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RAIN RATE TREND-LINE ESTIMATION MODELS AND WEB APPLICATION FOR THE GLOBAL ITU RAIN ZONES

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ABSTRACT

The International Telecommunication Union (ITU) published data on rain rate exceeded for the following percentage of time; 99%, 99.7%, 99.9%, 99.97%, 99.99%, 99.997% and 99.999% in the ITU-R Recommendation p.838-3. This paper presents the development of trend line models and web application for estimating rain rate based on the published rain rate data in the ITU-R Recommendation P.838-3. The trend line models and web application make it possible for users to estimate the rain rate exceeded for any given percentage of time. An Online Nonlinear Regression (ONLR) tool is used to develop the trend line models for estimating the rain rate for each of the 15 rain zones in the ITU-R Recommendation p.838-3. The web application is developed using Visual Basic for Application programming tool in Microsoft excel. The models generated along with the web application are useful in communication link analysis and design; they will facilitate the computation of rain attenuation for any given link availability.

INTRODUCTION

Microwave links suffer fading due to a range of mechanisms including absorption by atmospheric gasses and scattering by hydrometeors such as cloud drops, sleet and rain. Attenuation due to rain generally causes the largest protracted fading for radio links operating above 10 GHz, as such; rain fading can significantly affect the availability of the links. The problem becomes more critical in tropical regions where there is high intensity rainfall in a year. Consequently, in any microwave communication system design, determination of the rain attenuation for the specific rainfall rate is very important Callaghan et al., (2008), Callaghan, (2004); Capsoni, (2009).

Many studies have been carried out in order to determine and predict the attenuation by considering the rainfall rate, elevation angel, effective slant path length, and other parameters Barclay, (2003); Deidda, (2000); Deidda, (1999); Feral et al, (2003); Gremontand Filip, (2004). The internationally recognised ITU-R Recommendation P.838-3 relates rain rate to an average specific rain attenuation, ITU, (2005); ITU (2001); ITU, (2004). Furthermore, precipitation is not identical in all areas which is why ITU released a recommendation Rec. ITU-R PN.837-1 for splitting the world into 15 regions (called rain zones) according to precipitation intensity. Accordingly, greater rain attenuation is expected in the areas with higher precipitation, Diaz, (2003); Hodges et al., (2003); Jeannin, (2007).

Over the years, the ITU rain rate statistics for the rain zones have been widely used across the globe. However, the published rain rate exceeded for the following percentage of time are available; 99%, 99.7%, 99.9%, 99.97%, 99.99%, 99.997% and 99.999%. Hence, this paper will use the published ITU-R Recommendation P.838-3 rain rate data, ITU, (2005); ITU (2007) along with a nonlinear regression analysis tool to derive trend line models for predicting the

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rain rate exceeded for any percentage of time in the 15 rain zones specified in the ITU-R Recommendation P.838-3. Furthermore, a web application is developed to perform the computations the rain rate exceeded for any percentage of time in the 15 rain zones based on the trend models derived in this paper.

LITRETURE REVIEW

Rain Attenuation

Rain attenuation is defined as signal loss in dB at the receiver due to rain events. When planning a link, well established models, such as ITU-R recommendation P.838-3, ITU, S (2005) provides the international recognized model to calculate specific rain attenuation for any given rain rate. The specific rain attenuation, γ_R (dB/km) is obtained from the rain rate, R (mm/hr) using the power law relationship:

$$\gamma_R = kR^{\alpha} \quad (1)$$

where k and α are frequency and polarization dependent coefficients. Values for the constants required to calculate k and α are provided by Rec. ITU-R P.838-3 ITU, (2005).

In practice, specific attenuation is more commonly associated with rain rate as this is a parameter that is widely measured and much is known of its statistics. Rain rate, or rain intensity, is measured in units of millimetres per hour (mm/hr) and vast databases of rain rate measurements exists spanning hundreds of years and many thousands of locations.

The most important meteorological statistic when planning a radio system is the rainfall rate exceeded for 0.01% or 0.001% of the time, R0.01% and R0.001%. These rain rates are highly geographical dependent. For temperate regions, R0.01% can be around 30 mm/hr while for arid regions it is only few mm/hr. For tropical regions that experience monsoon seasons, the R0.01% can be as large as 150 mm/hr. Normally, radio engineers will design a terrestrial fixed link to have 99.99% availability in an average year, and to fail when it experiences rain rates higher than R0.01%.

Several procedures exist to estimate the statistics of rain rate in a particular region. Empirically, rain rate statistics can be directly measured using a rain gauge and/or rain radar. A rain gauge is a device utilised by hydrologists and meteorologists to quantify the amount of liquid precipitation over a set period of time. Rain radar is a type of weather radar that can be used to locate and estimate precipitation or rain. Statistics of rain rate can also be found in Rec. ITU-R P.837-5, ITU, (2007), or in the Global Crane model, Crane, (1996). The Rec. ITU-R P.837-5, ITU, (2007) model provides the annual distribution of rainfall rate with an integration time of 1 minute for the entire globe, derived from numerical weather prediction, but recommends the use of locally measured rain rates if available.

Applications Of The ITU Rain Rate

Across the globe, the ITU rain rate data has been used for various communication system link design and performance evaluations. In Malaysia, the ITU rain rate data was used to predict the rain attenuation and to compare predicted rain attenuation with measured attenuation, Islam, Abdulrahman, and Rahman, (2012). Abdulrahman, et al., (2012) used the ITU rain data for computation of rain attenuation and comparison of various rain attenuation prediction models for Malaysia environment. Similar study was conducted for estimating the rain attenuation for the 'K' rain zone in India, Kestwal, Joshi and Garial, (2014), as well as for various regions in India, Sulochana, Chandrika and Rao, (2014). In Pakistan's tropical region, the ITU rain rate data was used for the computation of microwave rain attenuation and prediction of rain outage, Siddique, Ahmad, and Raja, (2011). Similar study was conducted for tropical regions in general, Kestwal, Joshi and Garial, (2014). Furthermore, in Saudi Arabia, rain map for radio wave propagation was developed through the use of the ITU rain rate data, Ali, Alhaider, and Shatila, (1986). Similarly, rain rate (mm/h) contour map was developed for Nigeria, Ojo, Ajewole, and Sarkar, (2008). In Turkey, Uslu and Tekin, (2003) used the rain rate data to compute path loss due to rain fading and precipitation for 26GHz frequency. Another study used the rain rate data to predict the coverage prediction method for local multipoint distribution systems operating at millimetre radio wave frequency, Panagopoulos et al, (2003).

