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Key Points:

- Novel physically based approach to modeling rain attenuation impairing terrestrial links, which is not affected by the limited availability of measurements and by their inaccuracies
- Definition of a simple analytical formulation for rain attenuation prediction, which receives as input only the local yearly rain rate statistics

Correspondence to:
A. Fanti,
alessandro.fanti@diee.unica.it

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A physically based rain attenuation model for terrestrial links

R. Ghiani[1], L. Luini[2,3], and A. Fanti[1]

[1]Department of Electrical and Electronic Engineering, University of Cagliari, Cagliari, Italy, [2]Dipartimento di Elettronica, Informazione e Bioingegneria, Politecnico di Milano, Milan, Italy, [3]Istituto di Elettronica e di Ingegneria dell'Informazione e delle Telecomunicazioni, Consiglio Nazionale delle Ricerche, Milan, Italy

Abstract This contribution presents a novel physically based approach to modeling the rain attenuation affecting terrestrial links. The model is devised by investigating the path reduction factor (PF) on terrestrial links, a typical element of rain attenuation prediction models introduced to take into due account the spatial inhomogeneity of rainfall. To this aim, a large number of PF values are analyzed by simulating the interaction of a hypothetical terrestrial link with a set of realistic synthetic rain fields. The dependence of PF on different parameters such as the path length, the operational frequency, and the rain rate measured at the transmitter is addressed, and the results are exploited to devise analytical expressions aiming to provide an accurate yet simple approach to predicting rain attenuation on terrestrial links. Finally, the prediction accuracy of the proposed method is discussed (and compared to the one of other two models) by considering experimental data collected worldwide.

1. Introduction

In the near future, the global data volume exchange of telecommunication systems is expected to increase dramatically, on one side, due to the gradual enrichment in high data rate broadcast and multimedia services offered to users and, on the other side, owing to the exponential increase in the number of devices connected to the Internet [*Dehos et al.*, 2014]. This calls for the enhancement of existing telecommunication networks and/or for the deployment of new infrastructures. A viable way to tackle this problem, especially in regions where laying wires and optical fibers are cumbersome or very expensive (e.g., remote areas), is to install wireless links at high frequencies (millimeter waves), which offer the large bandwidth necessary to support the required high data rates (e.g., in future 5G systems [*Rappaport et al.*, 2013]).

As is well known, the impairments induced by the atmosphere on millimeter waves steeply increase with the operational frequency, mainly because of hydrometeors, which cause strong absorption and scattering of the impinging electromagnetic energy [*Riva et al.*, 2014]. As a result, accurate models able to predict rain attenuation affecting terrestrial links are of paramount importance for the design of reliable communication systems. Several models have been proposed so far to that aim, mainly in documents submitted to the ITU-R (International Telecommunication Union-Radiocommunication sector) to propose updates to recommendation P.530 [*ITU-R*, *Recommendation P.530-16*, 2015], all of which rely on the concept of *path reduction factor*, PF. The key idea is that the rain attenuation A can be calculated as if the rain rate R measured at a given position (typically, at the transmitter) were constant along the whole link, whose length, however, is turned into an effective one (L_{eff}) by means of PF. Indeed, the main difference among the models devised so far lies in how the path reduction factor is defined. For example, the model proposed by the Australian Administration in *ITU-R Doc. 3M/27-E* [2001] defines a PF which only depends on the local rain rate value exceeded for 0.01% in a year ($R_{0.01\%}$), while the methodology presented by the UK Administration in *ITU-R Doc. 3M/28-E* [2003] extends the dependence of PF also to path length L and receives as input the full Complementary Cumulative Distribution Function (CCDF) of the rain rate (also known as $P(R)$), rather than just $R_{0.01\%}$. This is also the case for the model proposed by *Silva Mello and Pontes* [2007], which, in addition, introduces a further dependence of PF on one of the power law coefficients (α) typically used to convert rain rate R into specific attenuation γ_R, i.e., $\gamma_R = kR^{\alpha}$ [*ITU-R Recommendation P.838-3*, 2003]. Whatever the approach used to defined the path reduction factor, most of the existing models, including the one currently adopted by ITU-R [*ITU-R*, *Recommendation P.530-16*, 2015], have been optimized by exploited large set of measurements (e.g., the most popular being the one made available by the Study Group 3 of ITU-R) with the aim of deriving empirically the regression coefficients included in the expressions relating PF to the input parameters such as frequency, path length, and rain rate. This approach typically guarantees a very good prediction performance, but it also implies two disadvantages. On one side, the higher is the number of regression coefficients involved, the higher will be the empirical degree of the model, which, in turn, might pose doubts on its reliability outside its applicability range, typically defined on the basis of the available measurements used the optimize the model by regressing its empirical coefficients (e.g., frequency limited to 80 GHz). On the other side, the push to increase the prediction performance by using a high number of regression coefficients (e.g., 10 in the model proposed by the Chinese Administration [*ITU-R Doc. 3M/25-E*, 2008]) will also increase the model's bias if the reference measurements are affected by inaccuracies, as it might be typically the case.

