Characteristics of 5G Wireless Millimeter Wave Propagation: Transformation of Rain Attenuation Applying Different Prediction Models

Péter Kántor[1], János Bitó[1], Árpád Drozdy[2]
[1] Budapest University of Technology and Economics, Department of Broadband Infocommunications and Electromagnetic Theory, Budapest, Hungary, kantor@hvt.bme.hu, bito@hvt.bme.hu
[2] Aalto University, Department of Communications and Networking, Finland, arpad.drozdy@aalto.fi

***Abstract*—The performance of rain rate and rain attenuation prediction models are vital for planning wireless networks consisting of millimeter wave links. As several different prediction models exist in literature we give a comparison of the performance of the most applied ones. Moreover, we introduce methods for transforming rain attenuation between different millimeter wave links based on the investigated prediction models. This transformation enables the exploitation of long-range link measurements to effectively plan networks comprised of short-range millimeter wave links (like 5G mesh networks). We identify the most suitable rain attenuation prediction model and verify the proposed transformation model with the ITU-P.530-15 model on long-term statistics. The purpose of this paper is to investigate different rain attenuation prediction models for terrestrial links and to find a suitable prediction method to perform a transformation of rain attenuation on millimeter wave links with different physical parameters (length, frequency, and polarization).**

***Index Terms*— 5G millimeter wave links, rain attenuation prediction, link transformation, millimeter wave propagation.**

I. Introduction

Currently there is a shortage of rain fading measurements on short range links. 5G millimeter wave mesh networks will require rain fading statistics for short links. This leads us to develop methods for generating "hypothetical measurements" from existing measurement data from long range links. High amounts of precipitation can cause the outage of millimeter wavelength links. If these links serve as mobile backhaul, then this can even lead to the disconnection of a considerable part of the network. In order to model the effects of rain on the performance of millimeter wave links several models exist in scientific literature. Some of these models are based on the rain rate that is exceeded for 0.01% of an average year ($R_{0.01}$), some of them apply full rainfall rate probability distribution. In this paper we do not intend to study the overall performance of the investigated prediction models; we focus only on the applicability of the models in respect of rain attenuation transformation between different link lengths. These models have not been evaluated previously according to the transformation of the rain attenuation over link lengths. This transformation (which we call link transformation) enables the planning of networks with short-range millimeter wave links more effectively (like 5th generation wireless networks), since they allow the use of existing data from previous measurements over long-range millimeter wave links. If a model determines the rain attenuation from the rain intensity accurately, it becomes possible to evaluate the rain intensity that caused the measured rain attenuation by solving the inverse problem. Moreover, if we can estimate the rain intensity it becomes possible also to calculate a hypothetical attenuation on a link with hypothetical parameters based on the same model. Therefore the transformation of rain attenuation time series and statistics over different millimeter wave links becomes possible. We used certain types of link transformation in various papers to evaluate the performance of future 5G short-range millimeter wave networks [1] and to investigate climate change based on the change in the statistics of rain attenuation on millimeter wave links [2].

II. Rain Attenuation Prediction Models

In this section we give an overview of the investigated rain attenuation prediction models. These models are based on the same equation for calculating the attenuation due to rainfall with the expression (1), where k and α are frequency and polarization dependent empirical coefficients [3]. $R(l)$ is the value of the point rain intensity in mm/h along the path at distance l, d is the path length of the link. The rain rate and the attenuation may vary significantly along longer paths and for practical use a path-average value is taken. Therefore the most important task when modeling rain attenuation is describing the distribution of the rain rate in space and time statistically. In different models this inhomogeneity is described by using different factors. Although each of these factors describes the inhomogeneity of the rain cell, we can distinguish between path adjustment factors and rainfall rate adjustment factors.

$$A^{[dB]} = \int_0^d k \cdot R^{\alpha}(l)dl \qquad (1)$$

A. Rain Attenuation Prediction without Full Rain Rate Distribution

Let $A(p)$ [dB] denote the threshold that the attenuation exceeds with a probability of p percent of the time. The most important input for millimeter wave link planning is the rain rate exceeded for 0.01% of an average year (with an integration time of 1 min) [4]. From the $R(p=0.01\%)=R_{0.01}$ [mm/h] rain intensity exceedance level the $A_{0.01}$ [dB] rain attenuation level which is exceeded with a probability of p=0.01% of the time can be calculated.

