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# COMPARATIVE STUDIES OF THE RAIN ATTENUATION PREDICTIONS FOR TROPICAL REGIONS

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**Abstract**—The radio waves propagating through the earth atmosphere will be attenuated due to the presence of atmosphere particles, such as water vapor, water drops and the ice particles. Meanwhile, the atmospheric gases and rain will both absorb and scatter the radio waves, and consequently degrade the performance of the link. The results of various studies conducted in temperate and tropical regions have been published in research papers. This paper presents the summary of comparative studies on different rain attenuation prediction methods for terrestrial microwave links tropical regions. Basically the models described in this paper include those of the ITU-R, revised Moupfouma, revised Silva Mello and Lin model. The objective of this study is to reveal the most suitable rain attenuation prediction model for the Malaysian tropical region. This paper will provide useful information for microwave engineers and researchers in making decision over the choice of most suitable rain attenuation prediction for terrestrial links operating in a tropical region. Even though the ITU-R model underestimates the rain attenuation at higher frequencies, the test results have clearly indicated that it is most suitable for predicting terrestrial rain attenuation in tropical Malaysia, compared to others.

## 1. INTRODUCTION

Generally at frequencies below 10 GHz, excess attenuation due to rainfall and atmospheric gaseous absorptions is small and can be neglected in radio system design. However at frequencies above 10 GHz, liquid rain drops in the form of absorption and scattering seriously contribute to transmission losses [1–4]. Moreover, considering

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the satellite and terrestrial paths, rain attenuation exhibits significant spatial inhomogeneity within the distances of interest [5, 6]. The convective rain cells model is used for the description of the rainfall spatial horizontal structure [7], while the Crane's model is used for the rainfall vertical structure. When line-of-sight propagation is insured, precipitation creates the impairment that mostly influences the physical channel, while multipath becomes a secondary fading mechanism [8, 9]. Rain can be classified into four categories [10]: stratiform, convective, monsoon and tropical. The stratiform type of rain is characterized as a medium and low intensity of rainfall rate with longer duration and extended over a wide area. The convective type of rainfall rate is characterized as rainfall with high rain rates for short durations and extending over a small area. The monsoon precipitation type rainfall is a sequence of bands of intense convection type followed by intervals of stratiform precipitation. The tropical storm is a type of rainfall that covers large regions, larger than 100 km and may contain regions of intense convection [10].

Absorption and scattering of radio waves due to rain reduce the received signal level. Most of the rain attenuation prediction models in the literature are based on data obtained from the temperate regions. However, these models do not accurately predict rain attenuation in tropical and equatorial regions [11, 12]. Therefore, more studies are needed in order to obtain better and more accurate prediction models, which are suitable for predicting attenuation in tropical and equatorial climates.

## 2. OVERVIEW OF RAIN ATTENUATION PREDICTIONS OVER TERRESTRIAL LINKS

Rain attenuation limits the availability and performance of the system, and in order to develop an adequate link margin, the rain attenuation to be expected for a given time percentage needs to be calculated. The three steps involved are: determination of the rain fall rate (mm/h) for the time percentage of interest, calculation of the specific attenuation of the signal at this rainfall rate in dB/km and careful estimation of the effective length of the propagation path [13].

Attenuation can be accurately predicted if the rain can be precisely described all the way along the path. Path attenuation is essentially an integral of all the individual increments of rain attenuation caused by the drops encountered along the path. Rain can be described accurately along the path without extensive meteorological databases, which do not exist in the most regions of the world. Most of the prediction models are based on semi empirical approaches, which calculate an effective path length, $L_{\mathit{eff}}$ (km) through the rain, over which the rain fall rates are assumed to be constant. The concept of constant rainfall rate leads to constant specific attenuation and path attenuation.

