

Rain attenuation prediction based on theoretical method with realistic drop shape for millimeter-wave radio in tropical region

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Abstract: This paper aims to investigate the effects of drop shape on rain attenuation prediction based on the theoretical approach. By comparing the predicted rain attenuation with the measurement results obtained in Skudai, Malaysia, the theoretical method based model utilizing the knowledge of scattering properties and raindrop-size distributions are found to produce better prediction results than the widely-used empirical ITU-R model, particularly at high rain rate. At 26 GHz and 38 GHz, results calculated using realistic drop shape were found to yield lower RMSE than using spherical shape.

Keywords: rain attenuation, realistic raindrop shape, tropical region

Classification: Antennas and Propagation

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1 Introduction

In recent decades, the unprecedented growth in radio communication systems has led to data traffic congestion in the lower microwave frequency bands and has resulted in the need for higher data capacity. To accommodate the ever-increasing data demands, service providers are compelled to migrate to millimeter-wave (mm-wave) band for the implementation of the next generation wireless network. The huge spectrum available in mm-wave band allows for larger channel bandwidth, greatly increasing the network data capacity. However, the reliability of radio communication at higher frequency tends to be heavily degraded due to atmospheric phenomena. Below 100 GHz, it is known that the attenuation due to precipitation is much more dominant than the loss induced by atmospheric gases and fog. In tropical regions with heavy rainfall throughout the year, the effect of rain attenuation on wireless communication is even more severe. Therefore, it is paramount to establish a model capable of accurately predicting the amount of attenuation caused by rain to achieve stable and reliable network performance.

In Malaysia, University Sains Malaysia (USM) and University Teknologi Malaysia (UTM) began collecting rain rate and DSD data through several measurement campaigns in the 1990s [1]. Various prediction models were developed focusing on different aspects such as path-reduction techniques, rain rate integration time conversion, and new sets of coefficients for the ITU-R model were also proposed. From the detailed literature review, it is identifiable that most works focused on the empirical approach, emphasizing on the modifications of effective path length and the coefficients of ITU-R model. Studies focused at tropical regions that employ theoretical approach and consider realistic drop shape are still relatively scarce.

This study aims to investigate the attenuation prediction using the theoretical method by comparing the measurement results with the results of different drop shapes. The paper is structured as follow. Section 2 provides a brief introduction to rain attenuation prediction methods with emphasis on the theoretical method. Section 3 presents the comparison between calculated and measured specific rain attenuation results. Finally, section 4 provides a summary of the main findings in this work.

2 Rain attenuation prediction methods

A fundamental quantity in the calculation of rain attenuation is the specific attenuation A , usually in dB/km. Two general approaches have been employed to calculate A :

2.1 Empirical method

The empirical approach is based on the approximate power-law relation between A and the rain rate R : $A = kR^\alpha$ where coefficients k and α are functions of frequency and polarization based on the fitting of empirical data. The validity of this empirical model was thoroughly examined by Olsen et al. [2] and was found to be accurate over a wide range of frequencies including the mm-wave range. Its simplicity also makes the empirical method practical for direct use by system designers and thus the method has been recommended by ITU-R P.838-3 [3]. However, recent studies have shown that the accuracy of the model is limited to temperate regions [4], where the temperature and rain rate are lower than in the tropical areas. Many researchers have also proposed local sets of coefficients k and α in various locations but they are not the focus of this work. The empirical method is simple and practical but it does not provide adequate insights into the physical properties of rain and the behavior of radio wave in rain.

2.2 Theoretical method

The theoretical method, or sometimes referred to as the physical method, provides more examination on the physical aspects of rain. The model is based upon the knowledge of total cross section (TCS), σ_t which represents the total power absorbed and scattered by a raindrop, and drop size distribution (DSD), $N(D)$ which describes the number concentration of raindrops of diameter D in a given volume.

$$A_{\text{theoretical}} = 10 \log(e) \times 10^3 \sum_{D_{\min}}^{D_{\max}} \sigma_t(D)N(D)\Delta D, \quad (1)$$

where e is the exponential constant and D_{\min} and D_{\max} generally have values of 0.25 mm and 6 mm, respectively.

2.2.1 Total cross section

Raindrops of different sizes exhibit different shapes. Small raindrops have nearly spherical shapes and for spherical raindrops, the TCS can be obtained using analytical solutions such as Mie theory, which has been used extensively in many related works.

