



Multiple Users Round Trip Time CDF Probability Models in IEEE802.11b WLANS

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ABSTRACT: Multiple Users Round Trip Time Cumulative Distribution Function Probability Models (MURTTCDFPM) in IEEE 802.11b Wireless Local Area Networks (WLANs) have been presented in this paper. To develop the models, field and validation data were collected for various Quality of service (QoS) traffic in three different environments namely: open corridor, small offices and free space for an infrastructure based IEEE802.11b WLAN. The data was categorised into four signal ranges namely: all signals considered, strong signals, grey signals and weak signals. By assuming a normal distribution for the collected field data, MURTTCDFPM were developed and correction factors were applied to improve their prediction accuracy. The MURTTCDFPM developed were compared with existing Single user Round trip time (RTT) Cumulative distribution function (CDF) probability models. The results and the tests conducted show that the MURTTCDFPM have good performances as root mean square (RMS) errors <11.9274495% were observed.

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The round trip time (RTT) is one of the most important metrics for determining the performance of data networks (Geier, 2008a). A maximum acceptable RTT limit is imposed on a wireless local area network (WLAN) if it is to be accepted to have provided sufficient and efficient coverage (Geier, 2008b). RTT is the time required for a signal pulse or packet to travel from a specific source to a specific destination and back again (Ali and Khuder, 2012). RTT can range from just a few milliseconds under excellent conditions (high SNR, short distance between transmitter and receiver, etc.) to several seconds when conditions become adverse (weak SNR, large distance between transmitter and receiver, congestion due to multiple users, etc.). Network designers and installers are in need of tools that help them to reliably predict the RTT and several important network metrics (like the throughput) so as to aid and enable fast and reliable decisions during design, installation or maintenance. During network design and installation one of the metrics easily measured is the received signal strength indication (RSSI) from which the signal to noise ratio is computed. Being able to predict the RTT directly from the measured RSSI will therefore be very useful.

Several work including Kavidha and Sadasivam (2010), Domenico and Stefan, (2011), Zobenko *et al.*, (2014), Li *et al.*, (2009), El Miloud, *et al.* (2013), Stephen, (2013), Nafei *et al.*, (2013) have extensively

studied the RTT and some have provided RTT models. However none of these researches directly predict RTT from the SNR computed from the received signal strength indication (RSSI) observed. Can the RTT be directly and reliably predicted from the computed SNR so as to make the prediction process easier?

Several research has shown that throughput in WLANs can be predicted directly from the SNR with reasonable accuracy (Henty, (2001); Oghogho *et al.*, (2014a); Oghogho *et al.*, (2014b), Oghogho *et al.*, (2015a), Oghogho *et al.*, (2015b), Oghogho, (2017), Oghogho *et al.*, (2017), Oghogho *et al.*, (2018). Among these researches, Oghogho *et al.*, (2014b) and Oghogho, *et al.*, (2015a) provided throughput CDF probability models based on different ranges of SNR observed. These throughput probability models help to predict the probability that the throughput observed will fall into a particular range of value based on the category of signal (strong, grey or weak signal).

In a similar way Oghogho (2018) provided single user RTT models that could directly predict RTT from the observed SNR for an IEEE 802.11b WLAN. These models were however not probability models. Oghogho (2019) provided single user RTT CDF probability models which can be used to predict the probability that RTT falls within a certain range for

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different ranges of SNR. However to the best of the author's knowledge, no multiple users RTT probability models based on observed SNR only exists. This paper is focused to fill this gap.

MATERIALS AND METHOD

The method used in Oghogho, *et al.*, (2014a), Oghogho *et al.*, (2014b) and Oghogho (2019) was also used in this work except that RTT multiple users data was collected instead of throughput data. The multiple users RTT data collected were categorized into four categories using the SNR namely: (i) All signals considered, (ii) Strong signals only (SNR>25dB), (iii) Grey signals only (25dB>SNR>18dB) (iv) Weak signals only (SNR<19dB) only. MURTTCDFPM for each SNR category to which correction factors were applied were developed by assuming a normal distribution to the collected RTT field data. The MURTTCDFPM can predict the probability that RTT falls into different RTT ranges for various SNR considered for multiple users on the network. The number of users was limited to seven users due to the work of Wu *et al.* (2011) where seven users represented saturation traffic where each client always has a packet to send. Validation data was collected

using the method used by Oghogho (2019). The models were compared with the validation data and the RMS errors were computed and used to test the performances of the models.

