Spatial variations of rain intensity over a short length propagation for 5G links based on a rain gauge network

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Article Info

Article history:

Received May 28, 2020
Revised Oct 11, 2020
Accepted Oct 23, 2020

Keywords:

5G network
Millimeter-wave
Rain attenuation
Rain gauge network
Spatial variations

ABSTRACT

Millimeter-wave (mm-wave) frequency range is among operating bands designated for terrestrial 5G networks. A critical challenge of link-budgeting in mm-wave 5G networks is the precise estimation of rain attenuation for short-path links. The difficulties are further amplified in tropical and subtropical regions where the rainfall rate has a higher intensity. Different models have been proposed to predict rain attenuation. The distance factor is an important parameter in predicting total attenuation from specific rain attenuation. This study investigates the distance factor based on rain gauge networks and measured rain attenuation at 26 GHz for a 300 m link in Malaysia. Considerable discrepancies between available models were observed especially when applied for shorter path links. Also, significant variability of rain intensity is observed from the rain gauge network. This study recommends further investigation of the distance factor for a shorter link. Hence, a measurement campaign incorporating rain gauge networks was established to examine spatial variations of rain intensity over a less than 1 km link. The motivation is to develop a suitable distance factor model for 5G mm-wave propagation.

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1. INTRODUCTION

5th generation (5G) millimeter-wave (mm-wave) communication system is a forthcoming technology that has been touted to provide high-speed data rates and large bandwidth. However, precipitation is a notable phenomenon that could disrupt mm-wave signals propagation [1, 2]. Attenuation due to precipitation at frequencies over 10 GHz could cause outages that compromise the accessibility and performance of the mm-wave links. For an environment experiencing rainfalls, the mm-wave signal could be dissipated, depolarized, and diffracted. In such circumstances, a careful forecast of rain fade characteristics is the basis to establish a reliable and uninterrupted link [3, 4]. Furthermore, another paramount factor that needs to be taken into account is the impact of high rain intensity [5-7]. To appropriately predict rain attenuation, raining event patterns such as rain distribution within rain cell need to be investigated. These phenomena have been reported to reduce raining effective length along the propagation path [8].

The measure of attenuation due to precipitation per unit path length is characterized as specific rain attenuation, γ_R, in dB/km. Assessing the γ_R principally relies on the rain intensity, frequency regression coefficients, and type of polarization. Consequently, the specific rain attenuation, γ_R, applying the coefficients of frequency-dependent is expressed as;

$$\gamma_R = kR^{\alpha} \qquad \text{dB/km} \tag{1}$$

where R (mm/h) is rainfall rate for a given year. The coefficient value of k and α are dependent on the value of the frequency, f (GHz), the polarization of the wave, and distribution of raindrop size [9-11]. Attenuation due to rain on a line-of-sight (LOS) path can be expressed by;

$$A = \gamma_R d_{eff} = \gamma_R \times d \times r \qquad \text{dB} \tag{2}$$

where d_{eff} is effective path length over which rain rate is considered uniform and d is actual path length in km. The distance factor, r, is horizontal inhomogeneity of rain along the propagation path. Precipitation is not invariantly dispersed along the total path length. Hence, d is not the same as d_{eff} [12-15]. This estimation is dependent on precipitation dispersion. Accordingly, attenuation of the signal due to rainfall rate is determined as a function of d_{eff}. At the point when this distance expands, it implies the precipitation will comprise a wider area between links, lead to more signal fading. Numerous mm-wave terrestrial link forecasting models had focused on d_{eff} and considered distance factor with a value of less than 1 as the rain fade estimation. These models proposed averaging out the spatial inhomogeneity of rainfall rate to be uniformly distributed along the propagation path of 1 km, specified as specific attenuation in dB/km. The perceived impression was that additional attenuation caused by rain is straightforwardly proportional to the active distance between the links [16]. To anticipate the aggregate sum of attenuation caused by precipitation that an mm-wave link might experience, a distance factor is required to account for the variability of rainfall rate along the propagation path for a short distance link. Forecasted rain-induced attenuation via the standard ITU-R P.530-17 model had been shown to overestimate the measured data for the short-path link [17]. This is due to the inclusion of distance factor, r, that was found to be inconsistent for path length less than 1 km. Hence, a modification for r in the ITU-R P530.17 model is required for short-path links in a tropical climate [18]. Since spatial variations of rain intensity along the propagation path directly affects r, this study proposes an experiment using rain gauge networks to investigate spatial variations of rain intensity over a shorter link of less than 1 km. It will be used to develop a suitable distance factor model for 5G links.

