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Evaluation of Rain Attenuation on 5G Millimetre-Wave Links Using Frequency and Path-Length Scaling Methods

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ABSTRACT

Attenuation due to rain becomes significantly dominant at frequencies above 10 GHz, thereby posing a challenge for planning fifth-generation (5G) wireless networks that rely on short-range millimetre-wave links. While several prediction models exist, these were developed primarily based on long-range links and exhibit decreased accuracy when applied to tropical regions. This paper introduces a novel method for predicting rain attenuation of 5G links, utilizing scaling of long-range link measurements with available prediction models. The predictions are then evaluated against long-term statistics of measurements collected at tropical sites.

1. Introduction

5G wireless mesh networks, currently under development, will heavily employ short-range millimetre-waves for backhaul links [1]. Several models can be used to predict the effect of rain attenuation on wireless terrestrial links, as discussed in previous works [2-7]. However, these models, developed mainly based on measurements collected with links longer than 1 km, are expected to be less accurate when applied to short links. On the other hand, available long link measurements can be exploited by using path length and or frequency scaling methods.

The available models predict rain attenuation from rain intensity statistics; some rely on the full rainfall rate distribution, while others utilize the rain rate exceeded for 0.01% of the year. Nonetheless, if rain attenuation measurements are available, they can be scaled to links with different lengths and or frequencies by inverting the models mentioned above. Some previous work discussed and applied such scaling methods [8-12], but used measurements collected in temperate areas. This paper extends these methods by focusing on tropical sites where more rain attenuation is expected and most of the known models severely underestimate the induced attenuation [13-18].

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This paper is organized as follows: some widely used prediction models are introduced in Section 2, Section 3 presents the measurement setup and describes the methods used, while the path-length and frequency scaling models are presented and discussed in Section 4 Finally, conclusions are presented in Section 5.

2. Rain Attenuation Prediction Models

Rain attenuation affecting a terrestrial link is usually calculated as the product of specific attenuation (dB/km), *R,* and the effective path length (km), d_{eff} :

$$A = \gamma_R \, . \, d_{eff} \text{ (dB)} \tag{1}$$

The effective path length consists of the real path length and the path adjustment factor, which is introduced to consider the inhomogeneity of the rainfall along the path. Various models describe this inhomogeneity using different factors to describe the variability of rainfall in space properly [5].

The ITU-R P.530-17 model [2] is the most widely used. Besides the electrical and geometrical features of the link, this model utilizes information on the rain rate exceeded 0.01% of the time, $R_{0.01}$(mm/h), as input the attenuation exceeded for 0.01 % of the time, $A_{0.01}$, can then be calculated as:

$$A_{0.01} = \gamma_R . d_{eff} = \text{k}. R_{0.01}^{\alpha} \, . d . r \tag{2}$$

where *d* (km) is the path length, *k* and *α* are frequency and polarization dependent empirical coefficients, respectively, and r is the adjustment factor. An extrapolation formula is then used to calculate Ap, the attenuation exceeded for other percentages of time, *p* (parameters *C1*; *C2* and *C3* are described in [2]):

$$A_p = C_1 . p^{-(C_2 + C_3 log_{10p})} . A_{0.01} \tag{3}$$

While the ITU-R model depends just on $R_{0.01}$ to predict rain attenuation, other methods depend on the full rainfall rate distribution by defining a relationship between *R*p and *A*p (the rain rate and the rain attenuation exceeded for p% of the time, respectively); this is the case in the model presented by Mello [4], which also introduces the concept of effective rain rate. *A*p, can then be calculated using:

$$A_p = k . [1.763 . R_p^{0.753 + \frac{0.197}{d}}]^{\alpha} . \frac{d}{1 + d/(119 . R_p^{-0.244})} \tag{4}$$

The work in [5] presents a physically-based model developed by considering results from a simulation of the interaction between terrestrial links and synthetic rain maps generated by MultiEXCELL [19], according to this model, the rain attenuation exceeded in an average year with probability p% is calculated as:

$$A_p = k . R_p^{\alpha} . d . (a . e^{-b . R_p + c}) \tag{5}$$

where the coefficients *a*; *b*, and *c*, which are functions of *d* and *R*p, are defined in [4].

