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RESEARCH PAPER

Comparison of measured rain attenuation and ITU-R predictions on experimental microwave links in Malaysia

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This paper presents the results of direct rain attenuation measurements carried out on four experimental microwave links, installed at UTM, Malaysia. The links operate at frequencies of 15, 22, 26, and 38 GHz and the cumulative distribution function for different rain rates have been generated from the measured 4-year rain gauge data. The experimentally measured attenuation data have been compared with International Telecommunication Union-R rain attenuation predictions; and it has been found that the latter have underestimated the measured values, especially at higher rain rates. The deviations have been modeled as a function of rain rate exceedances $R_{\%p}$. It is hoped that the study will provide useful information for estimation of rainfall attenuation on microwave links in tropical regions that have similar situation to Malaysia.

Keywords: Prediction Errors, Rain Attenuation, Regression parameters, Wet Antenna Losses

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I. INTRODUCTION

Rainfall is a major cause of signal impairment for both terrestrial and earth–satellite systems operating at frequencies above 10 GHz; the effect being more severe in tropical regions that are characterized by heavy rainfall intensity and 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].

The major problems caused by propagation impairment on communication systems as a result of inadequate rain-measurement data from tropical regions have been the major concerns of many international bodies such as the European Space Agency (ESA), the International Telecommunication Union (ITU), and European Cooperative Program (COST). This has become imperative because of the peculiarity of the tropical regions, which are characterized by heavy intensity rainfalls, and the increased presence of raindrops with large diameters when compared with the temperate regions [3].

The rain-attenuation analyses are important for the study of rain fade characteristics, which is a useful piece of information in the link budget estimation for predicting the expected outage due to rain attenuation on a microwave link [4]. It has been reported in a number of published research works that the ITU-R rain attenuation predictions underestimate the measured values in tropical regions [5, 6]. The aim of this paper, therefore, is to emphasize on the difference between the measured rain attenuation in tropical Malaysia and the ITU-R predictions. The results may also be extrapolated for use in tropical regions that have similar situation.

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II. RAIN-RATE AND RAIN ATTENUATION PREDICTION MODELS

Rain attenuation can either be obtained directly from microwave link measurements, or estimated from the rain rate and rain drop-size distribution data. Recommendation ITU-R P.530-12 [7] has provided a step-by-step approach for predicting the long-term statistics of rain attenuation over the terrestrial line-of-sight systems. The primary input to the procedure is the 1 min rainfall rate, $R_{0.01}$ (mm/h), exceeded for 0.01% of time for the location under consideration. If this information is not available from long-term measurements carried out at the link location, then an estimate may be obtained from rainfall rate maps provided in Recommendation ITU-R P.837-4 [8].

A large number of rain rate and rain attenuation prediction models could be found in the literature. These include the revised version of the Crane's two-component model, Excell model, Bryant model, Flavin model, DHA model, simple attenuation model (SAM) by Stutzman and Dishman, among others. Comprehensive information on these models can be obtained from *COST 255* [9].

According to Ajayi *et al.* [10] a methodological approach had been provided for estimating rain-induced attenuation from available rain statistics. In their work, the traditional method of moment of regression analysis was used for estimating the number of rain drop sizes and the results were compared with those obtained by using the log-normal distribution. According to specific attenuation of Law and Parsons (1943), raindrop size distribution is nearly the same as the rain-specific attenuation obtained from power-law parameters of ITU-R. However, Wei and Nader [11] have recommended that, for the calculation of specific attenuation, an expanded set of power-law parameters for various raindrop size distributions should be used. According to whom, the gamma raindrop size distribution is more reasonable for high-altitude geographical locations, whereas the log-normal raindrop size distribution should be more appropriate for tropical regions. This is in conformity with the model developed by Moupfouma and Martin [12], which approximates a log-normal distribution at low rates, and a gamma distribution at high rain rates.