This contribution presents an alternative physically based approach to devise a new model aimed at predicting rain attenuation affecting terrestrial links. The key idea is to avoid relying on measurements but to investigate and model the path reduction factor by simulating the interaction of a hypothetical terrestrial link with a set of realistic synthetic rain fields. The dependence of PF on the path length, the operational frequency and the rain rate measured at the transmitter, is first addressed, and afterward the contribution defines simplified yet accurate analytical expressions to predict rain attenuation on terrestrial links, requiring as input the local $P(R)$. The remainder of the paper is organized as follows: section 2 presents the development of the proposed prediction model, going from the numerical calculation of rain attenuation to the definition of the analytical approach. The prediction accuracy of such a method is then discussed (and compared to the one of other two models) in section 3 by considering experimental data collected worldwide, while section 4 draws some conclusions.

2. A Physically Based Rain Attenuation Prediction Model

2.1. Rationale of the Model

The rain attenuation prediction model proposed in this contribution relies on taking into due account the spatial variability of precipitation along terrestrial links, which is achieved by simulating the interaction between electromagnetic waves and realistic synthetic rain maps. Given the complexity of this approach, the results obtained from such simulations are afterward further exploited to derive analytical expressions with the aim of providing an accurate yet simpler approach to predicting rain attenuation on terrestrial links. This is achieved by resorting to concept of path reduction factor, whose dependence on the rain rate and the path length is duly investigated and modeled. More details on the whole model derivation are provided in the next sections.

2.2. Rain Map Synthesis: MultiEXCELL

The development of the proposed rain attenuation prediction method relies on MultiEXCELL, first presented in *Luini and Capsoni* [2011a], a global rainfall model oriented to the analysis and prediction of the atmospheric radio propagation impairments. MultiEXCELL allows to generate a set of synthetic rain fields (an example of which is shown in Figure 1a), whose ensemble preserves the input local $P(R)$ and reproduces the rainfall spatial correlation.

Synthetic rain fields, whose spatial resolution is 1 km × 1 km and whose lateral dimension can range between 200 and 300 km, result from the arrangement of multiple synthetic exponential cells according to the natural rain cells' aggregative process observed in a real rain environment and by reproducing the statistical distribution of the rain coverage area. To this aim, the model includes a methodology that estimates, on a global basis, the distribution of the fractional area of a map affected by rain, starting from the ECMWF (European Centre for Medium-Range Weather Forecast) ERA-40 database [*Uppala et al.*, 2005]. As a result, MultiEXCELL is suitable not only for small-scale applications, such as the estimation of the attenuation impairing Earth-space microwave links, but also for scenarios, such as the one considered here, in which the knowledge of the spatial distribution of rain on a medium/large scale is of key importance (the path of a line-of-sight terrestrial link may be several kilometers long). A key advantage of MultiEXCELL is that a relatively small set of synthetic rain fields (around 400/500 maps) is sufficient to reliably represent the local rainfall process and, thus, to allow the efficient simulation of the interaction between a millimeter wave telecommunication system and precipitation.

2.3. Rain Attenuation Prediction: The Numerical Model

MultiEXCELL has been successfully used to simulate the interaction of rain fields with millimeter wave communication systems in different scenarios, including terrestrial links [*Luini and Capsoni*, 2010;