3. Measurement Setup and Scaling Methods

Rain attenuation data were collected for two consecutive years using three parallel links installed at Universiti Teknologi Malaysia: two short links (d = 301:32 m) operate at 38 GHz and 26 GHz [20-22], while the third link operates at 26 GHz with path length d = 1:3 km [13]. The Ericsson E-mini link CN 500 was used in the installation and measurements were collected every second via the data acquisition system. The automatic gain control output in volts, AGCV, was converted to the received signal level, *RSL* in dBm, using the following mathematical expression defined by the manufacturer [13]:

$$RSL_{(dBm)} = 40\,.AGCV120 \quad (6)$$

The link antennas were covered with radomes. However, the losses due to the wet surfaces of the radomes can be significant at millimetre-wave frequencies [23] and can severely limit the accuracy in measuring rain attenuation. In general, the measured path attenuation *A*m (dB) can then be defined as:

$$A_m = A_p + A_{wa} \quad (7)$$

where *Ap* is the rain attenuation along the path (dB), and *A*wa is the attenuation induced by the wet antenna. The procedure to extract *A*wa from *A*m typically requires the knowledge of the antenna/radome characteristics under rainy conditions. These were assessed by carrying out a simulated rain attenuation experiment, as described in detail in [24], and the results were used to estimate and remove the attenuation due to the wetness of the antennas using a method based on dual-frequency measurements proposed by [25]. This method assumes that the ratio between the rain attenuation at the two frequencies is known and is equal to predictions using the ITU-R frequency scaling method from the ITU-R P.530-17 recommendation [2].

Along with the rain attenuation data, 1-minute rain intensity were also collected over the two years using a Casella rain gauge of 0.5 mm sensitivity installed on the receiver side. Figure 1. shows the complementary cumulative distribution functions (CCDFs) of the attenuation due to rain and the CCDF of the 1-minute integrated rain intensities measured at the same location. The rain rate exceeded for 0.01% of the time is 116 mm/h, which was used as input to the ITU-R prediction model [2].

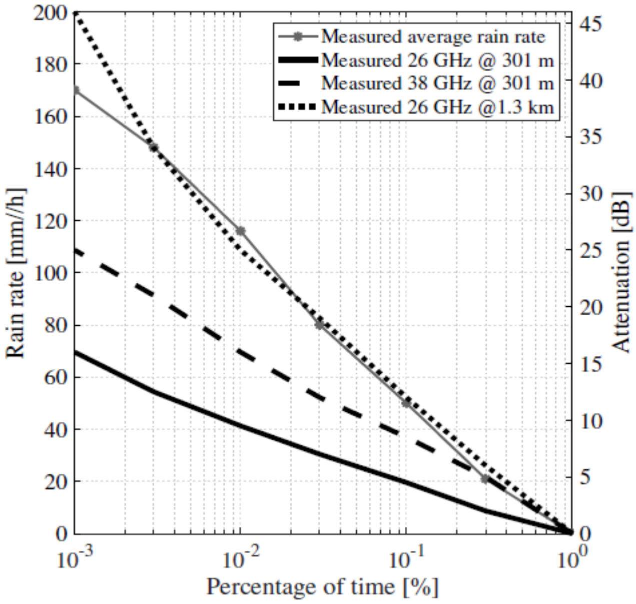

Fig. 1. Measured rain attenuation and rain rate CCDFs

The measured rain attenuation time series are used as input to the inverse equations of the above-mentioned models to compute the effective rain intensity values. These values are then used to predict the attenuation time series (and the attenuation statistics) of the link characterized by the new path length and/or frequency. As an example, for the ITU-R model, this can be achieved using the closed-form Eq. (8), which is derived from Eq. (2):

$$A_2 = K_2 . \left[\frac{A_1}{k_1 d_1 r_1}\right]^{\left[\frac{\alpha_1}{\alpha_2}\right]} . d_2 . r_2 \quad (8)$$

where subscripts 1 and 2 refer to the link providing measurements and the hypothetical link for which predictions are required, respectively. Eq. (2) relates $A_{0.01}$, and $R_{0.01}$; however, for short links, the distance factor r turns out to be always limited to 2.5, as indicated in [2].

The value of Rp as a function of Ap for the other models, can be numerically approximated using Eq. (4) and Eq. (5).