2. DISTANCE FACTOR MODELS

Precipitation in a given area has a rainfall rate that is higher at the focal point of the rain falling area and diminishes quickly near to the boundary. This is due to precipitation's natural characteristic that is convectional. The distance factor, r is essential for the unevenness of rainfall rate along the path between the terrestrial links. Thus, r is a significant parametric quantity when forecasting signal fade due to rain.

2.1. ITU-R P-530-17

From International Telecommunication Union's ITU-R P.530.17 [19], this r is given by (3) with frequency, f is in GHz and α is similar to that of (1). The highest value of r is 2.5 and should be used when the denominator value of (3) is less than 0.4.

$$r = \frac{1}{\left(0.477 \times d^{0.633} \times R_{0.01}^{0.073\alpha} \times f^{0.123}\right) - 10.579\left(1 - exp(-0.024d)\right)} \tag{3}$$

The rain-induced attenuation for different percentages of time, p, in the range between 0.001% and 1% is derived by power-law relationship given by;

$$\frac{A_p}{A_{0.01}} = C_1 p^{-(C_2 + C_3 \log_{10} p)} \tag{4}$$

where the values of C_1, C_2 and C_3 are shown in ITU-R P.530.17 [19]. ITU recommended the use of this model with regional measured rainfall rate data or with the use of ITU recommended map. The model could be used for rain attenuation at f in the range of 1 and 100 GHz for a maximum distance up to 60 km.

2.2. AbdulRahman model

AbdulRahman [20] developed a model to estimate the r as expressed in (5) where d represents the actual distance between the transmitter and receiver of the link and $R_{0.01}$ is the rain rate at 0.01% percentage of the time.

$$r(R_{0.01}, d) = \frac{1}{1+\left[\frac{d}{2.6379(R_{0.01})^{0.21}}\right]} \quad (5)$$

This model uses multiple non-linear regression techniques. The rain-induced attenuation for different percentages of time, p, is derived by (6).

$$A_{\%p} = \gamma_R \times d_{eff} = \{k(R_{\%p})^{\alpha}\} \times \frac{d}{1+\left[\frac{d}{2.6379(R_{0.01})^{0.21}}\right]} \quad (6)$$

2.3. Lin model

This model [21] reported measurement works associated with the variability of rainfall rate along the propagation path. r in this model is shown in (7).

$$r = \frac{1}{1+\left(\frac{d}{d(R)}\right)} \quad (7)$$

where $d(R)=2636/(R-6.2)$ and d represents the actual link distance. R is the rainfall rate. The rain-induced attenuation for different percentages of time, p, is derived by (8).

$$A_{\%p} = \gamma_R \times d_{eff} = \{k(R_{\%p})^{\alpha}\} \times \frac{d}{1+\left(\frac{d}{d(R)}\right)} \quad (8)$$

2.4. DA Silva Mello model

This model [22, 23] applies numerical coefficients that are determined for effective rainfall rate across identical rain cell distances, acquired through various nonlinear regressions of accessible measured data. r in this model is shown in (9);

$$r = \frac{1}{1+\left(\frac{d}{d_0(R_p)}\right)} \quad (9)$$

where $d_0=119R^{-0.244}$ and d is the actual path length between the links. d_0 represents equivalent rain cell diameter. The rain-induced attenuation for p is derived by (10);

$$A_{\%p} = \gamma_R \times d_{eff} = k[R_{eff}(R_p, d)]^{\alpha} \times \frac{d}{1+\left(\frac{d}{d_0(R_p)}\right)} \quad (10)$$

where R_{eff} is the effective rainfall rate as a function of d and R_p. The regression coefficients of (11) as shown below;

