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Comparison of ITU models performance in predicting Malaysia's tropical Rainfall Rate and Rain Attenuation at 26GHz mm-wave propagation

Liyth A. Nissirat and Aida Alsamawi, Ibraheem Shayea, Marwan Azmi, Mustafa Ergen and Tharek Abd Rahman

Abstract—This paper investigates the performance of different ITU models in predicting Malaysia's tropical rainfall rates and rain attenuation. This investigation is considered at 26GHz mm-wave frequency, and three datasets collected at different regions in Malaysia with emphasize on the latest dataset in Skudai in 2012. The data collected has rainfall rate and rain attenuation measurements for a continuous year at 1 spm sampling rate. Nonlinear regression is used to estimate best fit parameters for comparison with ITU-R p.837-1 with rain zone data, ITU-R p.837-6 as method 1 and ITU-R p.837-7 as method 2. Results show that ITU method 2 outperforms all the models with RMSE in the range of 12.72 mm/hr and 3.51 dB/km for rainfall rate and rain attenuation respectively. Conversely, absolute error at 0.01% of time showed superiority of ITU-R p.837-1 tropical recommendation with absolute error in the range of 0.39 mm/hr and 4.16 dB/km for rainfall rate and rain attenuation respectively. All models showed significant deviation from the measurements and the best fit at lower than 0.01% of time, with minimum deviation observed for of ITU method 2 in that range. Worst month parameters estimation using ITU method2 is in good match to the best fit estimation.

Index Terms—millimeter wave, propagation, rain attenuation, worst month statistic, microwave 5G link, tropical regions, fifth generation systems

I. INTRODUCTION

THE key function of wireless communications is to dispatch information from the transmitter to receiver. In practice, the receiver obtains a collection of significant replicas of the transmitted signal and noise. A variety of physical phenomena experienced on the propagating signal during the course of communication characterize multipath propagation in the wireless communication channel. Reflections, diffraction, scattering and depolarization are the most significant physical phenomena experienced upon the propagating signal. These physical effects generate replicas of the signal at different power levels and phase angles. The signal and its replicas in addition to the channel noise generated from other sources are collected at the receiver side. The significance of each physical phenomenon on the propagating signal is correlated to the nature of propagation path and signal properties. For

instance, obstacles dispersion and orientation play a major role in the total attenuation experienced on the signal during the course of propagation. Propagation path length, similarly, is a key contributor in the attenuation level experienced upon the propagating signal. In Line of Sight (LoS) communication scenarios, propagating signal experiences loss in the order of the second power of the propagation path length. Whereas, in non-Line of Sight scenarios, the signal power decays at much higher rates in relation to propagation path length. From the perspective of signal properties, the ratio of the obstacles physical dimension to the propagating signal wavelength is of particular importance in characterizing the significance of different physical phenomena. For instance, at millimeter wavelength, scattering from small objects is expected to have dramatic effects on the total attenuation experienced on the propagating signal. Thus, snow or heavy rain would increase the complexity of attenuation experienced on the propagating signal at mm-wave range [1–4].

Rain drops, as small objects in the propagation path, form a frequency selective attenuator of the signal [5]. At low frequency, long wavelength, the influence of heavy rain on the propagating signal is noticed, mainly, through absorption and reflection [1, 6]. As the signal frequency increases and, hence, the ratio of signal wavelength to the raindrop size approaches fraction of unity, the influence of raindrops on the signal power would be more noticed through scattering. The effect of raindrops on the propagating signal quality is of particular importance in tropical and equatorial climatic regions. The distinguished raindrop size and high rain rates in such regions raise serious concerns about the feasibility of mm-wave and Multi-Input Multi-Output (MIMO) applications [7, 8]. The tropical and equatorial rain characteristics would cause a severe signal attenuation at mm-wave range that may hinder the operation of modern wireless communication systems in certain cases [9, 10]. The complexity of signal attenuation provoked an extensive research to gain a comprehensive understanding of the frequency response of wireless communication channel at mm-wave range.

The interest in characterizing the mm-wave signal attenuation due to high rain rates is dated back to 1946, when Mueller [11] introduced empirical measurements of the rain attenuation at 6 mm-wave range (50 GHz). In the same year, Robertson [12] empirically studied the effect of rain at 10 and 30 mm-waves (equivalent to 30 GHz and 10 GHz respectively). Anderson [13], in 1947, studied the effect of heavy rain on the propagation of 12.5 mm-wave (24 GHz).

