

EVALUATION OF THE FREQUENCY SCALING PREDICTION TECHNIQUES USING EXPERIMENTAL DATA

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Long-term statistics of measured slant-path attenuation above K_u-band are severely scarce in the tropical climate; due to the huge capital costs involved in the experimental setup and receiver margin required, which is very difficult to obtain by using a spectrum analyzer. The received signal becomes masked at heavy rain rates owing to the high noise level therefore the signal level could not be monitored. Therefore the frequency scaling technique is a useful and powerful tool for estimating the attenuation at a desired frequency when the measurement data are available at a particular, usually lower, frequency. The results of measured rain attenuation from a tropical climate in Malaysia were used to investigate the performance of a few frequency scaling techniques. The experimental results were obtained from the four experimental microwave links (15, 22, 26, and 38 GHz at a separation distance of 300 m) installed at UTM campus, Johor Bahru, Malaysia. The results of the statistical analysis show that the ITU-R model is the most suitable for the lower frequency (26 GHz), while the DruFuca model is most suitable one for the higher frequency (38 GHz).

KEY WORDS: *frequency scaling technique, rain attenuation statistics, huge receiver margin, tropical climates*

1. INTRODUCTION

Wireless communication usage is following a sharp upturn because it provides relatively large data rates and bandwidth which is allowable for more users [1]. It is also not costly and time consuming as optical fiber and coaxial cable communication systems [2]. Due to spectral congestion, as a result of the growing demand of lower microwave frequency band, the need to study the feasibility of the use of higher frequency band is very important.

The most fundamental constraint in planning and designing microwave communication system operating at frequencies above 10 GHz is attenuation due to rain [3]. The rain scatters and absorbs radio waves, leading to signal attenuation and the reduction of system availability and reliability. Due to the scarcity of reliable long term slant-path attenuation statistics in tropical climates, frequency scaling provides an alternative for predicting the magnitude of a propagation effects (attenuation, scintillation, and depolarization) at a given frequency from the knowledge of its magnitude at another, generally lower, frequency [4, 5].

Several frequency scaling models have been developed theoretically as well as from empirical data obtained from various propagation experiments [4]. G. Drufuca [6], I.E. Owolabi and G.O. Ajayi [7], F. Dintelmann [8] and Law Model based on OLYMPUS data [9] had proposed simple power law models, in which the rain attenuation for a desired frequency can be estimated by multiplying the measured rain attenuation at a given frequency with the frequency scaling factor. D. Hodge [10] proposed the model which uses the rain rate statistics and the k and a parameters of the ITU-R specific rain attenuation prediction model for both frequencies. H.N. Kheirallah [11] proposed a model derived from ITU-R rain attenuation model, which is simpler than the Hodge model. The International Radio Consultative Committee (CCIR) [12] proposed a model in which rain attenuation statistics has a non-linear relationship with frequency. B. Segal [13] proposed linear models based on rain attenuation statistics for terrestrial microwave links in Canada. A more complicated model that include base attenuation as well as both frequencies as the power was proposed by ITU-RP.610-12 [14].

2. OVERVIEW OF EXISTING FREQUENCY SCALING MODELS

Frequency scaling is used to predict the attenuation at a desired frequency usually higher, from the knowledge of measured attenuation at another frequency usually lower. Frequency scaling for rain attenuation prediction models can be found in literature based on theoretical and experimental studies of slant path attenuation made in the past. Some of the models are:

2.1 Simple Power Law Model

The simple frequency-scaling model [4] is a power-law scaling model and its simplicity makes it very useful for making estimates. The statistical attenuation ratio (ARS) is given as

$$ARS_n = \frac{A(f_2)}{A(f_1)} = \left(\frac{f_2}{f_1} \right)^n. \quad (1)$$

Several researchers have proposed different power values of n across 12 GHz to 30 GHz frequency range in various models. Some ones are shown in Table 1 [1].