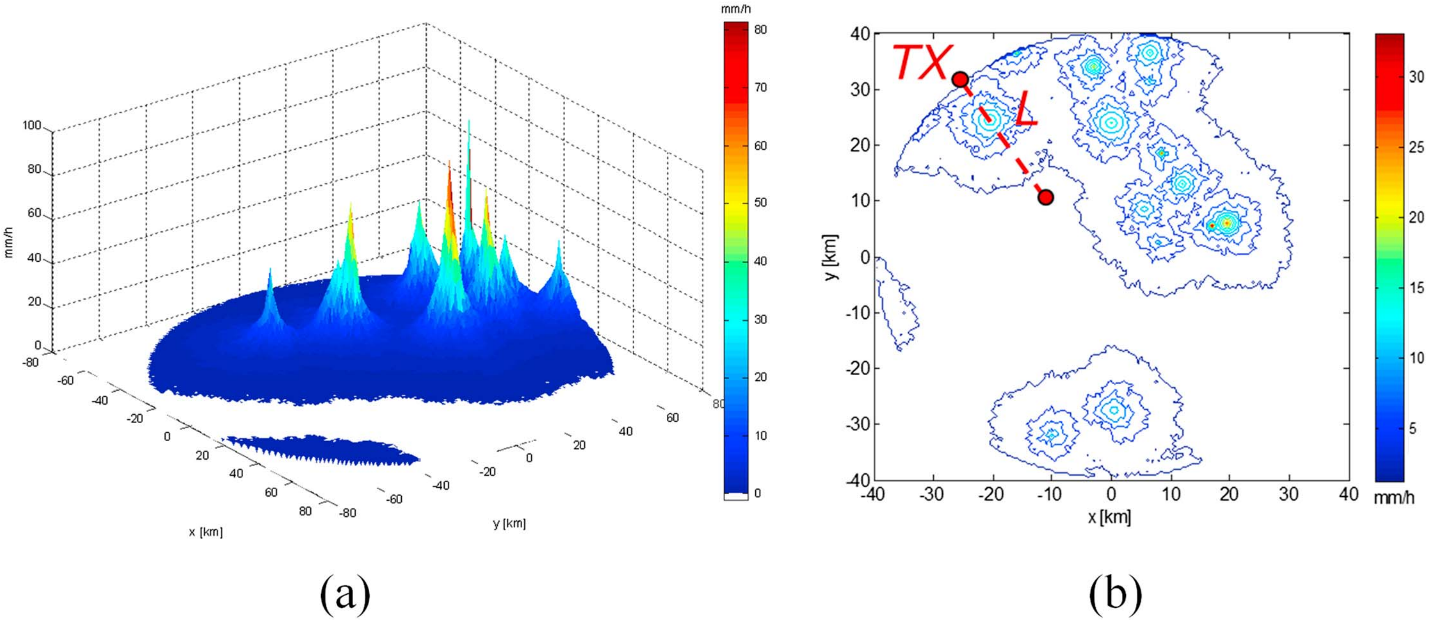


Figure 1. (a) Example of the synthetic rain fields generated by the MultiEXCELL model [*Luini and Capsoni*, 2011a]. (b) Numerical calculation of the path attenuation along a terrestrial link using MultiEXCELL.

Luini and Capsoni, 2011b; *Luini and Capsoni*, 2013; *Capsoni et al.*, 2010]. Specifically, results reported in *Luini and Capsoni* [2010] show a very good performance in predicting the CCDF of rain attenuation A affecting terrestrial links, which is achieved by numerically integrating the specific attenuation γ_R along the link as follows:

$$A = \int_L \gamma_R(l)\,\mathrm{d}l = \int_L k\,R(l)^{\alpha}\,\mathrm{d}l \tag{1}$$

In (1), L is the length of the link, k and α are rain-to-specific attenuation conversion coefficients extracted from recommendation ITU-R P.838-3 [*ITU-R Recommendation P.838-3*, 2003], while $R(l)$ is the rain rate at position l along the path, associated to a pixel of the rain map (refer to Figure 1b). By moving the link in different positions, the rain map is turned into an attenuation map, as shown, for example, in Figure 2 (frequency f = 30 GHz, path length L = 5 km, vertical wave polarization).

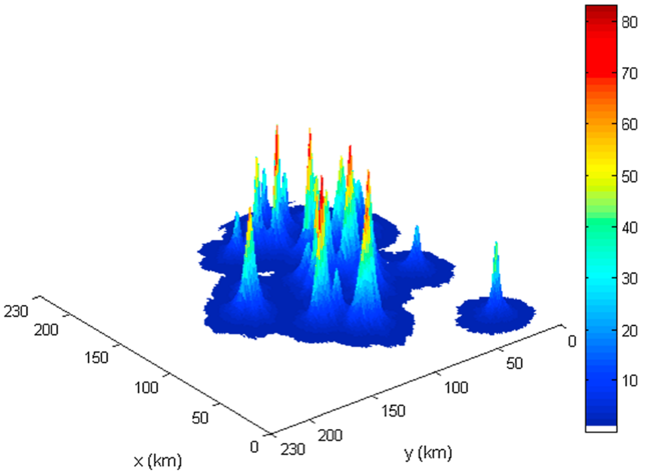
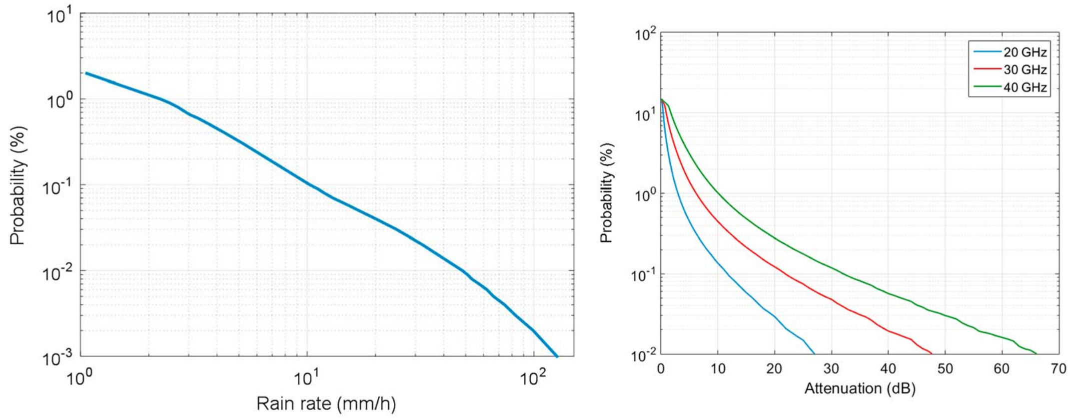


Figure 2. Sample rain attenuation maps obtained by applying (1) for all possible positions of the link across the map: frequency f = 30 GHz, path length L = 5 km, vertical wave polarization.

