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SHORT RESEARCH LETTER

Rain attenuation predictions on terrestrial radio links: differential equations approach

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ABSTRACT

The results of rain attenuation on terrestrial microwave links in a tropical climate has been reported in this paper. The results are presented in the form of rate of change of attenuation with respect to rain rate, denoted by $S(R_{\%p})$. This is in turn used for predicting the expected rain attenuation at any $\%p$ of the time rain rate is exceeded in any tropical location. The predictions of the proposed model have been validated using the data collected in six locations in Malaysia and experimental results reported in other tropical locations that have a similar rainfall regime. The Malaysian data consist of 1-year measured rain attenuation over six DIGI MINI-LINKs operating at 15 GHz, and rainfall rates measured with both 1-minute and 1-hour integration times at the respective locations. The validity of the proposed model is further validated by comparing its estimates with the method of ITU-R Radiocommunication Sector of ITU and two classical rain attenuation prediction models particularly developed for tropical regions.The test results have shown that the proposed method seems to be more accurate than the proposed method seems to be more accurate than ITU-R and the other two prediction models in Malaysia. The method could be used as an alternative approach for predicting rain attenuation over any terrestrial microwave links in Malaysia and similar tropical climates. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS
exponential law; total differential; rain attenuation; regression parameters; tropical climates

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1. INTRODUCTION

Heavy traffic in the lower bands has forced telecommunications service providers to migrate to higher frequency bands, which have enough bandwidths to support numerous users. Therefore, systems operating above 10 GHz offer unique features for reliable and competitive services in point to point and point to multipoint applications [1]. Unfortunately, signal propagation is seriously impaired by rain-induced attenuation at frequencies above 10 GHz, more especially in tropical regions that experience heavier rainfall intensities [2]. Therefore, attenuation because of rainfall plays a significant role in the design of terrestrial and Earth-satellite radio links especially at frequencies above 10 GHz. The engineers and system designers working on higher bands are faced with a major difficulty of balancing the trade-off between bandwidth availabilities and rain attenuation issues.

The ITU-R has provided Telecommunication Union Radiocommunication Sector (ITU-R) has provided a methodological approach for predicting rain attenuation on any terrestrial radio link; however, the model does not perform well in tropical climates because the ITU model is based on data collected from temperate regions of the world [3]. Emphasis on the inappropriateness of the ITU-R method in tropical regions has been reported in a number of published research works [4]. Generally, the required inputs in most of the attenuation prediction models on terrestrial radio links are the rainfall rate exceeded at $\%p$ of time, the effective propagation path length, and the link's operating frequency [5].

Studies have shown that the use of 1 min rain rate gives the best agreement with available radio link [6]. Therefore, the use of rainfall rate measured with 1 min integration has become a tradition for most of the rain attenuation predictions. This paper presents a new method of predicting rain attenuation on terrestrial radio links in Malaysian tropical climate. The approach was derived by differentiating measured rain attenuation with respect to rainfall rate. The results are presented in the form of a slope $S(R_{\%p}) = \mathrm{d}A_{\%p}/\mathrm{d}R_{\%p}$, which in turn is used for predicting the expected rain attenuation at any $\%p$ of the time on a given link.

2. BACKGROUND

2.1. Definitions

Rain attenuation is defined as the product of specific attenuation (dB/km) and the effective propagation path length (km). The product of path reduction factor and the physical path length of a microwave link is referred to as the effective path length, which is defined as the ratio of rain attenuation to specific attenuation corresponding to the point rain rate (typically measured at one end of the link). The concept of effective path length is thus a way of 'averaging out' the spatial inhomegeneity of rain rate and thus specific attenuation. Because the degree of spatial inhomogeneity in rain rate generally varies with rain intensity, the variation of path length reduction factor can be expressed as a function of rain rate or the corresponding time exceedance.

Attenuation can be obtained from direct measurements or predicted from the knowledge of long-term rainfall rate. $A_{\%p}$ exceeded at $\%p$ of time is calculated as follows:

$$A_{\%p}[\gamma(R_{\%p}), d_{\mathrm{eff}}(R_{\%p,d})] = \gamma_{\%p} d_{\mathrm{eff}} \tag{1a}$$

$$\gamma_{\%p} = kR^{\alpha}_{\%p} \tag{1b}$$

$$d_{\mathrm{eff}} = dr_{\%p} \tag{1c}$$

where$R_{\%p}$ (mm/h) is the rain rate exceeded at $\%p$ of the time, $r_{\%p}$ is the path reduction factor at the same time percentage, d(km) is the radio path length. Parameters k and α depend on frequency, rain temperature, and polarization; and their values can be obtained from ITU-R P.838-3 [7].

2.2. Overview of rain attenuation prediction models

A brief overview of the ITU-R prediction method and two other classical rain attenuation prediction models, particularly developed for tropical climates, is presented in this subsection.

