

ETSI TR 104 140 V1.1.1 (2025-05)



**Propagation measurement and modelling for
PtP radio links in the E, W and D bands**

ReferenceDTR/ATTMTMmWT-0030

Keywordschannel modelling, millimetre wave, mWT,
propagation

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Foreword

This Technical Report (TR) has been produced by ETSI Technical Committee Access, Terminals, Transmission and Multiplexing (ATTM).

Modal verbs terminology

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Executive summary

The present document deals with Electro-Magnetic (EM) wave propagation for terrestrial PtP links in the millimetre-wave (mm-wave) range (30 - 300 GHz), where rain plays the most relevant role since rain drops absorb and scatter electromagnetic energy inducing significant path losses, due to their size (about 1 - 5 mm) being comparable to the EM wavelength.

When dealing with attenuation due to rain there are several factors to be considered:

- Specific attenuation due to rain γ_R (dB/km), which is dependent not only on frequency and rain rate but also on the particular Drop Size Distribution (DSD).
- Total attenuation due to rain along the radio link (dB), which is dependent on the spatial variation of the specific attenuation along the link.
- Attenuation due to rain but not related to the propagation path (dB), such as the wet antenna effect.

As for the specific attenuation, several models of DSD have been developed based on both experimental rain data and analytical models of rain attenuation mechanisms. All the analyses converge on the fact that the DSD model is highly dependent on the type of rain in the specific rain zone and in the specific season.

Recommendation ITU-R P.838-3 [i.3] is based on the Laws-Parsons drop size distribution model which describes typical continental temperate rainfall of stratiform kind. When considering a convective type of rain, typical of tropical regions, a different modelling of DSD is needed and different results would be obtained.

As for the total link attenuation, several models of the path reduction factor have been developed in order to take into account the spatial inhomogeneity of rain along the link. All models describe a path reduction factor which decreases below 1 with increasing link length, where the link length is much larger than the length over which the rain rate can be considered homogeneous. Instead when dealing with short links, below about 1 km, where rain rate can be considered constant along the path, the path reduction factor should be reasonably slightly less than or equal to 1.

Recommendation ITU-R P.530-18 [i.4] is based on a model which gives a path reduction factor increasing well over 1 with a decreasing link length, which seems to be not physically sound and gives as a consequence an overestimation of the attenuation due to rain along the link. A proper adaptation of the model limiting the path reduction factor to 1 could be a good way forward to have a more accurate prediction model for short links.

The wet antenna attenuation, due to the thin water film deposited by rain over the antenna of the radio equipment, is a cause of attenuation that should be separated from the propagation loss due to rain along the link. This effect could be the cause of some measurements apparently giving a path reduction factor much higher than unity with short links.

Finally it is important noting that there is no physical reason why the range of applicability of a terrestrial rain attenuation prediction model for mmWave systems should be limited to 100 GHz, as it is currently the case in Recommendation ITU-R P.530-18 [i.4]; as a matter of fact in the mmWave frequency range (30 - 300 GHz) the main attenuation mechanisms are absorption and Mie scattering and only when going towards higher frequencies, well over the mmWave range, the geometric optics scattering model becomes valid.

Introduction

The present document deals with Electro-Magnetic (EM) wave propagation at millimetre-wave (mm-wave) for terrestrial PtP links, with particular consideration of frequencies about and over 100 GHz, in the:

- E (71 - 86 GHz);
- W (92 - 115 GHz); and
- D (130 - 175 GHz) bands.

In this frequency range propagation is subject to several atmospheric effects induced by:

- Gases (mainly oxygen and water vapour).
- Suspended water droplets (fog).
- Hydrometeors (rain, snow, hail).

Among them, at frequencies higher than 10 GHz rain plays the most relevant role since rain drops absorb and scatter electromagnetic energy, thus inducing significant path losses; this effect becomes more and more relevant as long as the wavelength is comparable to the rain drop size (about 1 - 5 mm), in particular in the mm-wave part of the EM spectrum (30 - 300 GHz).

That is why it is of paramount importance to investigate atmospheric effects impairing millimeter-waves, specifically rain attenuation, which is greatly dependent on the operational frequency, on the rain rate and on the rain drop dimensions, described by the Drop Size Distribution (DSD).

As a matter of fact, there are two ITU-R Recommendations dealing with rain attenuation effects:

- Recommendation ITU-R P.838-3 [i.3], which provides specific attenuation as a function of the rain rate and operational frequency.
- Recommendation ITU-R P.530-18 [i.4], which presents a rain attenuation model for terrestrial links.

Both theoretical analysis and field measurements highlight the importance of considering the microphysics of rain when predicting specific attenuation due to rain, in particular the DSD that is function of the rain type and of the rain zone.

Moreover when considering short radio links (in the order of a few hundred meters and up to about 1 km), which would be typical with systems at D band, a proper evaluation of the spatial variation of rain rate along the link length should be performed; the effective path length over which the rain rate can be considered uniform is given by the link length multiplied by the path reduction factor and is highly dependent on the rain rate; in case of high rain rate, typical of convective events, the effective path length can be expected to be small, whilst for low rain rate, typical of stratiform events, the effective path length would tend to be large.

Both theoretical analysis and field measurements highlight that in case of short radio links (less than 1 km) the path reduction factor should be less than or equal to 1, according to the rain rate; this is not the case for the model currently adopted in Recommendation ITU-R P.530-18 [i.4].

Finally it is important noting that there is no physical reason why the range of applicability of a terrestrial rain attenuation prediction model for mmWave systems should be limited to 100 GHz, as it is currently the case in Recommendation ITU-R P.530-18 [i.4].

The present document is structured in the following clauses:

- Clause 4 deals with the different atmospheric propagation phenomena impacting EM waves.
- Clause 5 deals with rain attenuation prediction based on the availability of rain data time series (event-based analysis), considering the relevance of Drop Size Distribution in determining the specific attenuation due to rain; it deals also with wet antenna attenuation.
- Clause 6 deals with rain attenuation prediction based on long term rain data collection (statistical analysis), considering different empirical and analytical models and the relevance of path reduction factor with short links.
- Clause 7 gives some information on measurements from field trials.
- Clause 8 summarizes some implications for link budget estimation.

1 Scope

The present document provides information about electromagnetic propagation at millimetre wave, considering the available models, both derived from physical analysis and from real data fitting and comparing them with measurements.

2 References

2.1 Normative references

Normative references are not applicable in the present document.

2.2 Informative references

References are either specific (identified by date of publication and/or edition number or version number) or non-specific. For specific references, only the cited version applies. For non-specific references, the latest version of the referenced document (including any amendments) applies.

NOTE: While any hyperlinks included in this clause were valid at the time of publication, ETSI cannot guarantee their long term validity.