The attenuation CCDF, hereinafter referred to as $P(A)$, can be straightforwardly calculated by cumulating the A values coming from all the rain maps. In this work, MultiEXCELL was applied to synthesize 578 rain maps, with lateral dimension of 230 km, for the reference site of Milan, Italy (latitude = 45.4°N and longitude = 9.5°E). The $P(R)$ required as input to the model was derived from high-resolution rain rate values (1 min integration time), in turn extracted from a local tipping bucket rain gauge (10 years of data). Figure 3a shows such input statistics, while Figure 3b depicts the CCDFs of the rain attenuation estimated using (1) for a 5 km link operating at 20, 30, and 40 GHz (vertical wave polarization): as expected, rain



(a) (b)

Figure 3. (a) $P(R)$ from Milan derived from the local tipping bucket rain gauge (10 year rain rate data with 1 min integration time). (b) CCDFs of the rain attenuation on a terrestrial link (frequency $f = 20$, 30, and 40 GHz, path length $L = 5$ km, vertical wave polarization) calculated from all the 578 MultiEXCELL rain maps (site: Milan, Italy).

attenuation quickly increases with frequency, which makes more and more cumbersome to guarantee high availability for the link.

2.4. Rain Attenuation Prediction: The Analytical Formulation

The key objective of this work is to devise a rain attenuation statistics prediction model for terrestrial links that combines the good performance of the approach described in section 2.3 (as shown in *Luini and Capsoni* [2010]) with the simplicity of the analytical method relying on the concept of path reduction factor, PF:

$$A = k\,R_{\mathrm{TX}}{}^{\alpha} L_{\mathrm{eff}} = k\,R_{\mathrm{TX}}{}^{\alpha} L\,\mathrm{PF} \tag{2}$$

As is clear from (2), the rain attenuation A can be calculated as if the rain rate R_{TX} measured at the transmitter were constant along the whole link, whose length is reduced to an effective one (L_{eff}) by means of PF. In fact, PF actually takes into account, in an equivalent way, the real spatial variability of the rain rate affecting the whole link.

By inverting (2), a very large number of PF values were obtained from all the 578 rain maps generated by MultiEXCELL with the aim of investigating the dependence of the path reduction factor on the path length (1 km $\leq L \leq$ 20 km), on the rain rate (1 mm/h $\leq R_{TX} \leq$ 200 mm/h) and the operational frequencies (10 GHz $\leq f \leq$ 50 GHz). As an example, Figure 4 shows the PF values as a function of R_{TX} (darker areas correspond to higher density of the scatterplot points) obtained for a 20 GHz link with L = 15 km (578 rain maps).

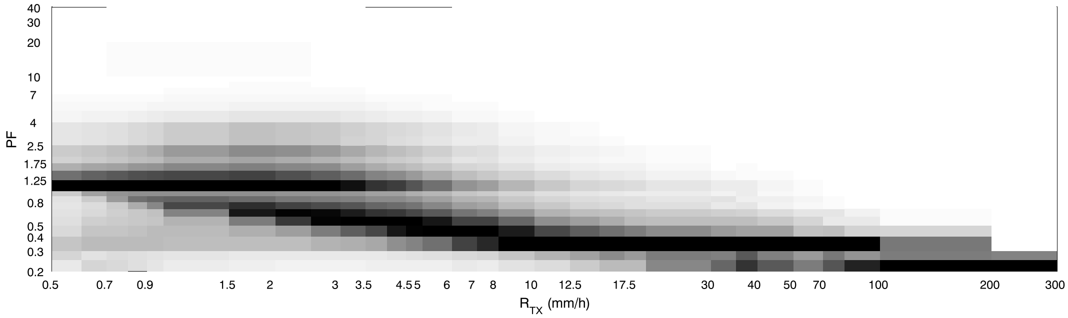


Figure 4. Path reduction factor density scatterplot derived from 578 MultiEXCELL rain maps by inverting (2), as a function of R_{TX} (f = 20 GHz and L = 15 km).