RESULTS AND DISCUSSION

Table 1 shows the computed empirical multiple users RTT field data probabilities for the different SNR categories while Table 2 shows other statistical parameters of the RTT multiple users field data. As can be seen from Table 1, the multiple user probabilities vary considerably for the different SNR categories in the respective RTT ranges. For all the signal categories considered, the probability of obtaining a RTT value < 1ms is 0% for multiple users. Also worthy of mentioning is in the weak signal range where the probability of obtaining a RTT <7ms is 0% implying that when the signal becomes weak, the RTT increases considerably for multiple users. From Table 2, the smallest RTT mean (148.437147ms), standard deviation (322.1813368ms) and variance (103800.814) were observed when all signals were strong.

Table 1: Computed Empirical Probabilities for Combined RTT Field Data (multiple Users)

RTT (ms)	Statistical Parameter	ALL (SNR)	Strong Signal	Grey signal	Weak Signal
>2000	Frequency	14	6	6	3
	Probability	0.0075922	0.0041351	0.0165746	0.09375
1000-1999.99	Frequency	31	9	22	0
	Probability	0.0168113	0.0062026	0.0607735	0.0000
500 -999.99	Frequency	70	34	35	2
	Probability	0.037961	0.0234321	0.0966851	0.0625
100-499.99	Frequency	769	584	168	14
	Probability	0.4170282	0.402481	0.4640884	0.4375
50-99.99	Frequency	326	264	56	8
	Probability	0.1767896	0.1819435	0.1546961	0.25
20-49.99	Frequency	255	214	38	4
	Probability	0.1382863	0.1474845	0.1049724	0.125
10-19.99	Frequency	122	114	8	0
	Probability	0.0661605	0.0785665	0.0220994	0.00000
7-9.99	Frequency	48	29	17	1
	Probability	0.0260304	0.0199862	0.0469613	0.03125
6-6.99	Frequency	23	23	0	0
	Probability	0.0124729	0.0158511	0.0000	0.00000
5-5.99	Frequency	30	27	3	0
	Probability	0.016269	0.0186079	0.0082873	0.000000
4-4.99	Frequency	41	39	2	0
	Probability	0.0222343	0.026878	0.0055249	0.00000
3-3.99	Frequency	49	46	3	0
	Probability	0.0265727	0.0317023	0.0082873	0.000000
2-2.99	Frequency	60	56	4	0
	Probability	0.032538	0.0385941	0.0110497	0.000000
1-1.99	Frequency	6	6	0	0
	Probability	0.0032538	0.0041351	0.0000	0.000000
0-0.99	Frequency	0	0	0	0
Sample Size (N)		1844	1451	362	32

Table 2: Statistical Parameter Values of RTT data for Different Cases of Received SNR.

Statistical Parameter	ALL RSSI (SNR) considered (63dB ≥ SNR ≥ 13dB)	Strong Signal (SNR ≥ 25dB)	Grey signal (25dB > SNR ≥ 19dB)	Weak Signal (SNR < 19dB)
N (Sample Size)	1844	1451	362	32
Mean	191.96329	148.437147	351.6677	459.9094
Median	93	78.9	177.2	223.3
Mode	2.9	2.9	7.1	89.3
Std. Deviation	403.8951	322.1813368	586.56516	813.6792
Variance	163131.2	103800.814	344058.683	662073.8
Skewness	7.442	10.331	4.497	2.857
Kurtosis	72.012	135.857	27.134	7.299
Range	5483.5	5483.5	5038.40	3161.8

The highest RTT mean (459.9094ms), standard deviation (813.6792ms) and variance (662073.8) were observed when all signals were weak. From the foregoing, it is clear that RTT increase with decrease in SNR for multiple users on the network. This can be explained as resulting from: (i) the after effect of the selection of lower transmission rates by the error control mechanism which aims to reduce errors in packet transmission as signal becomes weak (ii) longer round trip times of packets to get to and return from their destination due to delays from packet queuing at the WLAN access point for multiple users.

The multiple users on the network increases the aggregate traffic flow on the network thus inducing appreciable longer delays and queuing as well as buffer over flows. (iii) Since RTT also depend on distance and weak signals usually occur at greater distances from the WLAN radio, the increased distance also adds to the increase in RTT.

Fig.1 shows the graph of Standard deviation and Average values of RTT observed for the field data against SNR for multiple users. From the graph of Figure 1, it can be seen that the Average RTT observed for the entire strong signal range is appreciably constant and low (<150ms). Also the standard deviation is low for strong signals. Figure 1 also shows the high standard deviation observed for RTT at the transition between strong and Grey signals (26dB to 24dB). The grey and weak signals also showed a sharp rise in standard deviation at 23dB, 19dB and 16dB.