TABLE 1: Values of power n and frequency pairs [1]

Frequency pairs (GHz)	Exponent value n	Literature
19/11	1.72	G. Druifuca (1974)
20/12 & 30/12	2.0	I.E. Owolabi and G.O. Ajayi (1982)
30/20	1.8	F. Dintelmann (1992)
20/12; 30/20 & 30/12	1.9	Power-law model based on OLYMPUS data (1995)
25/22	2.36	Md. Rafiqul Islam, Malaysia (2002)
37/22	1.16	
37/25	0.67	

2.2 The Hodge Model

D. Hodge [10] suggested that the rainfall along the propagation path on a given link is a Gaussian function and derived a statistical attenuation ratio given by:

$$\frac{A_2}{A_1} = \frac{k_2}{k_1} \left(\frac{A_1}{k_1} \sqrt{\frac{\alpha_1}{\pi}} \right)^{\left(\frac{\alpha_2}{\alpha_1} - 1 \right)} \sqrt{\alpha_1 / \alpha_2}. \quad (2)$$

2.3 The Kheirallah Model

The Kheirallah frequency scaling model [11] was derived from the ITU-R rain attenuation model by assuming that the path length (L) and the reduction factor (r) parameters are the same at both frequencies so that

$$\frac{A_2}{A_1} = \frac{\gamma_{R2} L_2 r_2}{\gamma_{R1} L_1 r_1} = \frac{\gamma_{R2}}{\gamma_{R1}}, \quad (3a)$$

where γ is the specific attenuation (dB/km), R is the rain rate (mm/hr), L (km) is the effective path length through the rain, and a and k are tabulated parameters dependent on frequency. Then the specific rain attenuation is equal to

$$\gamma = a R_p^\alpha. \quad (3b)$$

And by making some approximation, H.M. Kheirallah concluded that

$$A_2 \approx k_2 \left(\frac{A_1}{k_1} \right)^{\frac{\alpha_2}{\alpha_1}}. \quad (3c)$$

2.4 The Battesti Model

B. Segal [13] suggested that, for terrestrial links, the attenuation is proportional to a linear function of the frequency as follows:

$$\frac{A(f_2)}{A(f_1)} = \begin{cases} \frac{f_2 - 6}{f_1 - 6} & f_1, f_2 \leq 20 \text{ GHz} \\ \frac{f_2 - 10}{f_1 - 10} & f_1, f_2 \geq 20 \text{ GHz} \\ 1.4 \frac{f_2 - 10}{f_1 - 6} & f_1 < 20 \text{ GHz}, f_2 > 20 \text{ GHz}. \end{cases} \quad (4)$$

2.5 The CCIR Model

The International Consultative Committee (CCIR) model [12] is an older version of the ITU-R frequency scaling model derived from G. Druvuca [6] and B. Segal [13]. The method proposed a model for 7 to 50 GHz frequency range in which RAS has non-linear relationship with frequency as follows [14]:

$$\text{ARS}_{\text{CCIR}} = \frac{A(f_2)}{A(f_1)} = \frac{\Phi(f_2)}{\Phi(f_1)}, \quad (5a)$$

where

$$\Phi(f) = \frac{f^{1.72}}{1 + 3 * 10^{-7} f^{3.44}} \quad (5b)$$

2.6 The ITU-R Model

The ITU-R frequency-scaling model [14] considers the dependency of the frequency scaling ratio with considered attenuation level for frequency range 7–55 GHz. The statistical attenuation ratio (ARS) as:

$$\frac{A(f_2)}{A(f_1)} = \left(\frac{\varnothing_2}{\varnothing_1} \right)^{1-H(\varnothing_1, \varnothing_2, A_1)}, \quad (6a)$$

where

$$H(\varnothing_1, \varnothing_2, A_1) = 1.12 * 10^{-3} \left(\frac{\varnothing_2}{\varnothing_1} \right)^{0.5} (\varnothing_1 A_1)^{0.55}, \quad (6b)$$

$$\mathcal{O}(f) = \frac{f^2}{1 + 10^{-4} f^2}, \quad (6c)$$

where A_1 and A_2 are the equiprobable values of the excess rain attenuation (in dB), at lower frequency f_1 and at upper frequency f_2 (in GHz).

