Rain Attenuation Measurements and Analysis at 73 GHz E-Band Link in Tropical Region

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***Abstract*—This letter presents the rainfall intensity and rain attenuation analysis in tropical region based on a one-year measurement using the 73.5 GHz E-band link of 1.8 km with three rain gauges installed along the path. The measured rain rate and rain attenuation were analysed and bench-marked with previous measurements and prediction models. The findings from this work showed that Malaysia agrees with the ITU-R rain prediction model of Zone P by 99.99% of time. The maximum measured rain attenuation exceeding 0.03% of the year is around 40.1 dB at the maximum rain rate of 108 mm/h.**

***Index Terms*—Millimeter-wave (mmWave) propagation, radio channel, rainfall, 73 GHz, rain attenuation.**

I. INTRODUCTION

THE use of data in major urban areas has significantly grown in recent years. Together with the increase in the amount of connected devices, the bandwidth of currently used microwave frequencies are almost fully occupied. Hence, new frequency bands, effective codes or new techniques must be acquired for huge data transmission [1]. The use of the millimeter-wave (mmWave) band in future wireless communication systems (5G and beyond) can largely enhance the system throughput. The E-band (71-76 and 81-86 GHz) with a regulated bandwidth of 10 GHz is one of the future broadband communication bands [2].

However, the radio channel at mmWave bands is more severely affected by a number of factors such as obstacles and weather conditions. Moreover, all mmWave frequency bands are influenced by rain attenuation which can severely degrade the radio wave propagation. The rain attenuation significantly rises with increasing frequency, restricting the path length of radio communication systems and limiting the utilization of higher frequencies for line-of-sight (LOS) microwave links [3], [4]. This leads to significant signal attenuation at the mmWave, which can further potentially affect the quality-of-service (QoS) of wireless systems operating at the mmWave frequency band [5]. In this regard, it is important to gain an insightful understanding on how rain affects the mmWave channel propagation characteristics.

Despite its importance, only a few studies have investigated rain attenuation at the E-band [6]–[11]. In the UK, the rainfall rate statistics and rain attenuation were investigated based on a one-year measurement data at 25.84 and 77.52 GHz in [6], and over a short measurement period at 77 and 300 GHz in [7]. To benchmark the possibility of wireless data transmission at 77 GHz during adverse weather conditions, the attenuation measurements under extreme rain conditions in a climate wind tunnel were conducted in [8]. The propagation loss with rain effect at 77 GHz was obtained over 180 m based on generated rain with rates of 33, 43, and 105 mm/h. The impact of rain on signal attenuation for 75 GHz and 85 GHz bands was analyzed and modeled based on ten months of measurements of a 1 km terrestrial link in Molndal, Sweden at 71-76 GHz bands [9]. To investigate the accuracy of the ITU-R models, further measurements for mmWaves were accomplished in South Korea along a 3.2 km experimental link at 75 GHz [10]. Based on measurements at 72 and 84 GHz in Albuquerque, USA, the connection between the raindrop size distribution and the rain attenuation was investigated in [11].

Among the aforementioned studies, non were conducted in tropical regions with high rainfall rates of up to 280 mm/h. Previous studies of rain effects on mmWave propagation in tropical regions did not cover the E-band [12]–[17]. In [12], the rain attenuation was measured over ten years in Singapore at 15, 21, and 38 GHz for a 1.1 km link. The rain drop size distribution (DSD) was fitted with a negative-exponential distribution [12]. Based on conducted measurement over one year at 11 GHz with a 3.2 km terrestrial link, the measured rain attenuation in [13] was compared with the empirical formula of specific attenuation in [18]. The results in [14] presented a significant difference between the fading prediction of ITU-R P.530-11 [19] and the conducted measurement data over one year at 38 GHz along a 2.1 km terrestrial link. Based on rain attenuation data measured at 15 GHz in two different locations and over seven terrestrial links, the path reduction factor models were analyzed in [15] and [16], respectively. The frequency scaling of rain attenuation models was investigated based on a one-year rain attenuation data measured at 23, 26, and 38 GHz in [17].