The following referenced documents are not necessary for the application of the present document but they assist the user with regard to a particular subject area.

- [i.1] Recommendation ITU-R P.676-12 (2019): "Attenuation by atmospheric gases and related effects".
- [i.2] Recommendation ITU-R P.840-7 (2017): "Attenuation due to clouds and fog".
- [i.3] Recommendation ITU-R P.838-3 (2005): "Specific Attenuation Model for Rain for Use in Prediction Methods".
- [i.4] Recommendation ITU-R P.530-18 (2021): "Propagation data and prediction methods required for the design of terrestrial line-of-sight systems".
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3 Definition of terms, symbols and abbreviations

3.1 Terms

Void.

3.2 Symbols

Void.

3.3 Abbreviations

For the purposes of the present document, the following abbreviations apply:

3GPP	3 rd Generation Partnership Project
5G	5 th Generation of Mobile Networks
CCDF	Complementary Cumulative Distribution Function
DBSG3	Data Base Study Group 3 (ITU-R)
DSD	Drop Size Distribution
EHF	Extremely High Frequency

NOTE: 30 - 300 GHz range, mm-wave range.

EM	ElectroMagnetic
MW	MicroWave
P	Pressure
PtP	Point to Point
RH	Relative Humidity
SC EXCELL	Stratiform/Convective EXponential CELL
SHF	Super High Frequency

NOTE: 3 - 30 GHz range (cm-wave range).

T	Temperature
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4 Propagation features at mm-wave

4.1 Tropospheric attenuation

The atmosphere is a thermodynamic system containing water in vapor, liquid and solid state, gases and aerosol, surrounding the Earth up to 100 km. As for the propagation of millimeter-waves and microwaves along terrestrial paths, only the lower layer close to the Earth surface is of concern. The atmosphere is commonly characterized through temperature, pressure, relative humidity and density of its main components (gases and water).

4.2 Gaseous attenuation

Oxygen and water vapour are the gaseous components of the atmosphere influencing the electromagnetic wave propagation in the frequency range from 10 up to 350 GHz. Other gases need to be taken into account only at higher frequencies (e.g. CO₂ for optical wavelengths). The weather condition with no fog is typically referred to as "clear sky" condition.

The oxygen absorption is mainly due to the resonance of oxygen molecules as magnetic dipoles, which occurs in specific bands: for example, oxygen attenuation is basically negligible up to 40 GHz, but it becomes important around 50 GHz and is dominant around 60 GHz.

The oxygen concentration depends on the air pressure and temperature. The former is characterized by a decreasing exponential profile with the height, while the latter is highly influenced by daily, seasonal and geographical variations. Oxygen absorption increases with the decrease in temperature.

The water vapour absorption, due to the molecular interaction with electromagnetic waves as electric dipole, can be calculated as the sum of two terms, which are linear and quadratic functions of the water vapour density, respectively. Water vapour absorption is linked to meteorological parameters like pressure, temperature and water vapour density.

In principle, the procedure to calculate the gaseous attenuation along terrestrial paths consists in two steps:

- 1) calculation of the specific attenuation due to gases γ_G (dB/km) at any point along the propagation path;
- 2) calculation of the total path attenuation due to gases A_G by integration of all the contributions.

In practice, this approach is unfeasible because it would require the knowledge at any time of the complete spatial distribution along the path of meteorological parameters like air pressure, temperature and gases concentration. However, as the attenuation due to gases is very stable in space (tens of kilometers) and in time (hours), γ_G is typically considered to be constant along terrestrial propagation paths, which is more and more true for short links (e.g. less than 1 km). In turn, this implies that the path attenuation can be simply calculated as:

$$A_G = \gamma_G L$$

where L (km) is the length of the terrestrial link.

The most acknowledged methodology for the prediction of $\gamma_G L$ is named MPM93 and was proposed by Liebe et al. in [i.8]. The model, which is currently adopted in Annex 1 of Recommendation ITU-R P.676-12 [i.1], defines the intensity and the width of oxygen and water vapor spectral absorption lines in the 1 - 1 000 GHz frequency range. The contribution of each line, which depends on pressure P , relative humidity RH and temperature T , is summed up to yield the overall specific attenuation due to gases.

The specific attenuation due to gases, calculated using the Liebe MPM93 model is shown in Figure 1, for the following standard reference meteorological parameters: $T = 15\text{ }^\circ\text{C}$, $P = 1\,013,25\text{ mbar}$ and water vapor content (which is tightly linked to RH) $\rho_v = 7,5\text{ g/m}^3$.

As is clear from the figure, the contribution coming from oxygen is mainly limited to the frequency bands around 60 GHz and 120 GHz, where the specific attenuation can reach values as high as 15 dB/km. On the other hand, the impact of water vapor is associated to three main absorption peaks (centered approximately around 22, 183 and 325 GHz), but it is also given by a linear term providing, in general, more attenuation than the one induced by oxygen (see especially the 210 - 310 frequency range).

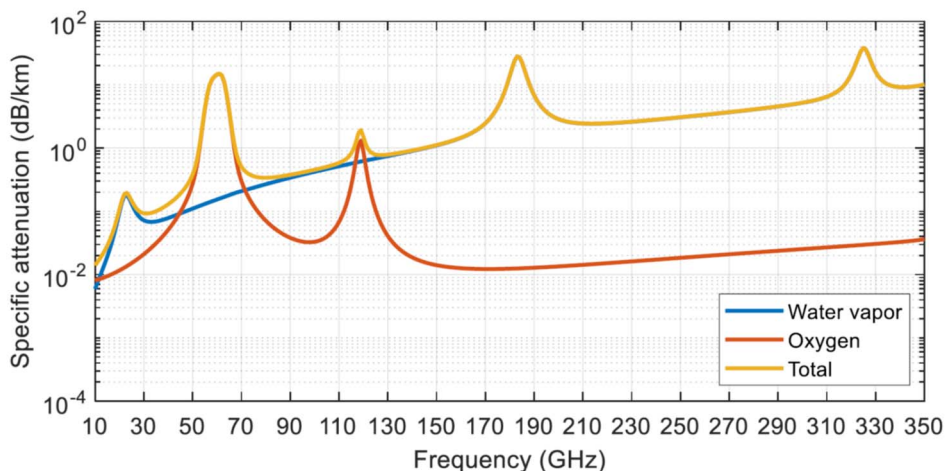


Figure 1: Specific attenuation due to gases as a function of frequency, calculated using the Liebe MPM93 model [i.8]

4.3 Fog attenuation

Fog is a suspension of microscopic water droplets (in the order of microns) formed by condensation of the atmospheric water vapor on the surface of suspended hygroscopic particles, named condensation nuclei. Fog is usually associated with values of relative humidity close to saturation (100 %).

