SHORT COMMUNICATION

Rain attenuation measurements over terrestrial microwave links operating at 15 GHz in Malaysia

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SUMMARY

This paper presents the experimental results of rain rate and rain attenuation measurements on six terrestrial microwave links in tropical Malaysia. The rain attenuation data were collected from six DIGI MINI-LINKs (DiGi Telecommunications Sdn. Bhd., Malaysia, Shah Alam, Selangor Darul Ehsan, Malaysia) operating at 15 GHz with 99.95 % availability. The experimental results were compared with the International Telecommunication Union Radiocommunication Sector (ITU-R) method and other existing rain attenuation prediction models. The main focus is on the ITU-R prediction method, which underestimates the measured rain attenuation, more especially at extremely higher rain rates. The relationship between ITU-R prediction errors and rainfall rates was studied, and it is shown that the two quantities are related by a quadratic function. The study will provide useful information on the design and planning of terrestrial radio links in Malaysia and similar tropical environments. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS: rain-induced attenuation; ITU-R prediction model; regression techniques; tropical environments

1. INTRODUCTION

Rain attenuation adversely affects the performance of microwave communication systems operating at frequencies above 10 GHz. The effect is more severe in tropical regions, which are characterized by heavy rainfall intensity and the presence of large raindrops [1]. Raindrop size distribution changes with geographical location and it can strongly influence rain-specific attenuation and, consequently, total rain attenuation [2].

Usually, propagation impairments have a significant effect only for less than 1 % of the time during a year; therefore, the system gain must be enhanced through an additional fade margin to meet the desired availability and QoS specifications [3]. One of the main objectives of the telecommunications community is to seek a model that can predict rain attenuation in any climate across the world with a better accuracy [4].

The International 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 it is based on data collected from temperate regions of the world [5]. Emphasis on the inappropriateness of the ITU-R method in tropical climates is needed.

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regions has been reported in a number of published research works [2, 5]. Thus, the knowledge of rain induced attenuation at the frequency of operation is necessary to design a reliable communication system at a particular location [6]. This paper presents the results of rainfall rate measurements and rain attenuation data collected from six terrestrial microwave links of DIGI Telecoms, operating at 15 GHz in Malaysia.

2. RAIN ATTENUATION PREDICTION MODELS

2.1. Background

Attenuation can be obtained from direct measurements or predicted from the knowledge of rain rate. Rain attenuation over a terrestrial path is defined as the product of specific attenuation (dB/km) and the effective propagation path length (km). The effective path length is determined from the knowledge of the link length and the horizontal distribution of the rain along the path. The rain attenuation $A$ (dB) exceeded at $p$ per cent of time is calculated as follows:

$$ A = \gamma_R d_{\text{eff}} = \gamma_R d_r $$

(1a)

$$ \gamma = k R^\alpha $$

(1b)

$$ d_{\text{eff}} = d r $$

(1c)

where $R$ (mm/h) is the rain rate exceeded at $p$ per cent of the time, $r$ is the path reduction factor at the same time percentage, $d$ (km) is the radio path length. Parameters $k$ and $\alpha$ depend on frequency, rain temperature, and polarization; and their values can be obtained from ITU-R P.838-3 [7]. Generally, the required inputs in most attenuation prediction models are the rainfall rate exceeded at $p\%$ of time, the effective propagation path length and the link’s operating frequency. It should be noted that the path reduction factor accounts for the inhomogeneities of rain on the entire propagation path.

The models compared with the measured data in this paper include those of the ITU-R, revised Moupfouma, revised Silva Mello and Lin models. Each of these models is briefly described in the following subsections.

2.2. ITU-R prediction rain attenuation prediction model

According to Recommendation ITU-R P.530-13 [8], rain attenuation $A_{0.01}$ (in dB) at 0.01 % of the time on any terrestrial microwave link is obtained by simply substituting $p = 0.01$ in Equation (1a). This method assumes that an equivalent rain cell of uniform rainfall rate and length $d_0$ can model nonuniform rainfall rate along the propagation path. The reduction factor is given by

$$ r = \frac{1}{1 + d/d_0} $$

(2a)

where $d_0$ is the equivalent rain cell diameter, and is defined as

$$ d_0 = 35e^{-0.015R_{0.01}} $$

(2b)

The predicted attenuation exceeded for other percentages $p$ of an average year may be obtained from the value of $A_{0.01}$ by using the following extrapolation:

$$ A_p = A_{0.01} \left( \frac{p}{0.01} \right)^{[-0.655+0.033\ln p-0.045\ln A_{0.01}-z\sin\theta(1-p)]} $$

(3)

where $p$ is the percentage probability of interest and $z$ is given by

For $p \geq 1\%$, $z = 0$

For $p < 1\%$, $z = 0$ for $|\phi| \geq 36^\circ$

$z = -0.005 (|\phi| - 36)$, for $\theta \geq 25^\circ$ and $|\phi| < 36^\circ$
rain attenuation measurements

\[ z = -0.005 \left( / \phi - 36 / \right) + 1.8 - 4.25 \sin \theta, \]
for \( \theta < 25 \) and \( / \phi / < 36^o \)

The predictions of the ITU-R method are valid for path lengths up to 60 km for frequencies up to 40 GHz. The expressions of Equations (2a) and (2b) 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 [8].