Majority of rain attenuation estimation in tropical regions are now based on the Moupfouma model because it yields good approximation for rain drop size. However, the "two and a half old" model has been substantially revised in one of his recent publications [13]. Serious design considerations must be given to the tropical regions with heavy rainfall. This will help to achieve accurate link budget predictions that will guarantee reliable and high-availability performance for both terrestrial and earth–satellite systems [14].

III. RAIN ATTENUATION DATA COLLECTION

Four experimental microwave links at 14.6, 21.95, 26, and 38 GHz were installed at UTM Campus in Johor Bahru, Malaysia. The links were set between Wireless Communication Centre (WCC) and the Base Transmit Station (BTS) tower, at a separation distance of 300 m within UTM, Malaysia. The maximum transmit power, antenna gain, and receive signal threshold for 10^{-6} BER with 2×2 Mbs traffic for all four experimental links are given in Table 1. The experimental setup for the 4-year concurrent measurements of rain attenuation and rain rate is shown in Fig. 1, whereas the average cumulative distribution (CDF) of the 4-year measured rainfall rate at UTM is presented in Fig. 2. Table 2 presents the measured rain attenuation at 0.01 % of time rain rate is continuously exceeded for the four links, and Table 3 shows the average rainfall rate at different time percentages.

The rainfall rates were measured for 4 years at UTM, with 1 min integration time. The rain rate data were collected from January 2003 to December 2006, using Casella rain gauge and 30 months using OSK rain gauge. Both gauges are tipping bucket type and having 0.5 mm sensitivity. Casella records the total rainfall occurring in each minute without recording non-rainy events; therefore, the rain rate is recorded as an integral multiple of 0.5 mm/min, or 30 mm/h. In contrast, OSK records the actual tipping time up to decimal of seconds.

UTM is located at Johor (Lat.: 1.45′N and Long.: 103.75′E), southern part of Malaysia peninsula close to Singapore. Malaysia is located in the South-Eastern part of Asia, and falls in the zone P of the ITU-R rainfall rate climatic zone 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 arise mainly from the maritime exposure of the country. The heaviest amounts of rainfall are noted to occur in the last 2 months of the year, that is November and December. The uniform periodic changes in the wind flow patterns result in seasons' classifications as: the south-west monsoon, the north-east monsoon, and the two shorter inter-monsoon seasons.

We have found that the recommendation ITU-R P.837-5 is not suitable for estimating $R_{0.01}$ in tropical Malaysian climate, because it substantially underestimates the measured rain rate values. For instance, the ITU-R P.837-5 has predicted a value of 105 mm/h for $R_{0.01}$ at UTM, whereas direct measurement has given an average value of approximately 125 mm/h, as shown in Fig. 2.

Rainfall rate is the major factor in determining the amount of attenuation likely to be experienced by any link. The most widely used statistics are those of annual rainfall, expressed as rain rate exceeded for a given percentage of the year. From rain rate measurements, we have found that the behavior of rain rate $R_{\%p}$ exceeded with respect to $\%p$ could be approximated by

$$R_{\%p} = 33.116 \, {}^{*}p^{-0.25}. \qquad (1)$$

Note that equation (1) is in conformity with Moupfouma's parameterization of rainfall rate as a function of duration [15]. The receive signal level (RSL) (dBm) for any terrestrial microwave link can be expressed as follows [16]:

$$\mathrm{RSL} = P_T + G_T + G_R - L_{fs} - A_G - A_R - A_W - L_R - L_t, \qquad (2)$$

where P_T (dBm) is the transmit power, L_t (dB) is the loss in the transmit system, G_T (dB) is the transmit antenna gain, L_{fs} (dB) is the free space loss, A_G (dB) is loss due to gaseous absorption, G_R (dB) is the receive antenna gain, L_R (dB) is the loss in

Table 1. Specifications of the four experimental links.

