Rain Attenuation Prediction Model for Satellite Communications in Tropical Regions

J. X. Yeo, Y. H. Lee, *Senior member, IEEE*, and J. T. Ong

***Abstract*—This paper proposes a model for predicting rain attenuation in the tropical region. Slant path rain attenuation measurements were carried out in Singapore by analyzing the beacon signals from two satellites, namely WINDS and GE23, operating at frequencies of 18.9 and 12.75 GHz respectively. Rainfall rates at the location of the beacon receivers were recorded. The cumulative distributions of the rainfall rate and the corresponding rain attenuation are presented and analyzed. It is found that the cumulative distribution of the measured rainfall rate is close to that predicted by the ITU-R model. Measurement data from a total of nine countries are compared with four existing rain attenuation prediction models, namely the Yamada, DAH, Karasawa and Ramachandran models. Results show that although three of these models have relatively good prediction capability for the tropical region, they could be improved. Therefore, in this paper, a slant path rain attenuation model suitable for the tropical region is proposed. This is done by using the complementary cumulative distributions of rain attenuation for satellite links measured in Singapore and five other tropical countries. The proposed model is found to outperform existing models.**

***Index Terms*—Rain Attenuation Model, Earth-Satellite Communication, Tropical Climate.**

I. Introduction

Propagation impairments that affect satellite links include gaseous absorption, cloud attenuation and rain fade in troposphere. Rain attenuation is considered as the dominant impairment as it gives rise to the largest amount of loss. This loss results in a degradation of the satellite to ground link and therefore affects the reliability and performance of satellite communication links [1]-[2]. As the frequency spectrum becomes increasingly crowded, satellite to ground communication links are shifting to higher frequencies, from C-band to the current Ku-band and Ka-band. However, path attenuation becomes much more severe in these higher-frequency bands. For example, according to the ITU-R model for specific attenuation [3], at a rainfall rate of 150 mm/hr that is not uncommon in the tropics, an attenuation of up to 14.5 dB/km is observed at 18.9 GHz in the Ka-band. The same rainfall rate causes a 5 dB/km attenuation at 12.5 GHz in the Ku-band. The amount of attenuation on satellite-to-ground slant path links not only depends on the rainfall rate and frequency, but also other factors such as elevation angle, slant path length, drop size distribution (DSD) and polarization. Therefore, in order to estimate the amount of rain attenuation on a satellite-to-ground slant path and to design cost effective satellite communication links in tropical regions, an accurate rain attenuation prediction model is essential.

Rain attenuation prediction models can be categorized into empirical and semi-physical models. An empirical model is constructed based on the statistical fitting of the measurement database. A physical model attempts to reproduce the physical behavior involved in the attenuation process [4]. Several rain attenuation prediction models have been developed based on measurement data collected from temperate regions. Most of these existing models do not perform well in high rainfall rate regions, such as the tropics.

The Bryant model [5], SC EXCELL model [6], and Crane two-component model [7] are examples of physical rain attenuation prediction models. Crane's two-component model distinguishes between the attenuation due to convective rain cells and the widespread debris that surround the cell. The model assumes the vertical profile of rainfall rate to be uniform. The SC-EXCELL model considers the effect of convective and stratiform rain separately and is based on the older EXCELL model [8, 9]. The Bryant model uses the concept of breakpoint in the rainfall rate exceedance curve. The attenuation exceedances depend on the shape of the measured rainfall rate exceedance curve. Two recent models from Greece [10, 11] suggest that rainfall rate and rain attenuation can be modelled with an inverse Gaussian (IG) or Gamma distribution, the latter exhibiting a better fit. Since the semi-physical models use the statistics of measured rain rate together with some site specific physical parameters, they show better prediction ability. However, not all the site specific physical parameters are available. Therefore, most of the widely accepted models for the prediction of slant path rain attenuation are empirical models instead of semi-physical models.

The ITU-R model is currently widely used by many researchers. ITU-R P.618-5 [12], also known as Yamada model [13], tends to underestimate the rain attenuation in the tropics since it was developed based mainly on measurement data from temperate regions. ITU-R P.618-11 [14], the DAH model [15], is the latest rain attenuation model recommended by ITU-R. It has a very good prediction performance for rain attenuation in temperate countries. However, this model tends to underestimate attenuation in the tropics [1, 2, 16-18]. Therefore, several rain attenuation prediction models were proposed especially for the tropical region. Karasawa's model [19] was accepted by the European Space Agency as a suitable model for the tropics. It was designed to enhance the prediction performance at lower probability exceedance levels. The Ramachandran model [20] is a modified version of the

Manuscript received xxx xx, 201x; revised xxxxx, 201x.

The authors are with the Division of Communications Engineering, School of Electrical and Electronic Engineering, Nanyang Technological University. (e-mail: jxyeo@ntu.edu.sg).

DAH model that uses the concept of a 'breakpoint'. At the breakpoint of exceeding 0.01% of time in the DAH model, this point is changed to exceeding 0.021% of time. By introducing this 'breakpoint', the Ramachandran model achieves a better prediction performance for the tropical region than the DAH model.

In this paper, the results of rain attenuation on both Ku-band and Ka-band satellite links in the tropical region are analyzed. The measured statistics of experimental results from nine tropical countries are compared with the four rain attenuation prediction models discussed above. The analysis shows that the existing models do not predict the slant path rain attenuation accurately. Therefore, based on the extensive satellite link measurement data mentioned above, a systematic approach is used to propose a rain attenuation model for the tropical region. This proposed model achieves high accuracy in the tropical climate and can be used to predict the cumulative distribution of rain attenuation.