2.2.1. ITU-R prediction method

According to Recommendation ITU-R P.530-12 [8], the rain attenuation (in dB) exceeded at 0.01% of the time on any terrestrial link is obtained by simply substituting in Equations (1a)-(1c). This method assumes that a non-uniform rainfall rate can be modeled by an equivalent rain cell of uniform rainfall rate and length along the propagation path. The path reduction factor at 0.01% of the time is given by:

$$r_{0.01} = \frac{1}{(1 + (d/d0))} \tag{2a}$$

where

$$d_0 = 35e^{-0.015R_{0.01}} \tag{2b}$$

The attenuation A%p (in dB) exceeded for other time percentages, p of an average year may be calculated from the value of $A_{0.01}$ by using the following:

$$A_{\%p} = 0.12A_{0.01}\,p^{-(0.546+0.043\log_{10}(p))} \tag{3}$$

The major shortcoming of the extrapolation approach of Equation (3) is that it does not perform well in tropical regions, especially at higher rain rates [3]. The ITU-R method generally underestimates the measured rain attenuation at lower rain rates, while it overestimates the measured values at higher rain rates. The analyses of experimental results presented in this letter have clearly shown the inappropriateness of the ITU-R method in tropical Malaysia.

2.2.2. Moupfouma's model.

According to Moupfouma [2], a terrestrial microwave link is characterized by its actual relay path length "L_{T}" that corresponds to the space between two ground stations. To determine its equivalent propagation path length "L_{eq}", an adjustment factor "δ" that makes the rain uniform on the whole propagation path has to be defined such that

$$L_{\mathrm{eq}}(R_{0.01}, L_{\mathrm{T}}) = L_{\mathrm{T}} \exp\left(\frac{-R_{0.01}}{1 + \xi(L_{\mathrm{T}})R_{0.01}}\right) \tag{4a}$$

where

$$\xi(L_{\mathrm{T}}) = -100 \text{ for any } L_{\mathrm{T}} \leq 7 \text{ km} \tag{4b}$$

and

$$\xi(L_{\mathrm{T}}) = \left[\frac{44.2}{L_{\mathrm{T}}}\right]^{0.78} \text{ for any } L_{\mathrm{T}} > 7 \text{ km} \tag{4c}$$

Therefore, the definition of rain attenuation is modified to

$$A_{0.01} = kR^{\alpha}_{0.01}.L_{\mathrm{eq}}(R_{0.01}, L_{\mathrm{T}}) \tag{5}$$

where $R_{0.01}$ and $A_{0.01}$ are the rainfall rate and path attenuation at 0.01% of the time, respectively.

The most notable drawback of this model is that it substantially overestimates the measured path attenuation, more especially at higher rain rates.

2.2.3. Da Silva Mello model.

Da Silva Mello *et al.* [3] have reported that the extrapolation procedure adopted by the current ITU-R [8] is the major limitation of the prediction method. This is because the same rain attenuation will be predicted for two regions with different rainfall rate regimes but similar values of $A_{0.01}$. To correct the inaccuracies, the method of using the full rainfall rate distribution is introduced as input for predicting the rain attenuation cumulative distribution (CD), and is given by

$$A_{\%p} = \gamma_{\%p} d_{\mathrm{eff}} = k\left(R_{\mathrm{eff}}(R_{\%p}, d)\right)^{\alpha} \frac{d}{1+\frac{d}{d_0(R_{\%p})}} \tag{6}$$

where R_{eff} is the effective rain rate, a function of d and $R_{\%p}$. The expression for R_{eff} and parameter d_0 are given by

$$R_{\mathrm{eff}} = 1.763 R_{\%p}^{0.753+0.197/d} \tag{7}$$

and

$$d_0 = 119 R_{\%p}^{-0.244} \tag{8}$$

The numerical coefficients in Equations (7) and (8) were obtained by multiple non-linear regressions, using the measured data available in the ITU-R data banks. It has been found that the power-law used for d_0 in Equation (8) provides better results than the exponential law used by the current ITU-R method in Equation (2b).

3. ANALYSES OF EXPERIMENTAL DATA

One-year-rain attenuation data were collected from six DIGI MINI-LINKs, operating at 15 GHz in Malaysia. In addition, 1-minute rainfall rate data were collected for 4 years at both campuses of Universiti Teknologi Malaysia (UTM-Skudai and UTM Kuala-Lumpur campuses). The Skudai campus is located at Johor in the southern part of the Malaysian peninsula close to Singapore with annual average accumulation as high as 4184.3 mm.

The average values of the 4-year rainfall rate measurements were correlated with the 1-year measured attenuation data for these two locations because of seasonal variability of the rainfall pattern. Because rain rate CD varies from year to year, most especially at higher rain rates, we assumed that 4-year CD will be fairly stable. For instance, the average annual value of the 4-year rainfall rate data will have a lower variance and thus smaller variation.

For the remaining four sites, the average of 12-year rain-rate data collected from the Malaysian Meteorological Station were used in the study. These rain data have 1-hour integration time, so we used Chebiland Rahman's model [9] for converting them to the equivalent 1-minute integration time. Chebil and Rahman's model was based on rainfall data of 1-hour integration time collected from over 70 locations in Malaysia, Indonesia, and Singapore. The conversion method was found to be quite accurate and reliable, within reasonable limits of statistical accuracy, for the Malaysian tropical region and other tropical regions [10]. However, the conversion method is limited to $0.001\% \leq p \leq 1.0\%$ of the time when rainfall rate is exceeded. Because of this constraint, the method could not offer accurate results for high rainfall rates when $p \leq 0.001\%$. Nevertheless, our analyses were limited to the time percentages within the validity range of the rain rate conversion method.