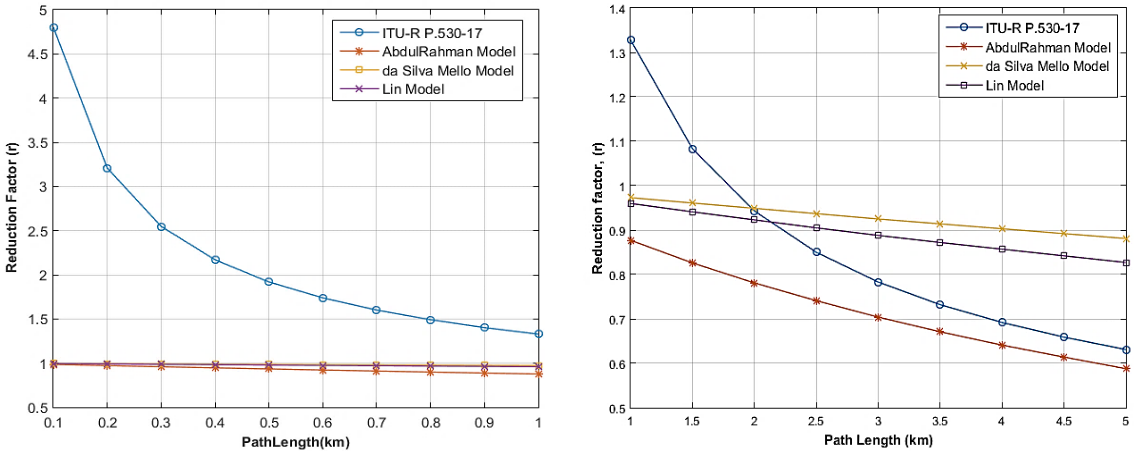
$$R_{eff} = 1.763R^{0.753+\frac{0.197}{d}} \quad (11)$$

were obtained by multiple nonlinear regressions using measured data in the ITU-R databanks.

3. INVESTIGATION OF DISTANCE FACTOR

Aforementioned, rain occurs in cells that are mostly convective by nature causes the rain rate to be higher at the center of the rain cell and taping rapidly at the edge. This eventually leads to unequal dispersion of rain in areas that are experiencing precipitation. The r proposed by the 4 models in section 2 were investigated for path lengths that are less and more than 1 km as presented in Figure 1.

From Figure 1 (a), it was observed that r values are constant with values that are approximately 1 for AbdulRahman, Lin, and da Silva Mello models. The ITU-R model in contrast resulted in r values that decline exponentially as path length increases from 100 m to 1 km. For 300 m distance, r values are 2.548, 0.959, 0.992 and 0.987 for the ITU-R, AbdulRahman, da Silva Mello and Lin Models respectively. From Figure 1 (b), it was observed that the values of r decrease linearly with increasing path length for AbdulRahman, da Silva Mello and Lin model. On the other hand, ITU-R model presented r values that decrease exponentially. The rain attenuation was forecasted using the four models as presented in Figure 2. Measured rain rate at $R_{0.01}$ of 116 mm/h [8] and path length of 300 m was considered for this simulation. f is 26 GHz with horizontal polarization. These predicted attenuations were compared with one-year measured attenuation in UTM Johor Bahru campus [24].