Nonlinear Regression Analysis

Regression is a means of predicting a dependent variable based on one or more independent variables. This is done by fitting a line or surface to the data points that minimizes the total error. The line or surface is called the regression model or equation. Nonlinear regression is a regression technique in which a nonlinear mathematical model is used to describe the relationship between two variables, Glantz & Slinker, (2001). Nonlinear regression is characterized by the fact that the prediction equation depends nonlinearly on one or more unknown parameters, Smyth, (2002).

METHODOLOGY

In this paper, an Online Nonlinear Regression (ONLR) tool is used to generate the trend line models (mathematical expressions) for estimating the rain rate for each of the rain zones in the ITU-R Recommendation p.838-3. Subsequently, a modified waterfall software development methodology of Fig 3.1 is used to develop the web application for the computation of the rain rate based on the trend line models presented in this paper.

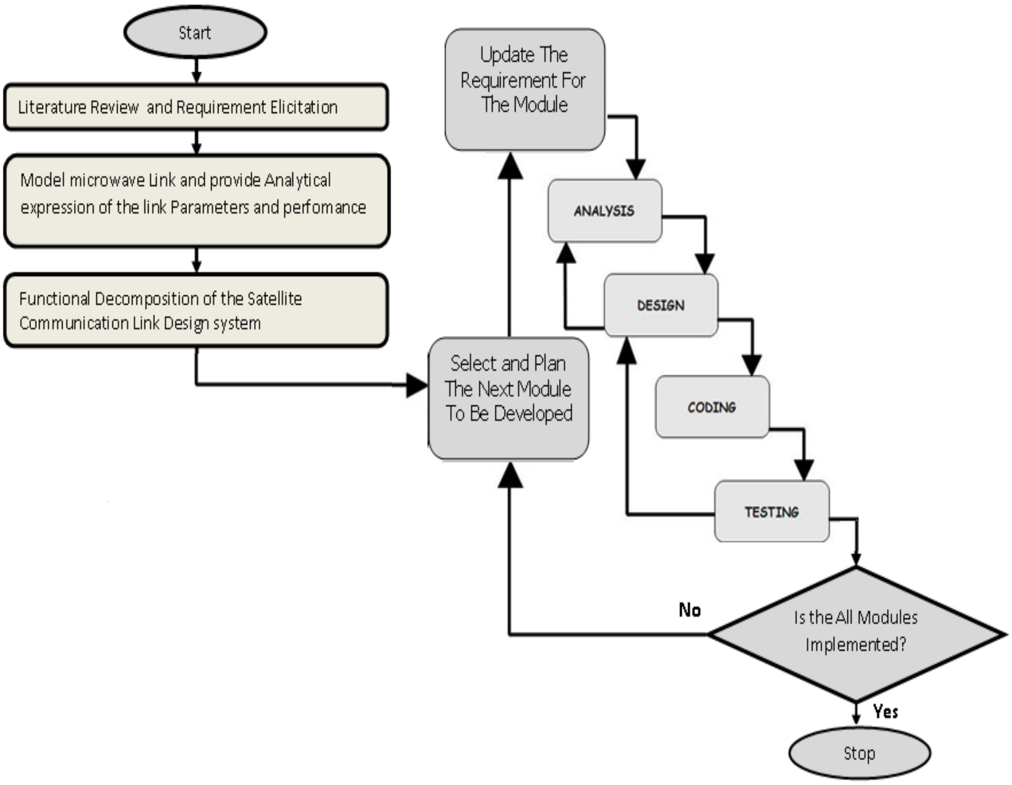

Figure 1, Research Process Based On The Modified Waterfall Software Development Methodology and

The set of rain rate data for each rain zone is fed into the ONLR tool (available at: http://www.xuru.org/rt/NLR.asp). The rain rate data set is presented in two columns, whereby, column two contains the Rain Rate (in mm/hr) and column one contains the percentage of time(in %) exceeded for the Rain Rate. The ONLR tool carries out nonlinear regression analysis (also known as nonlinear least squares fittings) on the data set through which it finds a list of functions that properly fit the given rain rate data. The list of functions are ordered by the residual sum of squares and shown from the best suiting to the worst suiting case. Figure 2 shows the content of the input textbox of the online nonlinear regression tool for Rain Zone A.

1	0.1
0.3	0.8
0.1	2
0.03	5
0.01	8
0.003	14
0.001	22

Figure 2 The Input Textbox Data for Rain Zone A On The The Online Nonlinear Regression

The ONLR tool generates a number of nonlinear models for each set of input data and it orders the models by the residual sum of squares, shown from the best suiting to the worst suiting case. The best suiting models for the 15 ITU rain zones are presented next.

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The Trend Line Model For Each Of The 15 Rain Zones In The ITU-R Recommendation P.838-3

$$Rpop = \left(1.260746645 * (X^{-0.4147529796})\right)(e^{-3.887618548*X}) + \left(\frac{1}{(0.00194911883*(X^{-3.834753933}) + 8.78973548)}\right) \quad (2)$$

where, X represents the percentage of time exceeded, Po.
R_{POP} represents the predicted rain rate for the given percentage of time exceeded, Po.