Point-to-point microwave links were used for rain attenuation measurements, and both the transmitting and receiving antennas are horizontally polarized and covered with radome to prevent wetting antenna conditions. The radio path length for each of the link is given in the caption of Figure 6. The reader is referred to Ref. [11] for comprehensive information on the rain attenuation and rain rate data collection. The MINI-LINKs have availability of 99.95% and their specifications are given in Table I.

Figures 1 and 2 show the rainfall rate and rain attenuation exceedance at $\%p$ of the time, while Figure 3 shows the equal probability plots of concurrently measured rainfall rate and rain attenuation exceedance at $\%p$of the time for the six links.

Table I. Specifications of the 15 GHz link.

Type of antenna	Front-fed parabolic	
Frequency band (GHz)	14.80–15.30	
Polarization	Horizontal	
Maximum transmit power (dBm)	+18.0	
10^{-6}BER (2X2 Mb/s) Received threshold (dBm)	–84.0	
Antenna beam width	2.3^{c}	
Dynamic range (dB)	50.00	
Antenna for both transmit and receive side	Size (m) 0.6	Gain (dBi) 37.0

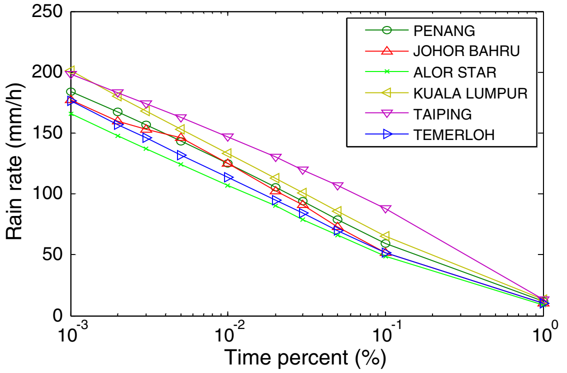


Figure 1. Rainfall rate exceedance at $\%p$ of the time for the six stations.

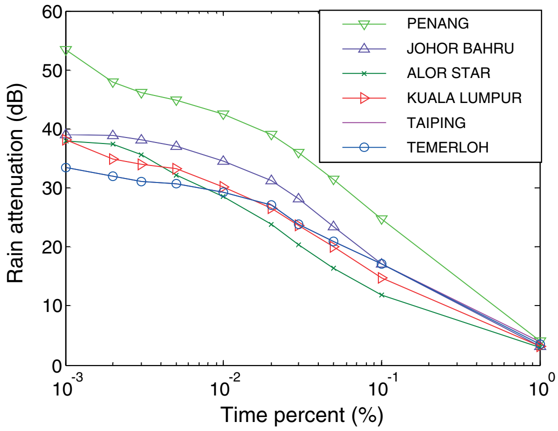


Figure 2. Rain attenuation exceedance at $\%p$ of the time for the six links.

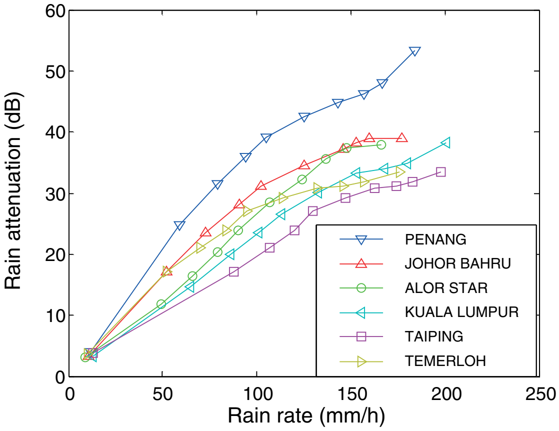


Figure 3. Equal probability plots of rain rate and rain attenuation exceedance at $\%p$ of the time for the six links.

4. MODELING OF RATE OF CHANGE OF ATTENUATION WITH RESPECT TO RAIN RATE

When the 10 GHz threshold is passed, rain attenuation may become the limiting factor for high system availability [12, 13]. In this formulation, it is assumed that the effective path length d_{eff} can be modeled as a power-law function of rainfall rate. This assumption is consistent with the previously published methods [3]. Using Equation (2) and the results of analyses of experimental data presented in Figure 3, the relationship between dimensionless parameter d_0 and rainfall rate is shown in Figure 4. Note that d_0 has dimension of length.

Parameter d_0, and hence rain cell diameter and path reduction factor, decreases with increasing rain rate $R_{\%}p$, as clearly shown in Figure 4. Note that d_0 has dimension of length.

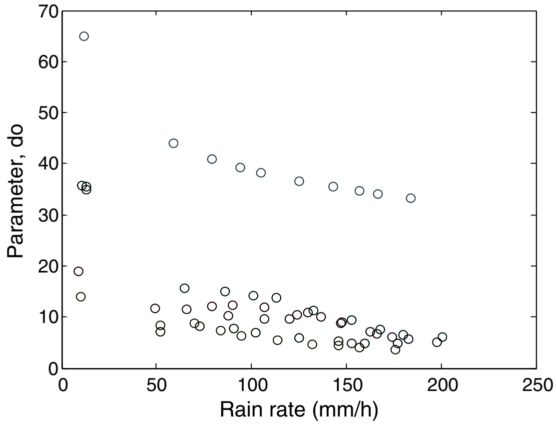


Figure 4. Modeling of parameter d_0 with respect to rainfall rate.