In meteorology, the term fog is used when the visibility is less than 1 km, whereas mist is an intermediate state where the relative humidity is above 60 % and the visibility exceeds 1 km. Finally, haze is any suspension of dry solid particles (smoke, dust, sand, salt, etc.) of microscopic size. Fog, produced by cooling of the air, can be classified into [i.9]:

- Radiation fog: generated by radiational cooling of the Earth surface that lowers the air temperature enough to reach saturation. It is usually observed at night during the cold season and in calm wind conditions and it is typical of continental areas.

- Advection fog: due to a wet and warm air mass moving over a cool surface. It is more frequent during spring and requires moderate or fresh breeze blowing. It is further divided into marine fog (produced by advection of marine air from warm to cold oceanic areas) and coastal or maritime fog (originated by warm air masses migrating inland from the sea).
- Upslope or hill fog: due to adiabatic cooling of air masses moved up by wind along hill or mountain flanks.

The effect of suspended water droplets on EM waves is markedly different from the one induced by gases. Every droplet has a twofold impact on the incoming EM wave: part of the electromagnetic energy is scattered in several directions around the particle, while part of it is absorbed by the particle itself, causing an increase in its temperature. In general, in the microwave and mm-wave region absorption prevails over scattering and the Rayleigh model applies [i.10].

The dimension of the water droplets forming fog is very small: they are in the order of microns. When considering EM waves in the 10 - 300 GHz, the shortest wavelength is $\lambda = 1$ mm (for $f = 300$ GHz), which is three order of magnitude larger than the size of fog droplets.

The specific attenuation due to fog γ_F is shown in Figure 2 as a function of frequency, for different liquid water contents (where T is fixed to 0 °C) [i.2].

The impact of fog increases continuously with frequency, reaching up to 7 dB/km at 300 GHz with $w = 0,5$ g/m³, which is considered as the limit value associated to extremely thick fog.

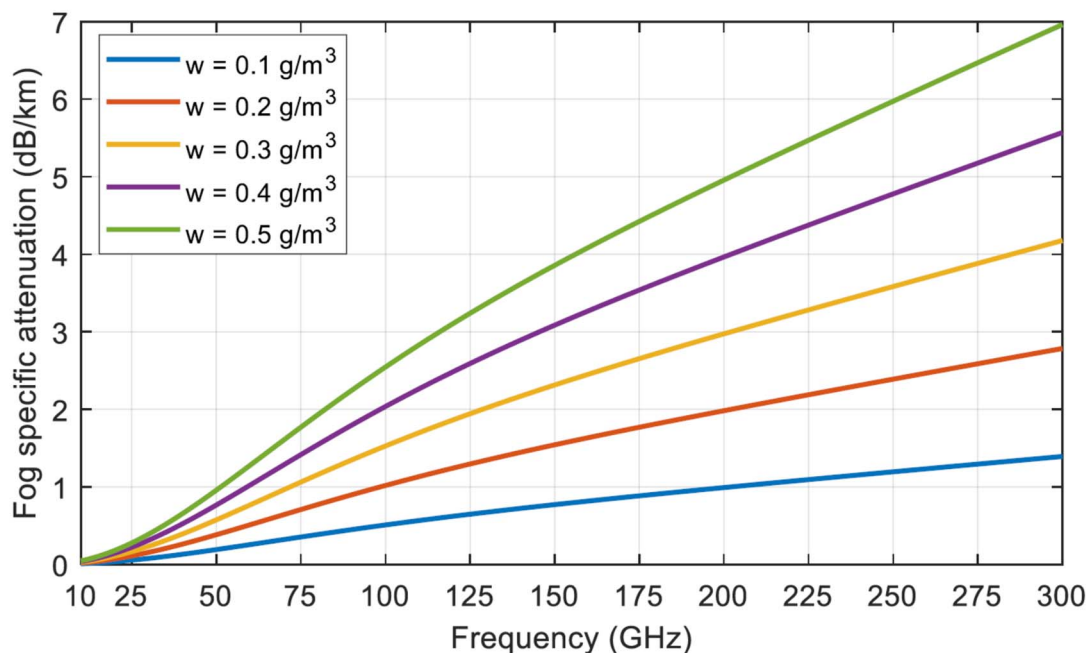


Figure 2: Specific attenuation due to fog (T = 0 °C) as a function of frequency and for different liquid water content values (Calculated according to Recommendation ITU R P.840 7 [i.2])

4.4 Rain attenuation

Rain is the prevailing phenomenon related to precipitating particles in the atmosphere and, depending on the site, it occurs for a period of time approximately comprised between 1 % and 10 % in a year (the year is considered as the basic repetition period for weather phenomena). Values as large as 3 % - 7 % are quite common in temperate climates [i.11]. Rain affects the lower part of the atmosphere; specifically, making reference to temperate climates, rain develops up to a few kilometers during winter because of the low height of the 0 °C isotherm layer (usually assumed as the vertical limit for the presence of water particles during stratiform events) and up to 10 - 15 km during thunderstorms (typical of summer periods) because of the strong updrafts/downdrafts which carry water/ice particles even to the highest layers of the atmosphere.

Rain consists of drops of spheroidal shape with equivolumetric diameters varying between few tenths of millimeters to a maximum of 6 millimeters (larger drops are not common because the cohesive force is not as strong as the aerodynamical force). In fact, the hydrometeor shape is far from being spherical if its dimension is large, because of the balance between the internal and external forces acting on the lower surface of the drop in its falling path. Measurements have shown that drops larger than about 1 mm in radius are of oblate spheroidal shape with flattened base [i.12].

As an example, Figure 3 depicts the typical shape of a falling rain drop, for different sizes. The black line represents the most probable shape derived from several drops within the same size class (figure extracted from [i.15]), which points out that the oblateness increases with the drop dimension.