(a) (b)

Figure 1. Comparison of *r* proposed by different prediction models against path length; (a) less than 1 km and (b) more than 1 km

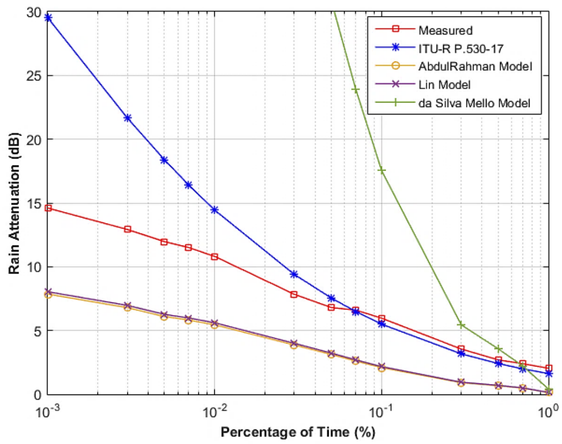


Figure 2. Comparison between measured attenuation with different attenuation prediction models at 26 GHz of frequency horizontal polarized for 300 m of path length

Figure 2 shows that the predicted attenuation results by ITU-R overestimated at 0.001% and 0.01% by 14.91 dB and 3.63 dB respectively but presented the closest estimation to measured attenuation at 0.1% with a difference of only 0.48 dB. Da Silva Mello model shows very high overestimation when compared to the measured attenuation for short path length. The results at 0.001%, 0.01% and 0.1% were overestimated by 98.58 dB, 56.8 dB and 11.57 dB respectively. Conversely, the AbdulRahman and Lin models show almost similar underestimated result trends when compared to the measured attenuation. The attenuation for AbdulRahman model at 0.001%, 0.01% and 0.1% were underestimated by 6.75 dB, 5.37 dB and 3.88 dB respectively. None of the forecasted attenuations reflect the measurement accurately at 300 m path length. Hence, further investigation of *r* is required for short-path less than 1 km link operating at mm-wave.

4. RAIN GAUGE NETWORK SETUP

In this study, five ONSET HOBO RG3-M (0.2 mm per tip) tipping bucket rain gauges as shown in Figure 3 were used to measure rainfall rate with a 1-sec time stamp. The time of all rain gauges had been synchronized weekly. During any rain event, the rain gauge would record rain data into its memory system. No data will be recorded when there is no rain.

The RG3-M rain gauge specification is shown in Table 1. The gauge comprises of two main components, namely a tipping bucket and a HOBO rain event/temperature data logger. The collector of the rain gauge is made of black-anodized aluminum knife-edged and funnel shapes that alter rainwater to a tipping-bucket system located in an aluminum structure. The aluminum structure has a white color enamel surface designed to withstand years of laying open to the environment as shown in Figure 3. The tipping-bucket system is designed such that one tip of the bucket is equivalent to 0.2 mm of rainfall. Each bucket tip is detected when a magnet attached to the tipping bucket activates a magnetic switch as the bucket tips, thus effecting a momentary switch closure for each tip. The spent rainwater then drains out of the bottom of the structure. The switch is connected to a HOBO rain event/temperature data logger, which records the time of each tip. The data logger is a rugged, weatherproof event logger with a 10-bit temperature sensor. It can record 16,000 or more measurements and tips. It uses a coupler and optical base station with a USB interface for launching and data readout by a computer [25].

Figure 3. ONSET HOBO RG3-M tipping-bucket rain gauge

Table 1. The technical specifications of the ONSET HOBO RG3-M tipping-bucket rain gauge

Rain Gauge	Logger
ONSET HOBO RG3-M (0.2 mm per tip)	Time stamp: Resolution 1.0 second
Calibration accuracy: ±1.0% (20 mm/hour)	Time accuracy: ± 1 minute per month at 25°C (77°F)
Resolution: 0.2 mm (RG3-M)	Operating range: -20° to 70°C (-4° to 158°F)
Calibration: Requires annual calibration	Battery: CR-2032 3V lithium battery; 1-year typical use
Operating temperature range: 0° to +50°C	64K bytes – 16K to 23K when recording events only; 25K to 30K data points when recording events and temperature;
Storage temperature range: -20° to +70°C	
Environmental rating: Weatherproof	
Housing: 15.24cm (6-in.) aluminum bucket	
Dimensions: 25.72 cm height x 15.24 cm diameter; 15.39 cm receiving orifice	
Weight: 1.2 Kg	