The Trend Line Model For Rain Zone B:

$$Rpop = \left(\frac{0.98}{(1.292193548 *(X^{0.6511923754}) + 0.01576793979)}\right) + (-3.899786856 * (X^2) + 4.21754715 * (x) - 0.5646390684) \quad (3)$$

The Trend Line Model For Rain Zone C:

$$Rpop = \left(1.995465279\ (X^{-0.4471194902})\right)(e^{-0.8348328995*X}) + \left(-0.1378000409 * \left(X^{(26.09462771)}\right)\right) \quad (4)$$

The Trend Line Model For Rain Zone D:

$$Rpo = \left(5.652308805\ (X^{-0.301684047})\right) - 3.498773758 \quad (5)$$

The Trend Line Model For Rain Zone E

$$Rpop = \left(2.746717026\ (X^{-0.4721192114})\right) - 2.344815382 + \left(0.16809996\ (X^{-0.4721192114})\right) \quad (6)$$

The Trend Line Model For Rain Zone F:

$$Rpop = \left(\frac{1}{(0.6167378619*(X^{0.6953114804}) + 0.007374574045)}\right) \quad (7)$$

The Trend Line Model For Rain Zone G:

$$Rpop = \left(9.344664854\ (X^{-0.2940310185})\right) - 6.319998626 \quad (8)$$

The Trend Line Model For Rain Zone H:

$$Rpop = \left(\frac{1}{(0.410819848\ *(X^{0.6010053054}) + 0.005592902346)}\right) + \left(\frac{\left(-0.3666172882 *\left(X^{0.8667021078}\right)\right)}{\left((X^{0.8667021078}) - 0.200751126\right)}\right) \quad (9)$$

The Trend Line Model For Rain Zone J:

$$Rpop = \left(44.8581819\left(X^{-0.1032198261}\right)\right) - 37.19980506$$
(10)

The Trend Line Model For Rain Zone K:

$$Rpop = \frac{\left(-2.367152273\left(X^{0.5982979441}\right) + 3.6447231\right)}{\left(X^{0.5982979441} + 0.02003494051\right)}$$
(11)

The Trend Line Model For Rain Zone L:

$$Rpop = \frac{\left(-1.220542228\ \left(X^{0.6782808341}\right) + 3.606552167\right)}{\left(X^{0.6782808341} + 0.0147430943\right)}$$
(12)

The Trend Line Model For Rain Zone M:

$$Rpop = \frac{\left(-2.787223759\left(X^{0.5809131552}\right) + 7.132906803\right)}{\left(X^{0.5809131552} + 0.04187894896\right)}$$
(13)

The Trend Line Model For Rain Zone N:

$$R_{Pop} = \left(\frac{1}{\left(0.1053467896 * X^{0.6197825122} + 0.004093309783\right)}\right) + \left(-3.893627184 * e^{\left(199.5959901 * e^{-22.25873246 * x}\right)}\right)$$
(14)

The Trend Line Model For Rain Zone P:

$$Rpop = 157.515815X^{-0.13535995} - 147.7155282 - 3.168046965\sin(5.394361457X - 0.1696520499)$$ (15)

The Trend Line Model Rain Zone Q:

$$Rpop = 53.91252725x^{-0.1667547492}e^{-0.8625475333x} - 4.012222726\sin(2.48341933x - 0.04048696865)^2$$
(16)

Validations of The Proposed Models

The validity of the proposed models is examined by the calculation of measures for goodness-of-fit, namely; coefficient of determination (R^2) and residuals. Generally, a very common procedure for choosing among alternative functions is to select the one that fits the best, that is, the one that has the highest Coefficient of Determination, R^2. The value of R^2 indicates if the overall fit of the model is or is not satisfactory. Important discrepancies may still exist, although the model may pass the R^2 test. These discrepancies often can be detected through an analysis of residuals and must be investigated before the model is finally adopted for use. Accordingly, the published ITU rain rate data is considered as a set of actual data where the dependent variable (rain rate) is represented as y and the independent variable (the percentage of time exceeded) is represented as x. The ITU rain data is predicted by a nonlinear regression model where the predicted dependent variable is represented as ŷ and the independent variable is x, then;

$$\hat{y} = f(x) \qquad (17)$$

where ŷ is the predicted data and f(x) is the nonlinear regression model equation; y is computed using the nonlinear regression model

Each published ITU rain rate data represented as ‘y’ may be expressed as the predicted value represented as ŷ+ a residual (error) represented as e, thus;

$$y = \hat{y} + e \qquad (18)$$

Residual – the difference between the true value and the predicted value.

$$e = y - \hat{y} \qquad (19)$$

Coefficient of Determination, R^2 is calculated as follows, Anderson-Sprecher, (1994); Kvalseth, (1985):

$$RSS = \sum_{i=1}^{n}\left(y_i - \hat{y}_i\right)^2 \qquad (20)$$

$$TSS = \sum_{i=1}^{n}\left(y_i - \bar{y}_i\right)^2 \qquad (21)$$

$$R^2 = 1 - \left(\frac{RSS}{TSS}\right) = 1 - \left(\frac{\sum_{i=1}^{n}\left(y_i - \hat{y}_i\right)^2}{\sum_{i=1}^{n}\left(y_i - \bar{y}_i\right)^2}\right) \qquad (22)$$

$$\text{where } \bar{y} = = \sum_{i=1}^{n}\left(\frac{y_i}{n}\right) \qquad (23)$$

ȳ is the mean of the published ITU rain rate data values, *RSS* is the residual sum-of-squares, *TSS* is the total sum-of-squares, *y is* the published ITU rain rate data values, ŷ is the predicted ITU rain rate data values .