II. System Description

A. Beacon Receiver Systems

The analysis of earth-satellite path rain attenuation is performed based on two sets of beacon rain attenuation measurements from WINDS and GE23 geostationary satellites, respectively. The measurement site is located at Nanyang Technological University (NTU) in Singapore (lat: 1.34˚ N, lon: 103.68˚ E).

The beacon signal from the "KIZUNA" Wideband InterNetworking engineering test and Demonstration Satellite (WINDS) satellite, located at 143˚E, has a frequency of 18.9 GHz, an elevation angle of 44.5˚, and is left-hand circularly polarized. The beacon signal from the General Electric 23 (GE23) satellite, located at 172˚E, has a frequency of 12.75 GHz, an elevation angle of 13.2˚, and is linearly polarized.

The WINDS beacon signal is recorded continuously by the beacon receiver at an average sampling rate of 516 samples per minute. The dynamic range of attenuation of the measurement is approximately 40 dB below the clear sky level [21]. The GE23 beacon signal is sampled at a rate of 43 samples per minute with an approximate dynamic range of 25 dB below the clear sky level.

All the measured beacon signals undergo a 6^{th}-order Butterworth low-pass filtering with the cutoff frequency of 40 mHz in order to remove spurious signals and scintillations [1]. Subsequently, rain attenuation data is obtained by measuring the difference in beacon signal strength during the rain event and 30 minutes before, in order to minimize the attenuation due to gaseous absorption, cloud and melting layer. A comparison of the rain attenuation measured by the beacon receivers with that simulated by Radar data shows a good match [22].

B. Weather Station

A weather station (Davis Instruments 7440 Weather Vantage Pro II) with tipping bucket rain gauge, anemometer, and solar sensor is installed beside the beacon receivers. It records weather data every minute including temperature, humidity, dew point, pressure, surface wind speed and direction, rainfall rate, solar radiation and solar energy. The resolution of the tipping-bucket rain gauge is 0.2 mm/tip. Hence, the equivalent rainfall rate step size per tip is 12 mm/hr.

III. Experimental Results

A. Rain-rate Analysis

The rainfall rate data from the years 2009 to 2012 are recorded by the tipping bucket rain gauge of the weather station. The yearly complimentary cumulative distribution functions (CCDF) of 4 years rainfall rate are shown in Fig. 1. The experimental measured statistics are compared with the ITU-R P.837-5 model [23]. Fig. 1 shows that the CCDF of rainfall rate predicted by the ITU-R model matches well with the measured data in the tropical region. The rainfall rate at 0.01% of the time, $R_{0.01}$, is about 106 mm/hr. This parameter will be used in the rain attenuation prediction model. For sites where $R_{0.01}$ is unknown, the ITU-R P.837-5 can be used to estimate the $R_{0.01}$ rainfall rate parameter. In this paper, the experimental measured rainfall rate will be used in the rest of analysis.

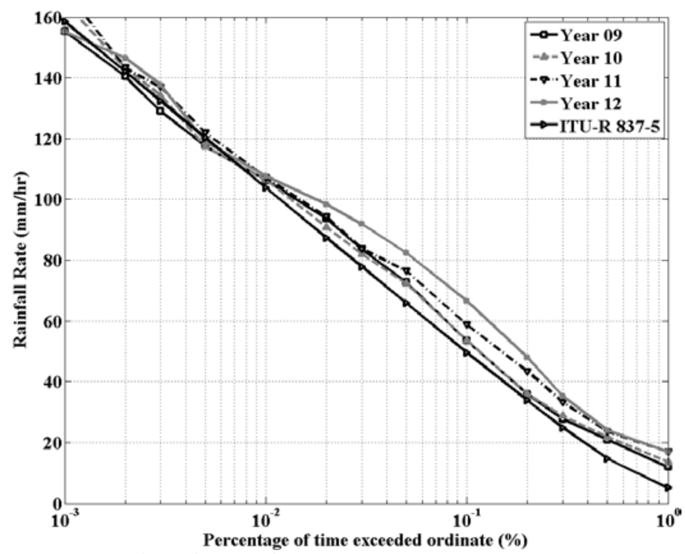

Fig. 1. CCDF of Rainfall Rate from the Year 2009 to 2012.

B. Rain Attenuation Analysis

The beacon signals from WINDS and GE23 satellites are recorded continuously from 2009 to 2012. However, due to the high system down time for the beacon receiver of the WINDS satellite in the year 2012, only 2009-11 are used in the analysis of rain attenuation.

The three year CCDF of rain attenuation along the WINDS propagation path is shown in Fig. 2. The CCDF is compared with ITU-R P.618-11 [14], which is also known as the DAH model. The yearly CCDFs are close to each other because of the similar rainfall distribution throughout the years. The DAH model can predict better at low attenuation (below 10 dB, below 0.5% of time) but tends to underestimate the higher attenuation (above 10 dB, above 0.5% of time). That may be due to the fact that the DAH model is based mainly on a rain attenuation database from the temperate region.

Rain events in the temperate region are mainly stratiform rain, commonly associated with lower rainfall rates. Rain events in the tropical region on the other hand are mainly convective rain and therefore commonly associated with high rainfall rates. More than 80% of the rain events in Singapore are convective [24]. Note that the dynamic range of the WINDS beacon receiver is about 40 dB, which is high enough to prevent saturation effects for the percentage of time larger than 0.01%.