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Similarly, in 1948, Wexler [14] presented the impact of rain on radar x-band range (8-12 GHz). Ultimately, the end of 20th century witnessed a remarkable increasing demand on wireless communication technologies. Millimeter waves were, therefore, proposed in modern wireless systems to facilitate the demand on wireless communication technologies. This brought back the importance of large-scale mm-wave path loss empirical studies and modeling to provide the planners with the required tools to design effective wireless communication systems. Climatic characteristics of tropical and equatorial regions, such as Malaysia, motivated the researchers to investigate the impact of rain at the mm-wave propagation. University Technology Malaysia (UTM) [15] and University of Science Malaysia (USM) [16] separately took the initiative to form a data collection campaign at early 1990's. Their studies demonstrated empirically the impact of rain rate and raindrop size on mm-waves propagation. Following the initiatives of UTM and USM, in 1997, intensive studies were performed that validated and examined the factors affecting rain attenuation in Malaysia. For instance, the work in [17] investigated the signal frequency attributes during heavy rain, whereas [18] employed frequency scaling technique to determine rain attenuation. Furthermore, studies were also conducted by [19–21] on path length reduction factor model, which was used to determine rain attenuation in tropical regions. In addition, researchers addressed different factors believed to have an impact on rain attenuation such as wet antenna impact [22], rain rate conversion [23], raindrop size distribution [24], and performance of rain fading [20]. The basis of the mathematical models was the empirical assessments of the frequency band relation [15, 17, 25], raindrop size effect [26–28], path length (PL) effect [25–29] and impact of rain rate [30–33]. Furthermore, mm-wave signal polarization and its relation to the level of attenuation experienced upon the propagating signal is comprehensively analyzed in [34–36]. Horizontally polarized mm-wave signal exhibits higher levels of attenuation as compared to the vertically polarized signal. The collective attenuation caused by different factors upon the propagating microwave signals is presented in [34–36]. The reviewed studies provided thorough understanding of the behavior of mm-waves during the course of propagation under different scenarios and various frequency bands. However, the majority of these studies investigated narrowband systems. Studies that address wideband systems that provide high data rates, including bands proposed in 5G and 6G systems, are still very limited. For instance, Akihiko et al. [4, 37] and Kallfass et al [38] . investigated the propagation properties of 120 and 240 GHz respectively. Those frequency bands, however, are not part of the operating frequencies proposed in 5G systems [39].

The advent of the fifth generation (5G) microwave link transmitting at millimeter waves (mm-waves) frequency band is a promising technology to accommodate the escalating demand on wireless services. In this frequency band, however, the behavior of the transmission channel and its climatic properties are a major concern. This is of particular importance in tropical regions where the climate is mainly rainy with large raindrop size and high rainfall rate that may interact

destructively with the propagating signal and cause total attenuation for the signal. International Telecommunication Union (ITU) introduced a global rain attenuation model to characterize the effect of rain on the propagating signal at wide band of frequencies. The applicability of ITU-R models for rainfall rate and rain attenuation is a subject of recent research at different levels of frequency and different locations over the globe [40–42]. However, the validity of this model in tropical regions is still an open question for research.

This work is dedicated to investigating rain attenuation characteristics in Malaysia at 26GHz frequency range and, moreover, it is a continuation of the earlier results published in [43, 44]. Data collection campaign conducted by Wireless Communication Center (WCC) team in Johor Bahru, Malaysia forms the basis for this study. The empirical data collected are used in [43] to estimate the worst month parameters in comparison to ITU worst month parameters prediction based on rain zones data. Provided that, linear regression methods are used in [44] to estimate the worst month parameters in Malaysia. The results in [44] provided a comprehensive understanding of the limitation of ITU prediction model, based on rain zones data, in Malaysia.

However, as ITU rain zone data is replaced by rain digital maps in the third recommendation release in Rec. ITU-R P.837-3, reconsidering the accuracy and suitability of ITU worst month prediction in Malaysia is, therefore, imperative. Subsequent releases of ITU-R P.837, that is releases 4, 5, 6, and 7, proposed different worst month and rain attenuation models based on digital map data. Those models are investigated in this work and their results are reported in comparison to empirical data. This is considered the main contribution of this paper. Moreover, the second contribution in this work is utilizing nonlinear regression method to estimate the worst month parameters empirically which provided more accurate prediction results as compared to the linear regression method. It is worth to mention that this study and the investigation of ITU model is based on three datasets collected at different periods of time and different locations in Malaysia. The first dataset was collected in Skudai area in 1996-2000, and 2012. The second dataset is from Kuala Lumpur and was collected in 1992-1993, and 1998-1999. Finally, the third dataset is from Tronoh and was collected in 1992-1993, and 1998-1999. In the next section of this manuscript, the effect of precipitation on mm-wave is discussed. Rain attenuation is computed in Section III and worst month estimation model is presented in Section IV. Section V, then, elaborates on the experimental test bed and system equipment, while the measurement outcomes and discussions are presented in Section VI. The final Section concludes the results and findings of this study and draws the recommendations.

II. PRECIPITATION IMPACT ON MM-WAVE PROPAGATION

Tropical regions, like Malaysia, have a very distinctive climatic features and rain characteristics. In general, tropical regions are characterized by high rainfall rate with large raindrop size and heavy thunderstorms throughout the year