3. ANALYSIS OF EXPERIMENTAL DATA

Secondary data [15] collected from the four experimental microwave links at 15, 26 and 38 GHz at a separation distance of 300 m at UTM campus, Johor Bahru, Malaysia were used for rain rate and attenuation $A_{0.01}$ of each links at 0.01 percentage of exceedance. The rainfall rate was measured with 1-minute integration time for four years (from January, 2003 to December, 2006) at UTM Campus and its average complementary cumulative distribution (CCDF) is shown and plotted, for illustration, in Table 1 and Fig. 1, respectively. Furthermore, the CCDF of measured rain attenuation at 15 GHz is presented in Fig. 2 [15].

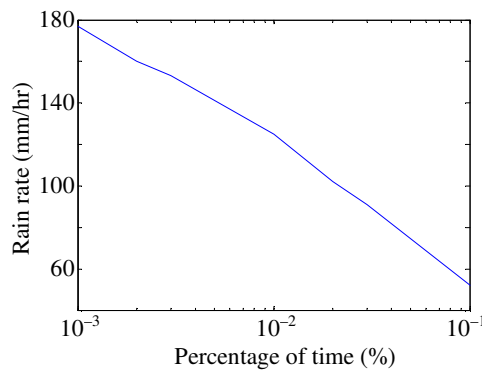


FIG. 1: Average rainfall rate CCDF at UTM Campus

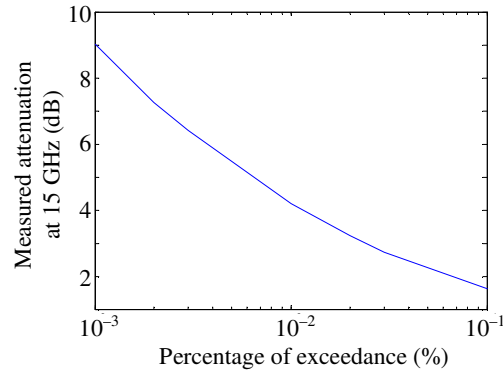


FIG. 2: Measured rain attenuation CCDF at 15 GHz

The frequency scaling models reviewed in Section 2 (Eqs. 1-6c) were used to scale the measured attenuation at 15 GHz in order to predict attenuation at 26 GHz and 38 GHz. The reason is that the measured values are available for these two frequencies at 0.01% of the time; for instance, the values are 10.98 dB (26 GHz) and 15.10 dB (38 GHz). Note also, for the purpose of validation, the Recommendation ITU-R P.530-15 [16] was used to extrapolate the measured $A_{0.01}$ (for the 26 GHz and 38 GHz links). Brief descriptions of the extrapolation technique are shown below.

$$\frac{A_p}{A_{0.01}} = C_1 p^{-(C_2 + C_3 \log_{10} p)}, \quad (7a)$$

$$C_1 = (0.07^{C_0}) [0.12^{(1-C_0)}], \quad (7b)$$

$$C_2 = 0.855C_0 + 0.546(1 - C_0), \quad (7c)$$

$$C_3 = 0.139C_0 + 0.546(1 - C_0), \quad (7d)$$

where

$$C_0 = \begin{cases} 0.12 + 0.4 \left[\log_{10} (f/10)^{0.8} \right] & f \geq 10 \text{ GHz} \\ 0.12 & f < 10 \text{ GHz} \end{cases}. \quad (7e)$$

4. RESULTS AND DISCUSSIONS

The results of the analysis performed in Section 3 are presented in this Section. The plots of frequency-scaled attenuation at 26 and 38 GHz against the measured attenuation at 15 GHz are demonstrated in Figs. 3 and 4. Furthermore, the comparison of measured and predicted attenuation CCDFs at 26 and 38 GHz are captioned in Figs. 5 and 6.

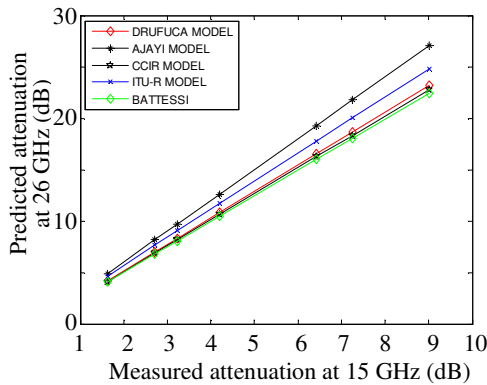


FIG. 3: Plots of frequency-scaled attenuation at 26 GHz predicted from the measured attenuation at 15 GHz