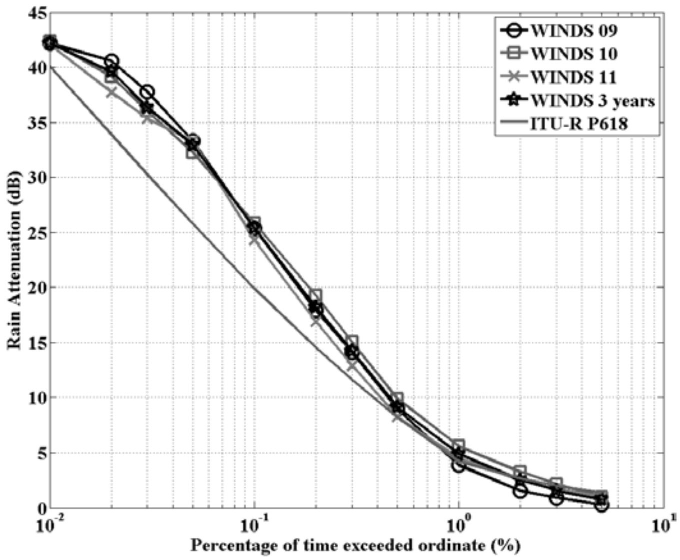

Fig. 2. CCDF of WINDS Attenuation from the Year 2009 to 2011.

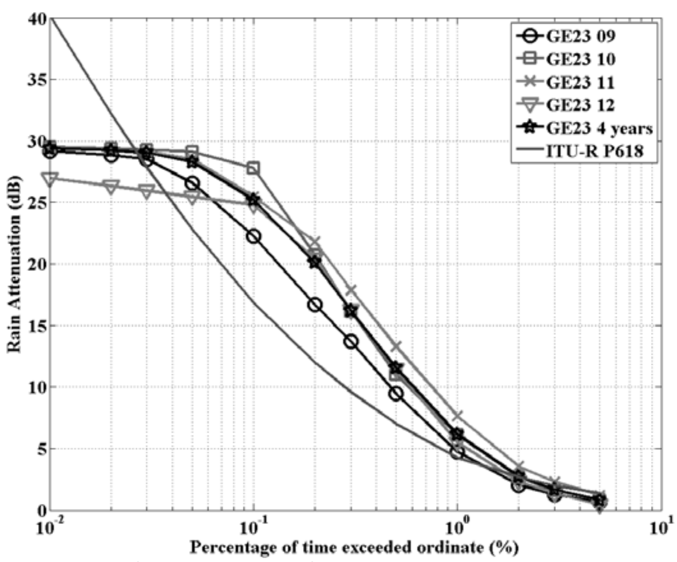

Fig. 3. CCDF of GE23 Attenuation from the Year 2009 to 2012.

CCDF of rain attenuation for four years suffered by the GE23 propagation path are shown in Fig. 3. Since the dynamic range of the spectrum analyzer used to record the GE23 beacon signal is about 25 dB, the CCDF saturates above the 25 dB level and should not be considered for analysis and modeling. Similarly for the WINDS link, the ITU-R model underestimates the attenuation of the GE23 link.

IV. Proposed Model

A. Model Description

The proposed rain attenuation prediction model is similar to the ITU-R model where the rainfall rate at 0.01% of probability level is used as one of the inputs to the model. Due to the inhomogeneity in rainfall along the slant propagation path, a path adjustment factor is used to account for this in the prediction model [15]. The attenuation exceeded for 0.01% of an average year can then be obtained as:

$$A_{0.01} = k\, R_{0.01}{}^{\alpha} \cdot L_S \cdot r \qquad (1)$$

where the frequency, link elevation and polarization dependent factors of k and α can be calculated from the equations for the ITU-R P.838-3 model [3]; $R_{0.01}$ is the rainfall rate exceeded for 0.01% probability level of an average year; L_S is the slant path length (km); and r is the path adjustment factor.

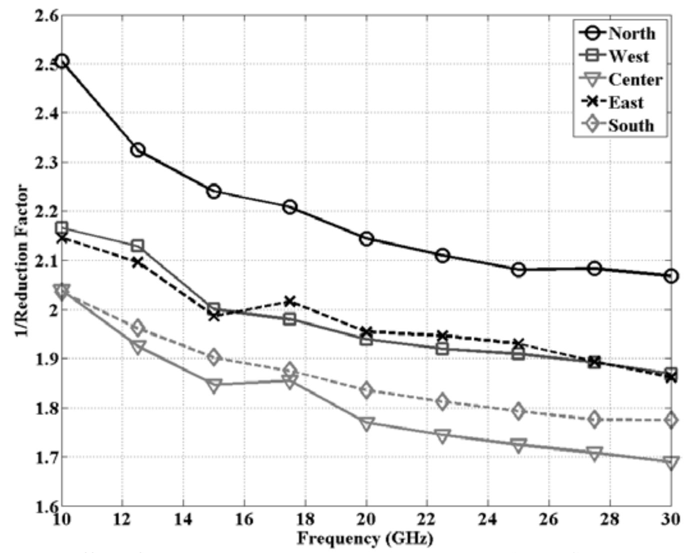

Fig. 4. Effect of Frequency on the Path Adjustment Factor (θ = 50˚).

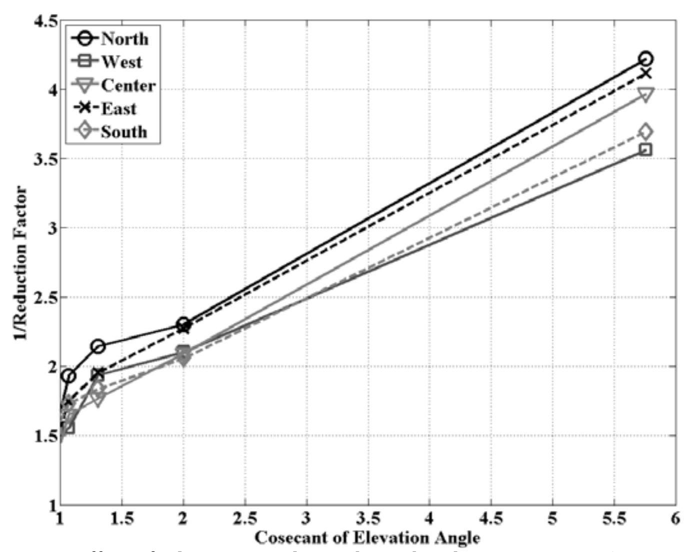

Fig. 5. Effect of Elevation Angle on the Path Adjustment Factor (F = 20 GHz).