A power law equation describes the relationship between point rainfall $R_{\%p}$ (mm/h) and specific attenuation $\gamma_{\%p}$(dB/km) at the same $p$% of the time. If the rainfall rate were uniform along the propagation path as in the case with light, stratiform rain, then the path reduction factor is assumed to be unity. Calculating the total attenuation for a given rain rate would be simple since the physical length through rain would be the same as the effective path length [13]. In this case, excess attenuation due to rain is defined as the product of specific attenuation and the physical path length. However, rainfall would not be uniform over practical path lengths exceeding 1.0 km. This is because the path would encounter highly variable drop sizes and rain fall rates, therefore the physical length $L$ has to be replaced by $L_{\mathit{eff}}$.

In this paper, comparison and discussions of four different path reduction factor models have been presented. The essence of reduction factor is either to reduce the point rain rate to the path averaged rain rate, or to reduce the actual path length filled with the uniform point rainfall. Several models have been proposed by researchers to account for the horizontal variation of rain fall. However the ITU-R model, revised Moupfouma and Silva Mello models are still the most relevant for rain attenuation predictions in tropical regions.

### 2.1. ITU-R Rain Attenuation Prediction Model

The Recommendation ITU-R P.530-13 [14] provides the rain attenuation at 0.01% of the time rain rate is exceeded, as follows:

$$A_{0.01} = kR_{0.01}^{\alpha} d r_{0.01} \tag{1a}$$

where $R_{0.01}$ and $r_{0.01}$ are the rain rate and reduction factor at 0.01% of the time, respectively. The latter is expressed as:

$$r_{0.01} = 1/(1 + d/d_o) \tag{1b}$$

and

$$\begin{aligned} d_o &= 35e_{0.01}^{-0.015R}, \quad R_{0.01} \leq 100\,\text{mm/hr}; \\ \text{and} \quad d_o &= 35e^{-1.5}, \quad R_{0.01} \geq 100\,\text{mm/hr} \end{aligned} \tag{1c}$$

The predictions of Equations (1a)–(1c) are valid for path lengths up to 60 km. The expressions of Equations (1b) and (1c) are based on two assumptions: (i) the spatial structure of the rain is modeled by an equivalent rain cell, with a rectangular cross section of length, and (ii) this rectangular cross section of the equivalent rain cell can assume any position with respect to the path [14]. However for high rain rates, this model produces decrease in the attenuation with the increase of rain rates, known as roll over effect [15]. To overcome this problem, a modification has been introduced provisionally in the method, limiting the use of expression (1c) to rain rates up to 100 mm/hr.

## 2.2. Revised Moupfouma Model

According to Moupfouma [16], a terrestrial microwave link is characterized by its actual relay path length "$L$" that corresponds to the space between two ground stations. To determine its equivalent propagation path length "$Leq$", an adjustment factor "$\delta$" that makes the rain to be uniform on the whole propagation path has to be defined such that:

$$Leq(R_{0.01}, L_T) = L_T * \exp(-R_{0.01}/1 + \zeta(L_T) * R_{0.01}) \tag{2a}$$

where

$$\begin{aligned} Leq(R_{0.01}, L_T) &= L_T * \exp(-R_{0.01}/1 + \zeta(L_T) * R_{0.01}), \\ \zeta(L_T) &= -100 \text{ for any } L_T \leq 7\,\text{km} \qquad (2b) \\ Leq(R_{0.01}, L_T) &= L_T * \exp(-R_{0.01}/1 + \zeta(L_T) * R_{0.01}), \\ \zeta(L_T) &= (44.2/L_T) \text{ for any } L_T > 7\,\text{km} \qquad (2c) \end{aligned}$$

Therefore, the definition of rain attenuation is modified to:

$$A_{0.01} = \gamma_{R0.01} \cdot L_{eq}(R_{0.01}, L_T); \quad \text{and} \quad \gamma_{R0.01} = kR_{0.01}^{\alpha} \tag{2d}$$