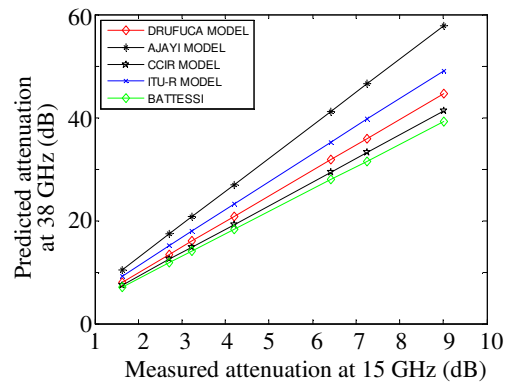


FIG. 4: Plots of frequency-scaled attenuation at 38 GHz predicted from the measured attenuation at 15 GHz

The Battessi, CCIR, DruFuca models accurately predict the measured attenuation at 26 GHz, especially at higher percentage of time in the range of 0.05% to 0.1% as shown in Fig. 5. However, at high rainfall rate (i.e., lower time percentages) none of the models accurately predicted the measured attenuation as clearly shown in Fig. 5.

More so, for the 38 GHz link as can be observed from Fig. 6 that all the models over-estimate measured values. The Battessi model prediction is close to the measured attenuation only at 0.1% of time. Generally, it was observed that the Battessi, CCIR and DruFuca models accurately predict the measured attenuation at low rainfall rates when $p > 0.1\%$, as deduced from Fig. 6 above. The inaccuracies of the models increase with increase in grain fall rate and increase in operating frequency. Therefore, these observations suggest that more empirical data are needed to further validate the results of the analysis carried out in this study.

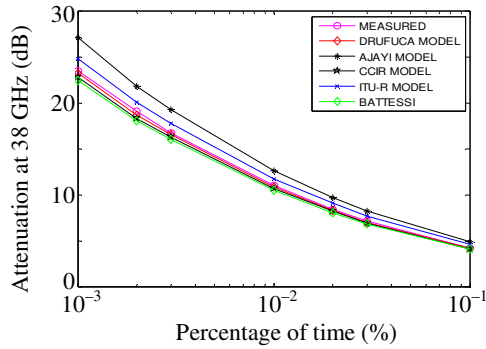


FIG. 5: Comparison of measured and predicted attenuation CCDFs at 26 GHz

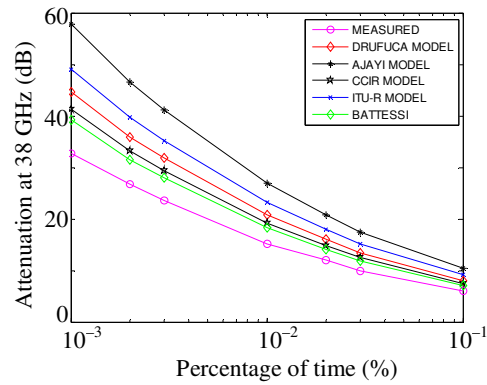


FIG. 6: Comparison of measured and predicted attenuation CCDFs at 38 GHz

4.1 Validation of the Models

The ITU-R test variable is used as the error; this variable is defined according to Recommendations ITU-R P.311-15 [17] as:

$$V_i = \begin{cases} \ln S_i \left(\frac{A_{m,i}}{10} \right)^{0.2} & \text{for } A_{m,i} < 10\text{dB} \\ \ln S_i & \text{for } A_{m,i} > 10\text{dB} \end{cases}, \quad (8a)$$

where A_p is the predicted attenuation (dB), A_m is the measured attenuation (dB) and

$$S_i = \frac{A_{p,i}}{A_{m,i}}. \quad (8b)$$

The mean error, μ_v , is defined as:

$$\mu_v = \frac{1}{N} \sum_{i=1}^N V_i. \quad (8c)$$

The standard deviation, σ_v , is defined:

$$\sigma_v = \sqrt{\frac{1}{N} \sum_{i=1}^N (V_i^2 - (\mu_v)^2)}. \quad (8d)$$

Root mean square (R.M.S) value, ρ_v are defined as:

$$\rho_v = \sqrt{(\mu_v^2 + \sigma_v^2)}. \quad (8e)$$

According to the evaluation procedures adopted by Recommendation ITU-R P. 311-15 [17], the model with lowest standard deviation, σ_v and a lowest R.M.S value, ρ_v for the test variable is the best predicting model. Table 2 shows the mean value, standard deviation and R.M.S. value of the frequency scaling models, for percentages between 0.001% and 0.1%. It can be seen in Table 3 that for all models, the error varies inconsistently and mean error increase, as standard deviation decrease with increase in operating frequency, from 26 GHz to 38 GHz. This shows that error is minimal at lower operating frequency compared to higher frequency in the models.