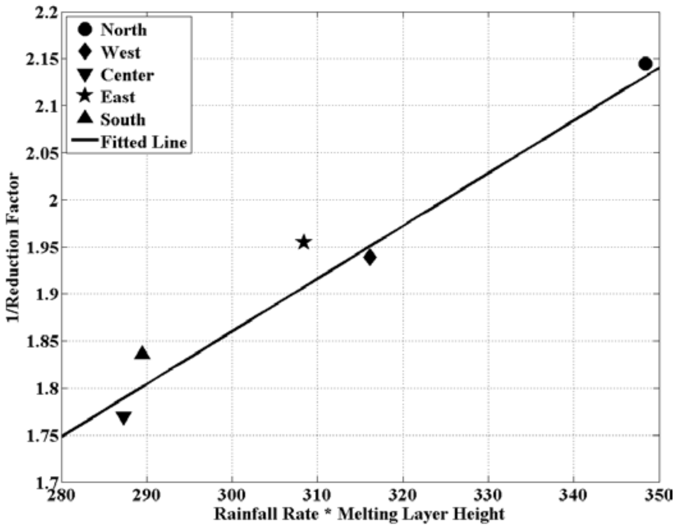

Fig. 6. Effect of Rainfall Rate and Rain Height on the Path Adjustment Factor (F = 20 GHz, θ = 50˚).

The frequency, path elevation angle and the point rainfall rate at the measurement site are expected to affect the value of the path adjustment factor, r. Radar data is used to find the relationship of r with these factors. As shown in [24], the rainfall rate and slant path attenuation can be calculated from the Radar reflectivity data. Therefore, the path adjustment factor of any propagation path can be obtained by:

$$r_{measured} = \frac{A_{0.01}}{k\, R_{0.01}{}^{\alpha} \cdot L_S} \quad (2)$$

Five measurement sites in different parts of Singapore, namely North, West, Center, East and South, are used to calculate the path adjustment factor. The Radar reflectivity along the earth-space path with elevation angles of 10˚, 30˚, 50˚, 70˚ and 90˚ at the 5 stations are extracted to calculate the attenuation for different frequencies. The frequency ranges from 10 GHz to 30 GHz at intervals of 2.5 GHz are examined.

Fig. 4 shows the effect of frequency on the adjustment factor for a constant elevation angle of 50˚. Fig. 5 shows the effect of elevation angle on the adjustment factor when the frequency is fixed at 20 GHz. Fig. 6 shows the effect of rainfall rate and rain height on the adjustment factor for elevation angle kept constant at 50˚ and frequency, at 20 GHz. As shown in the figures, it is found that the inverse of the adjustment factor is related linearly to the frequency (F, GHz) [Fig. 4], cosecant of the elevation angle (θ, deg) [Fig. 5], and also to the product of rainfall rate at 0.01% of time ($R_{0.01}$, mm/hr) and rain height (H, km) [Fig. 6]. Therefore, the path adjustment factor can be deduced as:

$$r_{proposed} = \frac{1}{\frac{a_1}{\sin\theta} + a_2 R_{0.01} \cdot (H - H_S) - a_3 F + a_4} \quad (3)$$

where H_S is the altitude of the ground site above sea level (km).

B. Model Parameters

The proposed model is derived based on measurement data from 6 tropical countries, namely, Brazil, Papua New Guinea, Indonesia, Malaysia, Thailand, and Singapore. The details of the measurement setup for the data collected are summarized in Table 1. The remaining data sources in Table 1, i.e. from Cameroon, Nigeria and the Netherlands, will be used as test sets to verify the performance of the proposed model. The data from the Netherlands is used to represent data from the temperate region.

By performing a least squares fitting to the 8 sets of measurement data, the constants of Eq. (3) are obtained to be:

$$a_1 = 0.3979,\ a_2 = 0.0021, a_3 = 0.0185, a_4 = 0.2337.$$

It should be noted that r should not be greater than 1, and so if $r > 1$, then $r = 1$.

Similar to the ITU-R model, the attenuation to be exceeded for other percentage of an average year (p) can be estimated from:

$$A_P = A_{0.01} \cdot \left(\frac{p}{0.01}\right)^{b_1 + b_2 \ln p + b_3 \ln A_{0.01} + \beta(1-p)\sin\theta} \quad (4)$$

where $b_1 = -1.0063, b_2 = -0.0591, b_3 = 0.1317,$

$$\beta = \begin{cases} 0 & \text{, if } p \geq 1\% \text{ or } |\varphi| \geq 36^\circ \\ -0.0055(|\varphi| - 36) & \text{, if } p < 1\% \text{ and } |\varphi| < 36^\circ \text{ and } \theta \geq 25^\circ \\ -0.0055(|\varphi| - 36) - 1.7008 + 7.8503 \sin\theta & \text{, Otherwise} \end{cases}$$

where φ is the latitude of the measurement site.