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

## 2.3. Revised Silva Mello Model

According Silva Mello, et al. [17], equivalent rain cell can intercept the link at any position with equal probability; therefore, their rain attenuation method is given as follows:

$$A_{\%p} = \gamma_{\%p} d_{\mathit{eff}} = k \left(R_{\mathit{eff}}(R_{\%p}, d)\right)^{\alpha} \frac{d}{1 + d/d_0(R_{\%p})} \tag{3}$$

$$R_{\mathit{eff}} = 1.763 R_{\%p}^{0.753+0.197/d} \quad \text{and} \quad d_o = 119R^{-0.244} \tag{4}$$

where $R_{\mathit{eff}}$ is the effective rain rate (mm/h), and $d_o$ is the equivalent cell diameter. It has been found that the power-law proposed by Silva Mello provides better results than the exponential law used in the current ITU-R method.

### 2.4. Lin Model

According to Lin [18], the reduction factor can be expressed as:

$$r = 1/1 + L/L(R) \tag{5a}$$

and

$$L(R) = 2636/R_{0.01} - 6.2 \text{ (km)} \tag{5b}$$

So that the overall rain attenuation is calculated by substituting the empirical value of r into the following:

$$A_{0.01} = \gamma_{R0.01} dr = kR_{0.01}^{\alpha} \cdot Lr \tag{6}$$

$$A_{0.01} = kR_{0.01}^{\alpha} \cdot \left( \frac{L}{1 + \frac{L}{2636/(R_{0.01} - 6.2)}} \right) \tag{7}$$

The factor accounts for the partially correlated rain rate variations along the propagation path of length $L$ such that the non linear factor (5a) equals one half when $L = L(R)$ is related to the diameter of rain cell. Based on measured distributions of 5 minute point rain rates (Aug. 1973–Jul. 1974) and 11 GHz rain attenuation on 42.5 km path at palmetto, Georgia, $L(R)$ was approximately described in Equation (5b). Lin model also largely overestimates the measured values at higher rain rates.

## 3. EXPERIMENTAL SET-UP

A link of path length 5.83 km was set up in Johor Bahru, Malaysia. Both the transmitter and receiver operate at a frequency of 15 GHz. The received signal levels were sampled every second. Two years precipitation data were collected from the Casella rain gauge installed at the measurement site (Jan. 2003–Dec. 2004). These data have

**Table 1.** Specifications of the 15 GHz link.

| Link location | Hop length (km) | Frequency band (GHz) | Maximum transmit power (dBm) | $10^{-6}$ BER ($2 \times 2$ Mbs) received threshold | Antenna for both transmit and receive side | |
|---|---|---|---|---|---|---|
| | | | | | Size (m) | Gain (dBi) |
| Johor Bahru | 5.83 | 15 | +18.0 | −84.0 | 0.6 | 37.0 |

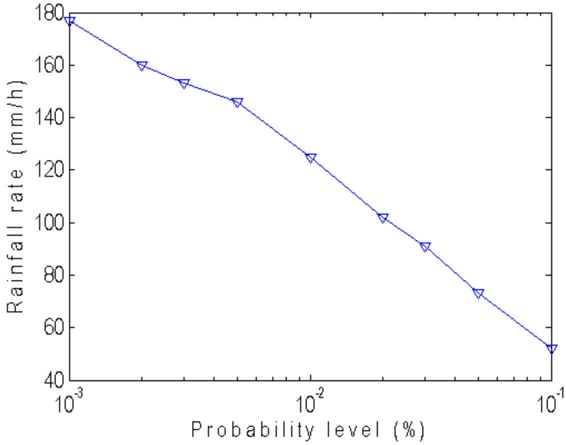


**Figure 1.** Rainfall rate CCDF for Johor Bahru (2 years).

been used to investigate the link. The gauge is a tipping bucket type and it has sensitivity of 0.5 mm. It records the total rainfall occurring in each minute without recording non rainy events; therefore the rain rate is recorded as an integral multiple of 30 mm/h or 0.5 mm/min. Table 1 shows the link specifications, while Figure 1 presents the complementary cumulative distribution function (CCDF) of the rainfall rate for an average of two years.