[43, 45, 46]. However, based on the spatial and temporal distributions of rainfall and raindrop size, locals distinguish two main seasons namely wet season and dry season. Wet seasons, also called monsoon seasons, are characterized by high average rain rates in the range of 200 mm/hr, whereas it is plunging to an average of 50 mm/hr during dry season [47]. The spatial distribution of rainfall monthly average is, furthermore, a noticeable feature of wet seasons in Malaysia. Monthly average rainfall in wet seasons may range from 118.765 mm up to 366.95 mm in some areas [47, 48]. Wet season rain characteristics are, generally, a close match to the equatorial regions' climate. Heavy rain with distinguishable large raindrop size and relatively short precipitation periods of time are the main features of equatorial rain [49–51]. These distinctive climatic features are observed in almost 36% of the total earth's landmass [52]. Temperate regions, on the other hand, constitute larger percentage of earth's landmass with different rain characteristics. Low rainfall rates with small raindrop size and diverse temporal distributions of precipitation are the characteristics of temperate regions rain seasons [53, 54]. Therefore, tropical regions rain characteristics could prove destructive on mm-wave propagation. Large raindrop size and high rainfall rates may provide high levels of obstruction between transceivers [4, 31, 55–58]. Attenuation caused by rain is a function of signal frequency, raindrop size and rainfall rate. Each raindrop would act as an obstacle that absorbs, reflect, scatter, or diffract mm-wave during the course of propagation [59–62]. Moreover, the accumulation of rain on the apertures of transceivers give rise to wet antenna phenomena that contributes significantly to mm-wave attenuation. Quantitative investigation study in [44] demonstrated a quasi-linear positive correlation between rain attenuation and rain rate at frequency range of 15 to 100GHz. Moreover, at a specific rain rate, a nonlinear correlation is observed between signal frequency and attenuation. For instance, at 130 mm/hr rain rate, rain attenuation ranges from 10.6 dB/km to 37.7 dB/km for the frequency range investigated in their work. Conversely, propagation path length demonstrates a non-linear correlation with rain attenuation [44, 63, 64]. Similar conclusions can be deduced from a study in [65] at frequency range from 5-40 GHz. Nonetheless, the spatial randomness nature of rainfall rate and raindrop size through the propagation path make it difficult to account for the physical distance between transceivers. Alternatively, effective path length concept was introduced in [66] to account for the randomness of rain rate and rain drop size. The total attenuation caused by uniform distributed rain rate and rain drop size through the effective path length is equivalent to the attenuation experienced upon the signal in the ambient conditions. The validity of this concept was the topic of many researchers such as Watson, P. A [35, 36, 66], Sujana Shrestha et al. [55], Morita et al. [34] and Per Thorvaldsen et al. [67]. A quantitative investigation of the signal polarization effect on rain attenuation revealed that horizontal polarized signal suffers higher levels of attenuation as compared to vertical polarized signal [55, 67]. Conclusively, the diversity of rain attenuation parameters and their randomness complicates the study and investigation of attenuation caused by rain. There-

fore, it is imperative to include these parameters in quantitative parametric modeling of rain attenuation.

III. QUANTITATIVE MODELING OF RAIN ATTENUATION

Mathematical modeling of rain attenuation is imperative to provide the tools for planners to implement effective and reliable mm-wave communication systems in different scenarios. To generalize the mathematical model, a Specific Rain Attenuation (SRA) concept is usually used to denote the total rain attenuation per unit distance (dB/km) [68, 69]. Mathematically, SRA, denoted as γ , can be written as:

$$\gamma = kR^\alpha \quad (1)$$

Where k , and α are parameters calculated by regression using site specific measurements. ITU Rec. P. 838-3 [68] includes the estimation of k , and α parameters for various situations, and R is the rainfall rate in (mm/h). The simplified model in (1) is site specific model that considers the complexity of environmental conditions and signal properties through the estimation of its parameters k and α [93, 70]. For homogeneous rain environment between transceivers, the total rain attenuation is, simply, the result of multiplication of SRA in (1) and the physical path length separating the transceivers. However, the assumption of homogeneity of rain environment is not valid for majority of rain environments. Thus, to accommodate the non-uniform distribution of rain fall and raindrop size through the propagation path length, effective path length, L_{eff} , is introduced and defined as [68, 71–74]:

$$L_{eff} = rL(km) \quad (2)$$

Where r is the distance factor, and L is the physical distance separating the transceivers in (km). International Telecommunication Union offered a procedure to estimate the distance factor based on the physical path length L , the 0.01 percentage rainfall rate $R_{0.01}$, the exponent α estimated in (1), and the propagating signal frequency f as follows [74]:

$$r = \frac{1}{0.477L_{0.01}^{0.073\alpha} f^{0.123} - 10.579(1 - \exp(-0.024L))} \quad (3)$$

The model in (3) is deemed accurate to estimate the distance factor for spatially distributed rain rates, however, its accuracy in tropical regions still questionable. Therefore, Researchers developed many models to estimate the distance factor, r , for different rain fall scenarios in tropical regions [21, 75]. The revised Silva Mello model [76], Lin Model [77], and Abdulrahman model [20] are examples of distance factor estimation models developed to provide accurate estimation for tropical regions. The equations developed in these models are summarized in Table I.

Specific rain attenuation and effective path lengths are usually determined through regression techniques using the rainfall and rain attenuation complementary cumulative distribution Function (CCDF) considering one-minute rainfall rate. International Telecommunication Union presented the total rain attenuation experienced upon the propagating signal

Table I
DISTANCE FACTOR ESTIMATION MODELS FOR TROPICAL REGIONS.

Model developer	Model	Parameters
Silva Mello, [76]	$r = \frac{1}{1 + \left[\frac{d}{d_o(R_p)} \right]}$	r is the distance factor, d is the physical distance between transceivers, d_o is the cell diameter, $d_o = 119R^{0.224}$, R is rainfall rate (avg), R_p the rainfall rate at p percentage of time
Lin, [77]	$r = \frac{1}{1 + \left[\frac{L}{L(R)} \right]}$	L is the physical distance between transceivers. $L(R) = \frac{2636}{R-6.2}$, where R is the average rainfall rate
Abdulrahman [20]	$r = \frac{1}{1 + \left[\frac{d}{2.6379(R_{0.01})^{0.21}} \right]}$	d is the physical distance between transceivers $R_{0.01}$ is the rainfall rate at 0.01% time

through the effective path length for 0.01% of time as [74, 78]:

$$A_{0.01} = kR^\alpha rL \quad (4)$$

where, $A_{0.01}$ is the total attenuation in dB over each of the effective path lengths at 0.01% percentage of time.