TABLE 1: MEASUREMENT SITES CHARACTERISTICS

	LAT (N)	F (GHZ)	ELE (DEG)	$R_{0.01}$ (MM/HR)	DURATION (YEARS)
BRAZIL (BELEM) [25]	-1.45	11.452	89	123	4
BRAZIL (RIO DE JANEIRO) [25]	-22.92	11.452	63	77	4
PAPUA NEW GUINEA (LAE) [26]	-7	12.75	72.8	110	4
INDONESIA (BANDUNG) [27]	-6.9	12.25	64.7	120	2
MALAYSIA (USM) [20]	4.37	12.26	40.0	115	2
THAILAND (KMITL) [28]	13.7	12.74	54.8	122	2
SINGAPORE (NTU, WINDS)	1.34	18.9	44.5	106	3
SINGAPORE (NTU, GE23)	1.34	12.75	13.2	106	4
CAMEROON [29]	4.05	11.6	47	102	1
NIGERIA [30]	7.33	11.6	48.3	81	1
NETHERLANDS, EINDHOVEN [15]	51.45	29.7	26.9	31	1

The step-by-step procedure of the proposed rain attenuation prediction model is given in the appendix at the end of the paper.

V. RESULTS AND DISCUSSION

In order to compare the performances of the prediction models, the errors between the beacon measured attenuation and the attenuations predicted from the five models are shown in Tables 2. The statistics of the attenuation difference are calculated based on the formula in ITU-R Rec. P.311-13 [31]. The numbers listed in Table 2 are the RMS error between the model and the measured data. Each model is given a ranking based on its fitness. Amongst the five models, the best model with lowest root mean square (RMS) error will have the ranking score of 5, whereas the worst model will have a ranking score of 1. The ranking scores are shown in the brackets that besides the values of RMS error.

The Yamada model has the worst prediction performance. The average RMS error of this model is the highest value at only 0.35, with the overall performance score of 17. This is as expected since the ITU-R replaced the Yamada model with the DAH model due to its poor performance.

The Karasawa model only has a poor prediction performance with the score of 15 (average RMS error of 0.34), even though it was designed for the tropical region. The Ramachandran model has a correction factor that depends on the elevation angle of the path. However, the formula of the correction factor is only applicable for elevation angles greater than 16.1˚. Therefore, the model has a large prediction error for the GE23 satellite path with elevation angle of 13.2˚ in Singapore as shown in Table 2. Otherwise, in general, the Ramachandran model achieves a good prediction performance, with best results for Papua New Guinea and Nigeria. Therefore, the overall score of the Ramachandran model is 28, with an average RMS error of 0.20 (excluding the site Singapore-GE23 because of the low elevation).

TABLE 2: ROOT MEAN SQUARE (RMS) ERROR OF MODELS PREDICTED ATTENUATION WITH BEACON MEASURED ATTENUATION

	YAMADA	DAH	KARASAWA	RAMACHANDRAN	PROPOSED
BRAZIL (BELEM)	0.40 (2)	0.19 (3)	0.45 (1)	0.17 (4)	**0.12 (5)**
BRAZIL (RIO DE JANEIRO)	0.25 (3)	0.32 (1)	0.26 (2)	0.19 (4)	**0.12 (5)**
PAPUA NEW GUINEA (LAE)	0.24 (2)	0.12 (4)	0.31 (1)	**0.10 (5)**	0.13 (3)
INDONESIA	0.20 (2)	0.17 (4)	0.23 (1)	**0.12 (5)**	0.17 (3)
MALAYSIA (USM)	0.47 (2)	0.54 (1)	0.43 (3)	**0.25 (5)**	0.28 (4)
THAILAND (KMITL)	0.28 (3)	**0.07 (5)**	0.29 (2)	0.32 (1)	0.25 (4)
SINGAPORE (NTU, WINDS)	0.37 (1)	0.20 (4)	0.28 (2)	0.25 (3)	**0.05 (5)**
SINGAPORE (NTU, GE23)	0.61 (2)	**0.11 (5)**	0.50 (3)	3.38 (1)	0.15 (4)
AVERAGE (TOTAL SCORE)	0.35 (17)	0.21 (27)	0.34 (15)	0.20 (28)	**0.16 (33)**

The DAH model is the most widely accepted global model of rain attenuation. It is the best empirical model that scored highest for the ITU-R rain attenuation data bank [32]. This model tends to underestimate the high rain attenuation in tropical region. However, due to the large data bank used to establish this model, including various tropical data, this model tends to perform relatively well with an overall performance score of 27 (average RMS error of 0.21).

Our proposed model has the highest overall performance score of 33 and lowest RMS error of 0.16. With its systematically derived path reduction factor, our model is highly accurate and best matches the measurement data in the tropics. As shown in Tables 2, it outperforms the other models almost everywhere. It has the lowest average RMS error of 0.16 and the best prediction performance in Brazil, Malaysia, and Singapore.

VI. VERIFICATION OF PROPOSED MODEL

In order to verify the prediction performance of the proposed model in other tropical countries and the temperate region, Fig. 7-9 show the CCDF of measured and predicted rain attenuation at Cameroon, Nigeria and Eindhoven as listed in Table 1.

The DAH model tends to underestimate the measured rain attenuation for Cameroon [Fig. 7], whereas the Ramachandran model overestimates the rain attenuation. The Yamada, Karasawa, and proposed models have the best prediction performance. A similar conclusion is drawn from Fig. 8 for Nigeria. The average RMS errors of the Yamada, DAH, Karasawa, Ramachandran, and proposed models are 0.17, 0.31, 0.16, 0.22 and 0.13 respectively. Again, the proposed model outperforms all others in tropical regions.