The most commonly used rain attenuation prediction model is the ITU-R P.530-15 model [3] that does not use full rain rate distribution but only one parameter, $R_{0.01}$. The model assumes an equivalent rain cell with EXCELL rainfall distribution, which can represent the effect of the non-uniform rainfall along the propagation path. ITU gives the following empirical formula (2), where d [km] is the path length and r is the distance factor. Assuming that the equivalent rain cell may intercept the link at any position with equal probability, the effective path length is the average length of the intersection between the cell and path, given by equation (2).

$$A_{0.01}^{[dB]} = k \cdot R_{0.01}^{\alpha} \cdot d_{eff} = k \cdot R_{0.01}^{\alpha} \cdot d \cdot r \tag{2}$$

The variation of the rain intensity along the path of the link is taken into account by the distance factor r (3), where f [GHz] is the frequency. ITU also states that the value of r should be capped at a maximum of 2.5.

$$r = \frac{1}{0.477\, d^{0.633} \cdot R_{0.01}^{0.073*\alpha} \cdot f^{0.123} - 10.579(1 - e^{-0.024d})} \tag{3}$$

To calculate the attenuation exceeded at other percentages of time between 1% and 0.001% an extrapolation formula is used [3] (the parameters of C_1, C_2 and C_3 are given in [3]):

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

B. *Rain Attenuation Prediction Models Based on Full Rain Rate Distribution*

While the previous model predicts rain attenuation based on only the rainfall rate for 0.01% of an average year ($R_{0.01}$), other methods depend upon the full rainfall rate distribution. Therefore these models give a relation between $R(p)=R_P$ and $A(p)=A_P$ respectively, not only between $A_{0.01}$ and $R_{0.01}$. In this paper we investigate the performance of the UK (2003 RAL) and the Brazil models.

1) *The UK (2003 RAL) Model*

The UK model was introduced in [5] as a proposed modification of recommendation ITU-R P.530-12. After obtaining the rainfall rate $R(p)$ and the specific attenuation exceeded for $p\%$ for the range of time percentages required, the path adjustment factor is calculated. This adjustment factor is multiplied with the actual path length to obtain the effective path length. The UK model can be described according to equation (5).

$$A_P^{[dB]} = k \cdot R_P^{\alpha} \cdot \frac{d}{0.874 + 0.0255 \cdot (R_P^{0.54} - 1.7) \cdot d^{0.7}} \tag{5}$$

2) *The Brazil Method*

The Brazil method is a semi-empirical model for the prediction of rain attenuation on terrestrial links [6]. The method retains the concept of an equivalent rain cell, which is the basis of the ITU-R method. However, it considers the full rainfall rate distribution for the prediction and also introduces the concept of an effective rain rate which applies to the whole path and depends on the path length which is used in addition to a path reduction factor. The attenuation exceeded at $p\%$ of the time can be given by equation (6). It must be noted that the Brazil model is not valid if d becomes small due to the 0.197/d term in the exponent of the effective rain rate.

$$A_P^{[dB]} = k \cdot [1.763 \cdot R_P^{0.753 + 0.197/d}]^{\alpha} \cdot \frac{d}{1 + d / (119 \cdot R_P^{-0.244})} \tag{6}$$

3) *Comparison*

The properties of the investigated rain attenuation prediction models are compared in Table I.

TABLE I. COMPARISON OF RAIN ATTENUATION PREDICTION MODELS

Model name	**Using full rain rate distribution**	**Applies path adjustment factor**	**Applies rainfall rate adjustment factor**
ITU-R P. 530-15	No	Yes	No
UK (2003 RAL)	Yes	Yes	No
Brazil	Yes	Yes	Yes

III. LINK TRANSFORMATION

In this section we introduce the necessary steps to perform a transformation of rain attenuation time series and rain attenuation statistics (i.e. complementary cumulative distribution functions - CCDF) between millimeter wave links with different physical parameters applying the previously reviewed prediction models.