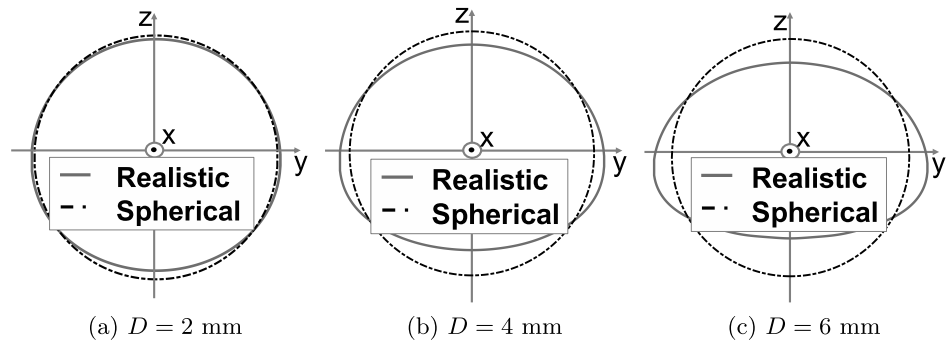


Fig. 1. In the realistic shape model [5], larger raindrops exhibit more obvious shape distortion. Note that the shape is rotationally symmetric about the z-axis.

However, large raindrops are found to have distorted shape, similar to an oblate spheroid with a flattened base, as depicted in Fig. 1 [5].

Some of the initial work on non-spherical drop shapes was done by Pruppacher et al. [6] who introduced a numerical solution for the pressure balance equation to describe drop shapes. More recent measurements of drop shapes by two-dimensional video disdrometer indicate that the Pruppacher model overestimates the concave deformation at the bottom of the drops [5]. Hence, the more realistic drop shape model proposed by Beard et al. [5] will be considered in this study.

For these realistic non-spherical drops, numerical approximations such as T-matrix method, Fredholm integral equation, spheroidal function expansion, and unimoment method are needed to compute the TCS. Detailed explanation on these methods can be found in the review papers by Oguchi [7]. It has been difficult to determine which method gives the most reliable results because of the inconsistency in the parameters used in various works. For example, different expressions for water refractive index, assumptions of drop shapes and temperature have been identified in the literature of rain attenuation studies.

In this work, a hybrid T-matrix approach [8], a method previously proposed to predict vegetation loss, is adopted here to compute the cross sections of raindrops. According to the optical theorem (also known as the forward scattering theorem), TCS is related to the imaginary part of the forward scattering amplitude, which can be obtained using $E_{\text{far}}^{\text{sca}}(0)$, the far-field scattered field in the same (forward) direction as the incident field.

$$\sigma_t = \frac{4\pi}{k} \text{Im} \left[\lim_{r \rightarrow \infty} r E_{\text{far}}^{\text{sca}}(0) \right], \quad (2)$$

where k is the propagation constant and r is the distance from the origin of scattering object to the observation point.

TCS of spherical and non-spherical raindrops with diameter 0.25 mm to 6 mm are calculated using Mie theory and hybrid T-matrix, respectively. The wave is incident on the side of the raindrop with horizontal and vertical polarization. Refractive index used is $5.2950 + j2.7935$ at 38 GHz (25°C) [9]. Results depicted in Fig. 2 show that in the case of horizontal polarization, realistic raindrops experience higher TCS than spherical drops due to the flattening shape. Also, distortion of the drop shape has a very obvious effect on the polarization dependency, in which horizontally polarized waves yield higher TCS than those of vertical polarization.