## 4. RESULTS AND DISCUSSIONS

The CCDF of measured rain attenuation at 15 GHz is compared with the predictions of ITU-R, revised Moupfouma, revised Silva Mello and Lin model. As seen in Figure 2, the measured rain attenuation is 17.08 dB and 34.5 dB, at 0.1% and 0.01%, respectively. In comparison, the predicted attenuations at 0.1% are 22.32 dB, 12.39 dB, 22.33 dB and 12.6 dB by Lin, Mello, Moupfouma and ITU-R models, respectively. Similarly, the corresponding predicted values at 0.01% are 64.33 dB, 24.49 dB, 57.14 dB and 32.39 dB, respectively. It is glaring that Lin and Moupfouma predictions are very close at 0.1% (almost 22.3 dB), which overestimate the measured value by 30.6%; whereas at 0.01%, the predictions are 64.3 dB and 57.4 dB, respectively.

Therefore the two models overestimate the measured attenuation at all percentages of time, worse still at higher rain rates. On the other hand, Silva Mello predictions largely underestimate the measured attenuation at 0.1% and 0.01% of the time. For instance, the prediction errors at these time percentages are 27.5% and 29%.

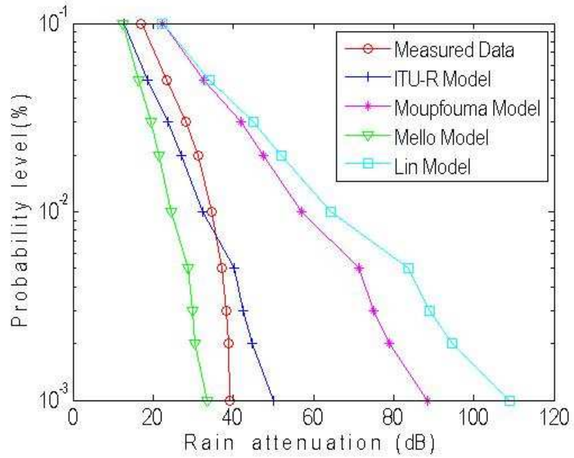


**Figure 2.** Comparison of rain attenuation CCDF at 15 GHz.

It has been observed that the ITU-R model closely agrees with the measured value at 0.01% of the time, with little error ($\approx$ 6%). However, it underestimates the measurements at other percentages, more especially at higher rain rates.

Further analyses have been conducted to study the effects of rain attenuation on this link at higher frequencies, 26 GHz and 38 GHz. The rain attenuation values at these frequencies have been obtained by inverting the available 15 GHz rain attenuation data, using the frequency scaling technique as follows [14]:

$$A_1(f_1)/A_2(f_2) = (\Phi_2/\Phi_1)^{1-H(\Phi 1,\Phi 2,A1)} \tag{8a}$$

$$\text{where,} \quad \Phi(f) = f^2/1+10^{-4}f^2 \tag{8b}$$

$$H(\Phi 1,\Phi 2,A1) = 1.12 * 10^{-3}(\Phi_2/\Phi_1)^{0.6}(\Phi_1 A_1)^{0.55} \tag{8c}$$

$A_1$ (dB) and $A_2$ (dB) are the equivalent probable values of the excess rain attenuation at frequencies $f_1$ (GHz) and $f_2$ (GHz), respectively.

Figures 3 and 4 compare the CCDFs of measured rain attenuation at 26 GHz and 38 GHz, respectively, with those predicted by Lin, Mello, and Moupfouma and ITU-R models.

