

A methodology for precise estimation of rain attenuation on terrestrial millimetre wave links from raindrop size distribution measurements

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Abstract

Attenuation by atmospheric rain is the most significant impairment in millimetre wave frequencies (mmWave). Modern instruments could provide detailed measurements of rain, such as raindrop size distributions (DSDs). The analysis of DSDs could estimate their effects on past or co-located links measurements. This study presents propagation analysis in the mmWave bands using measurements of two terrestrial links working at 26 GHz and 38 GHz carried out in Johor, Malaysia. Statistics obtained have been analysed in detail to extract any excess attenuation. The DSDs provided by a disdrometer have been used to estimate rain attenuation. The derived results show that the estimation can provide reasonable accuracy after extracting the wet antenna effects and having the advantage of the availability of measurements from various types of equipment.

Keywords: millimetre wave propagation, rain attenuation, raindrop size distribution, wet antenna effects

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1. Introduction

The move toward millimetre-wave (mmWave) radio communications requires improvement in the prediction of the propagation impairments [1–3]. Rain-induced attenuation plays the major rule degrading the quality of millimetre-wave systems [4–6]. Absorption and scattering of electromagnetic signals due to raindrops result in signal attenuation and in a reduction of overall system availability and performance. As precipitation changes with geographical location, the effect becomes very critical in tropical regions, as precipitation rates are much higher and more frequent than in temperate regions [7–10]. In spite of that, a more detailed analysis of rainfall is required [11, 12]. The Modern meteorological equipment provides detailed analysis or raindrop size distribution (DSD), which can be used to estimate the induced attenuation on such links [13–15]. However, the required process to find these attenuations need measurements data of both rain DSDs and links attenuation for validation.

A propagation measurement was carried out in Universiti Teknologi Malaysia (UTM), Malaysia. The availability of both mmWave links and the co-located meteorological equipment makes it possible to develop practical procedures to accurately estimate the rain induced attenuation on the link from the DSD [16, 17]. This contribution presents some findings on the effects of rain attenuation on mmWave systems. The DSDs provided by advanced meteorological equipment have been used to estimate rain attenuation. The experimental equipment is presented in section 2, whereas section 3 the data processing procedures are described and section 4 is dedicated to the rain attenuation estimation from drop size distributions. The wet antenna effects on these estimations were extracted in section 5, and finally, section 6 provides a statistical analysis of the estimated and measured data. Section 7 concludes the study with a summary of the main results and their possible applications.

2. Experimental Equipment

The experimental mmWave Ericsson mini-links operating at 26 GHz and 38 GHz, with horizontal polarization, were installed at UTM main campus for the period of 2 years

(1998-2000) [18], as shown in Figure 1, with a path-length of 300 m. The links provided automatic gain control voltages (AGCV) through a data acquisition system, which was sampled every second. The received power level (P_{Rx}) is determined from the AGCV level using calibration chart supplied from Ericsson. The system employs a common antenna for the transmitter and the receiver, which includes a duplexer. The main system parameters are summarized in Table 1. Additionally, a tipping-bucket rain gauge with 0.5 mm sensitivity was set up near the receiver end on the roof of Wireless Communication Research Lab (WCRL) building, which provided a simultaneous one-minute integrated rain rate to assist the links measurements.

The raindrop size distribution was experimentally measured by a 2-dimensional video disdrometer (2DVD) that records orthogonal image projections of raindrops as they cross its sensing area, and can provide detailed information, including velocity, contour and drop axis ratios, of individual raindrops [14]. The 2DVD was installed on the same WCRL roof for three years (2015-2018) accompanied by Automated weather station that provided rain-rate, wind speed/direction, temperature and humidity, and used to validate the 2DVD rain-rate [5]. Both systems are shown in Figure 2.



Figure 1. Path of Ericsson mini-links installed in UTM

Table 1. System Specifications for the Ericsson Links

Parameters	Specification	
	Frequency (GHz)	38
Polarization	Horizontal	Horizontal
Path-Length (Km)	0.3	0.3
Antenna Size (m)	0.6	0.6
Antenna Gain (dBi)	44.9	41
Transmitter Power level (dBm)	15	3
Receiver Power Level (dBm)	-25.3	-36.2



Figure 2. 2-dimensional video disdrometer (2DVD), and the co-located automated weather station installed on the roof of WCRL

3. Data Processing

Taking into consideration the integration time of the rain rate data and to relate it with the received power, all the data collected by the Ericsson links are averaged over the 1-minute integration time. Figure 3 shows the received signal level P_{Rx} ($f=38$ GHz), on the 14th July 1999, with the original sampling period (1-second) and after applying the 1-minute averaging. From the figure, a strong event can be observed between 10 am and 12 pm.