Frequency band (GHz)	Polarization	Maximum transmit power (dBm)	10^{-6} BER (2×2 Mbs) receive threshold (dBm)	Antennas for both transmit and receive side	
				Size (m)	Gain (dBi)
15	Horizontal	+18.0	−84.0	0.6	37.0
22	Horizontal	+20.0	−83.0	0.6	40.2
26	Horizontal	+18.0	−82.0	0.6	41.0
38	Horizontal	+15.0	−79.0	0.6	44.9

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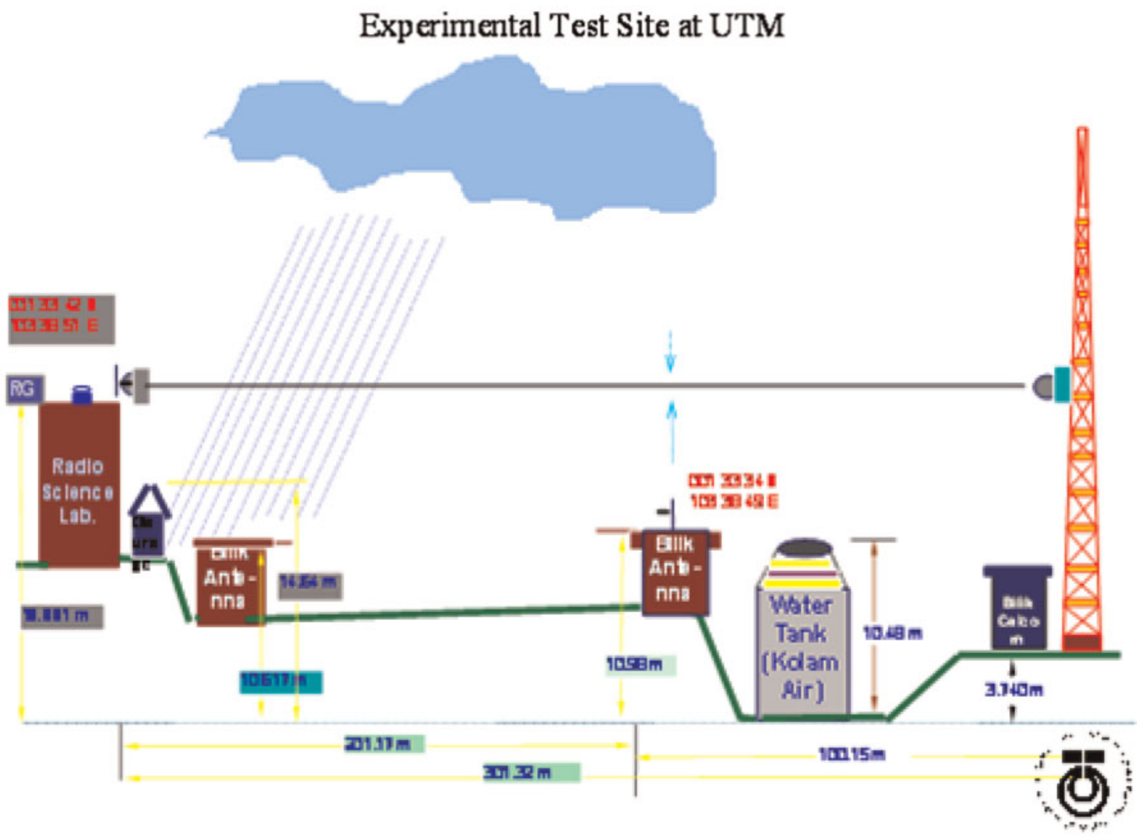

Fig. 1. Experimental setup for rain attenuation and rain rate measurements.

receive systems, A_R (dB) is the excess attenuation due to rain on propagation path and A_W (dB) is the wet antenna loss on both antennas during rain, i.e. ($A_{W,transmit}$+$A_{W,receive}$).