RESULTS AND DISCUSSION

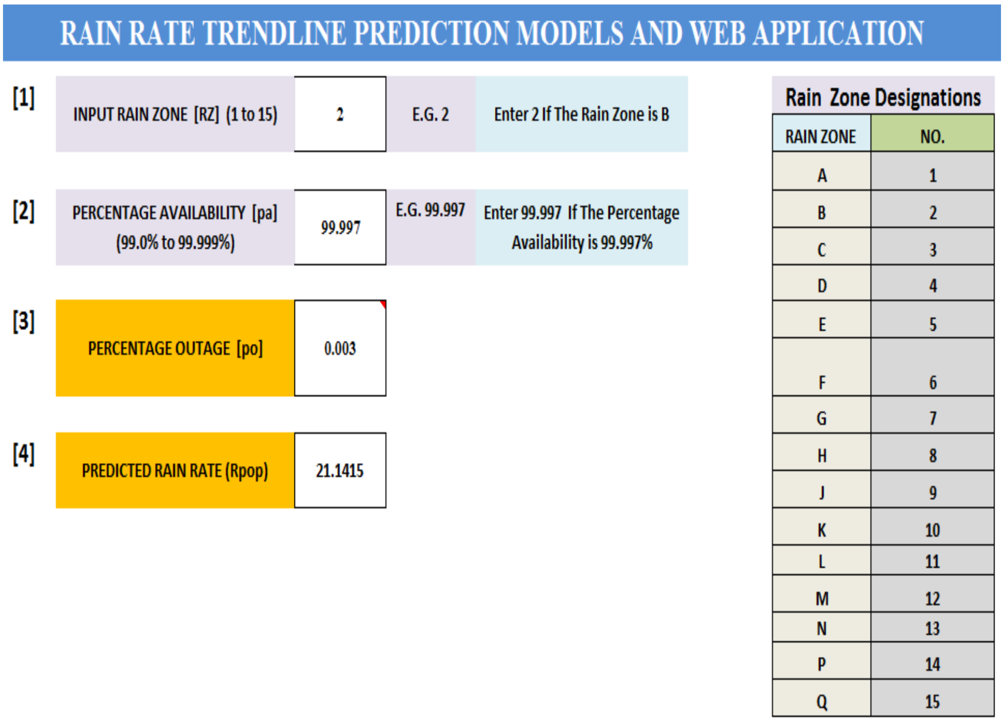

Figure 3, The Web Interface For users To Generate The Rain Rate Estimate Based on The Models Developed in This Paper.

Figure 3, shows the web interface for users to generate the rain rate estimate based on the models developed in this paper. Specifically, in Figure 3, the prediction of rain rate for Rain Zone B is shown for percentage of time exceeded (po) of 0.03%.Furthermore, the predicted rain rates for various percentage of time exceeded is presented in six tables. Table 1 and Table 2 are for the first two rain zones, A and B respectively while Table 3 and Table 4 are for the last two rain zones, P and Q respectively. The tables also show the values of the model validation parameters, namely; coefficient of determination (R2), and the percentage errors. Also Figure 4 and Figure 5 show the bar charts for the ITU Rain Rate Data and The Predicted Rain Rate for the first two rain zones, A and B respectively while Figure 6 and Figure 7 show similar bar charts for the last two rain zones, P and Q respectively.

Table 1 The Predicted Rain Rate (ŷ), Coefficient Of Determination (R^2) And Residuals (e) For ITU Rain Zone A

ITU Rain Zone A								
	x	y	Ŷ	Residual		$(y-\hat{y})^2$	$(y-\bar{y})^2$	R^2
Pa (%)	Po(%)	Rpo (mm/hr)	Rpop (mm/hr)	E	e%			
99	1	0.14	0.1396	0.0004	0.2627	0.0000	52.9984	
99.7	0.3	0.8	0.7635	0.0365	4.5630	0.0013	43.8244	
99.9	0.1	2	2.0004	-0.0004	-0.0184	0.0000	29.3764	
99.97	0.03	5	4.8032	0.1968	3.9367	0.0387	5.8564	
99.99	0.01	8	8.1894	-0.1894	-2.3669	0.0359	0.3364	
99.997	0.003	14	13.8655	0.1345	0.9610	0.0181	43.2964	
99.999	0.001	22	22.0393	-0.0393	-0.1788	0.0015	212.5764	
		$\bar{y}$ = 7.42				$\Sigma(y-\hat{y})^2$ 0.0956	$\Sigma(y-\bar{y})^2$ 388.2648	0.99975

Where

- X represents the percentage of time exceeded, Po.
- RPOP represents the predicted rain rate for the given percentage of time exceeded, Po.
- RPO represents the actual ITU published rain rate for the given percentage of time exceeded, Po.
- e% represents the percentage error

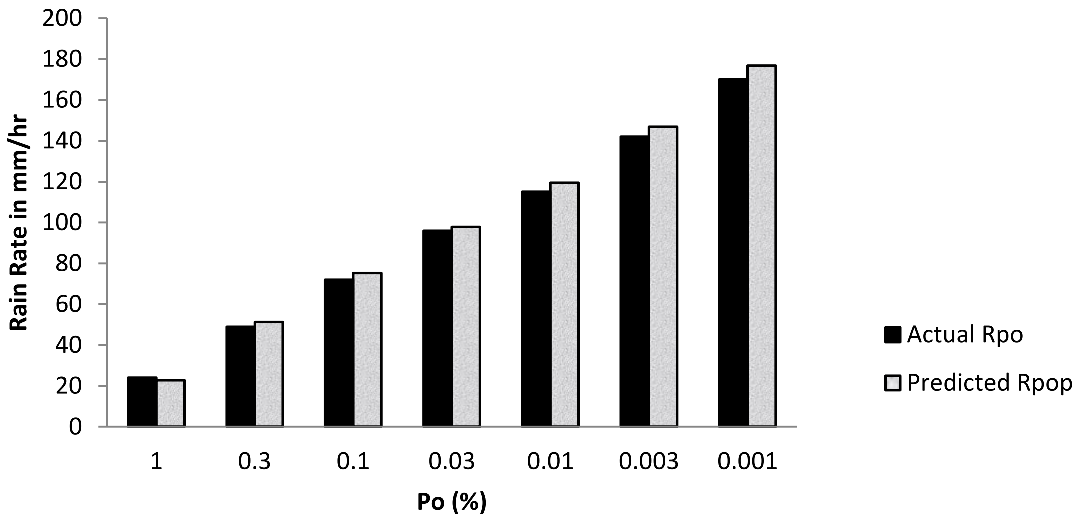

Figure 4, ITU Rain Rate Data and The Predicted Rain Rate For ITU Rain Zone A

Table 2 The Predicted Rain Rate(ŷ), Coefficient Of Determination (R^2) And Residuals (e) For ITU Rain Zone B