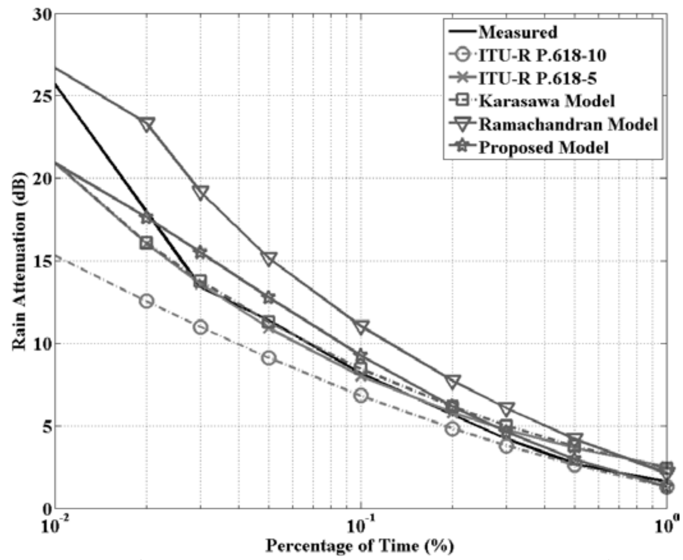

Fig. 7. CCDF of Rain Attenuation at Cameroon (F = 11.6 GHz; θ = 47˚).

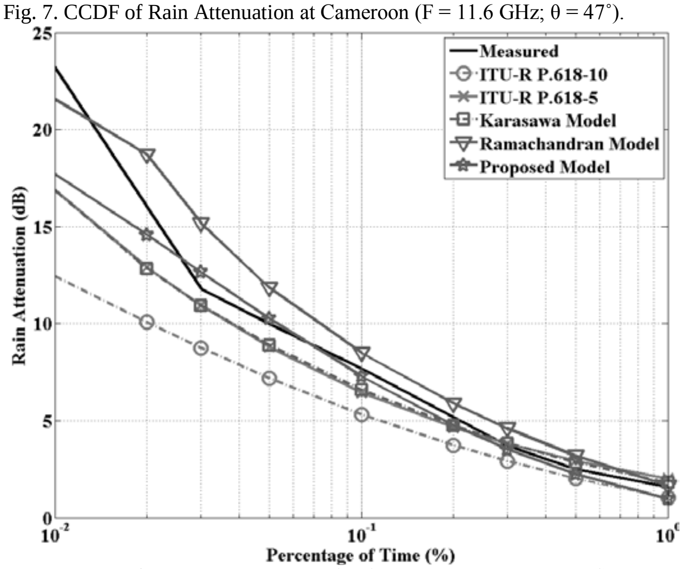

Fig. 8. CCDF of Rain Attenuation at Nigeria (F = 11.6 GHz; θ = 48.3˚).

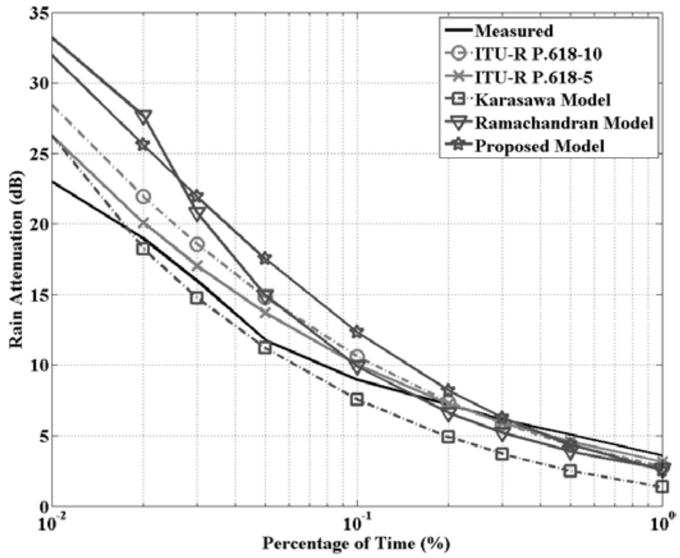

Fig. 9. CCDF of Rain Attenuation at Eindhoven (F = 29.7 GHz; θ = 26.9˚).

The ITU-R models (DAH and Yamada) do well in the temperate climate as shown in Fig. 9 for the data from Eindhoven. The average RMS errors of the Yamada, DAH, Karasawa, Ramachandran, and proposed models are 0.09, 0.16, 0.39, 0.25 and 0.25 respectively. The proposed model ranks third amongst five models, as it tends to overestimate rain attenuation in the temperate region.

VII. Conclusions

In this paper, an accurate rain attenuation prediction model is proposed for the tropical climate. Rainfall rate and rain attenuation measurements for the tropical region in both the Ka-band (WINDS) and Ku-band (GE23), together with measurement data from five other tropical countries were used to design the model. The path reduction factor is found to be dependent on the elevation angle, rainfall rate at 0.01% of time, rain height, and frequency. It was derived systematically by allowing only one of these parameters to vary at any point in time.

The measured rain attenuation is compared with the proposed rain attenuation model and four existing rain attenuation prediction models (Yamada, DAH, Karasawa, and Ramachandran). The Yamada model has the worst prediction result for all measurement results obtained from the tropical region. Both the Karasawa model and the Ramachandran model can predict the rain attenuation in the tropical region fairly well. The DAH model tends to underestimate the rain attenuation from convective rain events with very high rainfall rate as is common in the tropical region. However, due to the large data bank used to derive this model, the DAH model performs well.

After testing our proposed model and four existing models on data from eight tropical countries, the model proposed in this paper is found to be the best. Furthermore, the proposed model is easy to implement by using only rainfall rate at 0.01% percentage of time, $R_{0.01}$, from either the local measured rainfall rate data or ITU-R P.837-5 model.

Acknowledgment

The research presented in this paper was funded by Defence Science and Technology Agency (DSTA).