Rain gauges RG1, RG2 and RG3 that have been installed at three different locations within Universiti Teknologi Malaysia (UTM) Johor Bahru Campus are shown in Figure 4. Another two rain gauges; RG4 and RG5 as shown in Figure 4 are in the process of installation. RG1 was installed on the roof of Microwave and Antenna Laboratory whereas RG2 was installed on the roof of a building near the laboratory. The distance between RG1 and RG2 is 206 meters. The RG3 was installed on the roof of UTM's Wireless Communication Center. The distance between RG2 and RG3 is 304 meters. The proposed RG4 will be installed on the roof of the UTM's Endowment Building with a distance between RG3 and RG4 being 297 meters. Next, RG5 will be installed near UTM's Observation Park with a distance between RG1 and RG5 being 918 meters. All the rain gauges locations are given in Table 2.

Table 2. Location of the rain gauges at UTM Johor Bahru Campus

RG1	RG2	RG3	RG4	RG5
1.561777°N, 103.645799°E	1.559859°N, 103.645652°E	1.558249°N, 103.643404°E	1.556272°N, 103.641852°E	1.569925°N, 103.644732°E

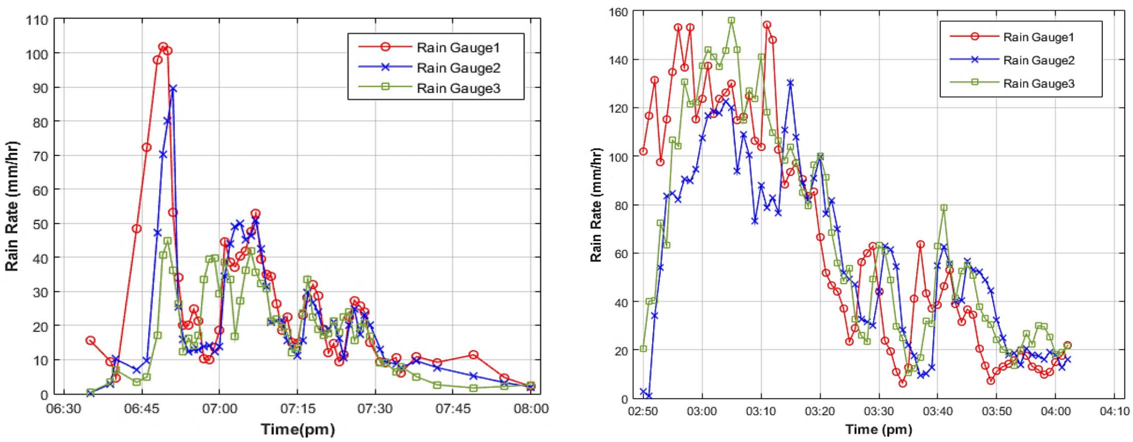
Figure 4. Location of the rain gauges at UTM Johor Bahru Campus

5. PRELIMINARY RESULTS AND DISCUSSION

The measured rainfall rate of the three installed rain gauges for two rain events that occurred on 21 January and 29 January 2020 is shown in Figures 5 (a) and 5 (b) respectively. From Figure 5 (a), it was observed that rainfall rate varies from 0.29 mm/hr to 101.90 mm/hr at RG1, from 0.27 mm/hr to 89.62 mm/hr at RG2 and from 0.53 mm/hr to 44.77 mm/hr at RG3. From Figure 5 (b), it was observed that the rainfall rate varies from 6 mm/hr to 155 mm/hr at RG1, from 1 mm/hr to 130 mm/hr at RG2 and from 10 mm/hr to 156 mm/hr at RG3.