As seen in Figure 3, the measured rain attenuation at 26 GHz is 43.18 dB and 87.23 dB, at 0.1% and 0.01%, respectively. In comparison, the predicted attenuations at 0.1% are 50.38 dB, 29.56 dB, 50.43 dB and 28.58 dB by Lin, Silva Mello, Moupfouma and ITU-R models, respectively. Similarly, the corresponding predictions at 0.01% are 129.74 dB, 53.67 dB, 115.24 dB and 65.33 dB, respectively. Also, it can be seen that Lin and Moupfouma predictions are very close at 0.1% (almost 50.4 dB), which overestimate the measured value

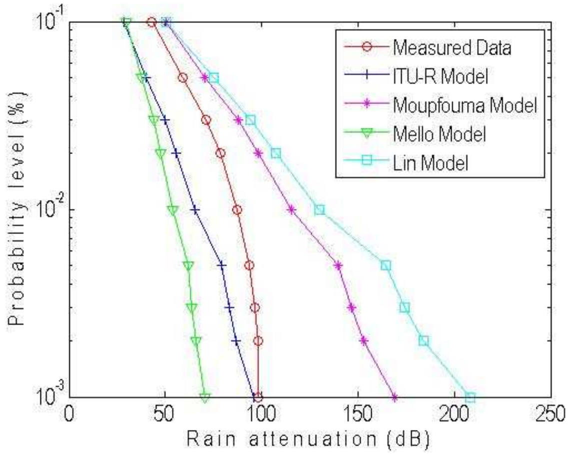


**Figure 3.** Comparison of rain attenuation CCDF at 26 GHz.

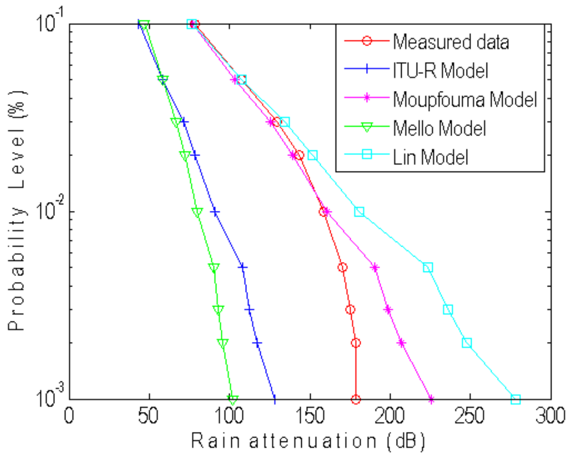


**Figure 4.** Comparison of rain attenuation CCDF at 38 GHz.

by 14.3%; whereas at 0.01%, the predictions are 129.74 dB and 115.24 dB, respectively. Therefore the two models largely overestimate the measured attenuation at all percentages of time, worse still at higher rain rates. On the other hand, Silva Mello predictions largely underestimate the measured attenuation at 0.1% and 0.01% of the time. For instance, the prediction errors at these time percentages are 31.5% and 38.5%.

From the figure it can be seen that Lin and Moupfouma predictions largely overestimate the measured attenuation at all percentages, compared to the other two models. At 0.1% of the time, both Lin and Moupfouma models predicted same value for rain attenuation, but the values are different at other percentages. In the case of ITU-R, the predictions are 28.58 dB and 65.33 dB, respectively. From these results, one can say that the ITU-R model most closely agrees with the measurements compared to other models. For instance, it has been observed that the percentage error, at 0.01% of the time, in ITU-R model is approximately 25%. The prediction errors are worse at higher rain rates, implying that the model is not suitable at higher frequencies.