ITU Rain Zone B								
	x	**y**	**Ŷ**	**Residual**		$(y-\hat{y})^2$	$(y-\bar{y})^2$	**R^2**
Pa (%)	**Po(%)**	**Rpo (mm/hr)**	**Rpop (mm/hr)**	**e**	**e%**			
99	**1**	**0.5**	**0.5024**	**-0.0024**	**-0.4758**	0.0000	108.7551	
99.7	**0.3**	**2**	**1.9675**	**0.0325**	**1.6253**	0.0011	79.7194	
99.9	**0.1**	**3**	**3.0390**	**-0.0390**	**-1.3013**	0.0015	62.8622	
99.97	**0.03**	**6**	**6.2031**	**-0.2031**	**-3.3857**	0.0413	24.2908	
99.99	**0.01**	**12**	**11.7002**	**0.2998**	**2.4984**	0.0899	1.1480	
99.997	**0.003**	**21**	**21.1415**	**-0.1415**	**-0.6738**	0.0200	101.4337	
99.999	**0.001**	**32**	**31.9462**	**0.0538**	**0.1680**	0.0029	444.0051	
		ȳ = 10.92857				$\Sigma(y-\hat{y})^2$ 0.1566	$\Sigma(y-\bar{y})^2$ 822.2143	0.99981

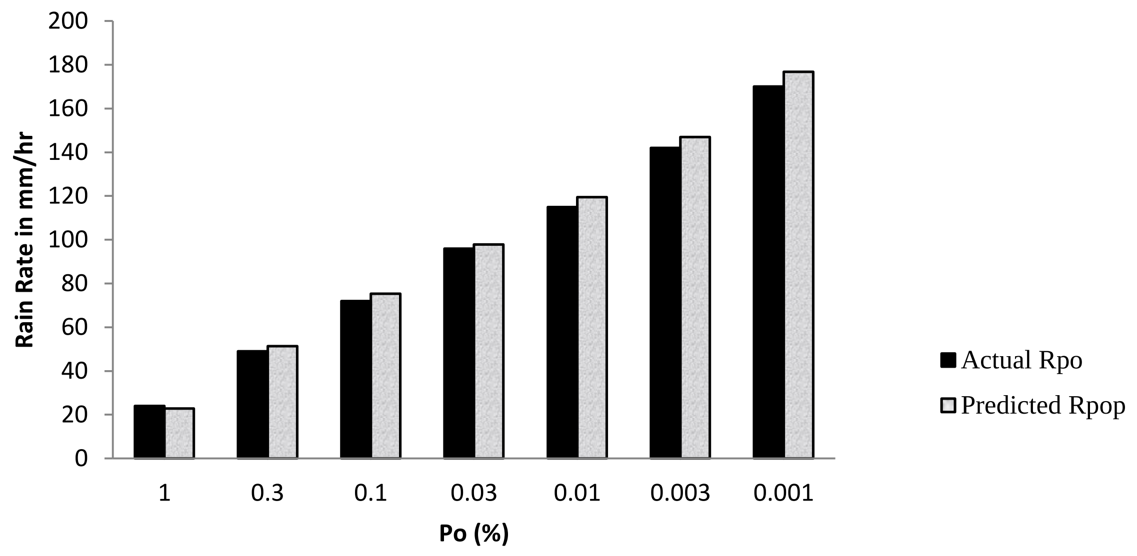

Figure 5, ITU Rain Rate Data and The Predicted Rain Rate For ITU Rain Zone B

Table 3 The Predicted Rain Rate (ŷ), Coefficient Of Determination (R^2) And Residuals (e) For ITU Rain Zone P

ITU Rain Zone P								
	x	**y**	**Ŷ**	**Residual**		**(y- ŷ)^2**	**(y- ȳ)^2**	**R^2**
Pa (%)	**Po(%)**	**Rpo (mm/hr)**	**Rpop (mm/hr)**	**e**	**e%**			
99	**1**	**12**	**12.561586**	**-0.5616**	**-4.6799**	0.3154	10786.3061	
99.7	**0.3**	**34**	**34.536302**	**-0.5363**	**-1.5774**	0.2876	6700.5918	
99.9	**0.1**	**65**	**66.261142**	**-1.2611**	**-1.9402**	1.5905	2586.4490	
99.97	**0.03**	**105**	**105.50765**	**-0.5076**	**-0.4835**	0.2577	117.8776	
99.99	**0.01**	**145**	**146.445**	**-1.4450**	**-0.9965**	2.0880	849.3061	
99.997	**0.003**	**200**	**198.56551**	**1.4345**	**0.7172**	2.0578	7080.0204	
99.999	**0.001**	**250**	**254.04232**	**-4.0423**	**-1.6169**	16.3403	17994.3061	
		ȳ = 115.8571				Σ(y- ŷ)^2 22.9373	Σ(y- ȳ)^2 46114.8571	0.99950