Furthermore, for percentages of time p in the range of [0.01% ,1%], rain attenuation can be estimated from $A_{0.01}$ and the effective path length as follows [74, 78]:

$$A_p = A_{0.01} C_1 P^{-(C_2 + C_3 \log_{10} P)} \quad (5)$$

Where

$$C_1 = (0.07^{C_o}) \left[0.12^{(1-C_o)} \right] rL \quad (6)$$

$$C_2 = 0.855C_o + 0.546(1 - C_o) \quad (7)$$

$$C_3 = 0.139C_o + 0.043(1 - C_o) \quad (8)$$

And C_o is a frequency dependent factor that is determined as follows:

$$C_o = \begin{cases} 0.12 + 0.4[\log_{10}(f/10)^{0.8}] & f \geq 10\text{GHz} \\ 0.12 & f < 10\text{GHz} \end{cases} \quad (9)$$

where f is the frequency of the communication link.

The significance of ITU recommendation is that it provides a systematic approach to model and estimate the total rain attenuation at different regions and scenarios. Rainfall rate and raindrop size, however, exhibit a significant yearly and monthly variation aside to their spatial distribution in tropical regions. Having this in mind, it would be difficult to generalize the empirical rain attenuation model introduced by ITU. Therefore, ITU group introduced the concept of worst month to facilitate a reliable and generalized modeling of rain attenuation in tropical regions [79].

IV. WORST MONTH PARAMETERS ESTIMATION MODEL

Worst month refers to that month in a period of twelve consecutive calendar months within a year that has received more than the standard level of rain for an extended time period [79]. Hence, yearly real time measurements can be used to determine the worst month statistics. Alternatively, in the lack of real time measurements, ITU group developed empirical model to estimate worst-month statistical parameters for different regions in the globe. The empirical model defines the average annual time percentage of excess, p , and the average worst-month annual time percentage of excess, p_w , to be linearly related as [80]:

$$p_w = Qp \quad (10)$$

Where Q is the conversion factor and it is in the range of $1 \leq Q \leq 12$.

The variable Q at $p(\%)$ is, furthermore, a function of Q_1 and β , which is expressed as follows:

$$Q_p = \begin{cases} 12 & \text{for } P < (\frac{Q_1}{12})(1/\beta)\% \\ Q_1 P^{-\beta} & \text{for } (\frac{Q_1}{12})(1/\beta) < P < 3\% \\ Q_1 3^{-\beta} & \text{for } 3\% < P < 30\% \\ Q_1 3^{-\beta} (\frac{p}{30})^{\frac{\log(Q_1 3^{-\beta})}{\log(0.3)}} & \text{for } p > 30\% \end{cases} \quad (11)$$

The parameters Q_1 and β are estimated in the Rec. ITU P.841-6 [80] for different regions along with detailed procedure for calculating p and p_w .

It can be noticed that Rec. ITU P.841-6 did not include any recommended parameters for Malaysia as tropical region. Nevertheless, the recommendation provided rain rate parameters for different tropical and subtropical regions in the globe. Furthermore, rain attenuation parameters are provided for Indonesia and Australia tropical regions [80]. Besides, it is important to note the diversity of rain rate and rain attenuation parameters for regions categorized to be tropical or subtropical. This is due, mainly, to the vast geographical area of tropical region and their climate diversity. Consequently, the applicability of tropical rain rate and rain attenuation parameters listed in ITU recommendation on Malaysia rain characteristics is still an open question. This motivated the researchers in WCC, UTM, in Johor Bahru, Malaysia to conduct an empirical study to validate the feasibility of ITU model in Malaysian climate [15]. Data collection campaign for several continuous years at three distinct locations provided the analytical data for this study at frequency ranges of 14.6 GHz and 21.95 GHz. One year rain attenuation and rain rate measurements are used in the investigation in [15]. Rain rate measurements are used to estimate Q_1 and β for the worst month in ITU model (11) using linear regression methods. The estimated worst month parameters are, then, verified by utilizing rain attenuation data at both frequencies considered in the study. The results of this investigation are summarized in Table II.

The predictions of Q_1 and β in II using three different datasets show a significant match. More importantly, the pre-

Table II
PREDICTED Q_1 AND β VALUES BASED ON REAL MEASURED DATA (1996 TO 2000) IN JOHOR BAHRU, MALAYSIA BY UTM [15].

Measurement	Q_1	β
Rain Rate	0.8913	0.29
Rain Attenuation at 14.6 GHz	0.9495	0.30
Rain Attenuation at 21.95 GHz	0.9078	0.32

Table III
 Q_1 AND β VALUES BASED ON A MEASUREMENT AND ITU MODEL [15, 16, 80]

Location	Q_1	β
UTM, Malaysia [104]	0.92	0.30
USM, Malaysia [104]	1.39	0.30
ITU Global	2.85	0.13
ITU Tropical regions	2.82	0.15
ITU Brazil Tropical inland	3.00	0.13
ITU Indonesia	1.7	0.22

diction results in [15] are in good match to those demonstrated in a study by USM, Malaysia [16] as can be depicted in Table III. Moreover, ITU Q_1 and β parameters recommendations for different tropical areas show a significant deficiency from the findings in [15, 16] as shown in Table III. The recommended factors in ITU recommendation emphasizes, furthermore, the uniqueness of climate properties for different tropical regions. As Brazil and Indonesia factors exhibit large deviation, though, they are both tropical. This signifies the study in this work.