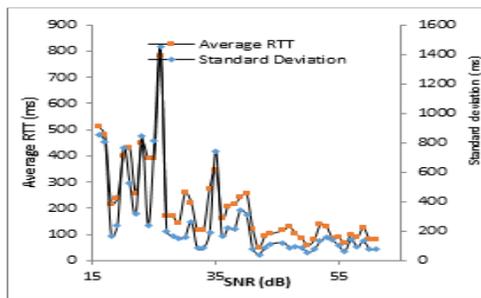


Fig.1 Graph of Standard deviation and Average values of RTT field data against SNR

Development of RTT Probability Models: To develop the models, a normal distribution was assumed for the multiple users RTT field data. From this, a general function for predicting the probability distribution function (PDF) and Cumulative distribution function (CDF) was derived. This was done to obtain RTT values for all the following categories of signal ranges namely (i) All SNR, (ii) Strong signals only (iii) Grey signals only (iv) Weak signals only. According to Ify, (2011), the normal or Gaussian distribution is defined by equation 1.

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1(x-\mu)^2}{2\sigma^2}} \quad (-\infty < x < +\infty) \quad \dots \dots 1$$

Where x is the variable (RTT) that is to be predicted, μ is the mean of the population, σ = population standard deviation, and. f(x) is the probability distribution function needed to obtain a RTT= x (ms).

The μ and σ are obtained from Table 2, and inserted into equation 1 to obtain the model equations of the probability distribution function presented in equation 2-5. The range of equations 2-5 is from 0 to infinity because RTT cannot be negative. The respective equations 2, 3, 4 and 5 give the probability of obtaining a RTT value =x (ms), if (i) SNR is any value (ii) SNR ≥ 25dB (Strong signals) (iii) 25dB > SNR ≥ 19dB (Grey Signals) (iv) SNR < 19dB (Weak Signals).

Equations 2-5 estimate the probability of obtaining a unique RTT value for the respective SNR category. They do not estimate the probability of obtaining ranges of RTT values hence they are limited in their practical application.

For example, in practical applications, it is of more interest to the researcher or WLAN designer or installer to know the probability that the RTT value falls above or below 5(ms) rather than the probability that it is equal to 5 (ms).

$$f(x) = 0.000987737e^{-3.06502E-06(x-191.96329)^2(0 < x < \infty)} \dots 2$$

$$f(x) = 0.001238254e^{-4.81692E-06(x-148.437147)^2(0 < x < \infty)} \dots 3$$

$$f(x) = 0.000680133e^{-1.45324E-06(x-351.6677)^2(0 < x < \infty)} \dots 4$$

$$f(x) = 0.000490294e^{-7.55203E-07(x-459.9094)^2(0 < x < \infty)} \dots 5$$

This limitation of the PDF leads to the need to evaluate the CDF in terms of standard units. To do this, equation 1 is transformed to the standard normal form as shown in equation 6 (Ify, 2011).

$$f(Z) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1(Z)^2}{2\sigma^2}} \dots \dots 6$$

Where $Z = \frac{x-\mu}{\sigma} \dots \dots \dots 7$

Equation 8, 9, 10 and 11 respectively can be used to estimate Z values for all values of SNR, strong signals, grey signals and weak signals respectively

$$Z = \frac{x-191.96329}{403.8951} \quad (0 \leq x \leq \infty) \dots \dots 8$$

$$Z = \frac{x-148.437147}{322.1813368} \quad (0 \leq x \leq \infty) \dots \dots 9$$

$$Z = \frac{x-351.6677}{586.56516} \quad (0 \leq x \leq \infty) \dots \dots 10$$

$$Z = \frac{x-459.9094}{813.6792} \quad (0 \leq x \leq \infty) \dots \dots 11$$

According to Ify (2011) cumulative distribution function (CDF) is given by equation 12

$$CDF=F(Z) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^Z e^{-\frac{1}{2}u^2} du \dots \dots 12$$

For any value of Z score in equations 8-11, the CDF can be obtained from the table for standard normal distribution. Table 3 shows the unadjusted CDF probability models values obtained using Z tables, the correction factors introduced and the the adjusted Multiple users RTT CDF probability models values for the different categories of signals.

To estimate the correction factors shown in Table 3, the unadjusted multiple users RTTCDF probability models values obtained from Z tables were compared with the probability values computed from the original field data presented in Table 1. The correction factors were obtained by subtracting the multiple users RTTCDF probability models values obtained from Z tables from the original RTT field data probabilities.

Performance Evaluation of Developed Models: The performances of the models were evaluated by comparing the MURTTCDFPM predicted probability values with the multiple users RTT validation data probabilities. By computing the RMS errors, the MURTTCDFPM developed in this work were also compared with existing Single user RTT CDF probability models developed by Oghogho (2019).