References

[1] Y. H. Lee, J. X. Yeo, and J. T. Ong, "Rain attenuation on satellite to ground link for beacon," 27th International Symposium on Space Technology and Science (ISTS 2009), July 2009.
[2] J. X. Yeo, Y. H. Lee, and J. T. Ong, "Ka-band satellite beacon attenuation and rain rate measurements in Singapore - comparison with ITU-R models," IEEE AP-S International Symposium on Antennas and Propagation, June 2009.
[3] ITU-R: "Specific attenuation model for rain for use in prediction methods," Recommendation ITU-R P. 838-3, Geneva, 2005.
[4] L. D. Emiliani, J. Agudelo, E. Gutierrez, J. Restrepo and C. F. Mendez, "Development of rain attenuation and rain-rate maps for satellite system designin the Ku and Ka Bands in Colombia", IEEE Antennas and Propagation Magazine, vol. 46, no. 6, pp. 54-68, 2004.
[5] G. F. Bryant, I. Adimula, C. Riva, and G. Brussaard, "Rain attenuation statistics from rain cell diameters and heights", International Journal of Satellite Communications, vol. 19, pp. 263-283, 2001.
[6] C. Capsoni, L. Luini, A. Paraboni, C. Riva, and A. Martellucci, 2009, "A new prediction model of rain attenuation that separately accounts for stratiform and convective rain", IEEE Transactions on Antennas and Propagation, vol. 57, no. 1, pp. 196-204, January 2009.
[7] R. K. Crane, "A two-component rain model for the prediction of attenuation statistics", Radio Science, vol. 17, no. 6, pp. 1371-1387, 1982.
[8] C. Capsoni, F. Fedi, C. Magistroni, A. Paranoni, and A. Pawlina, "Data and theory for a new model of the horizontal structure of rain cells for propagation applications," Radio Sci., vol. 22, no. 3, pp. 395-404, May-June 1987.
[9] C. Capsoni, F. Fedi, and A. Paranoni, "A comprehensive meteorologically oriented methodology for the prediction of wave propagation parameters in telecommunication applications beyond 10 GHz," Radio Sci., vol. 22, no. 3, pp. 387-393, May-June 1987.
[10] S. A. Kanellopoulos, A. D. Panagopoulos, C. I. Kourogiorgas, and J. D. Kanellopoulos, "Satellite and terrestrial links rain attenuation time series generator for heavy rain climatic regions", IEEE Transactions on Antennas and Propagation, vol. 61, no. 6, pp. 3396-3399, June 2013.
[11] C. I. Kourogiorgas, A. D. Panagopoulos, " A new physical-mathematical model for predicting slant-path rain attenuation statistics based on Inverse Gaussian distribution'", IET Microwaves, Antennas & Propagation, vol. 7, no. 12, pp. 970-975, 2013.
[12] ITU-R: "Propagation data and prediction methods required for the Design of earth-space telecommunication systems," Recommendation ITU-R P. 618-5, Geneva, 1997.
[13] Yamada, M., Y. Karasawa, and M. Yasunaga, "An improved prediction method for rain attenuation in satellite communication operating at 10–20 GHz," Radio Science, vol. 22, no. 6, 1053–1062, 1987.
[14] ITU-R: "Propagation data and prediction methods required for the design of earth-space telecommunication systems," Recommendation ITU-R P. 618-11, Geneva, 2013.
[15] A. Dissanayake, J. Allnutt and F. Haidara, "A prediction model that combines rain attenuation and other propagation impairments along earth-satellite paths", IEEE Transactions on Antennas and Propagation, vol. 45, no. 10, pp. 1546-1558, 1997.
[16] T.Boonchuk, N.Hemmakorn, P.Supnithi, M.Iida, K.Tanaka, K.Igarashi and Y.Moriya: "Rain Attenuation of Satellite link in Ku-band at Bangkok", *International Conference on Information, Communications and Signal Processing ICICS 2005*, pp. 1093-1095, 2005.
[17] D. Lakanchanh, A. Datsong, N. Leelaruji and N. Hemmakorn: "Rainfall Rate and Rain Attenuation in Ku-Band Satellite Signal in Thailand and Laos", *SICE-ICASE International Joint Conference 2006*, pp. 3928-3932, 2006.
[18] S. J. S. Mandeep, S. I. S. Hassan, M. F. Ain, F. Ghani, I. Kiyoshi, T. Kenji and I. Mitsuyoshi: "Earth-To-Space Improved Model for Rain Attenuation Prediction at Ku-Band", *American Journal of Applied Sciences 3 (8)*, pp. 1967-1969, 2006.