V. EXPERIMENTAL TEST BED AND SYSTEM EQUIPMENT

Data collection test bed was constructed to collect rainfall rate measurements and transmitted and received signal powers. The setup considers Line of Sight (LoS) scenario where the transceivers are separated at fixed 1.3 km distance, and both are operating at fixed frequency of 26 GHz. One radio base station (RBS) located in Wireless Communication Center (WCC) is communicating with the RBS in Balai Cerapan at UTM, Skudai, Johor Baru as shown in Google map in Figure 1. The block diagram in Figure 2 shows that each RBS comprises a radio frequency (RF) unit, antenna, and automatic gain control (AGC). A rain gauge (RG) unit is used to record the rainfall measurements. Measurements are synchronized and recorded using data logger (DL) and personal computer for analysis. The antennas are mounted on a tower at a height that ensure the value of the foremost Fresnel zone to be more than 0.6 for LoS communication scenario as in Figure 3 and 4 [81]. Telecom software ATDI ICS is used to determine the value of the foremost Fresnel zone in this work. Communication system setup is summarized in Table IV. A MATLAB program is developed to process the measurements and extract the correlations between RF power measurements and the rainfall rates. For brevity, the configuration, and details of the equipment used in this work can be found in [44]

Figure 1. Location of the path link from Google map [82]

Figure 2. Block diagram of the experimental test bed system

Figure 3. Antenna mounting for testbed

VI. VI MEASUREMENT RESULTS AND DISCUSSION

Since 2001, *ITU - R* went through a series of revision resulted in introducing remarkable enhancement in the predictions. Revision *ITU - RP.873 - 2* replaced rain zones in *ITU - RP.873 - 1* [44, 83] by digital maps collected by European Center of Medium-range Weather Forecast (*ECMWF*) covering 15 years weather forecast. Accordingly, the model and prediction of both rainfall rates and rain attenuation has been updated [83, 84]. Revisions 2, 3, and 4 used the 15-year digital maps and recommended the calculation of p_o as follows [85] :

Figure 4. Fresnel zone clearance for 26 GHz link

Table IV
COMMUNICATION SYSTEM SETTING

Parameters	Details
Standard of the system	IEEE 802.16
Operating frequency	26 GHz
System bandwidth	28 MHz
Number of channel	4 Channel
Modulation scheme	QPSK
Data rate	386Mbps
Maximum Transmission power	18 dBm
Sensitivity	-84 dBm
Antenna Gain	41.0 dBi
Application	Board casting Mobile
Frequency Band Type	Licensed

$$p_o(lat, long) = p_{r6}(lat, long) \left(1 - e^{-0.0117 \left(\frac{M_s(lat, long)}{p_{r6}(lat, long)} \right)} \right) \quad (12)$$

Where the parameters p_{r6} and M_s are extracted, from the provided digital maps, at the surrounding closest four latitude and longitude locations and approximated at the given location using bi-linear interpolation [85].

From (12), the rainfall exceeded for $p\%$ of the average year, R_p , where $p \leq p_0$, is estimated as:

$$R_p(lat, long) = \frac{-B + \sqrt{B^2 - 4AC}}{2A} \quad (13)$$

where

$$A = ab,$$

$$B = a + c \ln(p/p_o(lat, long)),$$

$$C = \ln(p/p_o(lat, long)).$$

and

$$a = 1.11,$$

$$b = \frac{M_c(lat, long) + M_s(lat, long)}{22932p_o}, \text{ and}$$

$$c = 31.5b.$$

Similarly, revisions 5 and 6 followed the same model described in (12) and (13) with updated version of the digital maps that covers 40 years weather forecast. The parameters M_c and M_s are replace by M_t and β in revisions 5 and 6, where M_c and M_s are calculated as:

$$M_c = \beta M_t, \text{ and } M_s = (1 - \beta) M_t$$

Moreover, the updated digital maps resulted in more accurate prediction of the factors $a, b, \text{ and } c$ as follows:

$$a = 1.09,$$

$$b = (M_c(lat, long) + M_s(lat, long))/(21797p_0), \text{ and}$$

$$c = 26.02b.$$

Finally, revision 7 of ITU-R p.837 has a major update where total monthly rainfall data generated from GPCC climatology version 2015 (50 years data) is used for land and the ECMWF IRA data covering 36 years forecast is used over water. Moreover, monthly mean surface temperature data in recommendation ITU-R P.1510 is utilized to account for temperature effects in the total attenuation. Recommendation of ITU-R p.837-7 [86] proposes the relation of percentage of time, P , and rainfall rate, R , as follows:

$$P = P_o \left(\ln \left(\frac{R_a}{R} \right) \right)^n \quad (14)$$

where

P_o, R_a , and n are parameters to be estimated.

Genetic optimization tool is developed by ITU-R p.837 group to provide accurate prediction of P_o, R_a , and the exponent n . Empirical data collected from the setup in this work can be used in the GA tool to predict the model parameters. Otherwise, in case of lack of empirical data, estimated rainfall rates can be extracted from the provided digital map data [ref for ITU-R p.837-7]. The GA estimation algorithm utilizes the percentage of time and rainfall rate datasets recorded for a specific period of time in minutes. The parameters in (14) are, then, estimated to best fit the dataset for the given period of time. The estimated parameters are used to predict 1 min percentage of time based on rainfall rate. genetic population size and number of iterations are fixed at 15000 and 50 respectively for all the experiments in this work. The discussion in this work would follow the progress of revisions in ITU-R p.837. However, as revisions 5, and 6 have minor updates with respect to 2, 3, and 4, the method in revision 6 is adopted and called ITU method 1 whereas revision 7 model is called method 2 in this manuscript.