**Table 2.** Prediction errors for the 15 GHz microwave link.

| Parameters | Models | Time of Percentages (%) | | | | |
|---|---|---|---|---|---|---|
| | | 0.1 | 0.05 | 0.03 | 0.02 | 0.01 |
| $\mu_{ei}$ | ITU-R | −0.038 | −0.036 | −0.034 | −0.033 | −0.028 |
| | Moupfouma | 0.019 | 0.021 | 0.026 | 0.027 | 0.036 |
| | Silva Mello | −0.035 | −0.041 | −0.042 | −0.044 | −0.043 |
| | Lin | 0.019 | 0.029 | 0.036 | 0.040 | 0.054 |
| $\sigma_{ei}$ | ITU-R | 0.205 | 0.205 | 0.204 | 0.204 | 0.203 |
| | Moupfouma | 0.425 | 0.425 | 0.424 | 0.425 | 0.424 |
| | Silva Mello | 0.345 | 0.345 | 0.346 | 0.346 | 0.346 |
| | Lin | 0.649 | 0.649 | 0.649 | 0.649 | 0.648 |
| $D_{ei}$ | ITU-R | 0.208 | 0.208 | 0.207 | 0.207 | 0.205 |
| | Moupfouma | 0.425 | 0.425 | 0.424 | 0.424 | 0.423 |
| | Silva Mello | 0.347 | 0.348 | 0.348 | 0.349 | 0.348 |
| | Lin | 0.649 | 0.649 | 0.648 | 0.648 | 0.646 |
| Parameters | Models | Time of Percentages (%) | | | | |
| | | 0.005 | 0.003 | 0.002 | 0.001 | - |
| $\mu_{ei}$ | ITU-R | −0.017 | −0.016 | −0.013 | −0.002 | - |
| | Moupfouma | 0.055 | 0.057 | 0.062 | 0.081 | - |
| | Silva Mello | −0.038 | −0.037 | −0.037 | −0.031 | - |
| | Lin | 0.083 | 0.088 | 0.097 | 0.125 | - |
| $\sigma_{ei}$ | ITU-R | 0.202 | 0.201 | 0.201 | 0.201 | - |
| | Moupfouma | 0.422 | 0.422 | 0.421 | 0.418 | - |
| | Silva Mello | 0.352 | 0.345 | 0.345 | 0.345 | - |
| | Lin | 0.645 | 0.644 | 0.643 | 0.638 | - |
| $D_{ei}$ | ITU-R | 0.203 | 0.203 | 0.202 | 0.202 | - |
| | Moupfouma | 0.419 | 0.418 | 0.416 | 0.410 | - |
| | Silva Mello | 0.347 | 0.347 | 0.347 | 0.346 | - |
| | Lin | 0.639 | 0.638 | 0.636 | 0.626 | - |

As seen in Figure 4, the measured rain attenuation at 38 GHz is 78.38 dB and 158.33 dB, at 0.1% and 0.01%, respectively. In comparison, the predicted attenuations at 0.1% are 76.66 dB, 46.99 dB, 76.74 dB and 43.5 dB by Lin, Silva Mello, Moupfouma and ITU-R models, respectively. Similarly, the corresponding predictions at 0.01% are 180.58 dB, 79.77 dB, 160.39 dB and 90.92 dB, respectively. At 0.1% of the time, it can be seen that both Lin and Moupfouma predictions are very close (almost 76.7 dB) to the measured value, with error as little as 2.1%, which is negligible; whereas at 0.01%, Moupfouma