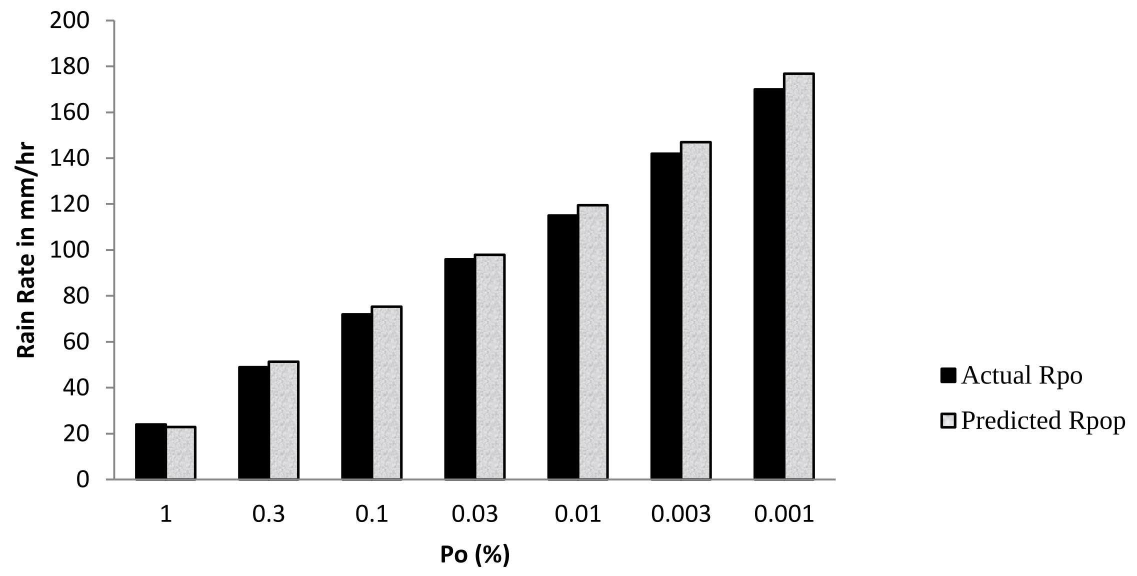

Figure 6, ITU Rain Rate Data and The Predicted Rain Rate For ITU Rain Zone P

Table 4 The Predicted Rain Rate (ŷ), Coefficient Of Determination (R^2) And Residuals (e) For ITU Rain Zone Q

ITU Rain Zone Q								
	x	**y**	**ŷ**	**Residual**		$(y-\hat{y})^2$	$(y-\bar{y})^2$	R^2
Pa (%)	**Po(%)**	**Rpo (mm/hr)**	**Rpop (mm/hr)**	**e**	**e%**			
99	**1**	**24**	**22.842427**	**1.1576**	**4.8232**	1.3400	5102.0408	
99.7	**0.3**	**49**	**51.28079**	**-2.2808**	**-4.6547**	5.2020	2155.6122	
99.9	**0.1**	**72**	**75.265274**	**-3.2653**	**-4.5351**	10.6620	548.8980	
99.97	**0.03**	**96**	**97.8261**	**-1.8261**	**-1.9022**	3.3346	0.3265	
99.99	**0.01**	**115**	**119.49683**	**-4.4968**	**-3.9103**	20.2214	383.0408	
99.997	**0.003**	**142**	**146.92669**	**-4.9267**	**-3.4695**	24.2723	2168.8980	
99.999	**0.001**	**170**	**176.76379**	**-6.7638**	**-3.9787**	45.7488	5560.8980	
		$\bar{y}$ = 95.42857				$\Sigma(y-\hat{y})^2$ 110.7812	$\Sigma(y-\bar{y})^2$ 15919.7143	0.99304

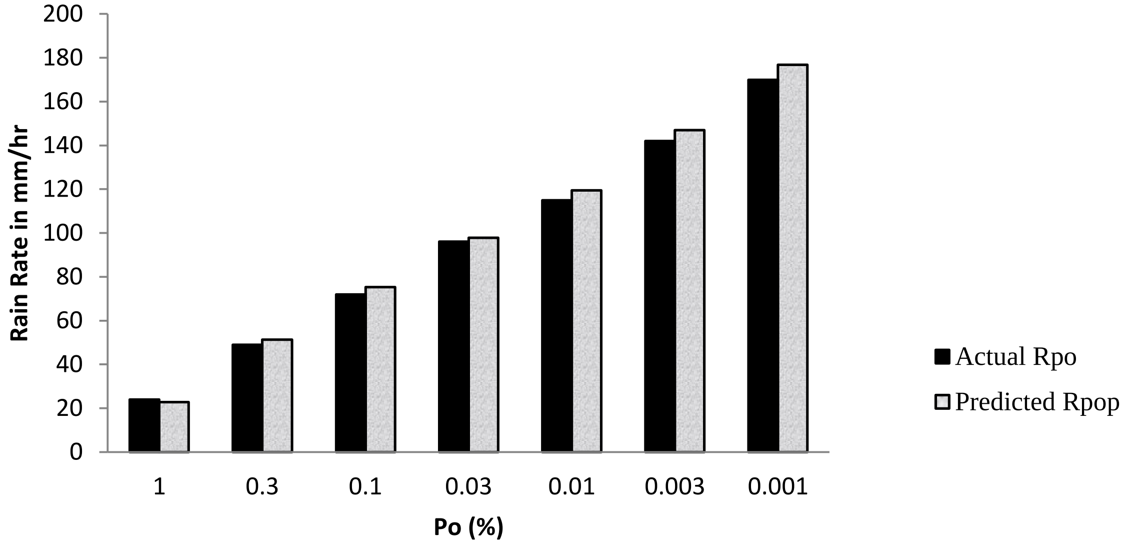

Figure 7, ITU Rain Rate Data and The Predicted Rain Rate For ITU Rain Zone Q

Table 5 The Coefficient Of Determination (R^2) For All The 15 ITU Rain Zones

S/N	RAIN ZONE	R^2
1	**A**	0.99975
2	**B**	0.99981
3	**C**	0.99699
4	**D**	0.99988
5	**E**	0.99972
6	**F**	0.99657
7	**G**	0.99997
8	**H**	0.99998
9	**J**	0.99892
10	**K**	0.99981
11	**L**	0.99996
12	**M**	0.99899
13	**N**	0.99873
14	**P**	0.99950
15	**Q**	0.99304

The value of R^2 is between -1.0 to1.0. According to Hiromasa et al., (2008) and Shanmugan and Breiphol (1988), a rough rule of thumb is that if R^2> 0.8, then the fit is good. From the results in Table 1 to Table 4 and also in Table 5, the values of R^2 for the predicted rain rate for each of the rain zones is greater than 0.993 which therefore implies that the proposed models are statistically reliable and have high predictive accuracies. The percentage errors are also minimal. For the six rain zones shown in Table 1 to Table 4, the percentage errors are within ± 5%.