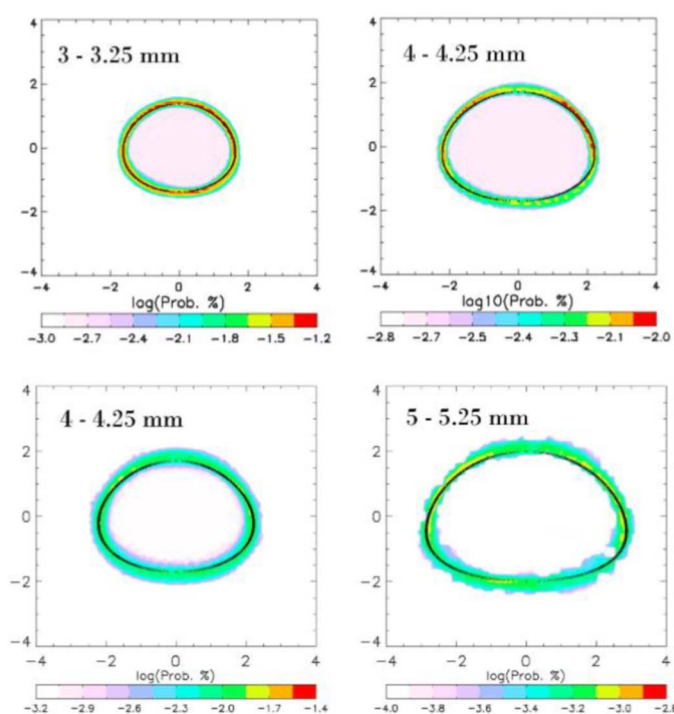


Figure 3: Typical shape of falling rain drops, for different sizes; the black line represents the most probable shape derived from several drops within the same size class (Source: [i.15])

For what concerns the impact of hydrometeors on electromagnetic waves, rain represents the main drawback to their propagation at frequencies above 10 GHz because the hydrometeor size is comparable with the wavelength of the incident wave. Other types of precipitation such as hail and snow are not considered in the present document because their effects on the propagation of the electromagnetic waves are marginal and their occurrence probability well below the one of rain.

Each rain drop causes scattering and absorption (i.e. attenuation, overall) on EM waves, however, contrary to the water droplets forming fog, the size of rain drops is of the same order of the wavelength considered in the 10 - 300 GHz range (3 cm-1 mm range). This has a twofold effect: on one side, absorption and scattering are comparable and, on the other side, the specific attenuation due to rain, γ_R , has a more complex expression compared to the case of fog. Indeed, γ_R depends on the size of each drop as follows [i.13]:

$$\gamma_R = 4,343 * 10^3 \int_D \sigma_{ext}(D, f)N(D)dD$$

where σ_{ext} is the extinction cross section, taking care of both scattering and absorption, D is the rain drop diameter, N is the number of drops with diameter D in unit volume, f is frequency.

This equation points out that the specific attenuation due to rain is obtained by weighting the fade induced by a rain drop with given diameter D with the number of rain drops with that size. This latter information is provided by $N(D)$ (typically referred to as Drop Size Distribution (DSD)), which indicates the number of rain drops with given diameter D contained in 1 m^3 . The DSD, whose units are $\text{mm}^{-1} \text{ m}^{-3}$, is typically measured by specific instruments, named disdrometers, which count and classify drops according to their size; the DSD can be derived from the output of a disdrometer as follows [i.13]:

$$N(D_i) = \frac{10^6 n_i}{S v(D_i) T \Delta D_i}$$

where n_i is the number of raindrops whose diameter falls in the i -th class (with mean diameter D_i), ΔD_i (mm) represents the width of each drop-size class, S (mm^2) is the disdrometer sampling area, T (seconds) is the instrument integration time, $v(D_i)$ (m/s) is the terminal velocity of rain drops, which, for example, can be extracted from the work of Gunn and Kinzer [i.16] or derived directly from the disdrometer measurements.

Besides measured from a disdrometer, the DSD can also be modelled using analytical functions. According to the ratio of the size of the drop to the wavelength inside the particle and to the shape of the drop, different electromagnetic techniques can be used to compute the extinction cross section σ_{ext} . In fact, if drops are small with respect to the wavelength, the Rayleigh scattering approach can be used; if they are of the same order of wavelength and spherical, the exact Mie solution can be applied; in the most general case, including oblate spheroids, approximate numerical methods have to be used.

As extensively shown in the literature [i.3], [i.13], the specific attenuation due to rain γ_R , obtained for different rain intensity values R (mm/h), can be fitted with good accuracy using the following power law equation:

$$\gamma_R = kR^\alpha$$

where k and α are coefficients that depend on the operational frequency f , the wave polarization (linear vertical for terrestrial links) and link elevation (zero for terrestrial links); when deriving the power law equation from theoretical analysis instead than from empirical fitting, it is found that k and α are also dependent on temperature and drop size distribution [i.22].

The specific attenuation due to rain γ_R is shown in Figure 4 as a function of frequency, for different rain rates, calculated according to Recommendation ITU-R P.838-3 [i.3]: while specific attenuation increases monotonically with R , reaching even values as high as 50 dB/km for 200 mm/h ($f \approx 115 \text{ GHz}$), γ_R increases with frequency up to 100 GHz, after which, depending on R , a stable or slightly decreasing trend emerges.

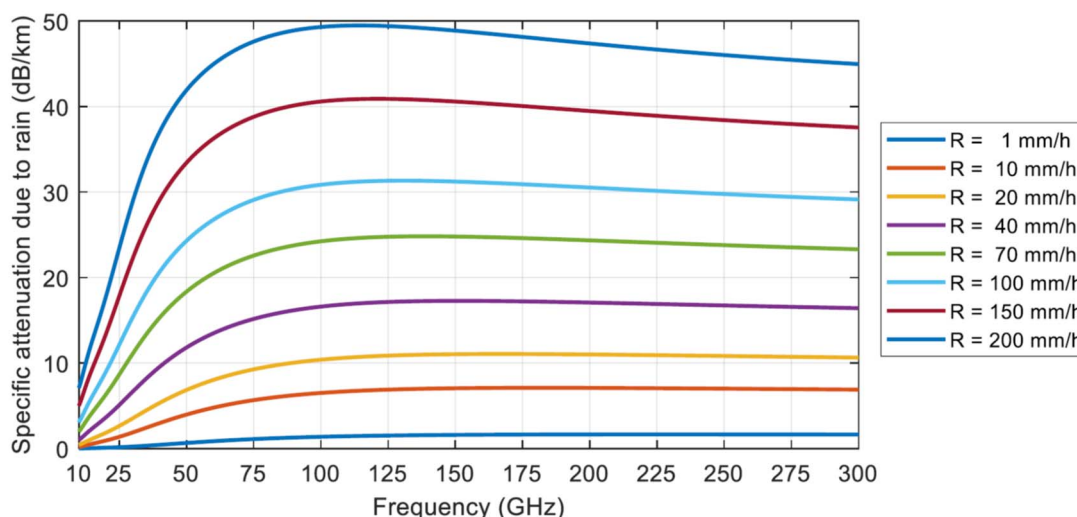


Figure 4: Specific attenuation due to rain as a function of frequency, for different rain rates, calculated according to Recommendation ITU-R P.838-3 [i.3]

It is important to consider that the attenuation curves shown in Figure 4 are actually just a reference to give a hint about how intense the fades caused by rain can be. Indeed, an accurate evaluation of the specific attenuation γ_R is to be done not simply as a function of rain rate R but more precisely as a function of DSD.