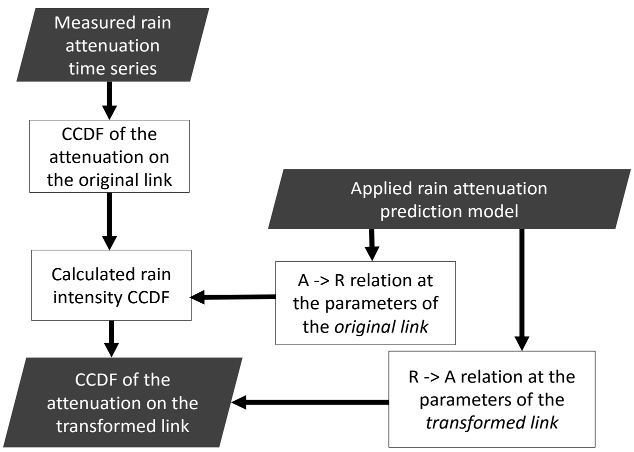

Fig. 1. Steps of transformation of rain attenuation (link transformation)

The algorithm and steps of the link transformation is depicted in Fig. 1. These steps are explained in detail in the following subsections. As it can be observed in Fig. 1, the "hypothetical measurements" are always based on real measurements through the applied rain attenuation prediction model. Transformed attenuation distributions are compared with the theoretical CCDF on long-term statistics calculated using equation (4) in Section IV/D. Please note, that although both equation (2) and (4) are given by ITU-R P.530-15, they are not related directly. By promoting link transformation we provide a way to describe the behavior of millimeter wave links with arbitrary parameters based on actual measurements. Since measured statistics always carry additional, unique information compared to theoretical statistics, application of a reliable transformation method is always preferable.

A. Link Transformation based on the ITU-R P.530-15 Model

In order to perform a transformation of the measured attenuation on a measured link to a hypothetical link the $A_{0.01}$ exceedance level has to be assessed from the measured attenuation data. By the numerical solution of expressions (2) and (3) the $R_{0.01}$ can be quantified as well, however there can be no closed mathematical formula given to solve this inverse problem. From the rain intensity exceedance level the r distance factor also can be assessed according to equation (3).

From the distance factor r and the parameters of the measured link the attenuation data can be converted to a corresponding rain intensity value using the formula of equation (7). This formula is the inverse form of equation (2). However, equation (2) is defined only to describe the connection between $A_{0.01}$ and $R_{0.01}$ exceedance levels, now we extend this relation for all values of R_P and A_P. At these rain intensity values the r distance factor may have different values than given in equation (3). Therefore, the current transformation method does not take this question into consideration. However, as it is shown in Subsection IV/D, this proposed rain attenuation transformation method which is based in the ITU-R P.530-15 prediction model shows good correspondence with the results of the ITU-P.530-15 model on long-term statistics (given by equation (4)) which describes the theoretical relationship between rain intensity and rain attenuation for any P probability between 1% and 0.001%.

$$R = \left[\frac{A_m}{k_m \cdot d_m \cdot r_m} \right]^{\left(\frac{1}{\alpha_m} \right)} \tag{7}$$

From the rain intensity values the attenuation on a hypothetical link can be calculated as well. This is represented by expression (8), where A_m is the attenuation on the measured real link, A_h is the attenuation on the hypothetical link, km and α_m are coefficients of the measured link, k_h and α_h are coefficients of the hypothetical link, r_m is the distance factor of the measured link and r_h is the distance factor of the hypothetical link.

$$A_h = k_h \cdot \left[\frac{A_m}{k_m \cdot d_m \cdot r_m} \right]^{\left(\frac{\alpha_h}{\alpha_m} \right)} \cdot d_h \cdot r_h \tag{8}$$

B. Link Transformation based on the UK and the Brazilian Methods

In these models the relation between R_p and A_p cannot be expressed in a closed form, however, this inverse problem can be solved with numerical calculation methods and equations (5) and (6). These rain attenuation prediction models describe monotonic functions between R_p and A_p, therefore numerical methods cannot find local optimal solutions. As the parameters of the measured and hypothetical links can be inserted into equations (5) and (6), from the calculated rain series or rain CCDF, the attenuation time series or attenuation CCDF of a hypothetical link can be assessed as well.