**Table 3.** Prediction errors for the 26 GHz microwave link.

| Parameters | Models | Time of Percentages (%) | | | | |
|---|---|---|---|---|---|---|
| | | 0.1 | 0.05 | 0.03 | 0.02 | 0.01 |
| $\mu_{ei}$ | ITU-R | −0.049 | −0.051 | −0.049 | −0.049 | −0.047 |
| | Moupfouma | −0.002 | −0.004 | −0.003 | −0.003 | 0.002 |
| | Silva Mello | −0.004 | −0.051 | −0.054 | −0.055 | −0.055 |
| | Lin | −0.003 | −0.000 | 0.005 | 0.007 | 0.016 |
| $\sigma_{ei}$ | ITU-R | 0.247 | 0.247 | 0.247 | 0.247 | 0.247 |
| | Moupfouma | 0.116 | 0.116 | 0.116 | 0.116 | 0.115 |
| | Silva Mello | 0.466 | 0.467 | 0.467 | 0.468 | 0.468 |
| | Lin | 0.279 | 0.279 | 0.279 | 0.279 | 0.278 |
| $D_{ei}$ | ITU-R | 0.252 | 0.253 | 0.252 | 0.252 | 0.251 |
| | Moupfouma | 0.116 | 0.116 | 0.116 | 0.116 | 0.116 |
| | Silva Mello | 0.468 | 0.469 | 0.471 | 0.471 | 0.470 |
| | Lin | 0.279 | 0.279 | 0.279 | 0.279 | 0.278 |
| Parameters | Models | Time of Percentages (%) | | | | |
| | | 0.005 | 0.003 | 0.002 | 0.001 | - |
| $\mu_{ei}$ | ITU-R | −0.041 | −0.039 | −0.038 | −0.032 | - |
| | Moupfouma | 0.013 | 0.015 | 0.018 | 0.029 | - |
| | Silva Mello | −0.052 | −0.052 | −0.051 | −0.048 | - |
| | Lin | 0.035 | 0.038 | 0.043 | 0.062 | - |
| $\sigma_{ei}$ | ITU-R | 0.246 | 0.246 | 0.245 | 0.245 | - |
| | Moupfouma | 0.115 | 0.115 | 0.113 | 0.112 | - |
| | Silva Mello | 0.467 | 0.467 | 0.467 | 0.466 | - |
| | Lin | 0.277 | 0.277 | 0.276 | 0.272 | - |
| $D_{ei}$ | ITU-R | 0.249 | 0.249 | 0.248 | 0.264 | - |
| | Moupfouma | 0.115 | 0.115 | 0.114 | 0.109 | - |
| | Silva Mello | 0.470 | 0.470 | 0.469 | 0.469 | - |
| | Lin | 0.275 | 0.274 | 0.273 | 0.265 | - |

prediction is approximately the same as the measured attenuation (158.33 dB), with very insignificant error (1.3%). However, both Lin and Moupfouma models overestimate the measurements at higher rain rates less than 0.01%. On the other hand, Silva Mello predictions largely underestimate the measured attenuation at 0.1% and 0.01% of the time. For instance, the prediction errors at these time percentages are approximately 40% and 49.66%.

In the case of ITU-R, the prediction errors at 0.1% and 0.01% of the time are 44.5% and 42.66%, respectively. From these results,

**Table 4.** Prediction errors for the 38 GHz microwave link.

| Parameters | Models | Time of Percentages (%) | | | | |
|---|---|---|---|---|---|---|
| | | 0.1 | 0.05 | 0.03 | 0.02 | 0.01 |
| $\mu_{ei}$ | ITU-R | −0.029 | −0.023 | −0.017 | −0.015 | −0.007 |
| | Moupfouma | 0.034 | 0.044 | 0.054 | 0.0585 | 0.073 |
| | Silva Mello | −0.031 | −0.034 | −0.034 | −0.035 | −0.032 |
| | Lin | 0.034 | 0.049 | 0.066 | 0.074 | 0.096 |
| $\sigma_{ei}$ | ITU-R | 0.067 | 0.065 | 0.063 | 0.062 | 0.061 |
| | Moupfouma | 0.790 | 0.789 | 0.789 | 0.788 | 0.787 |
| | Silva Mello | 0.262 | 0.262 | 0.262 | 0.262 | 0.262 |
| | Lin | 1.077 | 1.077 | 1.076 | 1.075 | 1.073 |
| $D_{ei}$ | ITU-R | 0.073 | 0.069 | 0.065 | 0.064 | 0.061 |
| | Moupfouma | 0.789 | 0.788 | 0.787 | 0.787 | 0.784 |
| | Silva Mello | 0.264 | 0.264 | 0.265 | 0.265 | 0.264 |
| | Lin | 1.077 | 1.076 | 1.074 | 1.073 | 1.069 |
| Parameters | Models | Time of Percentages (%) | | | | |
| | | 0.005 | 0.003 | 0.002 | 0.001 | - |
| $\mu_{ei}$ | ITU-R | 0.010 | 0.013 | 0.017 | 0.032 | - |
| | Moupfouma | 0.102 | 0.107 | 0.114 | 0.141 | - |
| | Silva Mello | −0.025 | −0.024 | −0.024 | −0.016 | - |
| | Lin | 0.139 | 0.148 | 0.159 | 0.199 | - |
| $\sigma_{ei}$ | ITU-R | 0.061 | 0.062 | 0.063 | 0.068 | - |
| | Moupfouma | 0.784 | 0.783 | 0.782 | 0.778 | - |
| | Silva Mello | 0.261 | 0.261 | 0.261 | 0.261 | - |
| | Lin | 1.069 | 1.067 | 1.066 | 1.059 | - |
| $D_{ei}$ | ITU-R | 0.062 | 0.063 | 0.065 | 0.075 | - |
| | Moupfouma | 0.777 | 0.776 | 0.774 | 0.766 | - |
| | Silva Mello | 0.262 | 0.262 | 0.262 | 0.261 | - |
| | Lin | 1.059 | 1.058 | 1.054 | 1.041 | - |