A. A Annual Rain Rate and rain attenuation Distribution

Location of Malaysia in equatorial region surrounded by oceans is the main reason for its distinctive climate. Northeast and Southeast monsoon seasons are usually witnessing peak rainfall rates. In Northeast, monsoon starts in October and ends in March, whereas in Southeast, April and September mark the start and end of monsoon season respectively. In general, in equatorial and tropical regions, rainfall intensities vary between shower, drizzle and thunderstorm during the year [87]. Malaysia, mostly, have thunderstorm category rainfall rate as the dominant one. Rainfall statistical studies, conversely, show that the peak rainfall rate in Malaysia is primarily in two seasons [15]. The first season starts in March and ends in May and the second starts in October and ends in December every year. More distinctively, rain intensities in Malaysia have a unique hourly distribution

Figure 6. CCDF of the annual rainfall rate based on measurement data conducted at UTM Skudai, Malaysia [June 2011- May 2012], ITU digital map (method 1), and ITU (method 2) predictions

within the day. Rainfall rate statistical analysis showed that heavy rainfall rates are observed between 01 : 00 pm and 07 : 00pm for more than 70% of the days in rainy season [15]. In about 96.8% of the days in rainy season, rainfall rate approaches 50 mm/hr whereas it approaches 165mm/hr for 79% of days in the season. During rainy day a unique rainfall increment is further noticed. Rainfall usually, starts at 50mm/hr from 01 : 00pm to 02 : 00pm, then rainfall intensify to 81 mm/hr the next hour. From 03 : 00pm to 04 : 00pm, 101mm/hr rainfall is observed, and it will keep increasing till reaching 165mm/hr between 05 : 00pm till 06 : 00pm [15].

The average rainfall rate received over time in different locations in Malaysia is shown in Figure 5 in comparison with ITU method 1 and method 2 models respectively. Rainfall dataset collected at KL, Skudai (Johor Bahru) and Tronoh are averaged and used to estimate the parameters in ITU method 2 as shown in Figure 5 (a). Furthermore, the ITU method 2 1-min estimation is compared with the ITU method 1 estimation and the average rainfall rates for the three locations in Figure 5 (b). Remarkable estimation improvement in ITU method 2 over method 1 is observed with RMSE average in the range of 11.5mm/hr and 38mm/hr between the measurements and method 1 and method 2 respectively as shown in Table V. The parameters estimated in ITU method 2 for Skudai, KL, and Tronoh average data are listed in Table VI. Recent data collected in Skudai, Johor Bahru in 2012, shown in Figures 6 and 7 for Rainfall rates and Rain attenuation respectively emphasized the superiority of ITU method 2 over method 1. Method 2 deviates from the measurements by 6.6mm/hr and 5.2dB/km for rainfall rate and rain attenuation as compared to 31mm/hr and 11.5 dB/km deviation of method 1 for the respective data. Furthermore, at 0.01% of time, measured specific rain attenuation is in the range of 34.5dB/km as compared to 29.2dB/km and 26dB/km in ITU method 2 and 1 respectively. This rain attenuation level would, furthermore, suggest that at 26 GHz frequency range, a severe attenuation is expected in the event of high rainfall rates that should be accounted for in large area coverage planning.

B. Worst Month Statistics

The concept of worst month in rain attenuation has been introduced by ITU to denote the most outstanding rain rate

Table V
RMSE BETWEEN RR DATA AND ITU METHOD 1 AND METHOD 2

Dataset (Rainfall Rate)	ITU method 1 (RMSE)dB	ITU method 2 (RMSE)dB
Skudai(Johor Bahru)	38.7	10.2
KL	37.5	12.6
Tronoh	38.2	11.6

Table VI
ITU METHOD 2 ESTIMATED PARAMETERS

Data area (Rainfall Rate)	P_o	R_a	n
Skudai (Johor Bahru)	0.0096373	375.5864	3.3483
KL	0.0092052	363.4325	3.3814
Tronoh	0.011254	328.2483	3.354

Figure 7. CCDF of annual rain attenuation based on measurement data conducted at UTM Skudai Malaysia [June 2011- May 2012], ITU digital map data (method 1) and ITU (method 2)

or rain attenuation exceeded for a given explicit percentage of time. Worst month is, usually, estimated through a month-to-month CCDF information investigation. Worst month statistics and modeling concept provides a valuable reference for mm-Wave system planning. Communication link planning based on worst month maybe viewed as worst case scenario design where it ensures the reliability of the communication link against highest levels of rainfall rates and percentage of rain occurrences in a given area. This section demonstrates worst month rainfall rates and rain attenuation in contrast to ITU model methods 1 and 2.

1) *1. Rain Rate and Rain Attenuation in the Worst Month:* The main aim of investigating rainfall rates and attenuation caused by rain for long period of time, one year or more, is to estimate worst month parameters. As worst month statistical parameters are essential information and tool in reliable communication link planning. Worst month, in general, is the month in the calendar year that exceeds a given threshold of a quantity. Thus, worst month is selected based on the quantity under investigation. In the context of rainfall rates and attenuation caused by rain, worst month is, particularly, selected as the month that exhibits highest rainfall rates and rain attenuation for longest time within the month in the calendar year. Worst month is, therefore, selected by averaging the monthly rainfall rate and rain attenuation data recorded and select the month with largest rainfall rates as compared to the yearly average as shown in Figures 8 and 9 for rainfall rate and rain attenuation respectively. Non-linear regression

Figure 5. CCDF of measurements for different regions of Interest in Malaysia, (a) Average rainfall rate (RR) measurements and ITU-R p.837-7 model prediction for 10 min and 1 min. (b) Comparison of the average rainfall rate measurements, ITU-R p.837-6 model (method 1) prediction and ITU-R p.837-7 model (method2) prediction.