This was done for all the signal categories as shown in Table 4. From Table 4, it can be seen that the MURTTCDFPM developed in this work performed better than the existing Single user RTT CDF models as they all showed lower RMS errors.

The MURTTCDFPM values, the existing Oghogho (2019) Single User RTT CDF probability model values and the validation data probabilities were plotted against RTT in Figure 2-5. Plots of the lower sections of the respective graphs are presented below the full sections to provide clearer view of those parts of the respective graphs. From Figure 2-5, the probability of obtaining a high RTT is low when a single user is on the network compared with when there are multiples users on the network. From Table 4, the developed multiple users RTT CDF Probability models gave good performances as they all showed RMS errors < 11.9274495% observed for the Grey model.

From Table 3, the probability of obtaining a RTT value < 1ms is 0% for multiple users on the network. Also from Table 3, the All SNR, Strong signals, Grey signals and Weak signals Multiple users RTT CDF probability models predicted the probabilities of having a RTT < 6ms as 10%, 4.6%, 3.3% and 0% respectively. Thus when signal has become weak, it is very unlikely to have a RTT < 6ms.

Figures 2-5 along with Table 4 show that the multiple Users RTT probability models developed in this work follow the validation data more closely than the already existing single user RTT probability models, hence justifying the work done to provide the additional models for multiple users in this paper.

Table 3: RTT Multiple Users CDF Probability Model Values, the Correction Factors and the Adjusted CDF Probability Model Values.

Statistical Parameter		ALL SNR			Strong Signals		
		CDF Probability model value from Z table	Correction factor for CDF Probability model (γ)	Adjusted CDF Probability Model values	CDF Probability model value from Z table	Correction factor for CDF Probability model(γ)	Adjusted CDF Probability Model values
RTT range (ms)							
>2000	Probability	0	+0.008	0.008	0	+0.004	0.004
1000-1999.99	Probability	0.0228	-0.006	0.0168	0.0041	+0.002	0.0061
500 -999.99	Probability	0.2008	-0.163	0.0378	0.1338	-0.11	0.0238
100-499.99	Probability	0.3674	+0.05	0.4174	0.4217	-0.019	0.4027
50-99.99	Probability	0.0458	+0.131	0.1768	0.0621	+0.12	0.1821
20-49.99	Probability	0.0296	+0.109	0.1386	0.0337	+0.114	0.1477
10-19.99	Probability	0.0072	+0.059	0.0662	0.011	+0.068	0.079
7-9.99	Probability	0.0036	+0.022	0.0256	0.0036	+0.016	0.0196
6-6.99	Probability	0	+0.013	0.013	0	+0.016	0.016
5-5.99	Probability	0	+0.016	0.016	0.0036	+0.015	0.0186
4-4.99	Probability	0.0036	+0.019	0.0226	0	+0.027	0.027
3-3.99	Probability	0	+0.026	0.026	0	+0.032	0.032
2-2.99	Probability	0	+0.033	0.033	0	+0.039	0.039
1-1.99	Probability	0	+0.003	0.003	0.0036	+0.001	0.0046
0-0.99	Probability	0.0036	-0.0036	0	0	0	0
Statistical Parameter		Grey signals			Weak Signals		
		CDF Probability model value from Z table	Correction factor for CDF Probability model (γ)	Adjusted CDF Probability Model values	CDF Probability model value from Z table	Correction factor for CDF Probability model(γ)	Adjusted CDF Probability Model values
RTT range (ms)							
>2000	Probability	0.0025	+0.014	0.0165	0.0294	+0.064	0.0934
1000-1999.99	Probability	0.131	-0.070	0.061	0.2252	-0.225	0.0002
500 -999.99	Probability	0.2678	-0.171	0.0968	0.2255	-0.163	0.0625
100-499.99	Probability	0.2651	+0.199	0.4641	0.1899	+0.2476	0.4375
50-99.99	Probability	0.0286	+0.126	0.1546	0.0215	+0.229	0.2505
20-49.99	Probability	0.0173	+0.088	0.1053	0.0139	+0.111	0.1249
10-19.99	Probability	0.0067	+0.015	0.0217	0.0034	-0.003	0.0004
7-9.99	Probability	0.0034	+0.044	0.0474	0.0035	+0.028	0.0315
6-6.99	Probability	0	0	0	0	0	0
5-5.99	Probability	0	+0.008	0.008	0	0	0
4-4.99	Probability	0	+0.006	0.006	0	0	0
3-3.99	Probability	0	+0.008	0.008	0	0	0
2-2.99	Probability	0.0034	+0.008	0.0114	0	0	0
1-1.99	Probability	0	0	0	0	0	0
0-0.99	Probability	0	0	0	0.0034	-0.0034	0

Table 4: RMS Errors for Multiple and Single User RTT CDF Probability Models.