The free space loss, gaseous absorptions, and excess rain attenuation are all dependent on operating frequency, propagation path length, and the location of the link. The free space loss can be obtained from the Friis expression:

$$L_{fz}\,(\mathrm{dB}) = 32.4 + 20\log_{10}(L_{T_{km}}) + 20\log_{10}(F_{MHz}), \quad (3)$$

where L_T (km) is the path length and F (MHz) is the operating frequency. According to Recommendation ITU-R P.530-12, the predicted rain attenuation exceeded for p% of an average year is obtained from

$$A_{R_{\%p}} = \gamma_{R_{\%p}} L_T r_{d\%p} + A_W, \quad (4)$$

where $\gamma_{R\%p}$ is the specific attenuation (dB/km) and $r_{d\%p}$ is the reduction factor at the same p% of time. The value of $\gamma_{R\%p}$ depends on rain rate, $R_{\%p}$ exceeded at p% in an average year, and ITU-R parameters k and α that depend on frequency, raindrop size distribution, rain temperature, and polarization [17].

The effect of antenna losses due to rain on point-to-point microwave links and the technique of extracting the losses from the measured rain attenuation have been researched at UTM. Each of the four links uses a 2-feet parabolic dish antenna. Both transmit and receive antennas are horizontally polarized (that is, the elevation angle is nearly zero degrees) and they were covered with radome during rain attenuation measurement. The measured total attenuation data consist of the measured excess attenuation and wet antenna factor, which must be extracted in order to predict rain attenuation accurately. The wet antenna losses are expressed as the difference between the RSL of the dry antenna and the RSL of the

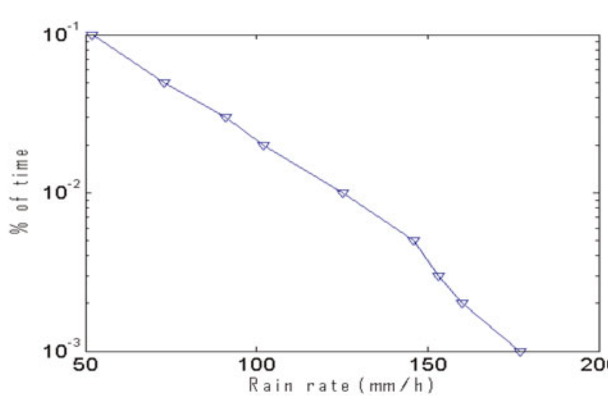

Fig. 2. Average measured rainfall rate CDF at UTM, Skudai UTM, Johor Bahru (4 years).

Table 2. Measured rain attenuation at 0.01% of the time for all four links.

Links	15 GHz	22 GHz	26 GHz	38 GHz
$A_{0.01}$(dB)	4.20	8.30	10.98	15.10

Table 3. Average measured rainfall rate at UTM.

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

wet antenna. That is,

$$A_W = RSL_{dry} - RSL_{wet} \quad (5)$$

The difference in the two measurements accounts for the wet antenna factor as clearly stated in equation (5). In order not to contaminate the rain attenuation analyses, if equation (5) is subtracted from equation (4), then the only remaining term on the RHS of equation (4) is the excess attenuation due to rain. The path reduction factor is also assumed to be unity since rain rate would be uniform along the path length (0.3 km), even though significant attenuation was recorded from direct measurement [18]. Gaseous absorptions are negligible at frequencies below 30 GHz. For instance the vapor absorption at 22 GHz is 0.16 dB/km. The losses in transmit and receive systems are also negligible in equation (2) with respect to free space loss (111.24 dB, at 15 GHz) and excess attenuation due to rain. Therefore the RSL can be calculated as follows:

$$RSL_{clear-air} = P_T + G_T + G_R - L_{fs}, \quad (6)$$

$$RSL_{rainy} = RSL_{clear-air} - \gamma_{R(\%p)} L_T r_{d(\%p)}. \quad (7)$$

Equation (7) represents the faded RSL due to rain and the second term on the RHS of the equation is equivalent to the rain-induced attenuation. The yearly average measured rain attenuation at 0.01% of the time $A_{0.01}$ have been provided in Table 2 for the four links. Therefore, the attenuation exceeded at other percentages of an average year, in the range of 0.001 – 0.1%, can be determined from the measured attenuation at 0.01% for an average year by using

$$A_{\%p} = 0.12^* A_{0.01}{}^* p^{(-(0.546+0.043+\log 10(p)))}. \quad (8)$$

The ITU-R predicted attenuation is obtained by substituting the values of measured rainfall rate CDF (see Fig. 2) in equation (4). Note that the second term A_w on the RHS of the equation is not considered in the ITU-R predictions.