Figure 8. CCDF rainfall rate statistic for measured and non-linear regression curve for the worst month

Figure 9. CCDF rain attenuation statistic for measured and non-linear regression curve of worst month

Table VII
WM PARAMETERS ESTIMATION AND RMSE CALCULATED USING
NON-LINEAR REGRESSION METHOD

Data	Q_1	β	RMSE
Average Rainfall rates	1.0638	0.23091	12.6 mm/hr
Average Rain Attenuation	1.2336	0.1635	3.3 dB/km

is, then, utilized to best fit the CCDF of the average rainfall rate and rain attenuation data in Skudai (Johor Bahru) with Q_1 , β and the respective RMSE computing between the best fit and the measurements are listed in Table VII. The estimated parameters in Table VII are considered as a benchmark for comparison of the ITU method 1 and method 2 estimation. From Figures 8 and 9, it can be noticed that at 0.01% of time, average rainfall rate is in the range of 140 mm/hr during worst month whereas the associated specific rain attenuation is recorded at the range of 42 dB/km at 26GHz frequency range. This significant attenuation is deemed to be destructive for mm-wave propagation. Planning and designing a reliable mm-wave communication link considering worst month rainfall rates and rain attenuation would ensure more than 95% availability and high quality of link.

C. C Modelling For the Worst Month

Worst month rainfall rates and rain attenuation in comparison to ITU recommendation with time zones is depicted in

Figures 10 and 11 respectively. It is clear from the Figures the significant deviation of ITU recommendations for worst month parameters from the measurements average. Parameters proposed in ITU for Indonesia, Tropical, and Global regions overestimating worst month rainfall rate and rain attenuation whereas recommended parameters for Brazil tropical region significantly down estimate worst month measurements in Malaysia. This shows the diversity of tropical and equatorial climatic properties. The computed RMSE between each recommended ITU model and the measured data listed in Table VIII shows the inadequacy of ITU recommendations based on rain zones [43, 44]. This is because of the large RMSE computed between the recommendations of ITU-R p.837-1 with rain zones and the measurements. However, by observing the absolute error at 0.01% of time, it can be concluded that the parameters recommended in ITU-R p.837-1 time zone model for tropical regions provided exceptional estimation. This indicates that at 0.01% of time, ITU recommendation for tropical regions is very adequate for mm-wave planning in tropical regions like Malaysia. The main distinction of the results of this work as compared to the previous work in [43, 44] is the method of evaluating the deviations. In the previous work the focus was to study the deviation in the worst month estimated parameters Q_1 and β , whereas in this work the RMSE and the absolute error at 0.01% of time were the criteria to draw the conclusion. Hence, the approach in this work provided different perspective and, in

Figure 10. CCDF for ITU rain zone data [44, 46] and annual average and worst month rainfall rate measurements

effect, derived different conclusions. On the other hand, ITU method 1 and method 2 in Figures 12 and 13 for rainfall rate and rain attenuation show a remarkable enhancement in the accuracy of ITU estimation algorithm. The estimated worst month parameters and computed RMSE with respect to the measurements are listed in Table VIII for comparison. The estimation of ITU method 2 is deemed advantageous over ITU method 1 as it produced the minimum computed RMSE. Moreover, by noticing the absolute error of predictions at 0.01% of time, it can be concluded that ITU method 2 provided remarkable enhancement over ITU method 1. This enhancement observed in ITU method 2 may be attributed to the robustness of the model presented as well as accounting for rain thermal effects in the estimation process. Moreover, ITU method 2 enabled the use of empirical data for estimating the parameters in (14) which has a positive effect to customize the model for specific site. Therefore, ITU method 2 provided reliability of estimation and modeling of rainfall rates and rain attenuation in Malaysia's like climate. It is deemed suitable tool for future mm-wave communication planning for 0.01% percentage of time.

As the results showed the performance of different ITU models and recommendations for planning at 0.01% of time and higher, ITU method 2 is deemed comparatively better choice for planning at lower than 0.01% of time. Recommendation of ITU tropical provided high rainfall rate and rain attenuation accuracy at 0.01% of time, however, it significantly overestimates both rain rates and rain attenuation at lower than 0.01% of time. Deviations of up to 70 mm/hr and 30 dB/km are observed at lower than 0.01% of time range for rainfall rate and rain attenuation respectively. Equivalently, large deviations can be observed in ITU methods 1 and 2 estimations at lower than 0.01% of time. Estimation errors average are up to 25 mm/hr and 5 dB/km for rainfall rate and rain attenuation respectively can be observed in ITU method 1. Similarly, ITU method 2 down estimate rainfall rates and rain attenuation by an average of 20 mm/hr and 9 dB/km respectively at that range of percentage of time.

VII. CONCLUSION

International Telecommunication Union recommendation group3 progressively deployed a series of recommendation for modeling rainfall rates and rain attenuation for mm-wave propagation. The models are applicable globally as the

Figure 11. CCDF for ITU rain zone data [43, 44] and annual average and worst month rain attenuation measurements

Figure 12. The CCDF worst month rain rate based on measured rain rate data and our predicted Q_1 and β values and RR worst month prediction by ITU method 1 and 2

Figure 13. The CCDF worst month rain attenuation measured data at 26 GHz over one year period with the predicted Q_1 and β values and worst month prediction by ITU method 1 and method 2

model parameters are estimated based on rainfall data recorded globally. The first release of ITU recommendation, ITU-R p.837-1, utilizes rain zone data dividing the regions all over the globe into a set of rain zones. The model, furthermore, recommended worst month estimation parameters for different regions. Following the first model, ITU released a series of models that replaced rain zone data with digital maps starting from ITU-R p.837-2 to ITU-R p.837-6 with minor variations in the methodology and data used in modeling. Last ITU model, ITU-R p.837-7, employed earth thermal maps and separated the digital maps to accommodate wet lands and dry lands. Moreover, new estimation model and GA optimization are proposed. The performance of each ITU model has been investigated in different regions in the globe and at different levels of rainfall rates and wide range of frequencies. This

Table VIII
RMSE, AND ABSOLUTE ERROR AT 0.01% OF TIME VALUES FOR WORST MONTH RAIN RATE AND RAIN ATTENUATION STATISTICS FOR DIFFERENT DATASETS AND DIFFERENT PREDICTION METHODS.