Section 4 reports the results of the tests of the proposed rain attenuation scaling methods; the dataset collected by the three links was used as both input and reference. As a further source of comparison, we have also applied the methodology from recommendation P.530-17 [2], included here as in Eq. (9), (valid for frequencies between 7-50 GHz), that relies on long-term rain attenuation statistics and frequency used:

$$A_2 = A_1 \left(\frac{\Phi_2}{\Phi_1}\right)^{1-(1.12*10^{-3}\left(\frac{\Phi_2}{\Phi_1}\right)^{0.5}(\Phi_1 . A_1)^{0.55}} \quad (9)$$

In Eq. (9) $\boldsymbol{\Phi}$ is a function of frequency f and is defined as:

$$\Phi = \frac{f^2}{1+10^{-4} . f^2} \quad (10)$$

4. Results and Discussion

In this section, we introduce a method for scaling rain attenuation time series and statistics between mmWave links with varying physical parameters, such as length and frequency. This link scaling approach ensures that the scaled values are consistently derived from actual measurements, utilizing the chosen rain attenuation prediction model. We then contrast the scaled attenuation distributions with the theoretical CCDF based on long-term statistics generated from these models. Building upon the concept of link scaling, by promoting link scaling, our study offers a methodology to characterize millimetre-wave link behaviours with arbitrary parameters, grounded in real-world measurements.

4.1 Path Length Upscaling and Method Assessment

Since all the models mentioned above are valid for path lengths longer than 1 km, the attenuation time series of the shorter 301-m link operating at 26 GHz was first upscaled to 1.3 km and compared with the measurements obtained from the link with the same path length. Figure 2 compares the results from direct application of the model (using input rain intensities extracted from the measured rain rate CCDF) and estimates using the scaling approach.

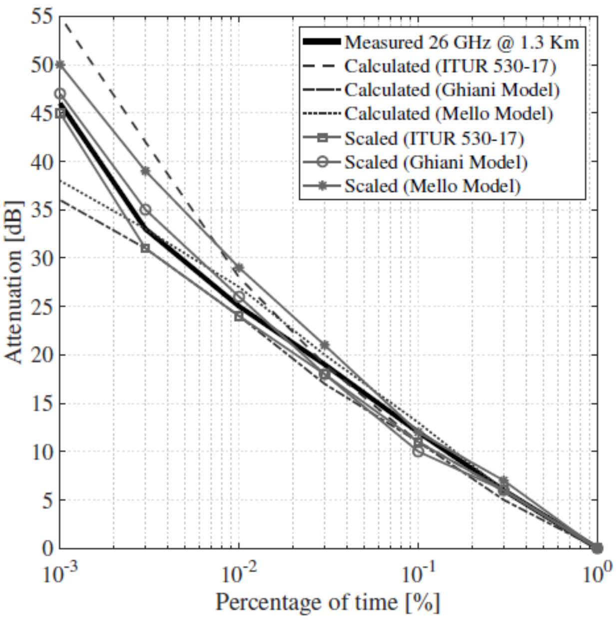

Fig. 2. CCDF of rain attenuation at 26 GHz (d = 1:3 km): Measurements, direct predictions, and scaling

Figure 2 indicates quite good prediction accuracy for all the models, but all are outperformed by the scaling approach. This is likely because of the additional information embedded in the time series of the rain attenuation measured along the shorter path. The results reported in Table 1 confirm this. Table 1 additionally provides a more comprehensive assessment of the prediction accuracy by reporting the following error value:

$$\boldsymbol{\varepsilon} = 100.\frac{A_p - A_m}{A_m} \quad (11)$$

where *A*m is the measured attenuation value exceeded p% of the time, and *A*p is the value extracted from calculated/scaled CCDFs exceeded p% of the time.

Table 1
Overall Performance of Prediction Methods:$\boldsymbol{\varepsilon}$ Mean, $\boldsymbol{\varepsilon}$ Rms And $\boldsymbol{\varepsilon}$ Std of The Prediction Error

	Calculated			Scaled		
	ITU-R	Mello	Ghiani	ITU-R	Mello	Ghiani
εmean	8.4	-2.1	-10.9	-4.3	11.7	-1.6
ε Rms	14.9	11.1	12.2	5.1	13.2	7.8
ε Std	13.5	11.9	6.1	2.9	6.8	8.3

4.2 Path Length Downscaling

Millimetre-wave links to be employed in future 5G systems are expected to be limited to 200 m for radio access and to some hundreds of meters for backhauling [1]. This section presents tests of the accuracy of path-length scaling methods, specifically of Eq. (8), in predicting rain attenuation of short links starting from measurements collected along longer Links. Figure 3 presents the results for both frequencies, 26 GHz, and 38 GHz, considering two reference path lengths: d = 100 m and d = 200 m.