IV. RESULTS AND DISCUSIONS

The comparison between measured rain attenuation CDF and ITU-R predictions are presented in Figs 3(a)–(d) for each of the four experimental links.

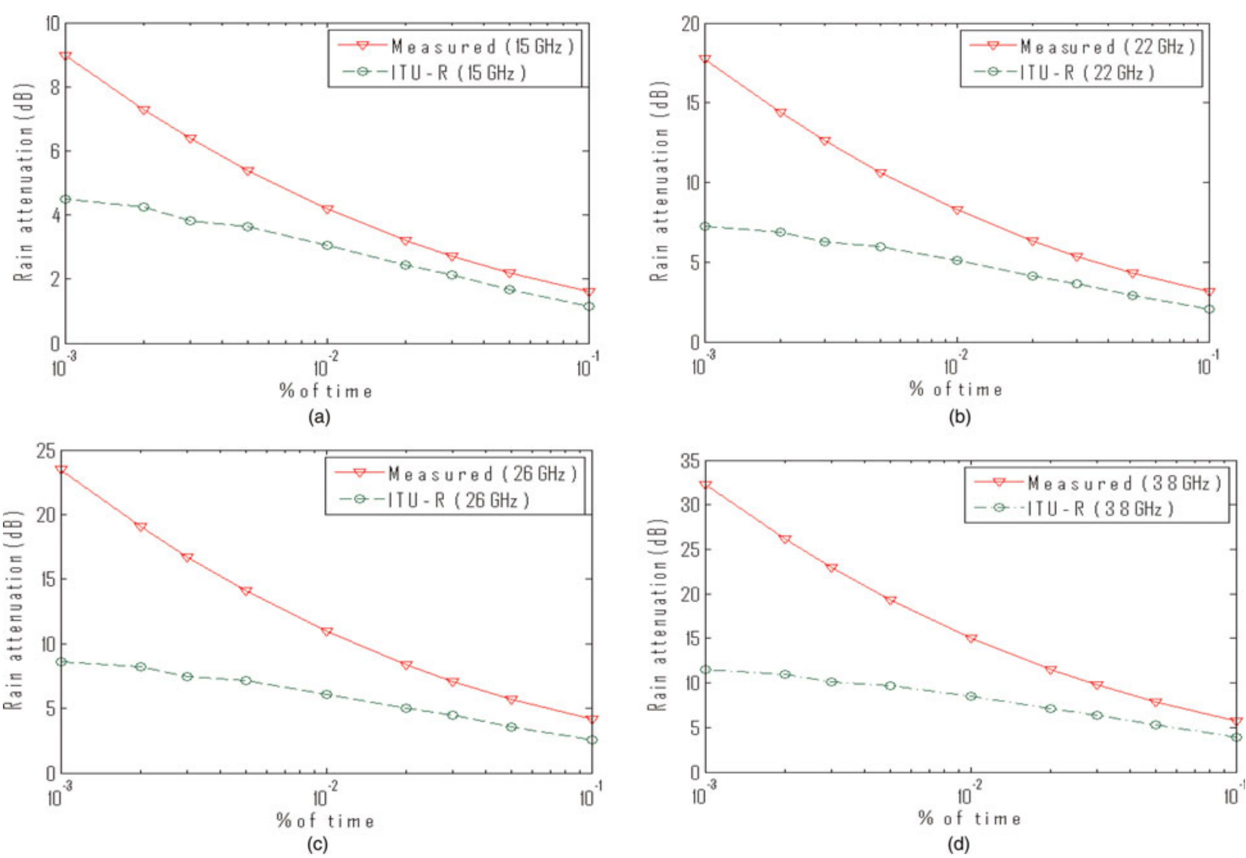

Fig. 3. Comparison of measured rain attenuation CDF with ITU-R predictions at: (a) 15 GHz, (b) 22 GHz, (c) 26 GHz and (d) 38 GHz.