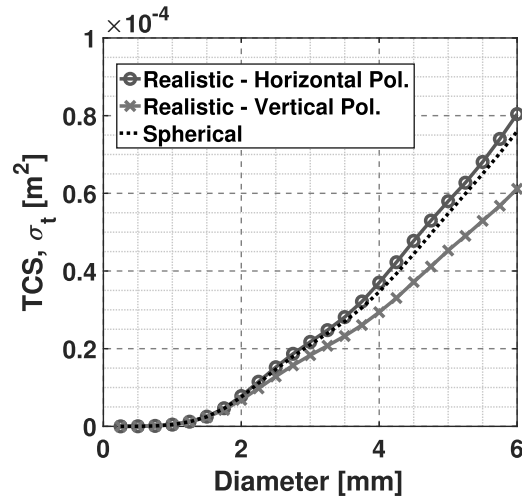


Fig. 2. Calculated TCS at 38 GHz

2.2.2 Drop size distribution

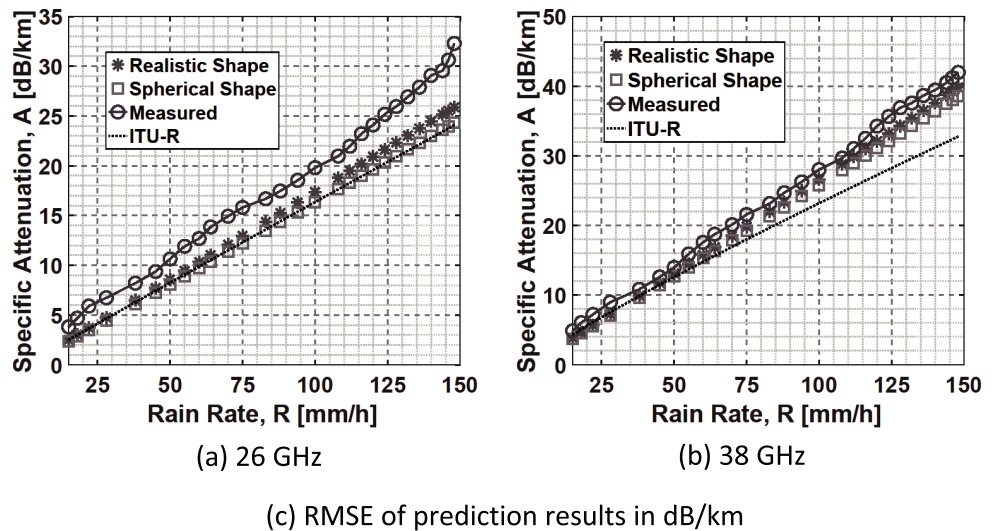
DSD describes the number concentration of raindrops with diameter D in a given volume of space. DSDs can be measured using equipment like disdrometers and the measured DSDs are usually fitted into analytical distribution forms such as negative exponential, Gamma distribution, Weibull model, and Log-normal distribution. Since DSD is idiosyncratic to the climate of a region, a single model may not be adequate to describe the physical reality of DSD in all region. Comparative studies [10] between several DSD models have shown that Log-normal models generally give the best fit to the measured DSD in tropical regions. Hence, in this work, the locally measured DSD in the form of Log-normal distribution presented in [11] is used

$$N(D) = \frac{N_0}{\sigma D \sqrt{2\pi}} \exp\left(-\frac{[\ln(D) - \mu]^2}{2\sigma^2}\right), \quad (3)$$

where $N_0 = 45.325R^{0.6703}$, $\mu = -0.39141 + 0.18734 \ln(R)$, $\sigma^2 = 0.40723 - 0.05862 \ln(R)$, and R denotes rain rate in mm/h.

3 Computation of specific rain attenuation

Two years of rain attenuation data at 26 GHz and 38 GHz were collected using the experimental mm-wave links of 0.3 km path length. Details on the experimental setup and data pre-processing are explained in [1]. Specific attenuation results are calculated using the theoretical method with the TCS obtained from hybrid T-matrix and the measured DSD. Comparison of specific attenuation of horizontal polarization between the theoretical values of spherical and realistic shapes, measurement results, and ITU-R model are shown in Fig. 3. The comparison obviously shows that the ITU-R model underestimates the attenuation at both frequencies and that the error of estimation increases with the rain rate. The difference in the prediction results is also clearly shown in Fig. 3(c), whereby the theoretical model considering realistic shape greatly improves the prediction results, especially in the case of 38 GHz whereby the root-mean-square error (RMSE) values are less than half of the error produced by the ITU-R model.



Freq (GHz)	ITU-R	Theoretical method	
		Spherical shape	Realistic shape
26	4.170	4.143	3.139
38	5.412	2.441	1.668

Fig. 3. Comparison of specific attenuation of horizontal polarization between different drop shapes at 26 GHz and 38 GHz.

4 Conclusion

In this work, a simple hybrid T-matrix approach is adopted to compute the TCS of realistic drops using frequency and temperature-dependent complex water refractive index. Polarization dependence is observed, whereby horizontal polarization yields greater TCS than vertical polarization due to the distortion of the shape. Using the theoretical method with the calculated TCS and measured Log-normal DSD, specific attenuation of different drop shapes are computed. The comparison with the measurement results shows that the theoretical method using realistic drops gives the best prediction. Also, the proposed theoretical method is found to be more accurate at higher frequencies as the prediction of 38 GHz is closer to the measurement results than that of 26 GHz.