Several drop size distribution models have been developed depending on the different types of rain in the different rain zones; in particular Recommendation ITU-R P.838-3 [i.3] is based on the Laws-Parsons drop size distribution model [i.20] which describes typical continental temperate rainfall of stratiform kind.

As an example of the relevance of the DSD, the specific attenuation obtained in three locations in India [i.25] with different DSD as compared with the Recommendation ITU-R P.838-3 [i.3] model are shown in Figure 5, where some curves overestimate the ITU-R model whilst others underestimate it depending on location, frequency and rain rate.

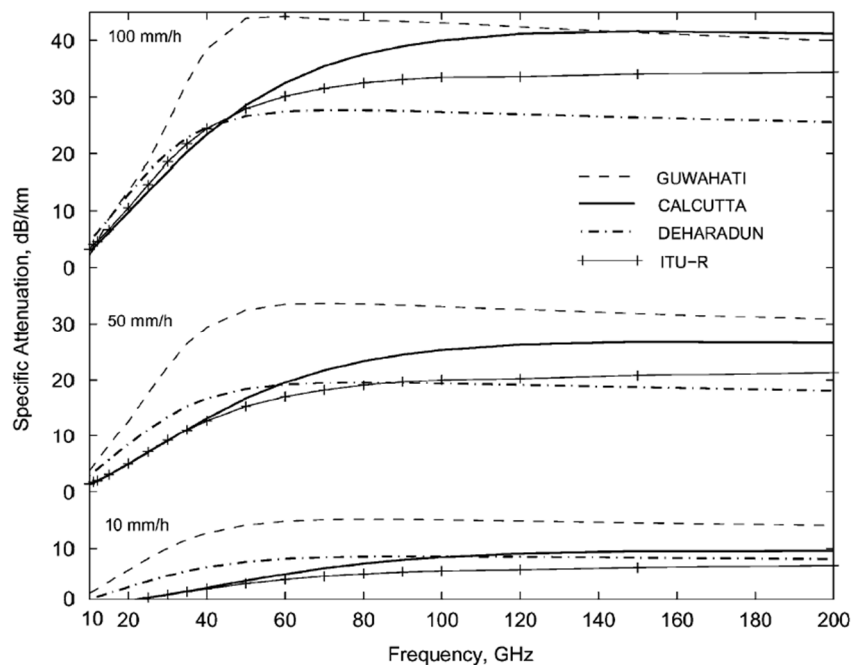


Figure 5: Specific attenuation variability with DSD, f and R in three locations in India [i.25]

From the physical point of view as long as the wavelength is much larger than the rain drop size, as it is in the cm-wave range, the Rayleigh scattering prevails and the rain attenuation is related to the total volume of water in the raindrops, that is to the rain rate, with the distribution of drop size being hardly relevant; instead when the wavelength becomes comparable with the drop size, as it is in the mm-wave range, Mie scattering becomes more relevant and the rain attenuation gets more sensible to the actual distribution of drop size. When the wavelength is much shorter than the drop size, well over the mmWave range, geometric optics scattering occurs.

A comparison among different models is shown in next clause on the base of experimental data.

5 Rain attenuation prediction: event-based analysis

5.0 Introductory concepts

This clause presents different methods that can be used to predict the time series of the rain attenuation starting from information on precipitation.

As noted in clause 4.1.3, there are two models that can be applied to predict the rain attenuation:

- A model based on a power law equation which is employed in Recommendation ITU-R P.838-3 [i.3], where the specific attenuation due to rain γ_R is function of rain rate R and frequency.
- A model considering the specific attenuation due to rain γ_R as a function of Drop Size Distribution.

In order to compare the accuracy of the two models a propagation experiment has been carried out since 2016 at Politecnico of Milan [i.5] considering a link with radios at E band (about 80 GHz) and D band (about 150 GHz) co-sited. The link length is about 325 m and measurement instruments are present on site such as a disdrometer, which allows to measure DSD, and a weather station, which allows to measure pressure P, temperature T and relative humidity RH.

The attenuation due to rain can be derived by measuring the received power at one link side and by evaluating the attenuation due to gases by means of Liebe MPM93 model (see clause 4.1.1) and from the measurement of P, T and RH. The attenuation due to rain as measured by the radio link can be compared to the one predicted by Recommendation ITU-R P.838-3 [i.3] and to the one predicted by disdrometric data for different rain events.

5.1 Wet antenna effect

When it is raining, a thin layer of water can be deposited over the surface of the antenna radome of the radio link, provoking an attenuation that is not related to propagation. The attenuation due to wet antenna extends in time after the end of the rain event, till the thin layer of water is dried. In order to perform the comparison of models with the measured rain attenuation, the wet antenna attenuation has to be properly evaluated and distinguished from rain attenuation along the propagation path.

This effect has been modelled in [i.14], where the attenuation grows with rain rate till a stationary value is reached according to a simple exponential law:

$$A_{wa} = a(1 - e^{-bA_T})$$

where A_T is the total attenuation obtained from the received power (depending on rain rate), a and b are coefficients depending on frequency and type of antenna radome and coating.

Other factors which affect the wet antenna attenuation are rainfall type, wind speed and direction.

In the propagation experiment at Politecnico of Milan [i.6], the wet antenna effect has been evaluated and filtered out from measured rain attenuation by leveraging on data collected by the disdrometer during stratiform rain events, where the rain rate can be assumed as constant over the link length. In Figure 6 the evaluated wet antenna attenuation on one link at E band is reported.

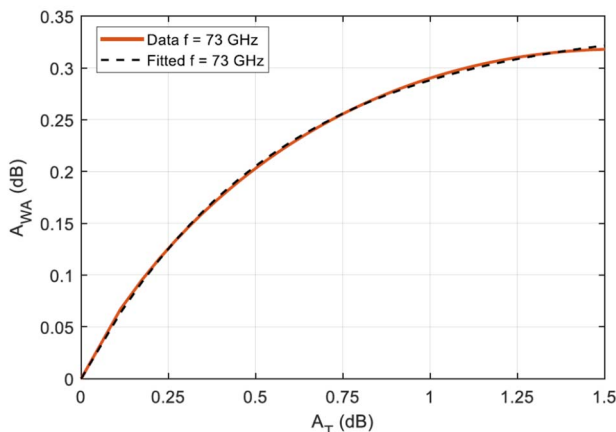


Figure 6: Estimated wet antenna attenuation as a function of total link attenuation got from disdrometer data (red line) and fitted by the power law coefficients at 73 GHz in Milan (Source: [i.6])

It is important to consider that the wet antenna attenuation in Figure 6 is obtained only during the rain event along the link (identified by means of the co-sited disdrometer) and the larger part of wet antenna attenuation occurring after the end of the rain event is not considered.