Signal Category	All SNR	Strong Signals	Grey Signals	Weak Signals
Multiple Users RTT CDF Probability Models RMS error(ms)	0.056884260	0.051411599	0.119274495	0.086100614
Oghogho 2019 Single User RTT CDF Probability Models RMS error(ms)	0.233609211	0.258315174	0.152113002	0.108517477

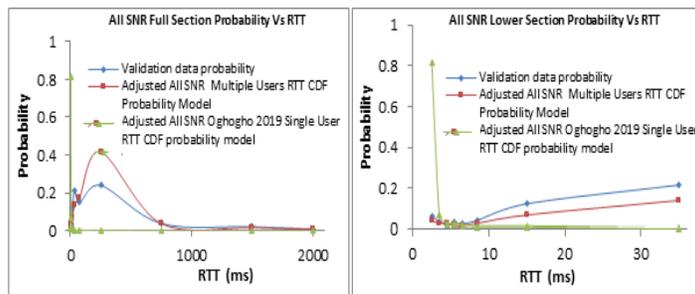


Fig. 2: All SNR RTT CDF Probability models values and validation data Vs RTT

Conclusion: Multiple users RTT Cumulative distribution function probability Models have been developed, validated and compared with already existing similar Single user RTT CDF models in this work. For a given category of SNR, the models can predict the probability that RTT will fall into a specific RTT range. The probability models showed low RMS errors (<11.9274495%) when compared

with validation data. They also performed better than similar existing single User RTT CDF probability models when their RMS errors were compared. The models will provide additional information needed by WLAN designers and installers for making better network design and installation decisions.

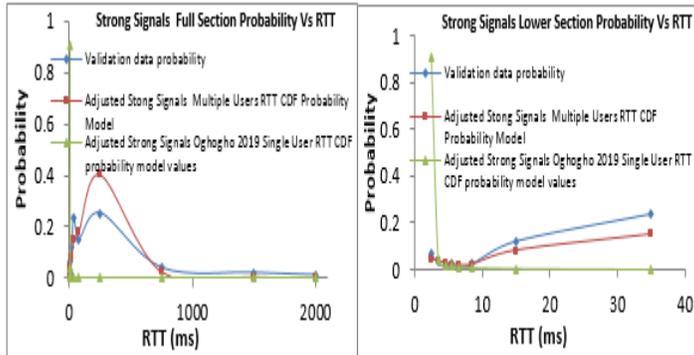


Fig. 3: Strong Signals RTT CDF Probability models values and validation data Vs RTT

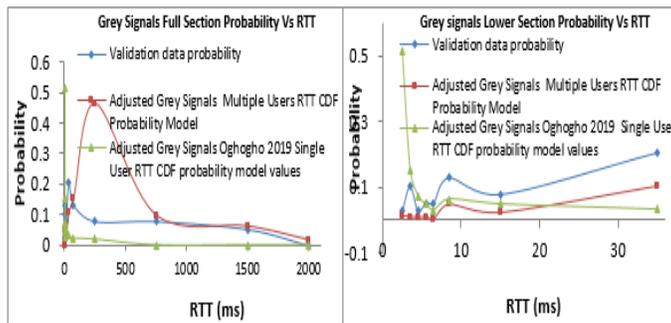


Fig. 4: Grey Signals RTT CDF Probability models values and validation data Vs RTT

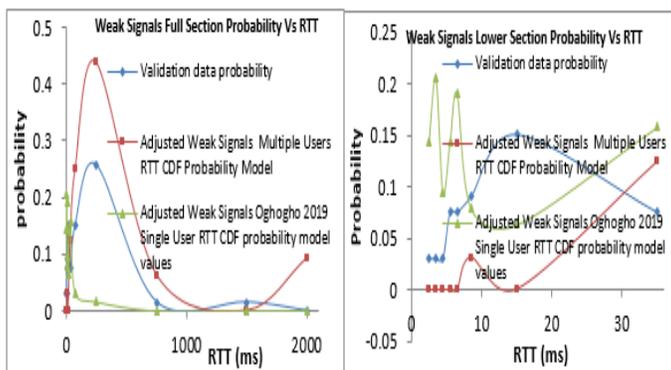


Fig. 5: Weak Signals RTT CDF Probability models values and validation data Vs RTT

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