To derive the total attenuation (A_T) rain events were first identified, as shown in Figure 4, which shows the same event on the 14th of July 1999. The upper graph shows the received signal level P_{Rx} ($f=38$ GHz), and the bottom graph shows the concurrent the 1-minute averaged rain-rate obtained using the rain gauge. It is assumed due to the short link length, and the near location of the rain gauge to the link, that the rain will affect the rain gauge and the link at the same time.

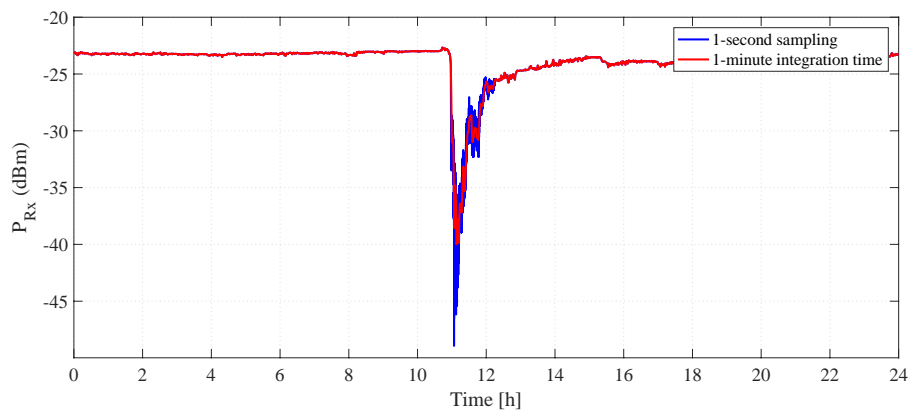


Figure 3. Received signal level at (38 GHz), on 14th of July 1999, showing the 1-second sampling and after applying 1-minute averaging

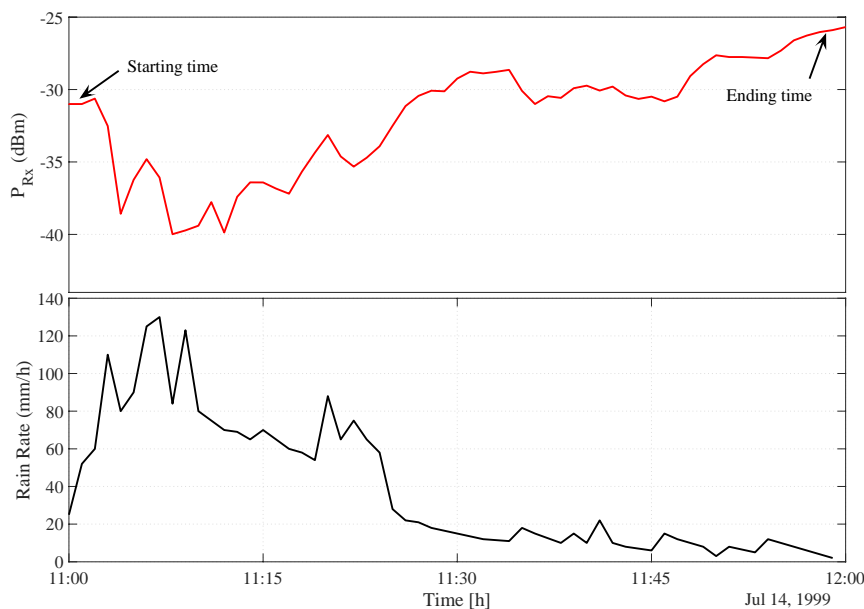


Figure 4. Identification of rain event at 38 GHz received signal level at the upper graph, and concurrent rain-rate at the bottom graph

The total tropospheric attenuation was then derived from the P_{Rx} , and a correction method was applied as follows:

- a. P'_{Rx} calculation
 - In the absence of rain: $P'_{Rx} = P_{Rx}$
 - During rain event: P'_{Rx} is calculated as the linear interpolation between the two levels at the start of the event (P_{Rx}^s) and the end of the event (P_{Rx}^e)
- b. Low pass filter was applied to remove the fast oscillations of the signal, and generate P''_{Rx}
- c. The attenuation different was then calculated, including the theoretically calculated gaseous attenuation (A_G):

$$A_{diff} = -P''_{Rx} - A_G \quad (1)$$

- d. From that the total tropospheric attenuation A_T was calculated:

$$A_T = -P_{Rx} - A_{diff} \quad (2)$$

The steps followed are displayed in Figure 5. This procedure defines the contribution of the tropospheric attenuation to the total attenuation and reduces the fluctuation of the received signal level. The extraction of the attenuation induced by rain (A_R) from A_T , is then calculated as:

$$A_R = A_T - A_G \quad (3)$$

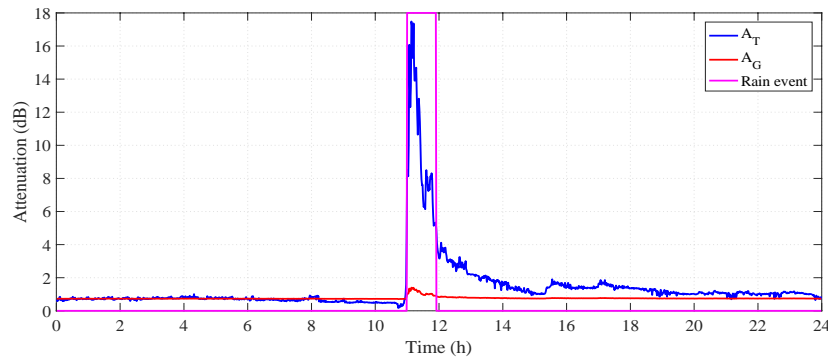


Figure 5. Time series of total attenuation and the gaseous attenuation with event identification using rain data ($f=38\text{GHz}$)

4. Estimation of Rain Attenuation

A simple analytical formula is provided by ITU-R recommendation P.838-3 [6] to calculate the specific attenuation induced by rain (γ_R), using that formula the Rain attenuation on the link path-length (L) can be defined as:

$$A_R^{ITUR} = \gamma_R^{ITUR} L = kR^\alpha L \quad (4)$$

where k and α are the power law coefficients dependent on the frequency (f), and the polarization of the link, R is the rain rate in mm/h. P.838-3 [6] also provides a set of k and α values for the frequency range from 1-1000 GHz. Assuming the rain rate is constant along the path (short path-length), this allow the calculation of rain induced attenuation by simply multiply the specific attenuation γ_R by the length of the link L .

The attenuation induced by rain is not only dependent on the rain rate R , it's also a function of the raindrops size distribution (DSD), drops shape and terminal velocity which can be calculated from the distrometric data provided by the 2DVD in ($\text{mm}^{-1}\text{m}^{-3}$) as [19]:

$$N(D_i) = \frac{1}{\Delta t \Delta D} \sum_{i=1}^{m_i} \frac{1}{A_i v_i} \quad (5)$$

In (5), m_i is the total number of raindrops within the class width (with mean diameter D_i), $\Delta D_i(\text{mm})$ represents the width of each drop size class, $A_i (\text{mm}^2)$ is the effective disdrometer sampling area, Δt is the integration time period in seconds, $v_i (\text{m/s})$ is the terminal velocity of drops which is derived directly from the disdrometer measurements.

The rain rate can also be derived from the disdrometer data as follow:

$$R = \frac{3600}{\Delta t} \sum_{i=1}^n \frac{V_i}{A_i} \quad (6)$$

where V_i (mm^3) is the drop volume, n is the total number of drops during the integration period. The specific attenuation γ_R (dB/km) at frequency f , for the drop density $N(D)$ is a function of the wavelength λ and the forward scattering coefficient S_0 [20].

$$\gamma_R^{DSD} = 4.343 \cdot 10^3 \frac{\lambda^2}{\pi} \sum_{i=1}^N Re[S_0(D_i, f)] \cdot N(D_i) \cdot \Delta D_i \quad (7)$$

The forward scattering coefficient S_0 are then calculated using the T-Matrix approach [21], following the axial ratio provided by the 2DVD data and described in [5]. The rain induced attenuation can then be calculated as:

$$A_R^{DSD} = \gamma_R^{DSD} L \quad (8)$$

Figure 6 is a sample to present the accuracy of each method outlined above in the estimation of rain attenuation, where the rain rates data recorded by the rain-gauge was used to identify the measured DSD to be used for the estimation. The measurements of the event on 14th July 1999 are compared to the attenuation estimations produced from the both methods. While the trend of the three results was similar, different results were obtained. The ITU-R approach slightly over-estimated the rain induced attenuation, as k and α are both independent of the DSD. This can be explained due to the use of high frequency, the DSD responds differently than for lower frequencies, on that it's appropriate to say that DSD allows more proper calculation of the specific attenuation.