To the best of our knowledge, this work is the only measurement campaign conducted in tropical region, to study the precipitation effects on the 1.8 km at 73.5 GHz E-band LOS terrestrial link. In this letter, the results of one year of rainfall intensity and attenuation in Malaysia are presented. Utilizing the collected data, the rain rates and rain attenuation distribution are analysed and subsequently bench-marked with ITU-R prediction models. The dispersion of the measured rain attenuation among different rainfall rate in one year is

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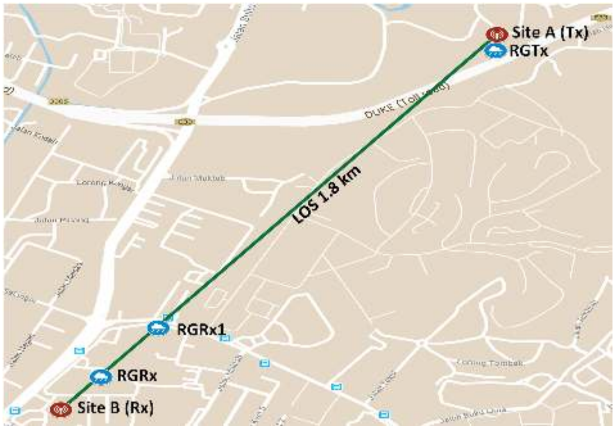

Fig. 1. Measurement Link Map in Kuala Lumpur, Malaysia for 1.8 km LOS path between KOLEJ SISWA JAYA (Tx site) and Menara Razak, Universiti Teknologi Malaysia (Rx site).

presented. The experimental data as well as the presented data analysis are useful in quantifying the influence of rain, which can improve the designing and planning of mmWave wireless communication systems in tropical regions.

II. Measurement Setup

The E-band transmitter (Tx) and receiver (Rx) equipment for this measurement campaign are manufactured by Ericsson, i.e. the Mini Link ML-6352. The specification details of the ML-6352 are provided in [20]. The 73.5 GHz E-band link setup has been operating from September 2018 to study the effect of rain. It is tuned to support up to 4.532 Gbps by using a bandwidth of 750 MHz channel and adaptive modulation of up to 256 QAM. The link parameters, including antenna specification are provided in Table I where both Tx and Rx adopted similar antenna specifications. The antennas were covered with acrylonitrile styrene acrylate (ASA) radomes. The data logger of the ML 6352 at Rx provides the maximum and minimum received signal level (RSL) values every 15 minutes. This link is located in Universiti Teknologi Malaysia, Kuala Lumpur, Malaysia, with link distance of 1.8 kilometer. The Tx, labelled Site A (3°11'7"N, 101°43'46"E), is located at the top of a 5-storey student residential building (49 m above sea level) outside the university campus. The Rx, labelled Site B (3°10'21"N, 101°43'10"E), is located on a level 16 in one of the high-rise management building (43 m above sea level) at the university campus. Fig. 1 provides the map of the measurement setup.

The precipitation data was collected from three HOBO data logging rain gauges. Two rain gauges were installed at the Rx site and the third was installed at the Tx site, as shown in Fig. 1. The two Rx rain gauges (named RGRx and RGRx1) are located on the rooftops of two different buildings separated about 130 m and 380 m from Rx, respectively. The Tx rain gauge (RGTx) is located on the rooftop of the building near the Tx building (about 50 m from the Tx antenna). The gauges are the tipping bucket type with a sensitivity of 0.2 mm. The rain gauges record the rainfall that occurs every minute; therefore, the rain rate is recorded as an integral multiple of 12 mm/h or 0.2 mm/min.