By using multiple non-linear regression techniques on the experimental data presented in Figure 4, parameter d_0 is related to rainfall rate as follows:

$$d_0 = 102.0448 R_{\%p}^{-0.18} \tag{9a}$$

Da Silva Mello *et al.* [2] have reported that the parameter d_0 is better approximated by a power-law rather than using the exponential law given in the current ITU-R method of Equation (2b). By inspecting Equation (8), based on the measured data available in the ITU-R data banks, and Equation (9a), based on experimental data presented in Figures 3 and 4, it seems d_0 can be reasonably modeled as

$$d_0 = aR_{\%p}^{b} \tag{9b}$$

Putting Equation (9b) into Equation (2a), the generalized expression for reduction factor becomes

$$r_{\%p} = \frac{aR_{\%p}^{b}}{aR_{\%p}^{b} + d} \tag{10a}$$

So that

$$d_{\mathrm{eff}} = d\left(\frac{aR_{\%p}^{b}}{aR_{\%p}^{b} + d}\right) \tag{10b}$$

By substituting Equations (1b) and (10b) into Equation (1a), the rain attenuation exceeded at $\%p$ is thus expressed as

$$A_{\%p} = \gamma_{\%p} d_{\mathrm{eff}} = kR_{\%p}^{\alpha} d\left(\frac{aR_{\%p}^{b}}{aR_{\%p}^{b} + d}\right) \tag{11}$$

If Equation (11) is differentiated with respect to rain rate, a slope $S(R_{\%p})$ is obtained, which is expressed as follows:

$$S(R_{\%p}) = \frac{\mathrm{d}A_{\%p}}{\mathrm{d}R_{\%p}} = \frac{\mathrm{d}}{\mathrm{d}R_{\%p}}\left[kR_{\%p}^{\alpha} d\left(\frac{aR_{\%p}^{b}}{aR_{\%p}^{b} + d}\right)\right] \tag{12}$$

The total differential of $A_{\%p}$ with respect to $R_{\%p}$ in Equation (12) is given by

$$S\left(R_{\%p}\right) = \frac{\mathrm{d}A_{\%p}}{\mathrm{d}R_{\%p}} = \frac{\mathrm{d}A_{\%p}}{\mathrm{d}\gamma_{\%p}} \cdot \frac{\mathrm{d}\gamma_{\%p}}{\mathrm{d}R_{\%p}} + \frac{\mathrm{d}A_{\%p}}{\mathrm{d}d_{\mathrm{eff}}} \cdot \frac{\mathrm{d}d_{\mathrm{eff}}}{\mathrm{d}R_{\%p}} \tag{13}$$

where

$$\frac{\mathrm{d}A_{\%p}}{\mathrm{d}\gamma_{\%p}} = d_{\mathrm{eff}}; \quad \frac{\mathrm{d}\gamma_{\%p}}{\mathrm{d}R_{\%p}} = k\alpha R_{\%p}^{\alpha-1}; \quad \frac{\mathrm{d}A_{\%p}}{\mathrm{d}d_{\mathrm{eff}}} = \gamma_{\%p};$$

and

$$\frac{\mathrm{d}d_{\mathrm{eff}}}{\mathrm{d}R_{\%p}} = d \cdot \left[baR_{\%p}^{b-1} \left[\frac{d}{(aR_{\%p}^{b} + d)^2} \right] \right] \tag{14}$$

Substituting Equation (14) into Equation (13) yields

$$S\left(R_{\%p}\right) = (d) \left(\frac{aR_{\%p}^{b}}{aR_{\%p}^{b} + d} \right) \cdot \alpha k R_{\%p}^{\alpha-1} + kR_{\%p}^{\alpha} \cdot d \left[baR_{\%p}^{b-1} \left[\frac{d}{(aR_{\%p}^{b} + d)^2} \right] \right] \tag{15}$$

Simplification of Equation (15), utilizing the expressions for $r_{\%p}$ and d_{eff},

$$S(R_{\%p}) = kR_{\%p}^{\alpha-1} d_{\mathrm{eff}} \left[\alpha + b(1 - r_{\%p}) \right] \tag{16}$$

Rearranging Equation (16), rain attenuation $A_{\%p}$ exceeded at $\%p$ of time can be extracted as follows:

$$A_{\%p} = \left[\frac{R_{\%p}}{\alpha + b(1 - r_{\%p})} \right] S(R_{\%p}) \tag{17}$$

For simplicity, Equations (16) and (17) may be reduced to the following:

$$\begin{aligned} S(R_{\%p}) &= \beta R_{\%p}^{\alpha-1} \\ A_{\%p} &= \mu[S(R_{\%p})] \end{aligned} \tag{18}$$

where

$$\beta = k[\alpha + b(1 - r_{\%p})]d_{\mathrm{eff}} \tag{19}$$

and

$$\mu = \left[\frac{R_{\%p}}{\alpha + b(1 - r_{\%p})} \right] \tag{20}$$

According to Equation (18), slope $S(R_{\%p})$ is related to the rainfall rate $R_{\%p}$ by a simple power-law expression. This relationship is shown in F5 for the six MINI-LINKs used in the proposed model validation. Note that b and $r_{\%p}$ are dimensionless, while $S(R_{\%p})$ is expressed in dB h/mm.