IV. Results

A. Rain Rates Calculated based on the Investigated Prediction Models

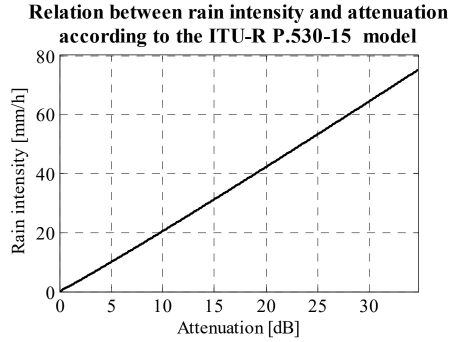

Fig. 2. Relation between rain intensity and rain attenuation according to the ITU-R P.530-15 attenuation prediction models for a link with parameters of f=38 GHz, d=1.5 km and horizontal polarization

In Fig. 2, 3 and 4 the calculated rain intensity values and the corresponding measured rain attenuation values are depicted for a link with parameters of f=38 GHz, d=1.5 km and horizontal polarization.

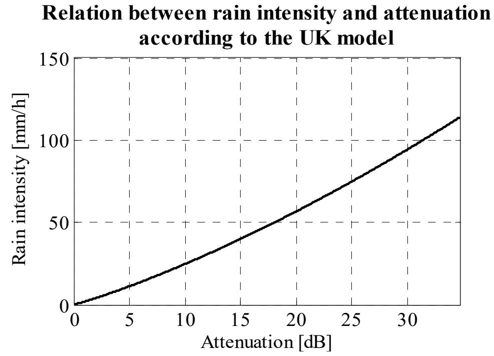

Fig. 3. Relation between rain intensity and rain attenuation according to the UK attenuation prediction models for a link with parameters of f=38 GHz, d=1.5 km and horizontal polarization

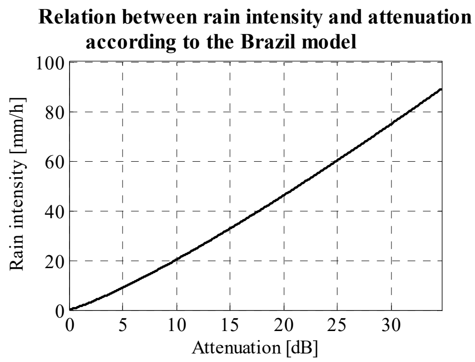

Fig. 4. Relation between rain intensity and rain attenuation according to the Brazil attenuation prediction models for a link with parameters of f=38 GHz, d=1.5 km and horizontal polarization

These presented relations can be used to transform rain attenuation time series to a corresponding rain intensity time series. Moreover, since CCDFs of rain attenuation and rain intensity are monotonic functions, these relations can be applied also to transform distribution functions directly.

B. *Calculated Rain Intensity Distributions based on the Investigated Prediction Models*

In Fig. 5 the calculated rain intensity distributions are depicted according to the applied prediction models. This CCDF curves are used to obtain the rain attenuation on the transformed links. At relatively high probabilities the results are similar for the investigated prediction models, however at small probabilities the results differ significantly. Unfortunately we do not have reliable rain intensity measurements at the site, so we cannot verify these calculated, intermediate rain intensity distributions.

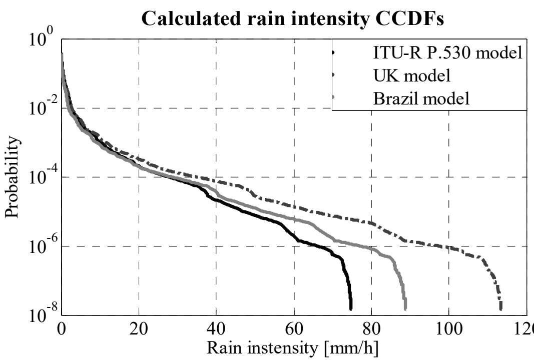

Fig. 5. Calculated rain intensity distributions based on the investigated prediction models

C. *Transformed Rain Attenuation Distributions based on the Investigated Prediction Models*

In Fig. 6, 7, 8 and 9 the CCDF calculated from the original measured rain attenuation time series on the link with parameters of *f*=38 GHz, *d*=1.5 km and horizontal polarization can be compared to the transformed, hypothetical rain attenuation CCDFs.