The wet antenna attenuation has been evaluated also by China Research Institute of radio wave propagation and Xidian University [i.21], by applying the exponential model to some radio links ranging in frequency between 37 and 137 GHz, whose dataset are contained in the ITU-R DBSG3, with the results shown in Figure 7.

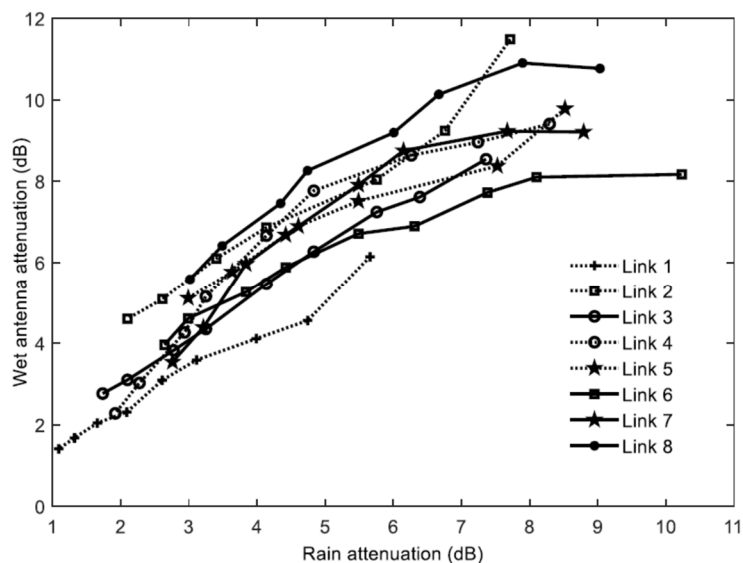


Figure 7: Wet antenna attenuation of some terrestrial links in the ITU-R DBSG3 dataset (each link is 0,5 km long) (Source: [i.21])

The wet antenna effect can be significantly reduced by using a suitable coverage and/or hydrophobic coating of the radome.

5.2 Comparison of models

A first sample of comparison among rain attenuation models at E band is given by the propagation experiment at Politecnico of Milan [i.5] and shown in Figure 8 considering:

- the data measured by the radio link as a reference;
- the data predicted by Recommendation ITU-R P.838-3 [i.3];
- the data predicted by the model based on DSD got by the disdrometer;

with respect to the measured rain rate reported in Figure 9.

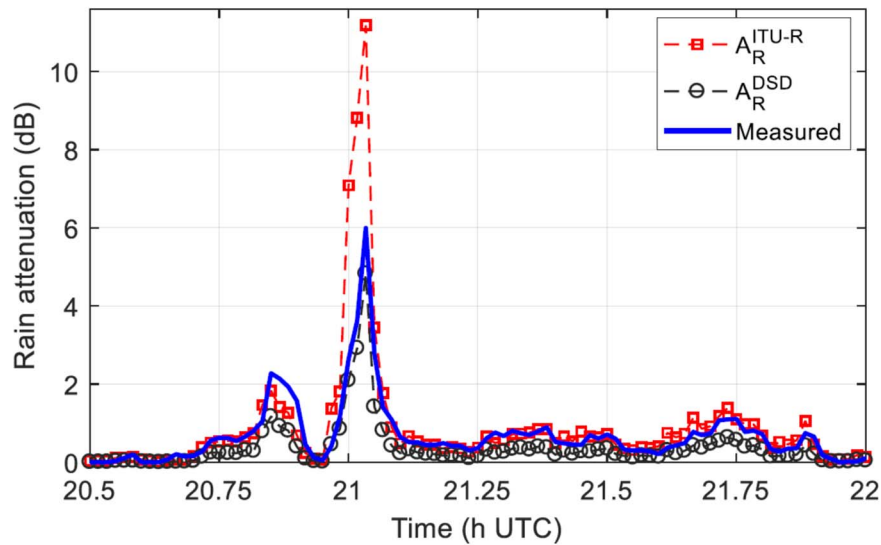


Figure 8: Rain attenuation on the E band link (73 GHz) in Milan: derived from the link (blue line), estimated by rain rate using Recommendation ITU-R P.838-3 (red line) and estimated by DSD data (black line) (Source: [i.5])

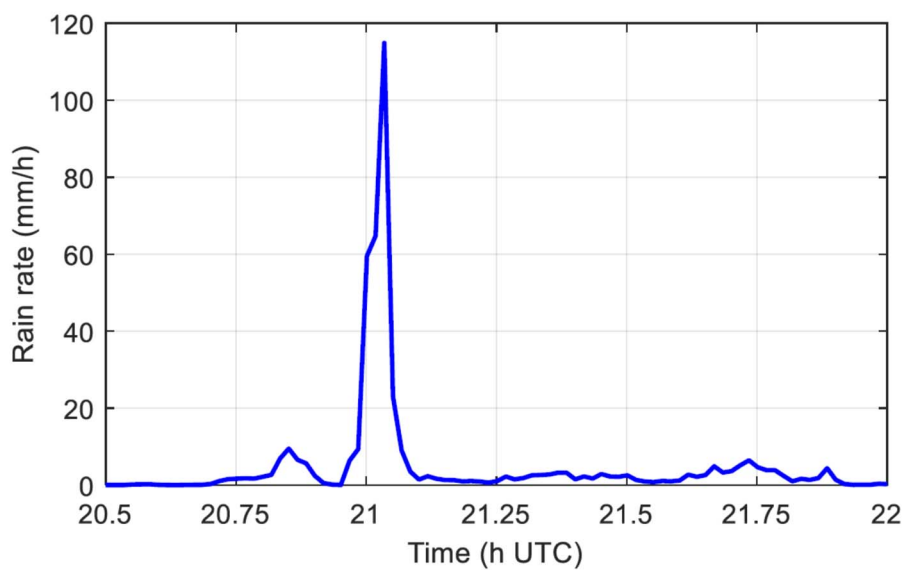


Figure 9: Measured rain rate (Source: [i.5])

As it can be seen the model based on DSD data gives a much better estimation of the rain attenuation than the model from Recommendation ITU-R P.838-3 [i.3]; this is due to the strong impact of DSD: with a very intense rain event (about 115 mm/h) the Recommendation ITU-R P.838-3 [i.3] model tends to overestimate the rain attenuation.

A second sample of comparison at D band is shown in Figure 10 with reference to the rain rate reported in Figure 11.