TABLE I
Link Parameters for Measurement

Descriptions	Specifications
Frequency	73.5 GHz
Bandwidth	750 MHz
Antenna Type	Directional 0.3 m (ANT2 0.3 80 HP)
Polarization	Vertical
Antenna Gain	46.5 dB
Antenna Half Power Beam width	0.8°
Maximum Tx Power[1]	15 dBm
10^{-6} BER Received Threshold	-75 dBm

Using the data collected by the three rain gauges, the rain rate of each location along the communication path was estimated using the inverse distance weighting (IDW) method [21]. IDW has been effectively utilized as one of the standard spatial interpolation procedures [22], [23]. In IDW the estimated value R_p is a weighted sum of the rain gauge values R_i given by

$$R_p = \sum_{i=1}^{N} w_i R_i \tag{1}$$

where N is number of rain gauges. The weight of each rain gauge value w_i on the estimated location p depends on the distance d_i in between, and is given by [24], [25]

$$w_i = \frac{d_i^{-2}}{\sum_{i=1}^{N} d_i^{-2}} \tag{2}$$

The average rain rate was then calculated from these estimated values together with the rain gauge readings, and applied in this study.

III. Rain Rate Distribution

The rainfall rate measurements were collected for one year, from the 6th of September 2018 until the 5th of September 2019, using three different rain gauges on the link path, as described in Section II. According to the ITU-R [26] classifications, Malaysia falls in rain Zone P. In this letter, the cumulative distribution function (CDF) of the measured rainfall rate along the link is compared with the ITU-R P.837-7 [27] and ITU-R PN.837-1 [26] using Zones N, P, and Q at time percentage $P\%$ for P from 0.001 to 1. The experimental CDF is also compared with the rainfall 1-hour integration time data collected from the Malaysian Meteorological Station (MMS) over 12 years [28]. Chebil and Rahman's model [28] was used for converting rain rate data to the equivalent 1-minute (min) integration time. The measured CDF in the link area is also compared with the l minute rainfall data measured over three years, from June 1992 to May 1995, in Kuala Lumpur, Malaysia (3"08'N, 101"39'E) using a tipping bucket rain gauge of 0.5 mm per tip [28].

A total of ten curves were plotted in Fig. 2 to present the cumulative distributions of the rain rate. Four curves (legends

[1]The link set up has obtained the Apparatus Assignment (AA) authorization from the Malaysian Communications and Multimedia Commission (MCMC), i.e. the Malaysian spectrum regulatory body. The AA application process requires the RSL to be calibrated and then checked by MCMC before AA can be awarded.

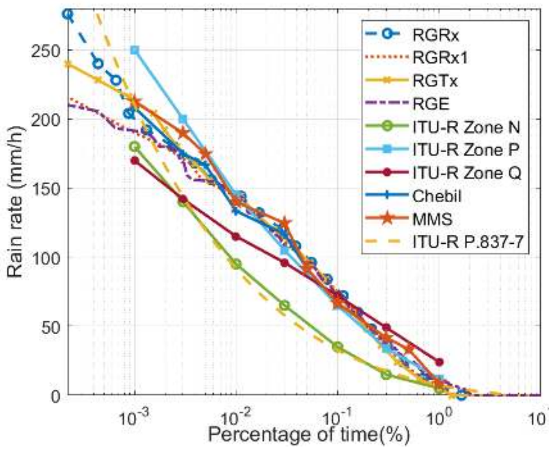

Fig. 2. Cumulative distribution for rain rate.

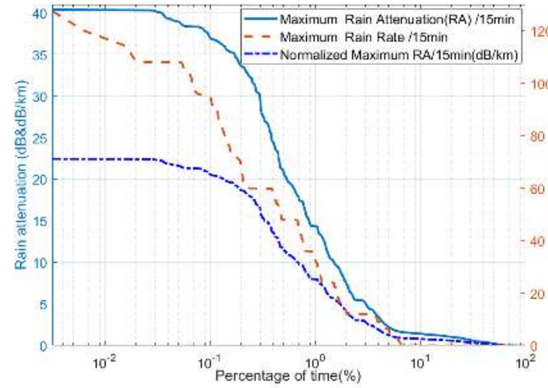

Fig. 3. Cumulative distribution for maximum attenuation and the corresponding maximum rainfall for the 1.8 km 73.5 GHz LOS terrestrial as well as the normalized maximum attenuation (dB/km).