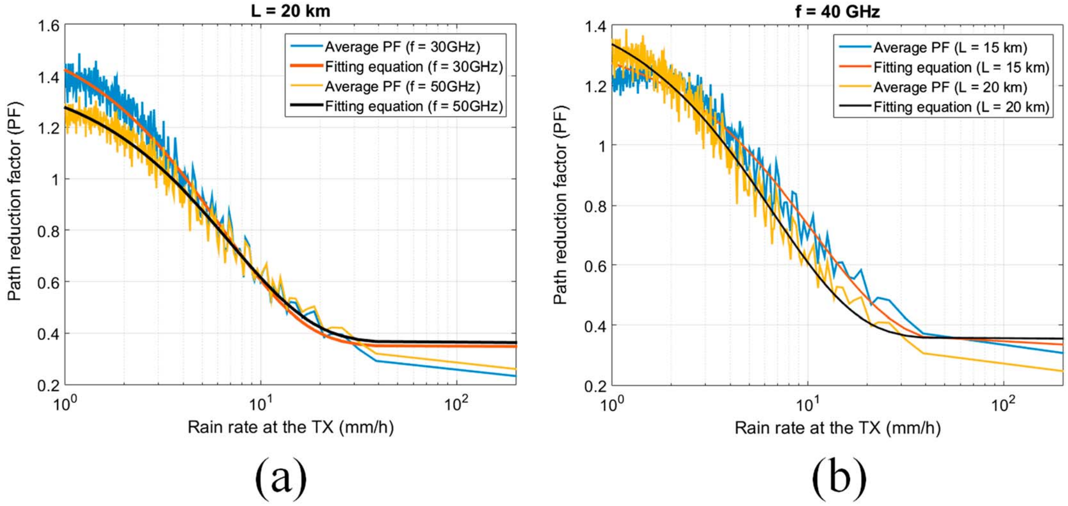


Figure 5. (a) Trend of the average path reduction factor $\mathrm{PF}_{\mathrm{av}}$ as a function of the rain rate, for a fixed path length $L = 20$ km and different frequencies (30 and 50 GHz); data retrieved from MultiEXCELL maps and regression curves (see equation (3)). (b) Trend of the average path reduction factor $\mathrm{PF}_{\mathrm{av}}$ as a function of the rain rate, for a fixed path frequency $f = 40$ GHz and different path lengths (15 and 20 km); data retrieved from MultiEXCELL maps and regression curves (see equation (3)).

As is clear from Figure 4, PF as a function of the rain rate is characterized by a large spread, regardless of the frequency *f* and the path length *L*. Moreover, it is worth pointing out that despite that PF is typically referred to as path *reduction* factor, which seems to imply that it should always be lower than 1, actually, PF values higher than 1 are quite common when R_{TX} is low: this is often the case for which the transmitter is located at the edge of a rain cell affecting the link, i.e., when the rain rate values along the whole link are mostly higher than R_{TX}.

With the aim of devising an analytical model, we have investigated the trend of the average PF ($\mathrm{PF}_{\mathrm{av}}$) conditioned to the rain rate, by selecting classes for *R* containing approximately the same number of samples. The investigation of such a trend revealed that $\mathrm{PF}_{\mathrm{av}}$ tends to follow the exponential function in (3):

$$\mathrm{PF}_{\mathrm{av}} = a(f,L)\,e^{-b(f,L)\,R} + c(f,L) \tag{3}$$

where *a*, *b*, and *c* are regression coefficients function of the path length and frequency.

Figure 5a shows a sample trend of $\mathrm{PF}_{\mathrm{av}}$ as a function of the rain rate for a given path length $L = 15$ km and two frequencies (30 and 50 GHz). Reported in the figure is also the regression curve (equation (3)), which fits the data with satisfactory accuracy. As expected, PF decreases with the increase in *R*: in fact, higher rain rate values are typically associated with convective precipitation, which is also characterized by limited spatial horizontal extent, i.e., high spatial inhomogeneity [*Capsoni et al.*, 2006]. Moreover, results indicate that $\mathrm{PF}_{\mathrm{av}}$ slightly depends on frequency: this is indeed expected, as the path reduction factor originates from the need to take into account the inhomogeneity of precipitation along the link. On the other hand, as shown in Figure 5b, the dependence of $\mathrm{PF}_{\mathrm{av}}$ on *L* is more pronounced. Indeed, these results suggest that the role of frequency in estimating rain attenuation by means of (2) can be limited to the coefficients *k* and α with no significant degradation of the expected prediction accuracy.

Besides offering a good fitting accuracy, the expression in (3), when regressed on the $\mathrm{PF}_{\mathrm{av}}$ data obtained at different path lengths, provides coefficients *a*, *b*, and *c* whose trend with *L* turns out to be quite regular. This is clarified in Figure 6, which, more specifically, reports the average value of *a*, *b*, and *c* for all the considered frequencies: as mentioned above, the dependence of $\mathrm{PF}_{\mathrm{av}}$ on *f* can be neglected.

As a result, based on all the findings illustrated in this section, the rain attenuation exceeded with probability *P* in an average year can be calculated as

$$A(P,L) = k\,R(P)^{\alpha}\,L\left[a(L)\,e^{-b(L)\,R(P)} + c(L)\right] \tag{4}$$

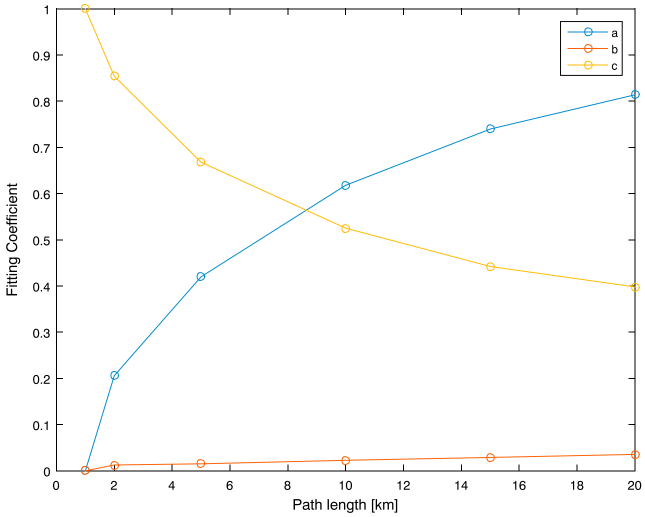


Figure 6. Trend of the regression coefficients *a*, *b*, and *c* of the expression in (3) as a function of the path length.

where $R(P)$, extracted from the local input rain rate CCDF, is the rain rate exceeded with probability P, while, according to the trends reported in Figure 6, coefficients a, b, and c are defined as

$$\begin{aligned} a &= -0.8743\,e^{-0.1111\,L} + 0.9061 \\ b &= -0.0931\,e^{-0.0183\,L} + 0.1002 \\ c &= -0.6613\,e^{-0.178\,L} + 0.3965 \end{aligned} \qquad (5)$$

with L expressed in kilometers.