The attenuation dependence on frequency is completely described by the parameters k and α, as it should be expected from the physical point of view. The input parameters needed for determining $S(R_{\%p})$ and $A_{\%p}$ are clearly highlighted in Equations (16) and (17). The values of k and α can be obtained from ITU-R P.838-3 for any frequency of interest, while the rainfall rates can be obtained by measurement at any location under study.

The values of parameters a and b used in the predictions are numerically 'tune' for the Malaysian data being modeled. Therefore, the empirically derived values of $a = 102.0448$ and $b = -0.18$ have been used to estimate the path reduction factor for Malaysian links in the validation of the proposed method. However, for other tropical locations where the values of a and b are not available from experimental data, the numerical coefficients of Equation (8), $a = 119$ and $b = -0.244$[3], may be used. This choice is based on the fact that the latter coefficients were obtained from the analyses of measured data available in the ITU-R data banks.

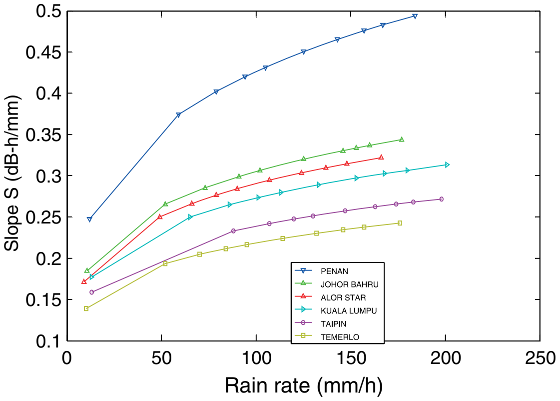


Figure 5. Modeling of slope with respect to rainfall rate.

5. NUMERICAL RESULTS AND DISCUSSIONS

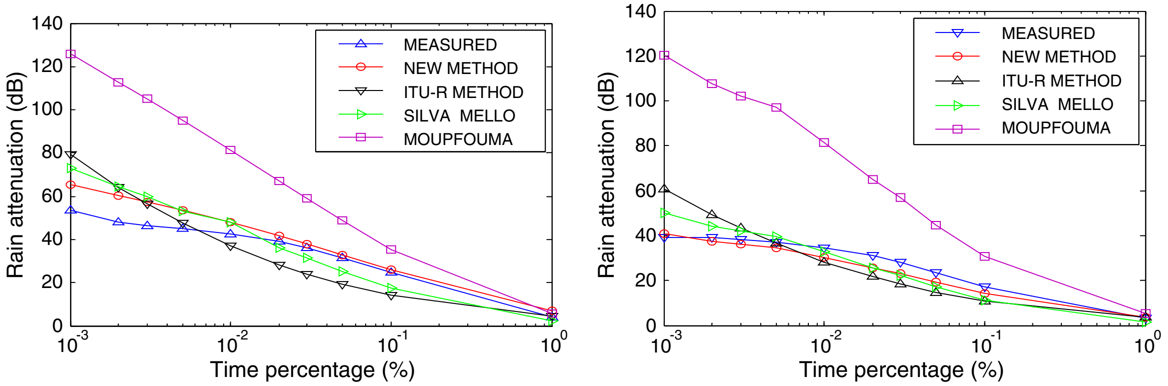
The predictions of the new method and those of the ITU-R, Moupfouma, and Da Silva Mello are compared with the experimental values, as shown in the captions of Figures 6(a)–(h). F6(a)–(f) show the comparison with Malaysian data, while Figures 6(g)–(h) compare the proposed model estimates with two other tropical regions (Brazil and Nigeria). The 1-year measured terrestrial rain attenuation of BARUERI-RIS link was used for Brazilian tropics [14]. The link's operating frequency is 15 GHz, path length is 21.7 km, and it is vertically polarized. Terrestrial data are not available for Nigeria, therefore the measured point rainfall rates of 1-minute integration time [15] were used for calculating the terrestrial attenuation, assuming horizontal polarization. The figures present the rain attenuation exceedance for the measured and predicted results.

As shown in the captions of Figures 6(a)–(e), the new method closely match the measured rain attenuation when $0.005 \le \%p \le 1.0$. The predictions of the proposed method closely match measurement data for Temerloh link at lower rain rates when $p \geq 0.1\%$ of the time, while underestimating the latter at higher rain rates when $p < 0.1\%$. For instance, the measured and predicted values at 0.01% of the time are 29.91 and 26.5357 dB, respectively; whereas at 0.001% the corresponding attenuation values are 40.78 and 33.5 dB.

The new method closely matches the measured attenuation when $0.005 \leq \%p \leq 0.03$ for the Barueri-RIS link. However, it underestimates the measurements both at lower rain rates when $p > 0.03\%$, and at extremely higher rain rates when $p < 0.005\%$. Nevertheless, the predictions of the proposed method are still fairly accurate for the Brazilian link within reasonable range of time percentages.