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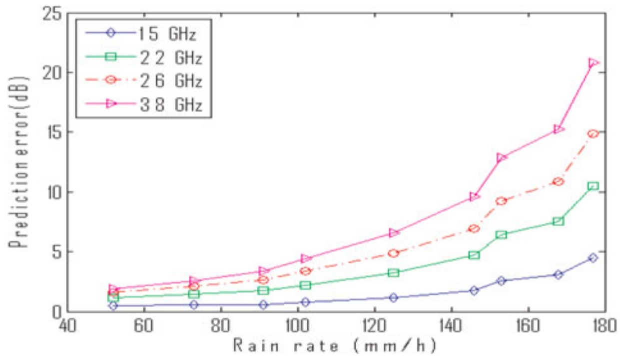

Fig. 4. Equal probability plots of measured rainfall rate and rain attenuation prediction errors.

Table 4. Regression coefficients.

Frequency (GHz)	k_1	k_2	k_3
15	0.00038	−0.059	2.7
22	0.00077	−0.110	5.2
26	0.00100	−0.140	6.7
38	0.00140	−0.200	8.8

As shown in Fig. 3, the measured rain attenuation is not in good agreement with the ITU-R predictions for all the four links. The predictions underestimate the measured rain attenuation at higher rain rates. For instance, at 0.01%, the measured rain attenuation values are 4.2, 8.3, 10.98, and 15.1 dB for the 15, 22, 26, and 38 GHz links, respectively. While the corresponding ITU-R predicted values are 3, 5.1, 6.1, and 8.5 dB, respectively. Moreover, the deviations are more pronounced at higher frequencies; for example, the deviations are approximately 5 and 6.5 dB at 26 and 38 GHz, respectively.

In order to investigate the relationship between these deviations in rain attenuation and rain rate, there is need to correlate their CDFs for the same %p of time. Figure 4 presents the equal probability plots of measured rainfall rate and the CDFs of the prediction errors for the four links. Based on the analyses of these results, it has been observed that the deviations (or prediction errors) between measured rain attenuation values and the ITU-R predictions could be modeled as a function of rain rate, $R_{\%p}$ at p% of time, as presented in Fig. 4.

The deviations are in the range of 0.48–4.52 dB at low rain rates (when $p \geq 0.1\%$), and 1.17–6.59 dB (when $p = 0.01\%$), depending on the link frequency. Worse still, significant deviations are observed at extremely high rain rates and higher frequencies. For instance at 0.001%, the values are as high as 4.52, 10.5, 14.86, and 20.79 dB, for the 15, 22, 26 and 38 GHz links, respectively. Further analyses have revealed that the deviations $\Delta A_{\%p}$ (dB) could be related to the rainfall rate $R_{\%p}$ exceeded at %p, according to the following quadratic function:

$$\Delta A_{\%p} = k_1 R_{\%p}^2 + k_2 R_{\%p} + k_3, \tag{9}$$

where k_1, k_2, and k_3 are regression parameters and their values depend on frequency and radio path length of the microwave link under consideration, as shown in Table 4. It is seen from the table that, coefficients k_1 and k_3 increase with increasing frequency, whereas k_2 decreases. Therefore, in order to improve ITU-R rain attenuation predictions for the Malaysian tropical climate, it is proposed that equation (9) should be added to the predicted values, as follows:

$$A_{\%predicted} = k\,\mathrm{R}_{\%p}^{\alpha} L_T \mathrm{r}_{\%p} + [k_1 R_{\%p}^2 + k_2 R_{\%p} + k_3]. \tag{10}$$