3. Assessment of the Model's Prediction Accuracy

This section evaluates the prediction accuracy for the analytical formulation of the proposed model by comparing the reference rain attenuation CCDFs calculated using the numerical approach described in section 2.3 with those obtained from (4) and (5). In both cases, the same input $P(R)$ depicted in Figure 3 was used. To this aim, the following error figure, $\varepsilon(P)$, defined on the basis of recommendation ITU-R P.311–15 [*ITU-R Recommendation P.311-15*, 2016], is used:

$$\varepsilon(P) = \begin{cases} \left(\dfrac{A_M(P)}{10}\right)^{0.2} \ln\left(\dfrac{A_E(P)}{A_M(P)}\right) & A_M(P) < 10 \text{ dB} \\ \ln\left(\dfrac{A_E(P)}{A_M(P)}\right) & A_M(P) \geq 10 \text{ dB} \end{cases} \qquad (6)$$

where $A_M(P)$ and $A_E(P)$ represent the path attenuations, both correspondent to probability level P, extracted respectively from the reference and the estimated $P(A)$.

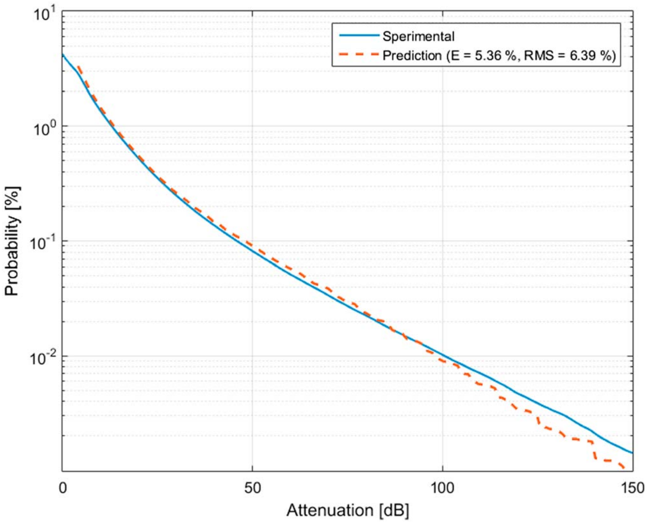


Figure 7. Prediction of the rain attenuation statistics obtained by (4) for f = 40 GHz and L = 15 km.

Figure 7 depicts an example of rain attenuation statistics prediction for f = 40 GHz and L = 15 km: the prediction accuracy is summarized by the average (E) and root-mean-square (RMS) value of $\varepsilon(P)$ (for $P \geq 10^{-3}$%), which is reported in the figure legend.

The agreement between the reference and the predicted curves in Figure 7 is very good, which is also valid for the other values of f and L. This is clearly shown in Figure 8a and Figure 8b, which depict the average E and RMS as a function of the frequency and of the path length, respectively: results indicate a very limited positive bias, while the RMS, only slightly dependent on the frequency and the path length, is always lower than 8%.

The results illustrated in Figures 7, 8a, and 8b mainly point out that the use of

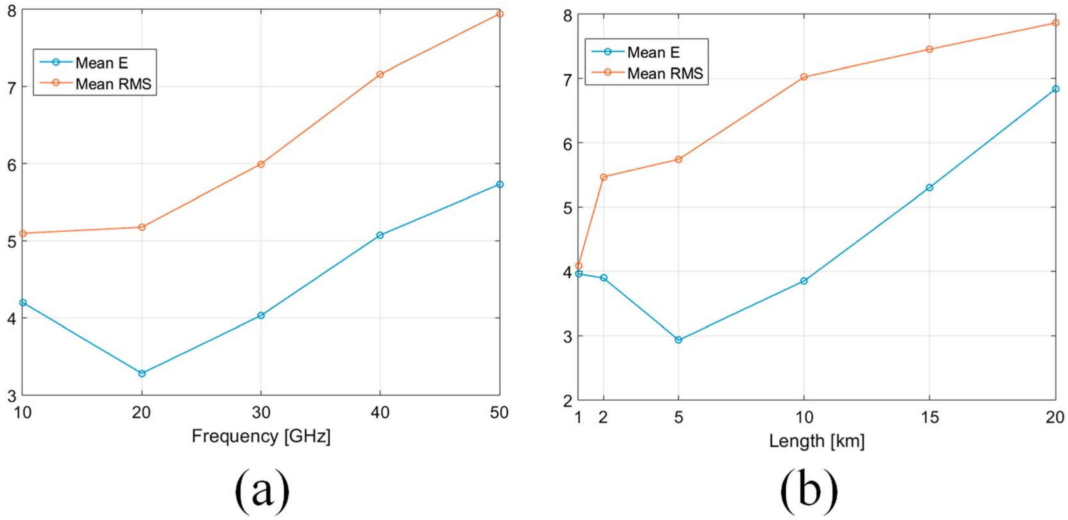


Figure 8. (a) Trend of *E* and RMS as a function of the link operational frequency. (b) Trend of *E* and RMS as a function of the path length.

an average path reduction factor (see equation (3)) is sufficient to predict the MultiEXCELL-derived rain attenuation statistics with very satisfactory accuracy. However, such results are not enough to properly validate the proposed prediction model: independent data are required.