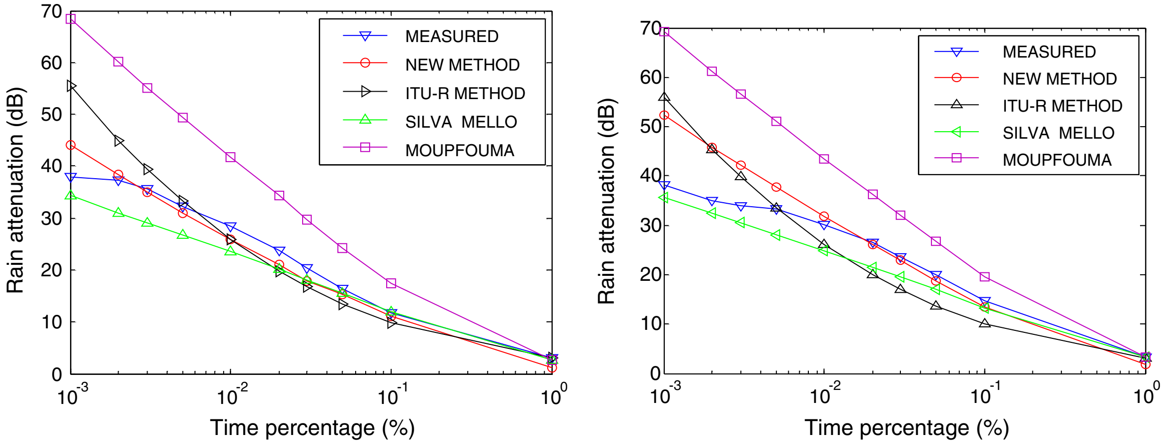
As can be seen from Figures 6(a)–(h), the ITU-R methods generally underestimate the measured attenuation at lower rain rates when $1.0 \leq \%p \leq 0.01$. More so, ITU-R predicted attenuation overestimates the measurements at extremely higher rain rates when $p < 0.003\%$. These results have justified the fact that the ITU-R methods are not suitable for predicting rain attenuation in tropical regions.

Moupfouma predictions largely overestimate the measured rain attenuation almost at all percentages of the time, worse still at higher rain rates. For example, the Moupfouma model overestimates the measured value by 42.3% and 55.9%, respectively at 0.01 and 0.001% of the time. One reason for the overestimation may be because



(a) Comparison of measured and predicted attenuation (Penang link: 14.8 GHz; 11.3 km; Lat.: $5.27^0 N$ and Long.: $100.29^0 E$).

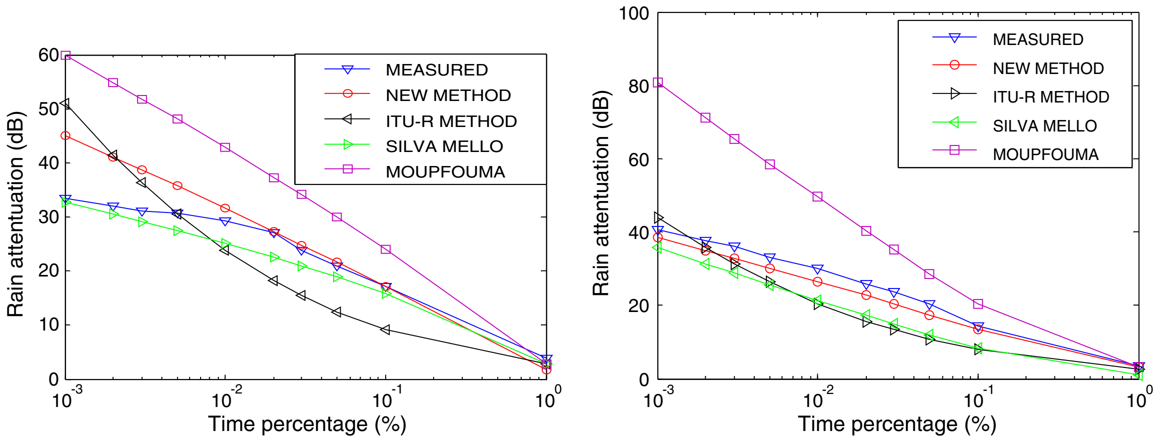
(b) Comparison of measured and predicted attenuation (Johor Bahru link: 14.8 GHz; 5.83 km; Lat.: $1.30^0 N$ and Long.: $103.43^0 E$).



(c) Comparison of measured and predicted attenuation (Alor Star link: 15.3 GHz; 4.85km; Lat.: $6.15^0 N$ and Long.: $100.25^0 E$).

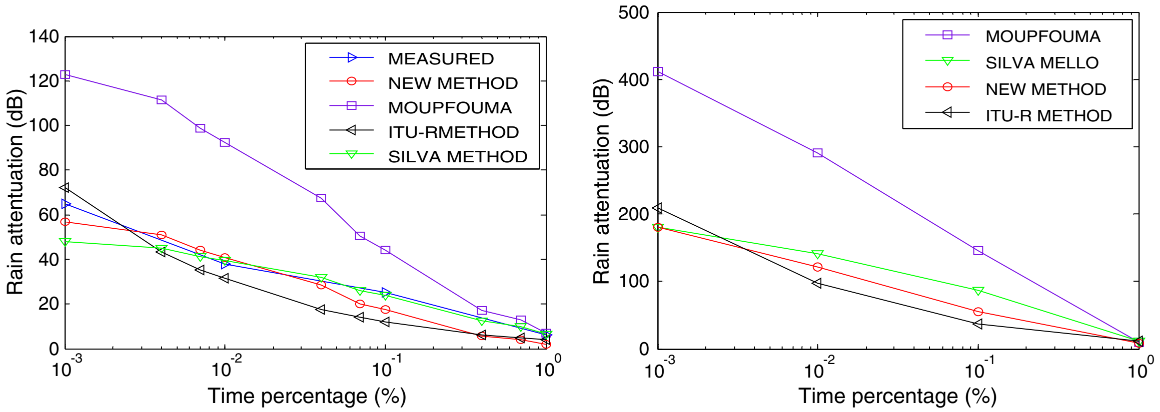
(d) Comparison of measured and predicted Attenuation (Kuala Lumpur link: 14.8 GHz; 3.96 km; Lat.: $3.04^0 N$ and Long.: $101.36^0 E$).