The Recommendations ITU-R P.311-13 [18] is employed for comparing the measured rain attenuation with ITU-R predictions, as shown in Table 5. The mean error μ_i, standard deviation σ_i, and root mean square (RMS) error of the ITU-R method for each of the four links are presented in the table. It can be seen from Table 5 that the mean error decreases with increasing frequency at respective time percentages, from 15 to 26 GHz; except at 38 GHz, when the values are a little bit higher than those of the preceding 26 GHz. On the other hand, the standard deviation and RMS increase as the frequency increases from 15 to 26 GHz, for the respective rainfall rates; except at 38 GHz again, when the values of standard deviation and RMS are a bit lower than those of the preceding 26 GHz.

The exception in the trend may be because of the fact that, in the computations of the mean error figures, the measured attenuation at 38 GHz is much greater than at 26 GHz. Since mean error is defined as the percentage ratio of prediction error to the measured attenuation, therefore, the denominator value by which the former is divided is much greater

Table 5. Percentage errors and RMS of ITU-R predictions.

Link (GHZ)	Parameter	Percentage of time								
		0.1	0.05	0.03	0.02	0.01	0.005	0.003	0.002	0.001
15	μ_i	−0.0323	−0.0265	−0.0239	−0.0271	−0.0303	−0.0362	−0.0447	−0.0464	−0.0554
	σ_i	0.3370	0.3365	0.3363	0.3366	0.3368	0.3374	0.3384	0.3387	0.3400
	RMS	0.3386	0.3376	0.3372	0.3376	0.3382	0.3394	0.3414	0.3418	0.3445
22	μ_i	−0.0392	−0.0363	−0.0354	−0.0389	−0.0430	−0.0489	−0.0562	−0.0580	−0.0656
	σ_i	0.4333	0.4330	0.4329	0.4332	0.4336	0.4342	0.4351	0.4354	0.4364
	RMS	0.4350	0.4345	0.4344	0.4350	0.4357	0.4370	0.4387	0.4392	0.4413
26	μ_i	−0.0431	−0.0413	−0.0413	−0.0448	−0.0491	−0.0549	−0.0615	−0.0634	−0.0703
	σ_i	0.4805	0.4804	0.4804	0.4807	0.4811	0.4817	0.4825	0.4828	0.4837
	RMS	0.4824	0.4821	0.4821	0.4828	0.4836	0.4848	0.4864	0.4869	0.4888
38	μ_i	−0.0358	−0.0366	−0.0383	−0.0429	−0.0487	−0.0554	−0.0622	−0.0645	−0.0715
	σ_i	0.4710	0.4711	0.4712	0.4716	0.4722	0.4729	0.4738	0.4741	0.4751
	RMS	0.4724	0.4725	0.4728	0.4736	0.4747	0.4762	0.4779	0.4785	0.4804

than that of the latter. However, the ITU-R prediction errors associated with the 38 GHz link is far greater than those of 26 GHz.

V. CONCLUSIONS

The rain-induced attenuation was measured on four experimental microwave links, operating at 15, 22, 26, and 38 GHz, at UTM, Skudai-campus, Malaysia. The experimental results seem to be underestimated by the ITU-R rain attenuation prediction model, even though the link length is as short as 0.3 km. This suggests that the deviations would be much larger for practical link lengths (greater than 0.3 km). The ITU-R prediction errors are tolerable at lower rain rates and lower frequencies, but they are more highly pronounced at higher rain rates and higher frequencies. One of the reasons for the difference may be because the 0.01% rain rate recommended by ITU-R P.837-5 is smaller compared to the actual measured value. It has been demonstrated that the deviations could be modeled as a function of rain rate, $R_{\%p}$, and that the regression coefficients depend on the microwave link under study. Note that the link dependence implicitly includes the link's operating frequency as well as the radio path length. It is expected that the study would provide useful information for rain attenuation predictions in Malaysia and other tropical climates that have similar situation.

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