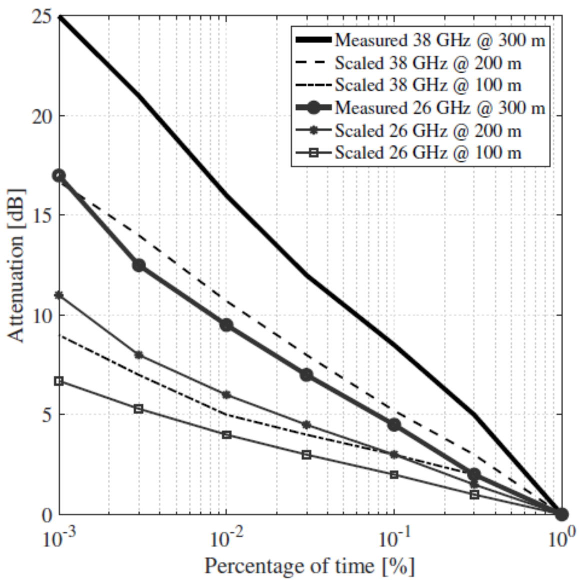

Fig. 3. CCDFs of rain attenuation at 26 GHz and 38 GHz: Measurements and down-scaled curves using Eq. (8)

Results in Figure 3 indicate a significant amount of rain attenuation affecting even links with path lengths shorter than 300 m. This highlights the importance of accurate predictions.

4.3 Frequency Scaling

When measurements at a lower frequency are available, recommendation ITU-R P.530-17 recommends using frequency scaling techniques (rather than prediction models) for better accuracy [2]. Figure 4 presents the rain attenuation CCDFs for some of the candidate 5G frequencies (26, 38 and 50 GHz) scaled using both the proposed approach and the model included in recommendation P.530-17; these are compared against measured data, when available. Both methodologies provide similar satisfactory results corroborating the use of Eq. (8) for both path-length and frequency scaling. Results again indicate significant amounts of rain attenuation affecting short terrestrial links in tropical sites.

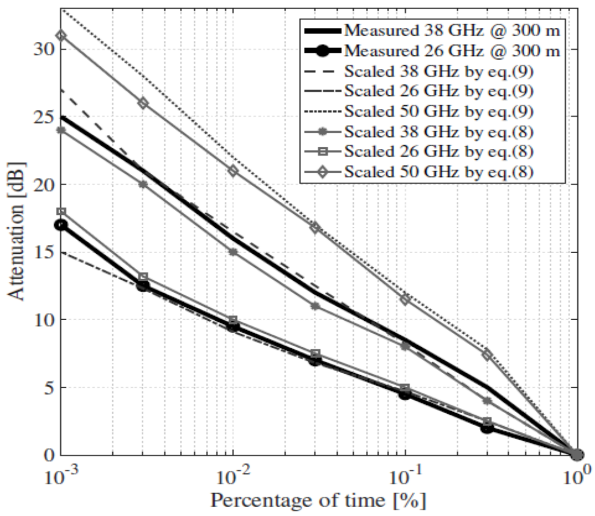

Fig. 4. Rain attenuation frequency scaling: CCDFs at 26, 38 and 50 GHz

More detail is included in Table 2, which uses Eq. (8) to list the estimated fade margin for a 200-m link for various 5G candidate frequencies and guaranteed link availabilities of 99.99%, 99.95% and 99.9%. As expected, the fade margin increases with the frequency and the availability requirement.

Table 2
Predicted rain fade margin for a 200-m link with horizontal polarization, to guarantee link availability of 99.99%, 99.95% and 99.9%

Availability			
Frequency (GHz)	99.90%	99.95%	99.99%
20	1.5	3.3	3.6
25	2.9	5.0	6.0
30	4.4	6.8	8.5
35	5.3	8.3	10.3
40	6.8	9.9	12.4
45	8.1	11.3	14.3
50	8.0	12.0	14.7
68	10.0	13.3	16.7
73	11.3	16.0	18.7
86	12.7	18.0	20.0

5. Conclusion

The combined methodologies for rain attenuation frequency and path-length scaling presented in this paper are an accurate tool to predict the effects of precipitation on future 5G millimetre-wave links. Results from tests of the accuracy of these methodologies indicate a very satisfactory prediction accuracy (for both path-length and frequency scaling methods). Moreover, results show that a significant amount of rain attenuation is expected to affect even very short links (d < 300 m), and this needs to be duly considered in the design of 5G systems in tropical regions. Further work could test these methodologies with similar measurements collected in equatorial or other tropical sites. The results obtained here can help in the design of future 5G networks, as well as provide a better expectation of tropical rain effects.

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