Figure 6. Comparison of measured and predicted attenuation: (a) Penang link: 14.8 GHz; 11.3 km; Lat.: 5.27° N and Long.: 100.29° E; (b) Johor Bahru link: 14.8 GHz; 5.83 km; Lat.: 1.30° N and Long.: 103.43° E; (c) Alor Star link: 15.3 GHz; 4.85km; Lat.: 6.15° N and Long.: 100.25° E; (d) Kuala Lumpur link: 14.8 GHz; 3.96 km; Lat.: 3.04°N and Long.: 101.36° E; (e) Taiping link: 14.8 GHz; 3.48 km; Lat.: 4.51° N and Long.: 100.42° E. (f) Temerloh link: 14.8 GHz; 5.36 km; Lat.: 3.26° N and Long.: 102.25° E; (g) Barueri-RIS link: 15 GHz; 21.7 km; Lat.: 23.55°S; Long.: 46.63° W; and (h) Lagos, Nigeria: 38 GHz; 10 km; Lat.: 6.3° N; Long.: 3.2° E.



(e) Comparison of measured and predicted attenuation (Taiping link: 14.8 GHz; 3.48 km; Lat.: $4.51^0 N$ and Long.: $100.42^0 E$).

(f) Comparison of measured and predicted attenuation (Temerloh link: 14.8 GHz; 5.36 km; Lat.: $3.26^0 N$ and Long.: $102.25^0 E$).



(g) Comparison of measured and predicted attenuation (Barueri-RIS link: 15 GHz; 21.7 km; Lat.: $23.55^0 S$; Long.: $46.63^0 W$).

(h) Comparison of measured and predicted attenuation (Lagos, Nigeria: 38 GHz; 10 km; Lat.: $6.3^0 N$; Long.: $3.2^0 E$).

Figure 6. *Continued.*

Table II. Percentage errors and RMS comparison.

Parameter		Time percentage (%p)						
		0.1	0.05	0.03	0.01	0.005	0.003	0.001
ITU	μ_{ei}	−0.0505	−0.0463	−0.0408	−0.0191	0.0007	0.0181	0.0456
	σ_{ei}	0.2096	0.2086	0.2074	0.2043	0.2034	0.2042	0.2084
	D_{ei}	0.2156	0.2137	0.2114	0.2052	0.2034	0.2050	0.2134
Moupfouma	μ_{ei}	0.0434	0.0488	0.0545	0.0709	0.0851	0.0851	0.1180
	σ_{ei}	0.7099	0.7096	0.7092	0.7077	0.7062	0.7050	0.7014
	D_{ei}	0.7086	0.7079	0.7071	0.7042	0.7010	0.6986	0.6914
Da Silva Mello *et al*	μ_{ei}	−0.0124	−0.0128	−0.0129	−0.0049	0.0069	0.0285	0.0275
	σ_{ei}	0.1606	0.1605	0.1605	0.1610	0.1609	0.1585	0.1587
	D_{ei}	0.1605	0.1605	0.1605	0.1609	0.1609	0.1585	0.1586
New method	μ_{ei}	−0.0090	−0.0060	−0.0031	0.0057	0.0136	0.0242	0.0370
	σ_{ei}	0.1200	0.1202	0.1203	0.1203	0.1196	0.1179	0.1145
	D_{ei}	0.1197	0.1200	0.1202	0.1201	0.1188	0.1153	0.1084

the model has allowed for path reduction value greater than unity. This implies that the equivalent path length will be greater than the physical path length, according to Equation (7a).

As can be seen in the caption of Figures 6(a)–(e), the predictions of Da Silva Mello *et al*. fairly match the measured values at lower rain rates when $0.05\% \leq p < 0.01\%$. For example, the Da Silva Mello *et al*. predictions are valid for $0.02\% < p < 0.01\%$, $0.01\% < p < 0.003\%$, $p > 0.03\%$, $p \geq 0.05\%$ and $p \geq 0.05\%$, respectively, in Figures 6(a)–(e). The prediction is only accurate at $p = 0.01\%$ for the Temerloh link. The major reason for Da Silva Mello's inaccuracies at both lower and extremely higher rain rates could be due to the differences in geographical considerations and the regression parameters used in Equations (5) and (6). However, the approach of Da Silva Mello *et al*. seems to yield better and more perfect results than both ITU-R and Moupfouma methods.

Table II shows the percentage errors comparison between the new method, ITU-R, Moupfouma, and Da Silva Mello *et al*. models, using the Recommendation given in ITU-R P.311-13 [16].