For an additional assessment of the proposed method, we have taken advantage of the extensive data set of measurements (DBSG3-DataBase of Study Group 3) assembled and made available by ITU-R. More specifically, the DBSG3 database for terrestrial links, the most complete of its kind, consists of 89 experiments set up in 16 different countries worldwide: the path length ranges from 0.5 to 58 km, whereas the operational frequency varies from 7 to 137 GHz. Besides including the main electrical and geometrical features of each terrestrial link, the DBSG3 database also contains, for each experiment, the local $P(R)$—concurrent with the reference $P(A)$—which is the most suitable input to the prediction models. On the other side, it is worth highlighting that the measurements included in the database should be treated with care, especially to the aim of assessing the accuracy of prediction models: as a matter of fact, some key information is missing (e.g., the indication on whether the attenuation data include all tropospheric effects, such as gaseous absorption, or only the effects of rain), or, in other cases, the data accuracy is rather doubtful. Examples of the latter case are given by experiments performed in the Chilbolton (UK) along short ($L = 0.5$ km) high-frequency (f ranging from 37 to 137 GHz) terrestrial links: additional information in the data table states that for those experiments, antennas were behind windows with hoods. Besides rain attenuation, this is expected to cause additional fade, as clearly shown in Figure 9a, for one of the experiments mentioned above ($f = 37$ GHz): the input $P(R)$ included in the database indicates $R = 54$ mm/h for exceedance probability $P = 0.001\%$, according to which $A = k(R^{\alpha})L \approx 4.4$ dB (k and α extracted from recommendation ITU-R P.838-3 [*ITU-R Recommendation P.838-3*, 2003]). In fact, given the very short path length, the rain rate along the link is expected to be quite constant, i.e., the PF approximately equals to 1. This is clearly not reflected in the ITU-R data, which, for the same probability level, show $A \approx 12$ dB: as expected due to the setup of the link, the data likely include additional contributions to attenuation that do not come from rain. Notwithstanding this, the Brazilian model [*Silva Mello and Pontes*, 2007] and the ITU-R method [*ITU-R*, *Recommendation P.530-16*, 2015] show a pretty good agreement to the data: this is mainly due to the fact that both models' parameters were adjusted to minimize the prediction error considering the whole set of measurements included in the DBSG3 database, disregarding any possible inaccuracy in the data.

In contrast with the results reported in Figure 9a, Figure 9b shows that for some experiments, the predictions achieved by all the models are very similar: this is the case for the experiment conducted in Mendlesham (UK), for which $f = 22.1$ GHz and $L = 2.9$ km. In addition, for some other experiments, the proposed model outperforms the other ones: this is depicted, for instance, in Figure 9, for experimental data collected in Piaseczno (PL), at $f = 11.5$ GHz, along a link of $L = 15.4$ km.