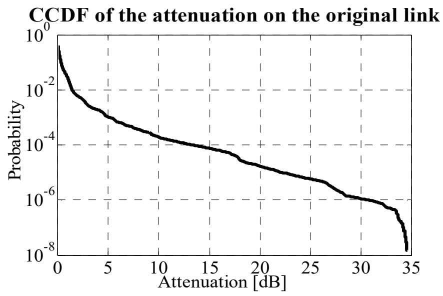

Fig. 6. Measured rain attenuation CCDF (with parameters of f=38 GHz, d=1.5 km and horizontal polarization)

The parameters of the hypothetical link are as follows: *f*=38 GHz, *d*=200 m and horizontal polarization was assumed. Please note that the short hypothetical path length was chosen because the future 5G millimeter wave networks will apply links in this range and to plan those networks the transformation of previously recorded measurements can be beneficial [1].

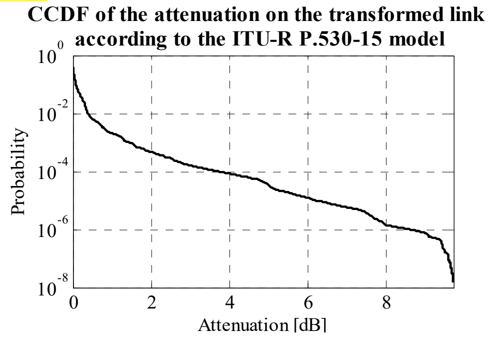

Fig. 7. Transformed CCDF of the hypothetical link (with parameters of f=38 GHz, d=200 m and horizontal polarization) applying the ITU-R P.530-15 attenuation prediction model

Please note, that the path adjustment factor *r* of the ITU-R P.530-15 model does not describe the inhomogeneity of the rain intensity along the path only, it takes the distribution of the rain cell into account as well. For short links (where the actual rain intensity can be considerably higher than the average rain intensity of the rain cell) the distance factor is higher than 1. For the investigated 200 m long hypothetical links *r*=2.5, therefore it cannot be excluded from equation (8).

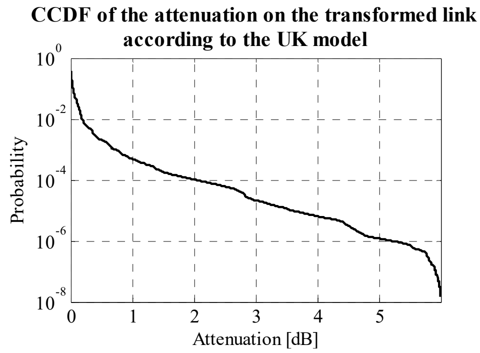

Fig. 8. Transformed CCDF of the hypothetical link (with parameters of f=38 GHz, d=200 m and horizontal polarization) applying the UK attenuation prediction model

It can be observed that the shape of the CCDF curves does not change significantly – this is because of the nearly linear relations between rain attenuation and rain intensity in Fig. 2.

For the ITU-R P.530-15 and the UK models the transformed attenuations are realistic – for validation of the transformation applying the ITU model see [2]. Moreover, if we compare the transformed CCDF curves with the ones produced by the extrapolation formula based on $A_{0.01}$ given in equation (4) we can get a very close match. However, the Brazil model produces unreasonably high attenuation values. This is because the model is valid till approximately 700-800 meters (depending on the applied frequency) as mentioned in Subsection II/C.2.

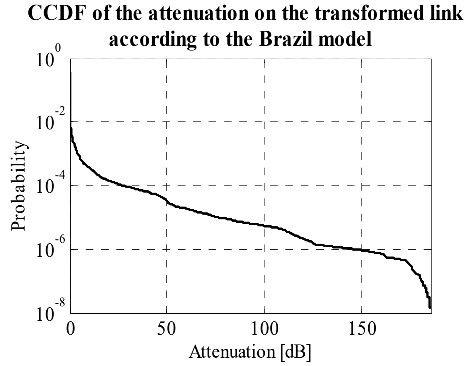

Fig. 9. Transformed CCDF of the hypothetical link (with parameters of f=38 GHz, d=200 m and horizontal polarization) applying the Brazil attenuation prediction model

D. Comparison of the Transformed Rain Attenuation CCDFs and the ITU-R P.530-15 Theoretical CCDFs on Long-Term Statistics

In this subsection we give a comparison of the transformed rain attenuation CCDFs and the theoretical rain attenuation long-term statistics obtained by applying expression (4).