Empirical evidences have indicated that these models underestimate the cumulative distribution of rain attenuation when applied to microwave links located in tropical regions, thereby leading to underestimation and a poor prediction [5].

2.3. Revised Silva Mello’s model

Silva Mello et al. [5] have reported that the extrapolation procedure in [8] adopted by the current ITU-R 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 \( A_{0.01} \). In order to correct the limitations, 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

\[ A_p = \gamma R d_{eff} = k \left( R_{eff}(R, d) \right)^{a} \frac{1}{1 + d/d_0(R)} \] (4)

where \( R_{eff} \) is the effective rain rate, a function of \( d \) and \( R \).

The expression for \( R_{eff} \) and equivalent rain cell diameter \( d_0 \) are given by

\[ R_{eff} = 1.763 R^{0.753+0.197/d} \] (5)

and

\[ d_0 = 119 R^{-0.244} \] (6)

The numerical coefficients in Equations (5) and (6) were obtained by multiple nonlinear regressions, using the measured data currently available in the ITU-R databanks. It has been found that the power-law for \( d_0 \) in (6) provides better results than the exponential law used by the current ITU-R method in Equation (2b).

2.4. Revised Moupfouma’s model

According to Moupfouma [4], 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 \( ' \delta ' \) that makes the rain uniform on the whole propagation path has to be defined such that

\[ L_{eq}(R_{0.01}, L_T) = L_T \exp \left( \frac{-R_{0.01}}{1 + \xi(L_T) R_{0.01}} \right) \] (7a)

where

\[ \xi(L_T) = -100 \quad \text{for any} \quad L_T \leq 7 \text{ km} \] (7b)

and

\[ \xi(L_T) = \left[ \frac{44.2}{L_T} \right]^{0.78} \quad \text{for any} \quad L_T > 7 \text{ km} \] (7c)

Therefore, the definition of rain attenuation is modified to

\[ A_{0.01} = k R_{0.01}^{a} L_{eq}(R_{0.01}, L_T) \] (8)

where \( R_{0.01} \) and \( A_{0.01} \) are the rainfall rate and path attenuation at 0.01% of the time.
The most notable drawback of this model is that it substantially overestimates the measured path attenuation, more especially at higher rain rates.

2.5. Lin model

According to Lin [9], the reduction factor can be expressed as

\[ r = \frac{1}{1 + L/L(R)} \]  

and

\[ L(R) = \frac{2623}{R - 6.2} \text{ km} \]  

The factor accounts for the partially correlated rain rate \( R \) (mm/h) variations along the propagation path of length \( L \) such that the nonlinear factor in Equation (9) equals one-half when \( L = L(R) \) is related to the diameter of the rain cell. On the basis of the measured distributions of 5-min point rain rates (Aug 1973–July 1974) and 11 GHz rain attenuation on 42.5 km path at Palmetto, Georgia, \( L(R) \) was approximately described in Equation (10).

The overall rain attenuation is calculated by substituting the empirical value of \( r \) into the following:

\[ A = k R^\alpha L r \]  

\[ A = k R^\alpha L \left( \frac{1}{1 + L/L(R)} \right) \]

The Lin model also largely overestimates the measured values at higher rain rates.

3. RAINFALL RATE AND RAIN ATTENUATION DATA COLLECTION

The rain attenuation data, sampled every second, were collected from six operational point-to-point microwave links of DIGI Telecommunications. Each of the microwave systems consists of a microwave MINI-LINK operating at 15 GHz with a data acquisition and processing system. Both antennas are horizontally polarized (that is, the elevation angle is approximately zero degrees) and they were covered with radome during rain attenuation measurement. The positioning of the antennas (transmitter and receivers) ensures that the radiation pattern is such that the sidelobes are not pointing to the ground. Therefore, the level of ground contamination (noise) entering the sidelobes is negligible. This implies that there would be negligible interference from any other radiating sources.