Location in Malaysia (Year)	RMSE	Q_1	β	Absolute error at 0.01% of time	fr[GHz]
UTM, JB (2011-2012), Rainfall Rate	Best Fit: 12.6 mm/hr	1.0638	0.2309	2 mm/hr	–
	ITU Method 1: 13.4 mm/hr	1.081	0.2380	47 mm/hr	
	ITU method 2: 12.72 mm/hr	1.0598	0.2312	2 mm/hr	
UTM, JB (2011-2012), Rain Attenuation	Best Fit: 3.3 dB/km	1.2336	0.1635	0.5 dB/km	26
	ITU method 1: 3.9 dB/km	1.198	0.1482	22 dB/km	
	ITU method 2: 3.51 dB/km	1.21	0.1501	5 dB/km	
UTM, JB M3 (1996-1999), Rainfall Rate	Best Fit: 13.1 mm/hr	0.8913	0.29	2.6 mm/hr	–
	ITU method 1: 13.89 mm/hr	1.0808	0.311	38.9 mm/hr	
	ITU method 2: 13.43 mm/hr	1.0512	0.2827	2.8 mm/hr	
UTM, JB M4 (1996-1999), Rain Attenuation	Best Fit: 2.9 dB/km	0.9495	0.3	0.3 dB/km	–
	ITU method 1: 3.65 dB/km	1.107	0.32	18.8 dB/km	
	ITU method 1: 3.21 dB/km	1.095	0.32	4.5 dB/km	
UTM, JB M5 1996-1999 Rain Attenuation	–	0.9078	0.32	–	21.9
USM, PG M6 1990-1991 Rain Attenuation	–	1.39	0.3	–	–
ITU Global, prediction	Rainfall Rate: 13.8 mm/hr	2.85	0.13	15.9 mm/hr	–
	Rain Att.: 10.8 dB/km			6.68 dB/km	
ITU Tropical, prediction	Rainfall Rate: 14.1 mm/hr	2.82	0.15	0.39 mm/hr	–
	Rain Att.: 10.4 dB/km			4.16 dB/km	
ITU Brazil Tropical, prediction	Rainfall Rate: 16.2 mm/hr	3	0.13	80.5 mm/hr	–
	Rain Att.: 14.6 dB/km			18.8 dB/km	
ITU Indonesia, prediction	Rainfall Rate: 14.5 mm/hr	1.7	0.22	24 mm/hr	–
	Rain Att.: 11.5 dB/km			8.89 dB/km	

work, particularly, aimed to provide a comparative study concerning the performance of different ITU models in predicting rainfall rates and rain attenuation with worst month

parameters estimation in Malaysia tropical climate at 26 GHz mm-wave propagation. Three rainfall rate and rain attenuation datasets collected at different regions in Malaysia and different frequency ranges are used in this investigation. the three datasets are collected at different period of time, where a particular emphasize is given to the latest data collected in Skudai, Johor Bahru in 2012. All datasets are recorded at 1 spm intervals and 1.3 km distance between transceivers. Monthly averages are used to extract the CCDF and worst month data. Nonlinear regression method is, then, used to estimate worst month statistical data and parameters as a benchmark for comparison with ITU models. Absolute error at 0.01% of time and RMSE are used to evaluate the performance of ITU methods. The results show that ITU models are, in general, indispensable tools to estimate the impact of rainfall on the propagation of mm-wave signals. For reliable link quality, ITU models may provide good estimation of rainfall rates and associated rain attenuation at the rainfall rates level recorded in Malaysia. More specifically, RMSE computed for ITU models showed that ITU method 2 outperforms other ITU models with RMSE as low as 12.72 mm/hr and 3.51 dB/km in comparison to the best fit RMSE of 12.6 mm/hr and 3.3 dB/km for rainfall rate and rain attenuation respectively. Conversely, minimum absolute error at 0.01% of time is observed in ITU-R p.837-1 tropical recommendation with absolute errors in the range of 0.39 mm/hr and 4.16 dB/km for rainfall rate and rain attenuation respectively. This exceptional absolute error demonstrates that tropical model in ITU-R 837-1 predicts malaysia's climatic properties reliably and is suitable for mm-wave communication planning at the frequency range of interest. Absolute errors at 0.01% of time for ITU method 2, are in the range of 2 mm/hr and 5 dB/km respective to rainfall rate and rain attenuation. Therefore, both tropical model and ITU method2 are showed a comparative performance in modeling rainfall rate and rain attenuation in the region of interest. Therefore, in total, the latest model deployed by ITU showed enhancement in predicting rainfall rates and rain attenuation over the earlier models. Moreover, at 0.01% of time, ITU tropical recommendation in ITU-R p.837-1 showed a remarkable accuracy and it could be used as benchmark for other models. Further studies are required in different tropical regions and different levels of frequencies to validate the performance of different ITU models. Moreover, datasets collected for more than three years would enhance the accuracy of prediction in ITU models as recommended by ITU recommendation group3.

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