6. CONCLUSIONS

The extrapolation approach adopted by the current ITU-R method is not suitable for predicting the rain attenuation CD from the $A_{0.01}$ knowledge in tropical Malaysia. The new method of Equation (18) can be used for predicting the expected rain attenuation on terrestrial radio links operating at different frequencies (rather than 15 GHz) in Malaysia and similar tropics, by using the following procedure.

The first step is to estimate the reduction factor $r_{\%p}$ from the knowledge of path length d (km) and rainfall rate $R_{\%p}$(mm/h), as expressed in Equations (9) and (10). Next is to determine the value of β using the empirical expression given in Equation (19). Slope $S(R_{\%p})$ is then estimated from the rainfall rates of the geographical location under study. The final step is to determine the value of parameter μ using Equation (20).

The results presented in Figures 6(a)–(h) and the results of comparative tests shown in Table II clearly show that the new approach seems to provide a better alternative for rain attenuation predictions on terrestrial links in Malaysia, compared with the other three rain attenuation prediction models. The proposed method is relatively simple and is more suitable for rain attenuation predictions in tropical Malaysia.

The final table shows improved prediction for both larger and smaller time percentages. It is observed that ITU-R mean errors (μ_{ei}) are less than those of the proposed model for smaller time percentages in the range, $0.005 \leq \%p \leq 0.001$ when rain events are rarest but most-intense. However, according to the evaluation procedures adopted by the Recommendations ITU-R P.311-13, a lower standard deviation (σ_{ei}) and a lower RMS value (D_{ei}) for the whole range or for the majority of time percentages of interest suggest a high accuracy of the proposed model.

Further research works are going on to exploit the possibilities of applying the proposed method for global use. In our future submissions, it is intended to test the proposed method against all data sets from tropical regions available in the ITU-R databank and make necessary modifications, as applicable.

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REFERENCES

1. Spiros N, Panayotis GC. Availability and Performance of Single/Multiple Site Diversity Satellite Systems under Rain Fades. *European Transactions on Telecommunications* September 2008; **12**(1): 55–65. Published online 12.
2. Moupfouma F. Electromagnetic waves attenuation due to rain. A prediction model for terrestrial or L.O.S SHF and EHF radio communication. *Journal of Infrared, Millimeter and Terahertz Waves* 2009; **30**: 622–632.
3. Da Silva MelloL AR, Pontes MS, De Souza RM, Perez Garcia NA. Prediction of rain attenuation in terrestrial links using full rainfall rate distribution. *Electronics Letter* 2007; **43**(25): 1442–1443.
4. Moupfouma F, Martin L. Modeling of the rainfall rate cumulative distribution for the design of satellite and terrestrial communication systems. *International Journal of Satellite Communications* 1995; **13**(2): 105–115.
5. Goddard JWF. *Propagation in rain and cloud: Spatial temporal structure of rain*, 2nd edition, Propagation of Radio Waves. The Institution of Electrical Engineers, IEE: U.K, 2003.
6. Ajayi GO. Some aspects of tropical rainfall and their effect on microwave propagation. *International Journal of Satellite Communications* 1990; **8**(3): 163–172.
7. "Specific attenuation model for rain for use in prediction methods," ITU-R Rec. P.838-3, 03/2005.
8. Recommendation ITU-R P.530-13: "Propagation data and prediction methods required for the design of terrestrial line-of-sight systems," International Telecommunication Union, Geneva, Switzerland, 2009.
9. Chebil J, Rahman TA. Rain rate statistical conversion for the prediction of rain attenuation in Malaysia. *Electronics Letters* 1999; **35**: 1019–1021.

10. Ojo JS, Ajewole MO, Sarkar SK. Rain rate and rain attenuation prediction for satellite communication in Ku and Ka bands over Nigeria. *Progress In Electromagnetics Research B* 2008; **5**: 207–223.
11. Abdulrahman AY, Rahman TA, Rahim SKA, Ul Islam MR. Empirically derived path reduction factor for terrestrial microwave links operating at 15GHz in Peninsula Malaysia. *Journal of Electromagnetic Waves and Applications* 2011; **25**: 23–37.
12. Kanellopoulos JD, Reppas A. Prediction of the Outage Performance of an Orbital Diversity Earth-Space System. *European Transactions on Telecommunications* September 2008; **2**(6): 729–735. Published online 12.
13. Emilio Matricciani. Rain attenuation predicted with a two-layer rain model. *European Transactions on Telecommunications* September 2008; **2**(6): 715–727. DOI: 10.1002/ett.4460020615. Published online 12.
14. Pontes MS, Da Silva Mello LAR, Souza RSL, Miranda ECB. Review of rain attenuation studies in tropical and equatorial regions in Brazil, In *Proceeding of the 5th International Conference on Information, Communications and Signal Processing (ICICSP '05) IEEE Xplore*, Bangkok, 2005.
15. Ojo JS, Ajewole MO, Emiliani LD. One-minute rain rate contour maps for microwave communication systems planning in a tropical country: Nigeria. *IEEE Antenna and Propagation Magazine* October 2009; **51**(5): 82–89.
16. ITU-R Recommendation P. 311-13: "Acquisition, presentation and analysis of data in studies of tropospheric propagation," October 2009. International Telecommunication Union.

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