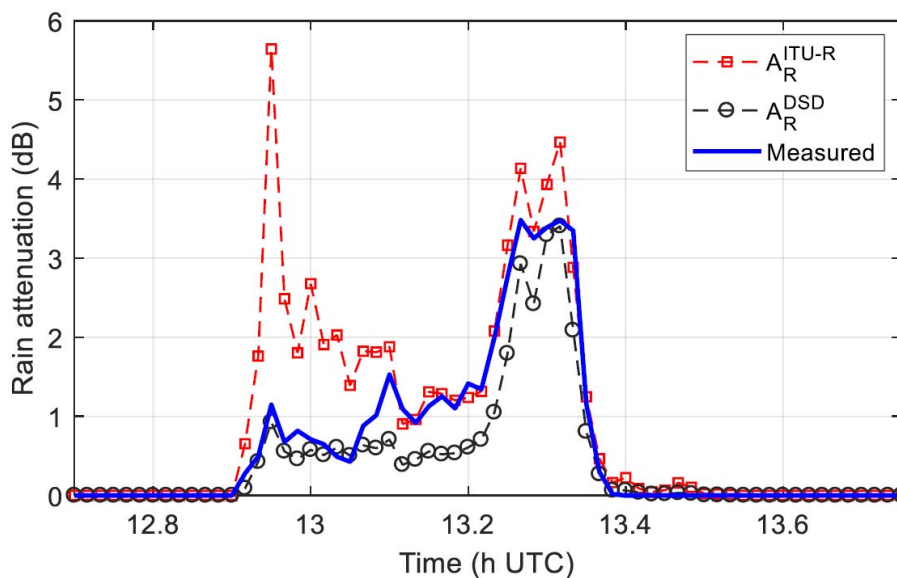


Figure 10: Rain attenuation on the D band link (148 GHz) in Milan: derived from the link (blue line), estimated by rain rate using Recommendation ITU-R P.838-3 [i.3] (red line) and estimated by DSD data (black line) (Source: [i.5])

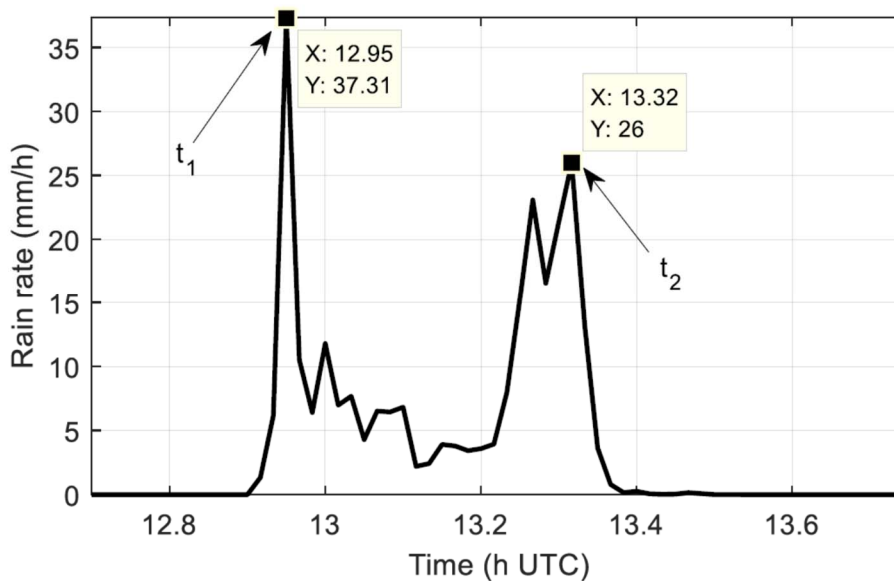


Figure 11: Measured rain rate (Source: [i.5])

Also in this case a significant overestimation of the rain attenuation is obtained by the Recommendation ITU-R P.838-3 [i.3] model, whilst the model based on DSD data is much more accurately following the measured curve.

It is interesting to investigate the different rain attenuation behaviours during the two different rain rate peaks; this comes out to be a consequence of the microphysics of the rain drops, as can be seen in Figure 12.

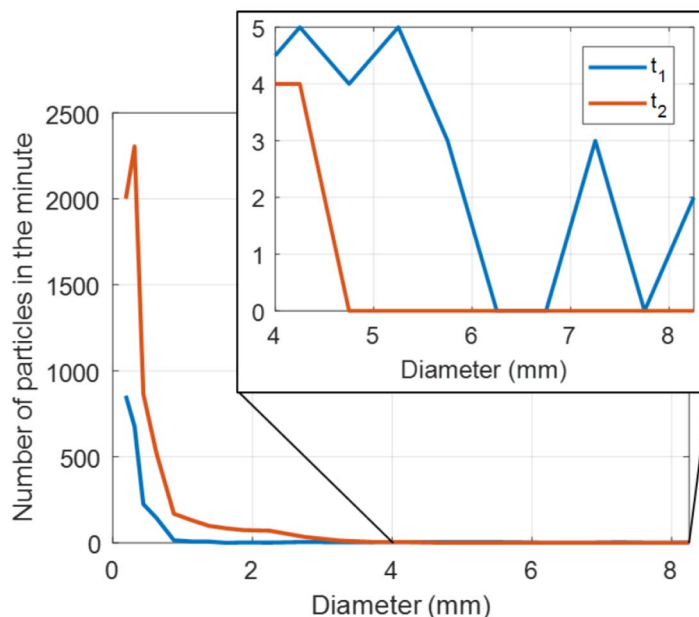


Figure 12: DSD relative to the two rain rate peaks labelled as t_1 and t_2 in Figure 11 [i.5]

While the DSD of t_2 contains much more small drops than that of t_1 , the key difference between the two spectra lies in the large rain drops measured in t_1 , but not in t_2 , i.e. those for which $D > 4$ mm. Though not many, such large drops have a dramatic impact in increasing the value of rain rate, while definitely quite a limited one on the rain attenuation.

This sample case definitely highlights the importance of using DSD data to achieve high accuracy in predicting rain attenuation. In particular at mm-wave, small (e.g. D around 0,5 mm) and large (e.g. D around 3 mm) drops have a different impact, which the information on the DSD allows to properly weigh in calculating specific attenuation due to rain.

It is to be considered that the DSD, being function of the type of rain event, is in general expected to be different in the different climatic areas of the Earth and in the different seasons. That is why a long term statistical approach is necessary in order to properly evaluate the effect of rain, as it is discussed in next clause.

6 Rain attenuation prediction: statistical analysis

6.0 Introductory concepts

The methods presented in the previous clause allow estimating the time series of the rain attenuation, but the main drawback of such approaches is obviously the need for the rain rate time series. Indeed, this kind of data is seldom available worldwide, even more with the necessary temporal resolution (at least 1 minute); on the other side, a statistical approach to link design can be achieved with simpler input data and it provides the atmospheric link margin to guarantee a given link availability.