The automatic gain control levels (volts) were converted to the corresponding receiver data in the form of equivalent power in dBm using the conversion chart supplied by the vendors (Ericsson) Sony Ericsson Mobile Communications Kista, Stockholm Sweden. The signal is relatively stable in the clear-sky conditions as it fluctuates within ±1 V, and the drop in automatic gain control levels during rain represents path attenuation. However, the conversion process is not stable and gives fluctuations of about ±4 dB. From our calibration, the maximum error that may be introduced by the conversion process is 2%, which means that the accuracy of rain attenuation data is 98%. The dynamic range of the maximum signal strength is about 50 dB for excess (i.e. rain) attenuation.

This is adequately suitable for covering the entire dynamic range of rain attenuation for this study, because the highest total path attenuation measured is 49.32 dB at 0.001% of the time.

Wet antenna losses have been extracted from the measured rain attenuation to achieve reliable results. More so, scintillations and other atmospheric absorptions along the propagation path have not been considered in the study.

The MINI-LINKs have availability of 99.95% and their specifications are given in Table I.

A Casella rain gauge, fitted with a programmable data logger, was positioned very close to the receiving antenna for the purpose of simultaneously recording the rain rate data. The gauge is of tipping bucket type and the bucket size is 0.5 mm of rain. The tipping time could not be recorded,
but the number of tips was recorded and stored in the built-in data logger of the rain gauge. The sensitivity of the rain gauge is 0.5 mm/min and the availability is 100%. The duration of measurement is 1 year. The rainfall rates were measured with 1-min integration time and all the six locations have similar rainfall pattern.

Malaysia falls in the region H of the ITU-R rainfall rate climatic zoning with annual average accumulation as high as 4184.3 mm. The Malaysian climate is tropical, and is characterized by uniform temperature, high humidity and heavy rainfall, which arises mainly from the maritime exposure of the country. Thunderstorm rainfall is the most common for Malaysian climates. The monthly cumulative distribution of rainfall is influenced by seasonal monsoons, namely the northeast monsoon from October to March and the southwest monsoon from April to September [6].

The 1-min simultaneous measurements of rainfall rate and RSL are shown in Figures 1(a) and (b), respectively, for one rainy day. As seen in Figure 1(b), the RSL (dBm) fluctuates around /NUL/ 45.5 dBm in the clear sky conditions. But after rain, it drops sharply up to /NUL/ 55.5 dBm, which corresponds to the highest rainfall rate (248 mm/h).

Figure 1. (a) Rain rate over the path link during a rainy day on 2 October 2005. (b) Receive signal level (RSL) over the path link during a rainy day on 2 October 2005. (c) Rain attenuation as a function of rain rate for one rainy day on 2 October 2005.
The corresponding path attenuation is calculated by finding the difference between the RSL during clear sky conditions and the RSL during rain, for horizontally polarized received signal at various rain rates. That is,

$$\text{Attenuation (dB)} = \frac{\text{RSL}_{\text{clear sky}} - \text{RSL}_{\text{rainy}}}{\text{RSL}_{\text{clear sky}}}$$

(13)

The scatter plot of 1-min rainfall rate against 1-min path attenuation for all data points in a rainy day is presented in Figure 1(c). As clearly shown in Figure 1(c), there is good correlation between the measured rainfall rates and path attenuation. The maximum value of rain attenuation (almost 10 dB) occurs when the rain rate is maximum (nearly 248 mm/h).

The rain rate CDs for the six locations investigated in this study are shown in Figure 2, while the equal probability plots of the concurrent CDs’ 1-min rainfall rate and path attenuation for all the six links are presented in Figure 3. Figure 3 also shows that rain attenuation varies with rain rate and that maximum rain attenuation occurs when the rain rate is maximum.

4. RESULTS AND DISCUSSIONS

Figures 4(a)–(f) show the comparison between the measured cumulative distributions and prediction models for all the six links considered in this study.
It can be observed from these results that the measured CDs of rain attenuation follow the usual log-normal behaviour. It is observed that the measured cumulative statistics of rain attenuation is underestimated by ITU-R predictions. The underestimation becomes highly pronounced at extremely higher rain rates. For instance, for the Johor Bahru MINI-LINK, the measured attenuation values are 17.08, 34.5 and 39.0 dB, respectively at 0.1, 0.01 and 0.01% of the time when rain attenuation is exceeded. In comparison, the corresponding predicted ITU-R values are 13.2, 25.5 and 33.5 dB, respectively. The ITU-R model predicts a log-normal variation. The model shows a monotonous decrease in rain attenuation, known as roll over effect [10].