as RGRx, RGRx1, RGTx, and RGE) present the measurement of rain rate along the E-band link. It can be seen that the CDFs for the measured rain rate from RGRx, RGRx1 and RGTx, and the estimated RGE based on (1) are very close to each other at percentage of time ($P \geq$0.01%). However, there are a few differences between them in the percentage of time less than 0.01%. These differences become more for high rainfall rates above 192 mm/h at 0.001% of time and below. Fig. 2 shows that the best agreement is between the measured rain rate of RGRx1 and the estimated rain rate from three rain gauges (RGE). The measured rain rates from all rain gauges at 0.01% are equal to the predicted one by the ITU-R Zone P with only a 1 mm/h difference. The measured rainfall rates are also close to the ITU-R Zone P at the percentage of time (P≥0.01%). The measured rain rate using RGE at 0.1% is equal to the predicted value by ITU-R Zone Q. At the time percentage of 0.001%, the predicted rain rate by ITU-R Zone N is close to the measurement rain rates of RGE and RGRx1 with a slight underestimation of 10 to 12 mm/h. However, the ITU-R Zone P's predicted value of 250 mm/h at 0.001% overestimated the RGRx, RGRx1, RGTx, and RGE measurement values by 50 mm/h, 60 mm/h, 38 mm/h, and 58 mm/h, respectively. It can be concluded that the rain climate in the experimental area falls between the rain of ITU-R Zone N and Zone P.

The measurements of the rainfall rate are also compared to the last version of the ITU-R P.837 series [27]. Fig. 2 demonstrates that the rain rates of the ITU-R P.837-7 model [27] are comparable with the measured rain rates in the high percentage of time 1% and above (low rain rate below 12 mm/h). At the time percentage of 0.6% to 0.002%, the ITU-R P. 837-7 rain rates are underestimated compared to the measured rain rates. At 0.01% of time, the ITU-R P.837-7 rain rate is 92 mm/h, however, the rain rates of the measurements are 146, 144, 146, and 144 mm/h for RGRx, RGRx1, RGTx, and RGE, respectively. This implies that the rain rate of ITU-R P.837-7 model at 0.01% had underestimated the measured rain rate by 52 to 54 mm/h and underestimated the rain rate of ITU-R P.837-1 Zone P by 53 mm/h. It is noted that the rain rates of ITU-R P.837-7 and ITU-R P.837-1 Zone N models are very close at the percentage of time 0.03% and above. At 0.001% of time, the rain rate of the ITU-R P.837-7 model has the best agreement with the measured rain rate of RGTx.

Fig. 2 also presents a comparison of our measured rain rate with the data from MMS and the real measurement conducted by Chebil et al. [28] near the experimental area. It can be seen that the MMS and Chebil's rain rate data are very close to the rainfall measurements by all rain gauges at the percentage of time (P≥0.01%).

IV. Rain Attenuation

We measured the maximum attenuation of the 73.5 GHz signal caused by rain. Then, the rain attenuation was calculated from the difference between the minimum RSL during clear sky conditions and the minimum RSL during rainy conditions. Here, the average wet antenna's radomes of 1.5 dB was calculated from the difference between the RSL in the clear sky condition period to the RSL during the first hour after rainfall has stopped and excluded from the rain attenuation. It is similar to the wet antenna attenuation calculated at the E-band in [29], [30]. Fig. 3 presents the CDFs for the maximum attenuation and the corresponding maximum rainfall every 15 minutes for the 1.8 km 73.5 GHz LOS terrestrial link. It also shows the normalized maximum attenuation (dB/km). It can be seen that the maximum rain attenuation with receiver sensitivity of -75 dBm is 40.1 dB (22.3 dB/km) at 0.03% of time. From the rain rate curve in this figure, it is worth noticing that for any rain rate above 108 mm/h, the link is down. This implies that the outage probability of the link is around 2.9×10^{-4}. The maximum rain attenuation varies between 2.2 to 38.9 dB (1.2 to 21.6 dB/km) with maximum rain rate range of 6 mm/h -107 mm/h at percentage of time decreasing from 5 to 0.05%, as depicted in Fig. 3.

