & SNR>39dB \\ a_1SNR + a_2SNR^2 + C\ Mbps & 40dB>SNR>16dB \\ 0.1Mbps & SNR<17dB \end{cases} \quad \ldots\ldots\ldots 4$$

Environment 3 single User TCP upstream throughput model 2 ($Env_3SU\ TCP_{up}T\ \ Model_2$) is a combination of $TCP_{up}T$ single user models each developed in the strong, grey and weak signal ranges with parameters presented in Table 2. Equation 5 shows the developed model equation for $Env_3SU\ TCP_{up}T\ \ Model_2$.

Table 2: Parameters of Developed Models and Test Results

Environment 1 TCPupT Single User Model

	Test			**Remark / Decision**
F Test	**Model₁ F value**		**Value from F Table**	H_0 is Rejected and Model accepted at 1% level of Significance
	$F_{0.01,1,647}$=116912.113		6.63	
T Test	**Coefficient/ Constant**	**Model₁ T Value**	**Value from T Table**	H_0 is rejected and Model accepted at 0.5% level of Significance
	a_1	341.924	$T_{0.005,647}$= 2.58	
R^2 Value	0.994			

Environment 2 TCPupT Single User Models

Type	**Model₁**			**Test**	**Model₂**			**Remark /Decision**
F Test	**F value**	**F Values from F Table**	**SNR Category**		**F values**		**F Values from F Table**	H_0 is rejected and both Models are accepted at 1% level of Significance
			Strong Signals		$F_{0.01,1,425}$ = 51902.914		6.63	
	$F_{0.01,1,727}$ = 4678.909	6.63	Grey Signals		$F_{0.01,1,203}$ = 1049.771		6.63	
			Weak Signals		$F_{0.01,1,97}$ = 256.036		7.08	
T Test	**Coefficient/ constant**	**Model₁ T value**	**T Values from T Table**	**SNR Category**	**Coefficient/ constant**	**Model₂ T value**	**T Values from T Table**	H_0 is rejected and both Models accepted at 0.5% level of Significance.
	a_1	1559.908	$T_{0.005,727}$ = 2.58	Strong Signals	a_1	227.822	$T_{0.005,425}$ =2.58	
				Grey Signals	a_2	680.390	$T_{0.005,203}$ =2.58	
				Weak Signals	a_3	16.001	$T_{0.005,97}$ = 2.66	
R^2 value	**Model₁**					**Model₂**		
	0.866				Strong Signals		0.992	
					Grey Signals		0.838	
					Weak Signals		0.725	

Environment 3 TCPupT Single User Models

Type	**Model₁**			**Test**	**Model₂**			**Remark/Decision**
F Test	**F value**	**F Values from F Table**		**SNR Category**	**F values**		**F Values from F Table**	$H_0$is rejected and both Models are accepted at 1% level of Significance
				Strong Signals	$F_{0.01,1,431}$ = 54702.425		6.63	
	$F_{0.01,2,590}$ = 1442.769	4.61		Grey Signals	$F_{0.01,1,112}$ = 98.148		7.08	
				Weak Signals	$F_{0.01,1,47}$ = 105.141		7.31	
T Test	**Coefficient/ Constant**	**Model₁ T Value**	**T Values from T Table**	**SNR Category**	**Coefficient/ constant**	**Model₂ T value**	**T Values from T Table**	$H_0$is rejected and both Models accepted at 0.5% level of Significance.
	a_1	34.078	$T_{0.005,590}$ = 2.58	Strong Signals	a_1	233.885	$T_{0.005,431}$ = 2.58	
	a_2	-27.354		Grey Signals	a_2	9.907	$T_{0.005,112}$ = 2.66	
	C	-27.830		Weak Signals	a_3	-10.254	$T_{0.005,47}$ = 2.70	
R^2 value	**Model 1**					**Model 2**		
	0.830			Strong Signals			0.992	
				Grey Signals			0.467	
				Weak Signals			0.691	

$$Env_3\ SU\ TCP_{up}T\ Model_2 = f(SNR) = \begin{cases} 5.79Mbps & SNR>41dB \\ SNR^{a_1} & 42dB>SNR>28dB \\ SNR^{a_1}+0.7Mbps & 29dB>SNR>24dB \\ a_2*SNR & 25dB>SNR>18dB \\ e^{\left(a_3/_{SNR}\right)} & SNR < 19dB \end{cases} \quad \ldots\ldots\ldots 5$$

Table 3: RMS Error values for our $TCP_{up}T$ Models and other models for Single user.