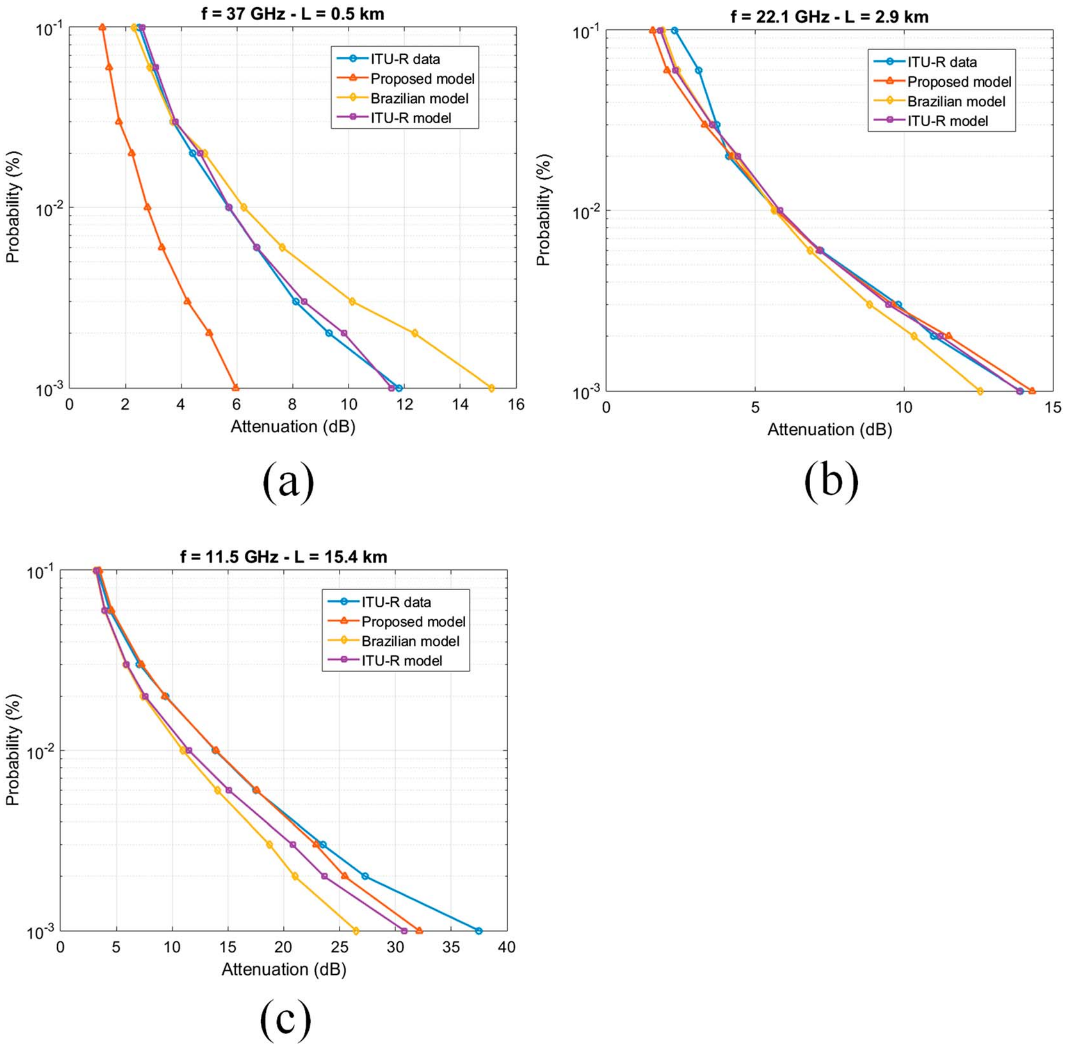


Figure 9. (a) Test of prediction models against data included in the DBSG3 database: site = Chilbolton (UK), duration = 1 year, *f* = 37 GHz, *L* = 0.5 km. (b) Test of prediction models against data included in the DBSG3 database: site = Mendlesham (UK), duration = 3 years, *f* = 22.1 GHz, *L* = 2.9 km. (c) Test of prediction models against data included in the DBSG3 database: site = Piaseczno (PL), duration = 5 year, *f* = 11.5 GHz, *L* = 15.4 km.

Table 1 provides a more comprehensive assessment of the models' accuracy: reported in the table are the mean *E* and RMS of the prediction error, considering all experiments, save for those mentioned above conducted in Chilbolton. As expected, the overall performance of the proposed model is lower than the one of the Brazilian and ITU-R models: indeed, the coefficients of the former were not optimized on the basis on the ITU-R data set (as for the latter), but they were determined starting from a physically based approach.

Though the scores listed in Table 1 are useful to gain a preliminary idea about the prediction models' performance, nevertheless, they cannot be considered as a solid indicator of the models' accuracy: indeed, considering, for example, the discussion in Figure 9a, a careful inspection of the experimental data included in the DBSG3 database for terrestrial links is required before fully relying on such a data set to develop, optimize, and/or assess prediction models.

Table 1. Overall Performance of Prediction Models: Mean *E* and RMS of the Prediction Error Against the ITU-R Data Set

	Mean *E*	Mean RMS
Proposed model	10.9%	27.1%
Brazilian model	−2.1%	22.3%
ITU-R model	−2%	21.1%

4. Conclusion

This contribution presents a novel physically based approach to modeling the rain attenuation affecting terrestrial links. The model is devised by simulating the interaction between terrestrial links and synthetic rain maps, which are specifically exploited to investigate the path reduction factor, introduced to take into due account, in an effective way, the spatial inhomogeneity of rainfall along the link. The values of PF show a large spread regardless of the parameters of the link, but on the other hand, the trend of the average path reduction factor PF_{av} with the rain rate turns out to be well modeled by a simple exponential function. Moreover, the regression coefficients of such function are found to follow quite regular trends with the path length, while the dependence on the operational frequency is found to be negligible. Starting from all these elements, an analytical expression is proposed for PF, which defines a simple yet accurate approach to predicting rain attenuation on terrestrial links as a function of the customary geometrical and electrical parameters (frequency, path length, and wave polarization) and of the local yearly rain rate statistics.

The accuracy of the proposed model was tested against the MultiEXCELL-derived rain attenuation statistics and against the independent set of experimental data included in the DBSG3 database made available by ITU-R: very satisfactory results were obtained in the first case, while in the second case the performance of the proposed model is quite in line with the one associated to the Brazilian and ITU-R models, though these models show better scores. Indeed, these latter findings are only useful to gain a preliminary idea about the prediction models' performance, but they cannot be considered as a solid indicator of the models' accuracy: a careful inspection of the experimental data included in the DBSG3 database for terrestrial links is required before fully relying on such a data set to develop, optimize, and/or assess prediction models. This is part of the future work, which will also include improving the proposed model's performance using as reference only the most reliable experiments of the ITU-R database.

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