Seven minutes rainfall rate variations that occurred on 21 January and 29 January 2020 are presented in Figure 6 and Figure 7 respectively. From Figure 6, it was observed that at 6.47 pm, the measured rain rates are 72.29 mm/hr, 9.79 mm/hr, and 4.93 mm/hr at RG1, RG2, and RG3 respectively. At 6.49 pm, the measured rain rates are 101.90 mm/hr, 70.28 mm/hr, and 40.70 mm/hr at RG1, RG2, and RG3 respectively. At instant 6.51 pm, the measured rain rates are 53.33 mm/hr, 89.62 mm/hr, and 36.34 mm/hr at RG1, RG2, and RG3 respectively. The results clearly show that rain intensity variations are not uniform within this short distance.

From Figure 7, it was observed that at 3.35 pm, the measured rain rates were 12.75 mm/hr, 21.89 mm/hr, and 10.43 mm/hr at RG1, RG2, and RG3 respectively. At 3.37 pm, the measured rain rates are 63.47 mm/hr, 9.23 mm/hr, and 16.90 mm/hr at RG1, RG2, and RG3 respectively. At 3.41 pm, the measured rain rates are 46.44 mm/hr, 62.57 mm/hr, and 78.70 mm/hr at RG1, RG2, and RG3 respectively.



(a) (b)

Figure 5. Rain intensity variation along the three rain gauges for two rain events occurred on (a) 21 January 2020 and (b) 29 January 2020

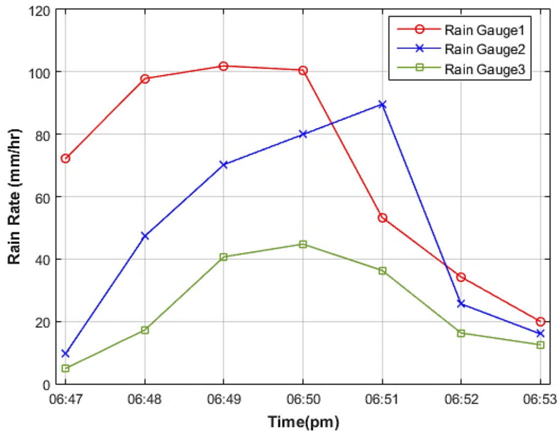


Figure 6. Rain intensity variations along with the three rain gauge stations for a short instant from 6:47 pm to 6:53 pm

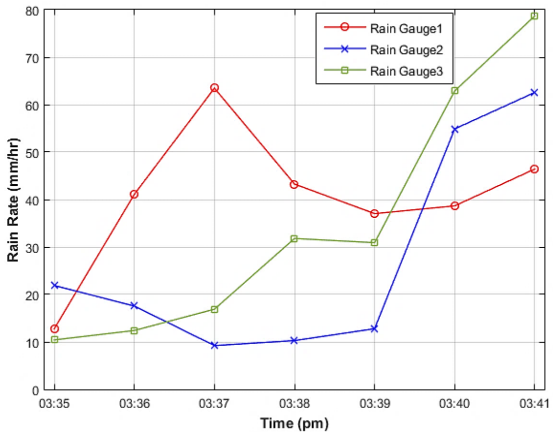


Figure 7. Rain intensity variation along with the three rain gauge stations for a short instant from 3:35 pm to 3:41 pm

6. CONCLUSION

Different models have been proposed to forecast rain attenuation. The distance factor, *r*, is the main parameter in modeling total attenuation from specific rain attenuation. This study investigated four models for *r* proposed from literature. A comparison was made between these models based on measured rain attenuation at 26 GHz for a 300 m link in Malaysia. All models were found to demonstrate considerable discrepancies when forecasting rain attenuation for a shorter link. Hence, an experiment using rain gauge networks was conducted to investigate spatial variations of rain intensity over a short length propagation for 5G links. Measured raining events at two different dates using three rain gauges have been analyzed and demonstrated that rain intensity variations are not uniform within 510 m distance. This study demonstrates that rain intensity distributions and its variations along a line can be soundly characterized using a rain gauge network to develop a novel distance factor for less than 1 km link.

ACKNOWLEDGEMENTS

This work has been funded by the Ministry of Education Malaysia and Universiti Teknologi Malaysia under ”FRGS” Vot. No. RJ130000.7823.4F958 and “IIIG” Vot. No. 01M28.

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