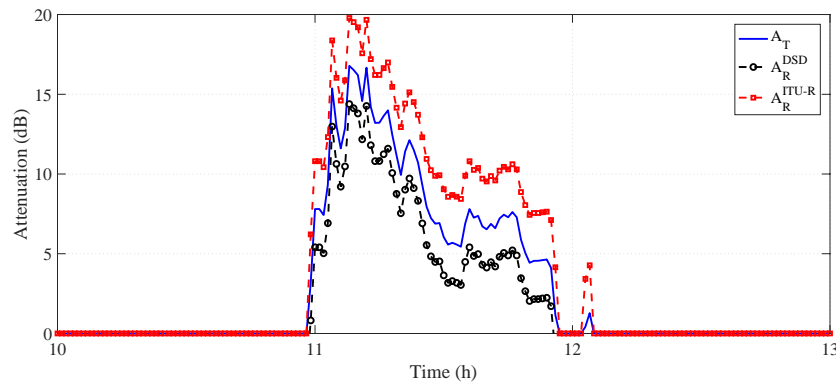


Figure 6. Rain attenuation (38 GHz) on 14th July 1999; derived from the link measurement, estimated using ITU_R P.838-3 and estimated using DSD data

5. Wet Antenna Effects

From the previous section it is obvious that A_R^{DSD} is always lower than A_R , which can be explained due to the existence of wet antenna effects adding extra attenuation to the rain induced attenuation. This will be extracted in this section. The antennas used for this measurement were covered with radome [22]. However, the losses due to water being on the radome surface are considerable at high frequencies. To this end, a simulated-rain experiment was carried on the receiver end of the links. The water was sprayed by a controllable hose pipe, connected to motor pumped the water about 10 m height. The main results of the experiment are presented in Table 2.

The procedure to extract wet antenna attenuation A_{wet} from the measured A_R requires the knowledge of the antenna characteristics, and the availability of measured data. To acquire the required boundaries for the antenna characteristics, extraction of the defining characteristics from the simulated-rain exterminate were done. Based on these characteristics, the wet antenna effects were investigated by taking the advantage of having links operating at two frequencies,

using method based on dual-frequency model proposed by [23] which assumes that the ratio between the path attenuation at the two frequencies is known and is equal to that predicted by the ITU-R frequency-scaling model [24]. The model can be described for the two frequencies used as:

$$A_{R,38} + A_{wet,38} = A_{T,38} \quad (9)$$

$$A_{R,26} + A_{wet,26} = A_{T,26} \quad (10)$$

If we denote the ration $A_{R,38}/A_{R,26}$ by S_R and that between $A_{wet,38}/A_{wet,26}$ by Λ the previous equations can be rewritten as (11).

$$S_R A_{R,26} + \Lambda A_{wet,26} = A_{T,38} \quad (11)$$

The value of S_R was almost constant at 1.82, while Λ was modelled as in [23]. Figure 7 represents the effect of applying the extraction of the wet antenna effects to the results already presented in Figure 6. A good agreement was obtained between the rain attenuation estimated from the link and using the DSD data.

Table 1. Average Simulated-rain Rate and Average Attenuation Measured for 26 GHz and 38 GHz Antennas

Volume of water flow	No. of tests	Average measured rain rate mm/hr	Measured averaged attenuation (dB)	
			38 GHz	26 GHz
Medium Light Spray	1	49	0.87	0.75
	2	48	1.19	1.15
	3	32	1.22	0.97
	4	52	1.53	0.74
Medium Heavy Spray	1	59	3.10	3.25
	2	61	2.75	2.59
	3	75	2.14	2.05
	4	86	2.89	2.68
Heavy Spray	1	160	3.91	4.16
	1	110	3.73	3.20

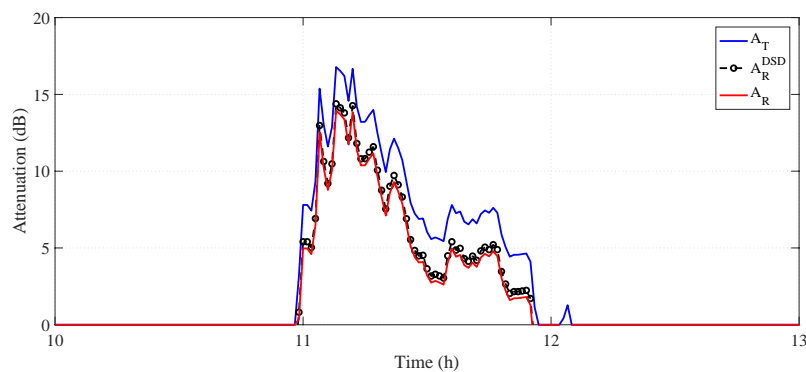


Figure 7. Rain attenuation (38 GHz) on 14th July 1999; derived from the link measurement, estimated using DSD data and rain induced attenuation after extracting wet antenna effects