The rain attenuation is calculated based on the ITU-R P. 530-17 recommendation [31] using the measured rain rate based on RGE and the predicted rain rate for ITU-R Zone P at 0.01%. Here, we compared our experimental data with the ITU-R Zone P since the Malaysia is located in ITU-R Zone P. Moreover, the ITUR-Zone P rain rate of 0.01% time percentage ($R_{0.01}$= 145 mm/h) is comparable with our measured

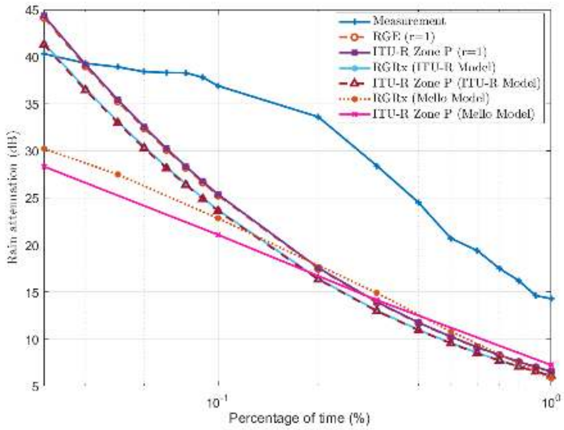

Fig. 4. Cumulative distribution for maximum rain attenuation every 15 minutes with different prediction models every minute for 1.8 km path length.

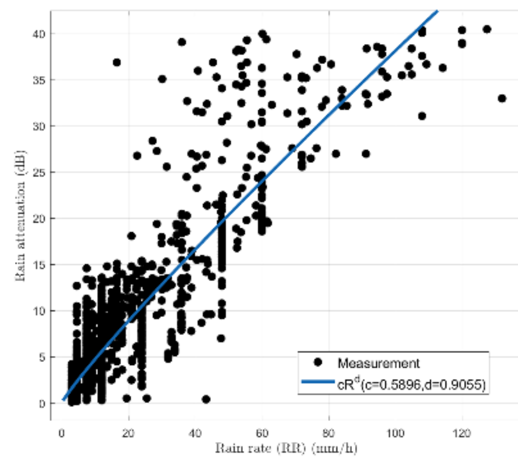

Fig. 5. Maximum attenuation dependency with maximum rain rate/15 minutes for 1.8 km path length for one year.

rainfall rate of $R_{0.01}$= 144 mm/h. The attenuation exceeding 0.01% of the year $A_{0.01}$(dB) is calculated as follows:

$$A_{0.01} = aR_{0.01}^{b}Lr \tag{3}$$

where the $a(1.0711)$ and $b(0.7150)$ coefficients depends on the polarization and frequency (f) specified in the ITU-R P. 838-3 [32], L 1.8 km) is the LOS path length and r is the distance factor calculated as [31]:

$$r = \frac{1}{0.477L^{0.633}R_{0.01}^{0.073b}f^{0.123} - 10.579(1 - e^{-0.024L})} \tag{4}$$

Here, r is assumed as 1 since the effect of rain distribution along the path has already been considered in (1). The attenuation exceedance for other percentages of time P in the range of 0.001%–1% of the year A_P(dB) can be calculated as follows:

$$A_P = A_{0.01}c_1P^{-(c_2+c_3\log P)}, \tag{5}$$

where

$$\begin{aligned} c_0 &= 0.12 + 0.4\log\left(f/10\right)^{0.8} \\ c_1 &= 0.07^{c_0}(0.12^{1-c_0}) \\ c_2 &= 0.855c_0 + 0.546(1-c_0) \\ c_3 &= 0.139c_0 + 0.043(1-c_0) \end{aligned} \tag{6}$$

The Mello model [33] utilizes the rain rate distribution R_P to correct the ITU-R model's underestimation of attenuation, especially in low latitude areas with serious precipitation regimes.