TABLE 2: Average measured rainfall rate at UTM, Malaysia

% p	0.1	0.05	0.03	0.02	0.01	0.005	0.003	0.002	0.001
Rainfall rate (mm/hr)	52	73	91	102	125	146	153	160	177

The % R.M.S. values increase with increase in operating frequency for of all the models with the exception of the DruFuca model. At 26 GHz, as illustrated in Table 3, the ITU-R model has the least R.M.S. value (5.61%); while the Ajayi model has the highest R.M.S. value (11.75%). On the other hand, for the 38 GHz, DruFuca model yielded the least R.M.S. value (6.00%), while the ITU-R model showed the highest R.M.S. value (39.8%). These results show that the Ajayi and ITU-R models seem to be the least suitable for frequency scaling predictions in the investigated tropical climate. Note that the path reduction factor was not considered in the experimental link (0.3 km) used in this study. Therefore, the deviations are expected to be moderate for the practical links, because of the inclusion of the path correction factor in the computations.

TABLE 3: The mean, standard deviation and R.M.S using the ITU-R P. 313-15

Models	Link (GHz)	Percentage of time (%)							Mean error μ_v	Std dev. σ_v	R.M.S ρ_v (%)
		0.1	0.03	0.02	0.01	0.003	0.002	0.001			
Drufuca	26	-0.1720	-0.0841	-0.0388	-0.0149	-0.0129	-0.0205	-0.0089	-0.0503	0.0552	7.47
	38	-0.0038	0.0685	0.0825	0.0661	0.0603	0.0500	0.0565	0.0543	0.0256	6.00
Ajayi	26	-0.0180	0.0699	0.1152	0.1391	0.1411	0.1335	0.1451	0.1037	0.0552	11.75
	38	0.4405	0.5676	0.5483	0.5795	0.5606	0.5532	0.5696	0.5456	0.0440	54.74
Battessi	26	-0.2063	-0.1184	-0.0730	-0.0492	-0.0471	-0.0548	-0.0432	-0.0846	0.0552	10.10
	38	0.0529	0.1800	0.1607	0.1918	0.1730	0.1655	0.1820	0.1580	0.0440	16.40
CCIR	26	-0.1906	-0.1027	-0.0573	-0.0335	-0.0314	-0.0391	-0.0275	-0.0689	0.0552	8.83
	38	0.1051	0.2322	0.2130	0.2441	0.2253	0.2178	0.2342	0.2102	0.0440	21.48
ITU-R	26	-0.0789	0.0032	0.0462	0.0661	0.0603	0.0500	0.0565	0.0291	0.0480	5.61
	38	0.3071	0.4274	0.4054	0.4319	0.4039	0.3934	0.4038	0.3961	0.0385	39.80

5. CONCLUSIONS

All the reviewed models overestimated the measured attenuation at 38 GHz especially at low time percentages when rainfall rates are extremely high. The statistical errors are at least within a tolerable limit at 26 GHz, but they become more pronounced at 38 GHz. Moreover, it was observed that for the 26 and 38 GHz links, the ITU-R and Drufuca models yield the lowest R.M.S values (5.61 and 6.0%), respectively. Hence, the two models seem to be the most suitable for the respective frequencies. The results presented in this study have demonstrated the usefulness of the frequency scaling techniques for predicting rain attenuation and probably fade margin in the design and planning of reliable terrestrial microwave links in the tropical climates. This will serve as an alternative approach for providing rough estimates for attenuation values at very high frequencies (above K_u -band), in a situation where the huge capital costs and the receiver margin required in the experimental setup can not be provided. The discrepancies observed in the results suggest that further research efforts need to be made in order to improve the performances of the ITU-R model.

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