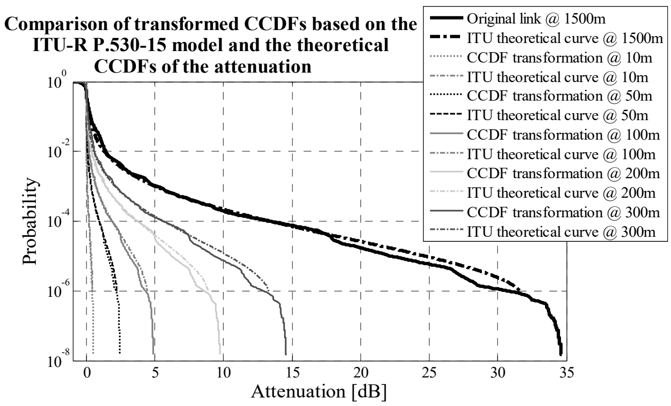

Fig. 10. Comparison of transformed CCDF curves of the attenuation based on the ITU-R P.530-15 model and the theoretical CCDF curves on long-term statistics of rain attenuation for different link lengths

It should be noted that however both the transformed and the theoretical curves are calculated according to ITU-R recommendations, the proposed link transformation utilizes real measurements while the theoretical results take no actual measurements into account.

To plan an actual 5G network (or a millimeter wave wireless network in general), actual measurements taken at the site are always important, since geographical location has a serious effect on the rain rate statistics.

In Fig. 10 the transformed CCDF curves of the rain attenuation based on the ITU-R P.530-15 model and the theoretical CCDF curves of the attenuation for different link lengths are depicted. It can be observed, that the CCDF belonging to the original, measured link (d=1500 m) slightly differs from the theoretical one. This difference is kept by the transformation; however the transformed CCDFs keep the resemblance as well for all the investigated transformed link lengths. This result supports the applicability of the proposed link transformation method.

V. Conclusions

In this paper we presented a summary on the most commonly applied rain attenuation prediction models and investigated their behavior when a transformation of measured rain attenuation data to attenuation on hypothetical links with different physical parameters is performed. We identified that although the ITU-R P.530-15 model considers the relation between the exceedance probabilities of rain attenuation and rain intensity ($A_{0.01}$ and $R_{0.01}$) only, this models performs better in link transformation than the ones that are based on full rain rate distribution. Therefore we rate the ITU-R P.530-15 model as a suitable and applicable prediction model to perform a transformation of rain attenuation on links with different physical parameters.

VI. References

[1] P. Kántor, L. Csurgai-Horváth, Á. Drozdy and J. Bitó, "Precipitation Modelling for Performance Evaluation of Ad-Hoc Microwave 5G Mesh Networks", 2015 9th European Conference on Antennas and Propagation (EuCAP2015), Lisbon, Portugal, 12-17 April 2015

[2] P. Kántor and J. Bitó, "Influence of Climate Variability on Performance of Wireless Microwave Links", 2013 IEEE 24th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC 2013), London, UK, pp. 896-900, 8-11 September 2013, ISBN: 978-1-4673-6234-4

[3] ITU Recommendations P.530-15, "Propagation data and prediction methods required for the design of terrestrial line-of-sight systems," 2013

[4] ITU Recommendations P.837-6, "Characteristics of precipitation for propagation modelling," 2012

[5] ITU-R, Working Party 3M, Input Document 3M/28, United Kingdom "Proposed modification to Recommendation ITU-R P.530-10: Propagation data and prediction methods required for the design of terrestrial line-of-sight systems", 12 November 2003

[6] Da Silva Mello, L. and M. S. Pontes, "Unified method for the prediction of rain attenuation in satellite and terrestrial links", Journal of Microwaves, Optoelectronics and Electromagnetic Applications, Vol. 11, No. 1, Jun. 2012.