	Model description	RMS (Mbps) Error Computed			
		All SNR	Strong Signals	Grey Signals	Weak Signals
	Environment 1 RMS Errors Comparison				
1	Env_1 SU $TCP_{up}T$ $Model_1$	0.370496	0.370496	Not applicable	Not applicable
2	Oghogho 2015 General TCPupT Single User Model	0.393824	0.393824	Not applicable	Not applicable
3	Oghogho 2015 SNR Categorized TCPupT Single User Models	0.822566	0.822566	Not applicable	Not applicable
4	Metreaud Multi tap Model C	0.432622	0.432622	Not applicable	Not applicable
5	Metreaud Multi tap model B	0.419134	0.419134	Not applicable	Not applicable
6	Metreaud Multi tap model A	0.382111	0.382111	Not applicable	Not applicable
7	Metreaud One tap Constant Channel	0.439551	0.439551	Not applicable	Not applicable
8	Henty Single User Exponential Model	0.356074	0.356074	Not applicable	Not applicable
	Best two models in each category	Model (8, 1)	Model (8, 1)		
	Environment 2 RMS Errors Comparison				
	Model description	RMS (Mbps) Error Computed			
		All SNR	Strong Signals	Grey Signals	Weak Signals
1	Env_2 SU $TCP_{up}T$ $Model_1$	0.764418	0.80596	1.000892	0.230968
2	Env_2 SU $TCP_{up}T$ $Model_2$	0.429866	0.311334	0.986266	0.299671
3	Oghogho 2015 General TCPupT Single User Model	0.530945	0.456634	0.971399	0.478158
4	Oghogho 2015 SNR Categorized TCPupT Single User Models	0.870519	0.256651	2.207100	1.157932
5	Metreaud Multi tap Model C	1.880661	0.583619	3.708812	3.391684
6	Metreaud Multi tap model B	1.760798	0.570354	3.689851	3.005769
7	Metreaud Multi tap model A	1.855241	0.533089	3.746734	3.317637
8	Metreaud One tap Constant Channel	2.462523	0.590393	3.718297	5.156534
9	Henty Single User Exponential Model	1.441237	0.500779	3.353917	2.152993
	Best two models in each category	Model (2,1)	Model (4,2)	Model (3,2)	Model (1,2)
	Environment 3 RMS Errors Comparison				
	Model description	RMS (Mbps) Error Computed			
		All SNR	Strong Signals	Grey Signals	Weak Signals
1	Env_3 SU $TCP_{up}T$ $Model_1$	0.844438	0.916811	0.825938	0.383037
2	Env_3 SU $TCP_{up}T$ $Model_2$	0.588809	0.520786	1.069935	0.311829
3	Oghogho 2015 General TCPupT Single User Model	0.974717	0.856175	1.753183	0.692781
4	Oghogho 2015 SNR Categorized TCPupT Single User Model	1.385548	0.58797	3.247595	1.723158
5	Metreaud Multi tap Model C	2.392163	0.577401	4.81028	4.277831
6	Metreaud Multi tap model B	2.269292	0.565033	4.790663	3.844934
7	Metreaud Multi tap model A	2.32983	0.530729	4.821098	4.067888
8	Metreaud One tap Constant Channel	2.848766	0.583744	4.820089	5.809439
9	Henty Single User Exponential Model	1.936944	0.504687	4.468296	2.869512
	Best two models in each category	Model (2,1)	Model (9,2)	Model (1,2)	Model (2,1)

**RMS error is estimated for all the models using TCP upstream throughput validation data for each specific environment.*

To test the developed models the author defines the following hypothesis: Null hypothesis 1; H_0= 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 a single user on the network. (This means that $TCP_{up}T$ is not significantly dependent on SNR for a Single User on the network). Alternative hypothesis 1; H_I= Proposed $TCP_{up}T$ 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 $TCP_{up}T$ is significantly dependent on SNR for a Single User on the network).

The model parameters and the F-distribution and T test results are shown in Table 2. From the decision and remark column in Table 2, it can be seen that H_0 was rejected (implying that H_1 should be accepted) and all the models were accepted at 1% level of significance at the respective degrees of freedom. The RMS errors computed by comparing the developed models in this paper with similar models are presented in Table 3. TCP upstream validation data for single user collected specifically for each environment were used to estimate the RMS errors.