CONCLUSION

Trend line models for estimating rain rates for each of the 15 ITU rain zones for any given percentage availability or percentage outage is derived. An Online Nonlinear Regression (ONLR) tool is used to develop the trend line models. Also, presented is the development of web application that performs computation of the rain rates based on the trend line models presented in this paper. Furthermore, the web application computes the effective rain fading (rain attenuation) for any given frequency (from 1GHz to 100GHz), for any given link percentage availability and for any given ITU rain zone. Sample computations of rain rate and rain attenuation are used to demonstrate the effectiveness of the web application.

RECOMMENDATIONS FOR FUTURE WORK

The paper presented the trend line estimation of rain rates for the ITU rain zones, as well as the computation of the rain attenuation for the rain rates. Generally, rain attenuation is only an aspect of the overall communication link analysis and design. Besides, ITU model is just one out of many other rain attenuation models which are not considered in this work. Therefore, further work is required to develop appropriate software for the other aspects of rain attenuation models and communication link analysis and design. Furthermore, additional work is required to integrate this work into the overall communication link analysis and design software suite.

REFERENCES

Abdulrahman, A. Y., Rahman, T. A., Rahim, S. K. A., Islam, M. R., & Abdulrahman, M. K. A. (2012). Rain attenuation predictions on terrestrial radio links: differential equations approach. Transactions on Emerging Telecommunications Technologies, 23(3), 293-301.

Adhikari, A., Das, S., Bhattacharya, A., & Maitra, A. (2011). Improving rain attenuation estimation: Modelling of effective path length using Ku-band measurements at a tropical location. Progress In Electromagnetics Research B, 34, 173-186.

Ali, A. A., Alhaider, M. A., & Shatila, M. A. (1986). Rain map for radiowave propagation design in Saudi Arabia. International journal of infrared and millimeter waves, 7(11), 1777-1793.

Anderson-Sprecher, R. (1994). Model comparisons and . The American Statistician, 48, 113-117.

Barclay L.,(2003) “Propagation of Radiowaves”, second edition, MPG Books Ltd, UK, 2003.

Bosisio V., Carlo Riva, (1998) “A novel on method for the statistical prediction of rain attenuation in site diversity systems: theory and comparative testing against experimental data”, International Journal of Satellite Communications, Vol. 16, Issue 1,pages 47-52, doi:10.1002/(SICI)1099-1247(199801/02)16:1<47::AIDSAT592> 3.0.CO;2-C, 1998.

Callaghan S. A., (2004) “Fractal Analysis and Synthesis of Rain Fields for Radio Communication Systems”, PhD thesis, University of Portsmouth, UK, 2004.

Callaghan S. A., Boyes, B., Couchman, A., Waight, J., Walden, C. J., and Ventouras, S., (2008) “An investigation of site diversity and comparison with ITU-R recommendations”,Radio Science, vol. 43, RS4010, doi:10.1029/2007RS003793, 2008.

Capsoni C., Luini L., Paraboni A., Riva C., (2009) Martellucci A., “A New Prediction Model of Rain Attenuation That Separately Accounts for Stratiform and Convective Rain”, in: Antennas and Propagation, IEEE Transactions on, vol. 57, pp 196 – 204, doi:10.1109/TAP.2008.2009698, 2009.

Crane R. K., (1996) "Electromagnetic wave propagation through rain", John Wiley&Sons, Inc., 1996.
Deidda R.: (1999) "Multifractal analysis and simulation of rainfall fields in space", Phys. Chem. Earth Part B - Hydrology, vol. 24, No. 1-2, pp. 73-78, 1999.
Deidda, R., (2000) "Rainfall downscaling in a space-time multifractal framework", Water Resources Research, 36, 1779-1794, 2000.
Diaz H. F., Eischeid J. K., C. (2003) Duncan, and R. S. Bradley, "Variability of freezing levels, melting season indicators, and snow cover for selected high-elevation and continental regions in the last 50 years", Kluwer Academic Publishers , Climate Change 59: pp 33-52, 2003.
Fenton G. A., and Vanmarcke E., (1990) "Simulation of Random Fields via Local Average Subdivision", ASCE Journal of Engineering Mechanics, 116(8), 1733-1749, 1990.
Feral L., Lemorton J., Castanet L., and Sauvageot H., (2003)"HYCELL: a new model of rain fields and rain cells structure", Proceedings of the 2nd International Workshop ofAction 280 Joint with COST272, ESTEC, NL, May 2003. In: www.cost280.rl.ac.uk/documents/WS2%20Proceedings/documents/pm-5-065.pdf. Accessed: 2011.
Glantz SA, Slinker BK (2001) Primer of applied regression & analysis of variance. 2nd ed. McGraw-Hill.
Gremont B., and Filip M., (2004) "Spatio-Temporal rain attenuation model for application to fade mitigation techniques", in: IEEE Trans. Antennas and Propagation, pp 1245- 1256, 2004.
Harrison D. L., Driscoll S. J. and Kitchen M., (2000) "Improving precipitation estimates from weather radar using quality control and correction techniques", in: Met. Appl., vol. 6, pp 135–144, 2000.
Hiromasa, K., A. Masamoto, and F. Kimito, (2008) "Development of a new regression analysis method using independent component analysis," Journal of Chemical Information and Modelling, Vol. 48, No. 3, 534–541, March 6, 2008.
Hodges, D., Watson, R., Page, A., Watson, P., (2003) "Generation of attenuation time-series for EHF SATCOM simulation", in: Military Communications Conference, 2003. MILCOM 2003. IEEE, Vol.1, page 505 – 510, ISBN 0-7803-8140-8, doi:10.1109/MILCOM.2003.1290154, 2003.
Islam, R. M., Abdulrahman, Y. A., & Rahman, T. A. (2012). An improved ITU-R rain attenuation prediction model over terrestrial microwave links in tropical region. EURASIP Journal on Wireless Communications and Networking,2012(1), 1-9.
ITU Series, P. (2013). Characteristics of precipitation for propagation modelling. ″ in Recommendation ITU-- -R P.
ITU-R Recommendation P.838-3, Specific attenuation model for rain for use in prediction methods. International Telecommunication Union (March 2005)
ITU-R. (2001) "Rain height model for prediction methods", in: Recommendations ITU-R P. 839-3, 2001.
ITU-R., (2003) "Prediction method of fade dynamic on Earth-Space paths", in: Recommendations ITU-R P. 1623-1, 2003.
ITU-R., (2005) "Specific attenuation model for rain for use in prediction methods", in: Recommendations ITU-R P. 838-3, 2005.
ITU-R., (2007) "Characteristics of precipitation for propagation modeling", in: Recommendations ITU-R P. 837-5, 2007.
Jeannin N., Castanet L., Lemorton J., Feral L., Sauvageot H. and Lacoste F., (2009) "A space-time channel model for the simulation on continental satellite coverages:overview of the modelling and potentiality for adaptive resource

management optimization", in press, IEEE Transactions on Antennas and Propagation, 2009.