it can be seen that the ITU-R model is definitely unsuitable at higher frequencies. Now the argument is that, we want to determine which one, out of these four models, is most suitable for predicting rain attenuation in Malaysian tropical climate. To do this, the Recommendation ITU-R P.311-13 [19] has been used for determining the prediction errors exceeding time percentages in the range 0.001% to 0.1%. Therefore percentage errors between measured terrestrial data $A_m$ (dB) and the model's predictions $A_P$ (dB) are calculated for each exceeding time percentage of interest on the microwave radio link, as follows:

$$\text{Error,} \quad E_i = |A_P - A_M|/A_M, \quad (i = 1 \text{ to } N) \tag{9a}$$

$$\text{If:} \quad |A_P - A_M| < 1 \quad \text{then} \quad E_i = 0 \tag{9b}$$

where $A_P$ and $A_M$ the predicted and measured rain attenuation, respectively.

The Standard Deviation, $\sigma_{ei}$ of the error distribution can be defined from:

$$\sigma_{ei} = \left(1/N_{i=1}\Sigma^N e_i^2 - (\mu e_i)^2\right)^{1/2} \tag{10}$$

where $\mu e_i$ is the mean square error for each exceedance time percentage and is given by:

$$\mu e_i = 1/N_{i=1}\Sigma^N e_i \tag{11}$$

The root mean square $De_i$ is given by:

$$De_i = \left[(\mu e_i)^2 - (\sigma_{ei})^2\right]^{1/2} \tag{12}$$

The comparison of errors in terms of $\mu e_i$, $\sigma_{ei}$ and $De_i$ are presented in Tables 2, 3 and 4, for the 15 GHz, 26 GHz and 38 GHz links, respectively.

## 5. CONCLUSIONS

From the results presented in Figures 2, 3 and 4, ITU-R predictions are the closest to the measured attenuation, compared to the other three models studied in this work. For instance for the 15 GHz link, it has been observed that the ITU-R model closely agrees with the measured value at 0.01% of the time, with little error ($\approx$ 6%). However, it underestimates the measurements at other percentages, more especially at higher rain rates. Another observation is that, the ITU-R prediction errors are much higher at 26 and 38 GHz, which suggest that it may not be suitable for predicting rain attenuation at higher frequencies.

More so, based on the results presented in the Tables 2, 3 and 4, it is evident that the ITU-R model seems to be most suitable for predicting terrestrial rain attenuation in tropical Malaysia, compared to other models. This is because it gives the smallest values for the mean error; standard deviation and root mean square RMS. According to the evaluation procedures adopted by the recommendations ITU-R P.311-13, a lower standard deviation and lower RMS value for the whole range or for the majority of time percentages of interest suggest a high accuracy for the prediction rain attenuation model.

In order to come to more concrete conclusions on the prediction errors for the higher frequency links, it is necessary to measure the actual rain attenuation at 26 GHz and 38 GHz, rather than using the frequency scaling techniques. More so, it is necessary to collect longer rainfall rate data in order to carry out further analyses in the future.

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