The Moupfouma model predicts 22.3, 59.8 and 88.4 dB, respectively at 0.1, 0.01 and 0.001% of the time; whereas the Lin model predicts 20.1, 46.9 and 63.5 dB, respectively. These two models predict nearly the same value at 0.1% of the time, which overestimates the measured value by almost

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30%. The Moupfouma model overestimates the measured value by 42.3% and 55.9%, respectively at 0.01 and 0.001% of the time. The Lin model overestimates the measured value by 26.4% and 38.6%. It is glaring that both Moupfouma and Lin predictions largely overestimate the measured rain attenuation at all percentages of the time, worse still at higher rain rates. One reason for the overestimation in the Moupfouma model’s predictions may be because the model allows for a 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). In the case of the Lin model, the overestimation arises from the fact that the path reduction factor model proposed in Equations (9) and (10) overestimates the experimentally derived path reduction values.

The Mello model predicts 14.4, 30.4 and 40.8 dB, respectively at 0.1, 0.01 and 0.001% of the time. The model results show poor agreement with the measured data at lower rain rates from 0.1 to 0.02% of the time levels, with percentage error between 15% and 18%. On the other hand, the model closely matches the measured values at higher rain rates, from 0.01 to 0.001% of the time, with percentage error between 4.5% and 12% of less than 10%.

The ITU-R method is not appropriate for predicting rain attenuation on microwave links in tropical Malaysia. To investigate the relationship between the ITU-R rain attenuation prediction errors and rainfall rates, there is a need to correlate their CDs for the same \( p \) of time. Therefore, the equal probability plots of measured rainfall rates CDs and that of the ITU-R prediction errors are shown in Figure 5 for the six links. Investigations of Figure 5 have shown that the polynomial of the second order is the best least-squares regression that fits the two sets of measured data, as given in Equation (14). The polynomial is given by

\[
\Delta A = \beta_1 R_{\%p}^2 + \beta_2 R_{\%p} + \beta_3
\]  

(14)

where \( \Delta A(\text{dB}) \) is the ITU-R prediction error at \( p \% \) of the time, \( \beta_1, \beta_2 \) and \( \beta_3 \) are regression coefficients. The numerical values of regression coefficients obtained for each of the MINI-LINKs are shown in Table II.

Table III shows the mean \( \mu_{e_i} \), standard deviation \( \sigma_{e_i} \) and root mean square \( D_{e_i} \) of the test variable for each method in accordance with ITU-R P. 311-13 [11].

Figure 5. Relationship between predicted ITU-R error and rainfall rate.

Table II. Regression coefficients.

<table>
<thead>
<tr>
<th>LINK</th>
<th>Regression coefficients</th>
<th>( \beta_1 )</th>
<th>( \beta_2 )</th>
<th>( \beta_3 )</th>
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<td>0.11</td>
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<td>0.34</td>
<td>-23.00</td>
<td></td>
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<td>ALOR STAR</td>
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<td>0.47</td>
<td>-29.00</td>
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<tr>
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<td>TAIPING</td>
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Table III. Percentage errors and RMS comparison.

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<th>0.003</th>
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5. CONCLUSIONS

This paper has presented the results of a one-year measurement of rain-induced attenuation of microwave signal propagation at 15 GHz on six MINI-LINKs in tropical Malaysia. The annual statistics of rain rate and rain attenuation have been derived from the measured experimental data. It is found that the experimental results are in good agreement with the predictions of the Silva Mello model at higher rain rates, from 0.01 to 0.001% of the time. Both Moupfouma and Lin predictions largely overestimated the measured rain attenuation at all percentages of the time.

The measured cumulative statistics of rain attenuation is underestimated by ITU-R predictions. The underestimation becomes highly pronounced at extremely higher rain rates. It has been demonstrated in this paper that the ITU-R prediction errors $\Delta A$ could be modeled as a function of rainfall rate $R$. Equation (14) may be incorporated in Equations (1a)–(3) to enhance the performance of the ITU-R method on terrestrial microwave systems operating at 15 GHz in the tropical Malaysian climate. The regression coefficients would depend on the microwave link under consideration. This dependence refers to the operating frequency and the physical path length of the microwave system. The study would provide useful information for rain attenuation predictions in Malaysia and similar tropical climates that have a similar situation.

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AUTHORS’ BIOGRAPHIES

Amuda Yusuf Abdulrahman obtained his bachelor’s and master’s degrees from University of Ilorin, Nigeria in 1999 and 2005, respectively. He is currently a full-time PhD research student at Wireless Communication Centre (WCC), Faculty of Electrical Engineering, Universiti Teknologi Malaysia (UTM), Skudai, Malaysia. His research interests include wireless mobile systems, radio propagation and rain attenuation studies, especially in the tropics. Abdulrahman, a member of IEEE, is currently working on development of a transformation model for inverting terrestrial rain attenuation data for satellite applications at Ku-band in tropical regions. He has published and coauthored more than eight papers in International Journals related to rain attenuation issues in tropical regions, and antenna design and measurement.

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