Joss J., and Waldvogel A., "Comments: Some observations on the Joss-Waldvogel Rainfall disdrometer.", in: Journal of Applied Meteorology, vol. 16, pp. 112 – 113,1977.

Kalnay E., Kanamitsu, M., Kistler, P. Collins, W. Deaven, D. Gandin, L. Iredell, M.Saha, S. White, G. Woollen, J. Zhu, Y. Cheillab, M, Ebsuzaki, W. Higgins, W. Janowiak, J. Mo, K. C. Ropelewski, C. Wang, J. Leetma, A. Reynolds, P. Jenne 1. And Joseph, D. , "The NCEP/NCAP 40-year reanalysis project", in: Bull. Amer. Meteor. Soc., 77, pp 437-470, 1996.

Kestwal, M. C., Joshi, S., & Garia, L. S. (2014). Prediction of Rain Attenuation and Impact of Rain in Wave Propagation at Microwave Frequency for Tropical Region (Uttarakhand, India). International Journal of Microwave Science and Technology, 2014.

Kvalseth, T. 0. (1985), "Cautionary Note About R2," The American Statistician, 45, 305-310.

Lempio G. E., Bumke K., and Macke A., "Measurement of solid precipitation with an optical disdrometer", published by Copernicus GmbH on behalf of the European Geosciences Union, doi:10.5194/adgeo-10-91-2007, 2007.

Lilley M., S. Lovejoy, N. Desaulniers-Soucy and D. Schertzer, "Multifractal large number of drops limit in rain", in: J. of Hydrology, vol. 328, Issue 1-2, pp 20-37, doi:10.1016/j.jhydrol.2005.11.063, 2006.

Liolis, K. P., A. D. Panagopoulos, and P.G. Cottis, "Multi-Satellite MIMO Communications at Ku Band and above: Investigation on Spatial Mutiplexing for Capacity Improvement and Selection Diversity for Interference Mitigation" in: EURASIP Journal on Wireless Communications and Networking, May 2007.

Luini L., and Capsoni C., "MultiEXCELL: a new rain field model for propagation applications", accepted for publication in IEEE Transactions on Antennas and Propagation, vol. 59, No. 11, doi: 10.1109/TAP.2011.2164175, 2011.

Ojo, J. S., Ajewole, M. O., & Sarkar, S. K. (2008). Rain rate and rain attenuation prediction for satellite communication in Ku and Ka bands over Nigeria. Progress In Electromagnetics Research B, 5, 207-223.

Panagopoulos, A. D., Papanikolaou, V. S., Papoutsis, J. E., Chatzarakis, G., Kanellopoulos, J. D., & Cottis, P. G. (2003). A new coverage prediction method for local multipoint distribution systems.

Paulson K. S., and Basarudin H., "Development of a heterogeneous microwave network, fade simulation tool applicable to networks that span europe," in: Radio Science, doi:10.1029/2010RS004608, 2011

Paulson K. S., and Xiaobei Zhang, "Estimating the scaling of rainrate moments from radar and rain gauge", in: Geophys. Res. – Atmos, vol. 112, doi:10.1029/2007JD008547, 2007.

Paulson K. S., and Xiaobei Zhang, "Simulation of rain fade on arbitrary microwave link networks by the downscaling and interpolation of rain radar data", in: Radio Science, vol. 44, RS2013, doi:10.1029/2008RS003935, 2009.

Paulson K. S., Usman I. S., and Watson R. J., "A general route diversity model for convergent terrestrial microwave links", in: Radio Science, vol. 41, RS3004, doi:10.1029/2005RS003411, January 2006.

Shanmugan, K. S. and A. M. Breiphol, (1988) Random Signals: Detection, Estimation and Data Analysis, John Wiley & sons, Inc.

Siddique, U., Ahmad, L., & Raja, G. (2011). Microwave attenuation and prediction of rain outage for wireless networks in Pakistan's tropical region.International Journal of Microwave Science and Technology, 2011.

ISSN 2056-5860

Smyth, G. K. (2002). Nonlinear regression. Encyclopedia of environmetrics.

Sulochana, Y., Chandrika, P., & Rao, S. V. B. (2014). Rainrate and rain attenuation statistics for different homogeneous regions of India. Indian Journal of Radio & Space Physics, 43, 303-314.

Tjelta T., and Bacon D., "Predicting Combined Rain and Wet Snow Attenuation on Terrestrial Links", in: IEEE Transactions on Antennas and Propagation, vol. 58, No. 5, 2010, pp. 1677-1682, 2010.

Tjelta T., Bråten L. E., Bacon D., "Predicting the attenuation distribution on line-of sight radio links due to melting snow", in: Proc. ClimDiff, Cleveland, U.S.A., 26-27, Sept. 2005

Trevor Manning, "Microwave Radio Transmission Design Guide", in: Artech House Microwave Library, Chapter 3, Second Edition, 2009.

Uslu, S., & Tekin, L. (2003). Path loss due to rain fading and precipitation in 26 GHz LMDS systems: consideration of implementation in Turkey. In Microwave and Telecommunication Technology, 2003. CriMiCo 2003. 13th International CriSmean Conference (pp. 68-72). IEEE.