The seven curves plotted in Fig. 4 show the maximum measured rain attenuation CDF every 15 minutes compared to the calculated rain attenuation every minute by different prediction methods. The maximum measured attenuation varies between 40.1 to 14.3 dB for the range of P from 0.03 to 1%. It can be seen that the calculated attenuation based on the ITU-R Model [31] using the measured rain rate of RGE and RGRx is totally matched with the attenuation of ITU-R Zone P. It is noted that the collected rainfall data from one rain gauge (RGRx) are utilized for the rain attenuation calculation based on r of (4), while for the RGE data, the assumption of $r = 1$ is used. Since the attenuation per minute must be equal to or less than the maximum attenuation per 15 minutes, from the visual inspection of Fig. 4, it is mentioning that the ITU-R model over estimates the attenuation exceeding 0.03% of the year by 1 dB to 4 dB. The attenuation exceedance for other percentages of time P from 0.04 to 1% of the year is less than the maximum measured attenuation every 15 minutes. Fig. 4 shows that by using the Mello model, the attenuation exceedance for percentage of time P from 0.03% to 1% of the year is less than the maximum measured attenuation per 15 minutes. The attenuation exceedance for the percentage of time $P \geq$ 0.03% to $P<$ 0.1% of the ITU-R model overestimates the attenuation of Mello model. However, the attenuation based on the ITU-R model is close to the attenuation based on the Mello model for other percentages of time P from 0.1 to 1% of the year.

Fig. 5 presents the variation of the maximum rain attenuation with the maximum rainfall rate every 15 minutes in the total period of measurements. The correlation between the maximum rain rate and maximum rain attenuation is 90%. In general, rain attenuation increases as the rain rate increases. The power law model can fit the rain attenuation data with coefficients ($c = 0.5896$, $d = 0.9055$), as shown in Fig. 5. It can be seen that the rain attenuation has dispersion features where it is large in certain rainfall rates. To further study this dispersion, the standard deviation of the maximum rain attenuation (σ_A) is calculated based on the mean values of the maximum rain rate (μ_R) as shown in Fig. 6. It can be shown that the σ_A of the rain attenuation dispersion varies from 2.3 to 6.5 in the range of μ_R for the maximum rain rate from 8.1 mm/h to 110 mm/h. The maximum dispersion of rain attenuation occurs with the range of σ_A from 5 to 6.5 for the μ_R maximum rain rate of 31 mm/h to 70 mm/h. From Figs. 5 and 6, the rain attenuation causes both attenuation and deviation of the received signal. The standard deviation of attenuation follows a nonmonotonic relationship with the maximum rain rate. Specifically, the standard deviation first increases with the maximum rain rate and then decreases after

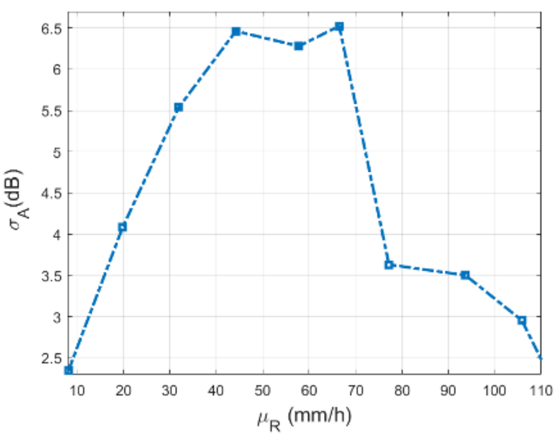

Fig. 6. Standard deviation of maximum attenuation according to mean values of maximum rain rate for 1.8 km path length for one year.

the maximum rain rate reaches a certain value. This is because the rain will cause less fluctuations or fading to the signal propagation when the rain rate is low (almost a clear LOS) or when the rain rate is high (leading to nearly blocked).

V. Conclusion

In this letter, based on the measurement campaign done in Malaysia, the rain rate and rain attenuation of the 73.5 GHz E-band link were analysed and discussed. This is the first experiment at E-band conducted in heavy rain tropical region. The CDF of the rain rate and rain attenuation were calculated and compared with some previous measurement results, the ITU-R and the Mello models. The maximum rain attenuation dispersion according to the maximum rain rate was presented for the first time. The maximum rain attenuations for one-year of measurements are about 14.3, 33.6, 36.9, and 40.1 dB for 1.8 km when the rain rates are 31.9, 70.4, 94.5, and 108 mm/h, respectively. Based on the maximum rain attenuation exceeding 0.03% of the year, the link outage probability is 2.9×10^{-4}. Applying these outcomes will help improve the design and operation of E-band wireless links which will be set up at other similar sites as well as other tropical regions.

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