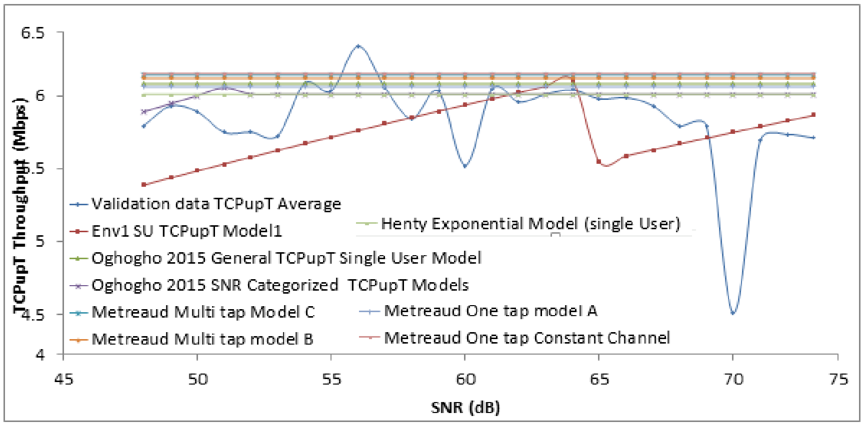

Fig. 2: Comparison of $TCP_{up}T$ Models in Environment 1

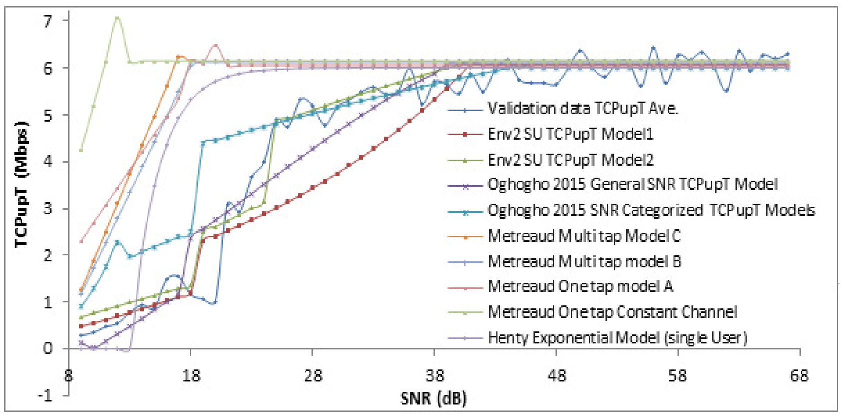

Fig. 3: Comparison of $TCP_{up}T$ Models in Environment 2

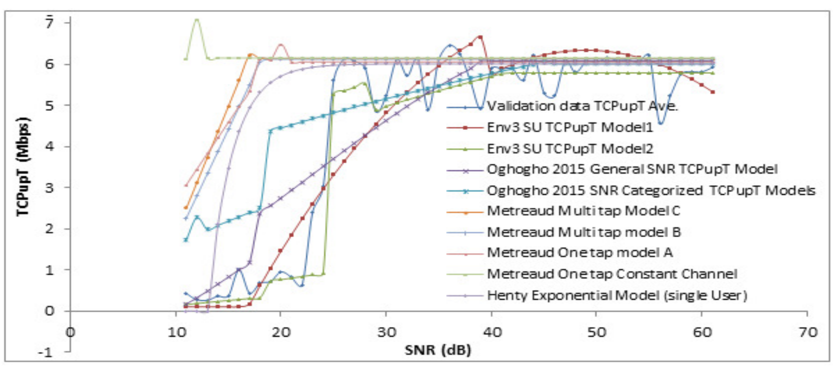

Fig. 4: Comparison of $TCP_{up}T$ Models in Environment 3

It can be seen from Table 3 that the $TCP_{up}T$ models developed in this work performed better than other similar $TCP_{up}T$ models developed in previous work. This has justified the need for carrying out this work. However the second model developed in this work (by first statistically generating model equations from data collected for each category of SNR and then combining the equations for the different signal categories to give one model equation for the entire SNR range) performed better in most cases considered as seen in Table 3. Fig. 2, Fig. 3, and Fig.4 show the graphs of $TCP_{up}T$ developed in this work plotted against SNR along with $TCP_{up}T$ Validation data average, and the other similar models with which they were compared in environment one, two and three respectively. It can also be seen that the models developed in this work follows the validation data more closely than the other models earlier developed in all the environments considered.

*Conclusion***:** In this paper, environment specific TCP Upstream Throughput ($TCP_{up}T$) models based on SNR for a single user in an IEEE 802.11b WLAN have been presented. TCPupT data for strong, grey and weak signals and different QoS traffic were collected for each environment and used to develop the respective models which passed the F and T tests and performed better than other similar existing models considered when the RMS errors were compared. These models serve as a useful predictive tool for WLAN installers and network designers needed to make better informed decision.

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