6. Statistical Analysis

By removing the wet antenna effects, similar results have been obtained for a large number of events analysed. Figures 8 and 9 show the Cumulative Distribution Functions (CCDFs) of the rain attenuation as derived from the link data and as estimated according to the procedures outlined in the previous sections. By comparing the link data and the estimated data statistically, the results show that ITU-R P.838-3 underestimate the measured data, while the estimation using the DSD data is in very good agreement with the experimental results.

Additionally, Figure 10 reports the rain rate CCDF measured by the disdrometer, and the probability of rain rate exceeds 0.01% is found to be=116 mm/h. Both the rain gauge and

disdrometer were in good agreement, considering the year to year variability of rainfall. Figure 10 also includes the rain rate CCDF predicted using recommendation ITU-R P.837-7 [25].

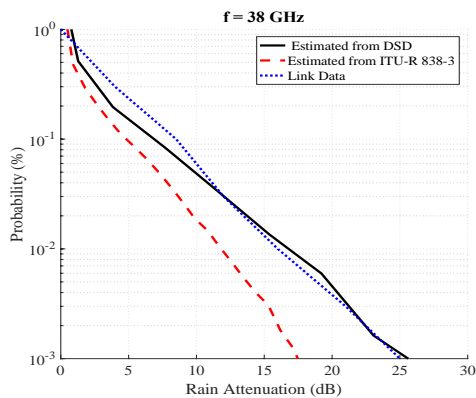


Figure 8. CCDF of the measured and estimated rain attenuation at 38GHz

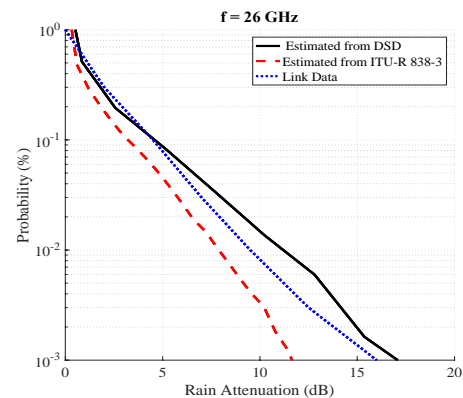


Figure 9. CCDF of the measured and estimated rain attenuation at 26GHz

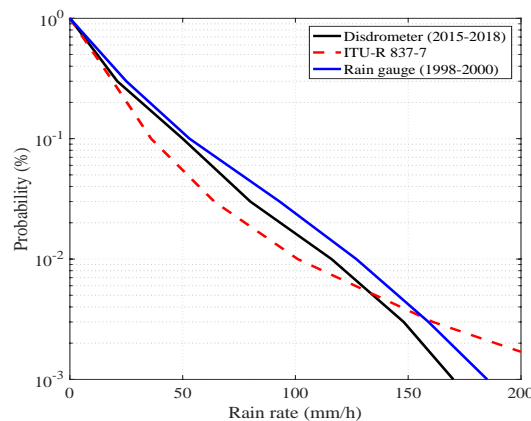


Figure 10. CCDF of the rain rate measured by the disdrometer, rain gauge and predicted by ITU-R P.837-7

7. Conclusion

In this study, the use of the 2-D Video Disdrometer has been applied for the field of millimeter-wave propagation. The estimated rain induced attenuation was derived by using the actual measured DSDs. Attenuation time series was also calculated and compared with experimental measurements of two links operating at 38 GHz and 26 GHz. After extracting the wet antenna effects, a good agreement was obtained between the rain attenuation estimated from the link and using the DSD data.

By comparing the link data, the theoretically predicted data, and the estimated data statistically, the results show that theoretical prediction by ITU-R P.838-3 underestimate the measured data, while the estimation using the DSD data is in very good agreement with the experimental results. The results presented here, can help in the design of millimeter-wave links, and in the development of fade mitigation techniques. The presented procedure can help in precise estimation of rain induced attenuation, which can be developed to present real time estimation that allows for the optimization of link operation.

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