[19] Y. Karasawa, "Consideration on prediction methods or rain attenuation on earth-space paths", CCIRIWP 5/2, Document 89/18, Japan, April 14, 1989.
[20] V. Ramachandran and V. Kumar, "Modified rain attenuation model for tropical regions for Ku-Band signals", International Journal of Satellite Communications and Networking, vol. 25, pp. 53-67, 2007.
[21] C.J. Kikkert, B. Bowthorpe, and Ong Jin Teong, "A DSP based satellite beacon receiver and radiometer", in Asia Pacific Microwave Conference, Yokohama, Japan, 8-11 December 1998.
[22] J. X. Yeo, Y. H. Lee, L. S. Kumar, and J. T. Ong, "Comparison of S-Band radar attenuation prediction with beacon measurements", IEEE Transactions on Antennas and Propagation, vol. 60, no. 10, October 2012.
[23] ITU-R, "Characteristics of precipitation for propagation modeling," Recommendation ITU-R P.837-5, Geneva, 2007.
[24] J. X. Yeo, Y. H. Lee and J. T. Ong, "Performance of site diversity investigated through Radar derived results", IEEE Transactions on Antennas and Propagation, vol. 59, no. 10, pp. 3890-3898, 2011.
[25] M. S. Pontes, E. C. de Miranda, L. A. R. da Silva Mello, R. S. L. de Souza and M. P. C. de Almeida, "Rainfall-induced satellite beacon attenuation in tropical and equatorial regions," Electronics Letters, vol. 39, no. 11, pp. 874-876, 2003.
[26] Qingwei Pan, G. H. Bryant, John McMahon, J. E. Allnutt and Fatim Haidara, "High elevation angle satellite-to-earth 12 GHz propagation measurements in the tropics," International Journal of Satellite Communications, vol. 19, pp. 363-384, 2001.
[27] J. Suryana, S. Utoro, K. Tanaka, K. Igarashi, and M. Iida, "Two years characterization of concurrent Ku-band rain attenuation and tropospheric scintillation in Bandung, Indonesia", International Conference on Information, Communications and Signal Processing (ICICS), pp. 1585-1589, 2005.
[28] J. S. Mandeep and S. I. S. Hassan, "Slant-path rain attenuation predictions in tropical regions," Journal of Atmospheric and Solar-Terrestrial Physics, vol. 68, pp. 865-868, 2006.
[29] D. K. McCarthy, J. E. Allnutt, W. E. Salazar, F. Wanmi, M. Tchinda, T. D. G. Ndinaya and C. Zaks, "Results of 11.6 GHz radiometric experiment in Cameroon: Second year," Electronics Letters, vol. 30, no. 17, pp. 1449-1450, 1994.
[30] D. K. McCarthy, J. E. Allnutt, W. E. Salazar, E. C. Omeata, B. R. Owalabi, T. Oladiran, E. B. Ojeba, G. O. Ajayi, T. I. Raji and C. Zaks, "Results of 11.6 GHz radiometric experiment in Nigeria: Second year," Electronics Letters, vol. 30, no. 17, pp. 1452-1453, 1994.
[31] ITU-R: "Acquisition, presentation and analysis of data in studies of tropospheric propagation", Recommendation ITU-R P. 311-13, Geneva, 2009.
[32] A. Paraboni, "Testing of rain attenuation prediction methods against the measured data contained in the ITU-R data bank," ITU-R Study Group 3 Document, SR2-95/6, Geneva, Switzerland, 1995.

Jun Xiang Yeo received the B. Eng. (Hons.) degrees in electrical and electronics engineering from the Nanyang Technological University, Singapore, in 2007. He is currently working toward the Ph.D. degree in the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore.

His research interests include the study of the effects of rain on performance of satellite communication and the mitigation technique to counteract rain fades.

Yee Hui Lee (S'96–M'02) received the B. Eng. (Hons.) and M. Eng. degrees in School of Electrical and Electronics Engineering from the Nanyang Technological University, Singapore, in 1996 and 1998, respectively, and the Ph.D. degree from the University of York, York, U.K., in 2002.

Dr. Lee is currently Associate Professor and Assistant Chair (Student) of the School of Electrical and Electronic Engineering, Nanyang Technological University, where she has been a faculty member since 2002. Her interests are channel characterization, rain propagation, antenna design, electromagnetic bandgap structures, and evolutionary techniques.

Jin Teong Ong received the B.Sc. (Eng.) degree from London University, London, U.K., the M.Sc. degree from University College, London, and the Ph.D. degree from Imperial College London, London.

He was with Cable & Wireless Worldwide PLC from 1971 to 1984. He was an Associate Professor with the School of Electrical and Electronic Engineering, Nanyang Technological (now Nanyang Technological University), Singapore, from 1984 to 2005, and an Adjunct Associate Professor from 2005 to 2008. He was the Head of the Division of Electronic Engineering from 1985 to 1991. He is currently the Director of research and technology of C2N Pte. Ltd.—a company set up to provide consultancy services in wireless and broadcasting systems. His research and consultancy interests are in antenna and propagation—in system aspects of satellite, terrestrial, and free-space optical systems including the effects of rain and atmosphere; planning of broadcast services; intelligent transportation system; EMC/I; and frequency spectrum management.

Dr. Ong is a member of the Institution of Engineering and Technology.

APPENDIX: STEP-BY-STEP PROCEDURE FOR ATTENUATION PREDICTION

Step 1: the path adjustment factor, r, can be deduced as:

$$r = \frac{1}{\frac{-0.3979}{\sin\theta} + 0.0021 R_{0.01} \cdot (H - H_S) - 0.0185 + 0.2337}$$

where $\theta$is the elevation angle of the path (deg); $R_{0.01}$ is the rainfall rate exceeded for 0.01% probability level of an average year (mm/hr); H is the rain height (km); H_S is the altitude of the ground site (km); and F is the frequency (GHz). if $r > 1$, then $r = 1$.

Step 2: The attenuation exceeded for 0.01% of an average year can then be obtained from:

$$A_{0.01} = k\, {R_{0.01}}^{\alpha} \cdot L_S \cdot r$$

where the frequency, link elevation and polarization dependent factors of k and α can be calculated from the equations for the ITU-R P.838-3 model [18]; L_S is the slant path length; and r is the path adjustment factor.

Step 3: The attenuation to be exceeded for other percentage of an average year (p) can be estimated from:

$$A_P = A_{0.01} \cdot \left(\frac{p}{0.01}\right)^{b_1 + b_2 \ln p + b_3 \ln A_{0.01} + \beta \sin\theta}$$

where $b_1 = -1.0063, b_2 = -0.0591, b_3 = 0.1317,$

$$\beta = \begin{cases} 0 & ,\text{if } p \geq 1\% \text{ or } |\varphi| \geq 36^\circ \\ -0.0055(|\varphi| - 36) & ,\text{if } p < 1\% \text{ and } |\varphi| < 36^\circ \text{ and } \theta \geq 25^\circ \\ -0.0055(|\varphi| - 36) - 1.7008 + 7.8503 \sin\theta & ,\text{Otherwise} \end{cases}$$

where φ is the latitude of the measurement site (deg).