This clause is devoted to investigating the accuracy of some statistical prediction models, specifically:

- the model adopted by Recommendation ITU-R P.530-18 [i.4], typically used as a reference for terrestrial link design;
- the Lin model [i.7], already showing a good prediction accuracy when used to estimate rain attenuation statistics at E band [i.6];
- the Abdulrahman model and the Da Silva Mello model [i.17];

- the model proposed by China research institutes [i.21], including the wet antenna effect;

the SC EXCELL model [i.18], which represents analytically rain spatial distribution as a set of exponentially decaying shaped rain cells.

It is worth remembering that the current model in Recommendation ITU-R P.530-18 [i.4] is recommended for operational frequencies up to 100 GHz.

6.1 Path reduction factor

Rain occurs in cells with the rain rate higher at the center of the cell and decreasing going to the edge of the cell, where the decrease rate is higher with convective events and lower with stratiform events.

As a consequence, in order to predict correctly the attenuation due to rain, the spatial distribution of the rain precipitation along the link length is to be considered. The attenuation due to rain can be expressed as:

$$A_R = \int_L \gamma_R(l) dl$$

In order to get the rain attenuation of the link the specific attenuation at each position along the link should have to be known, which is hardly possible. A practical alternative is to assume the specific attenuation constant along the link for an effective length L_{eff} , introducing a factor r which takes into account the spatial inhomogeneity of rain:

$$A_R = \gamma_R L_{\text{eff}} = \gamma_R L r$$

where L_{eff} is the effective length over which the rain rate can be considered homogeneous, L is the link length and r is the path reduction factor.

Different expressions of path reduction factor are given by different models; in particular in Recommendation ITU-R P.530-18 [i.4] it is expressed as:

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

where d is the link length, f is the frequency, R is the rain rate exceeded for 0.01% of the time, α is the parameter within γ_R .

Instead in the Lin model it is expressed as:

$$r = \frac{1}{1 + d / (\frac{2632}{R_p - 6.2})}$$

where R_p is the rain rate exceeded for $p\%$ of the time.

The different behaviour of path reduction factor with link length and rain rate can be clearly understood looking at Figure 13 (model in Recommendation ITU-R P.530-18 [i.4]) and Figure 14 (Lin model), where on the left the behaviour is described on a 5 km span whilst on the right there is the detail up to about 350 m link length [i.18].

In both cases the expected decrease of path reduction factor with rain rate is observed, since the higher is the rain rate, the more convective is the event, the more uneven is the spatial distribution of the rain rate along the path.

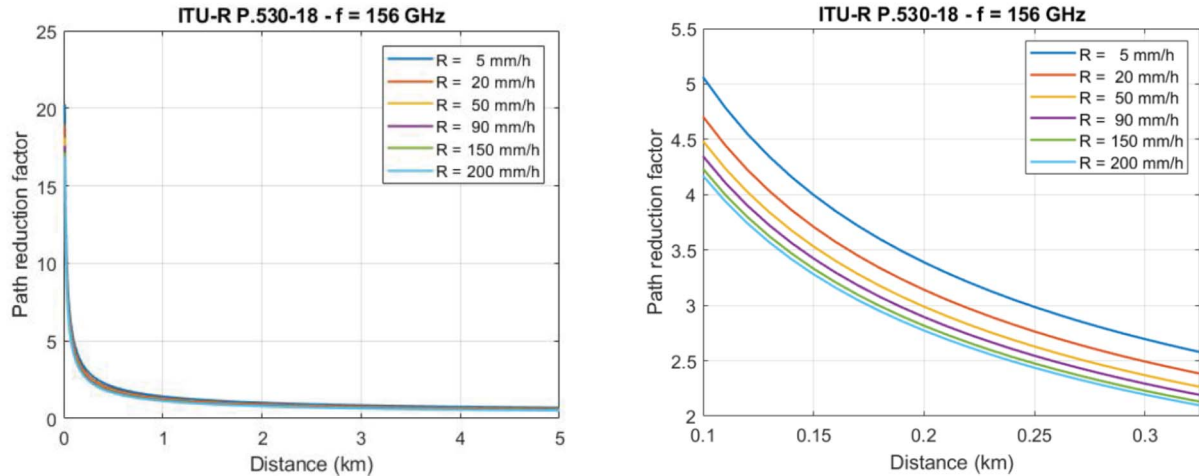


Figure 13: Path reduction factor as a function of link length according to the model in Recommendation ITU-R P.530-18 [i.4]

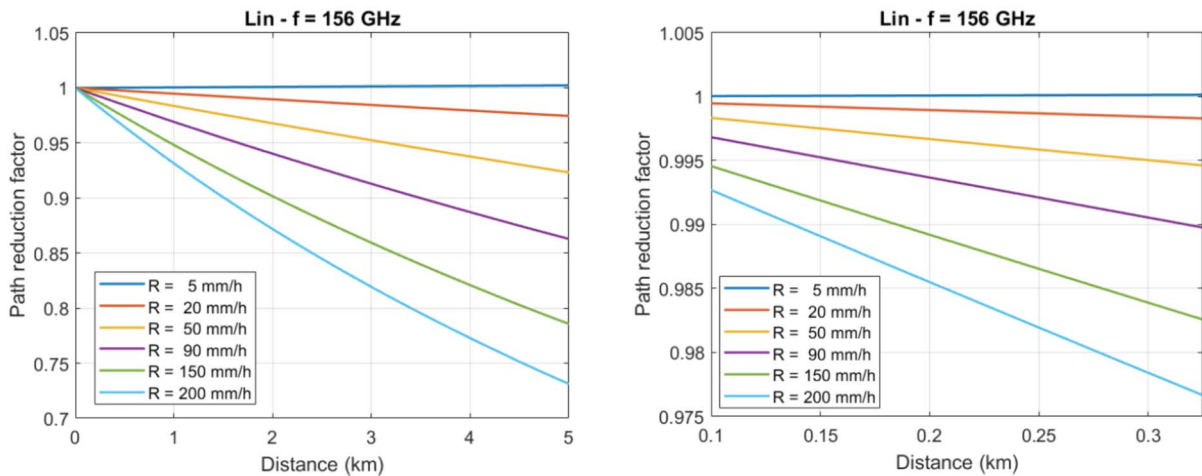


Figure 14: Path reduction factor as a function of link length calculated according to the Lin model [i.19]

The difference in the evaluation of the path reduction factor between the two models is particularly huge when considering short links (less than 1 km) where r grows exponentially well over 1 with decreasing link length in the ITU-R model, whilst it remains slightly less than 1 in the Lin model.

This discrepancy has been found also in other analysis considering alternative models, such as the Abdulrahman model and the Da Silva Mello model [i.17]. These models share with the Lin model a path reduction factor less than 1 for link length shorter than 1 km, as shown in Figure 15.

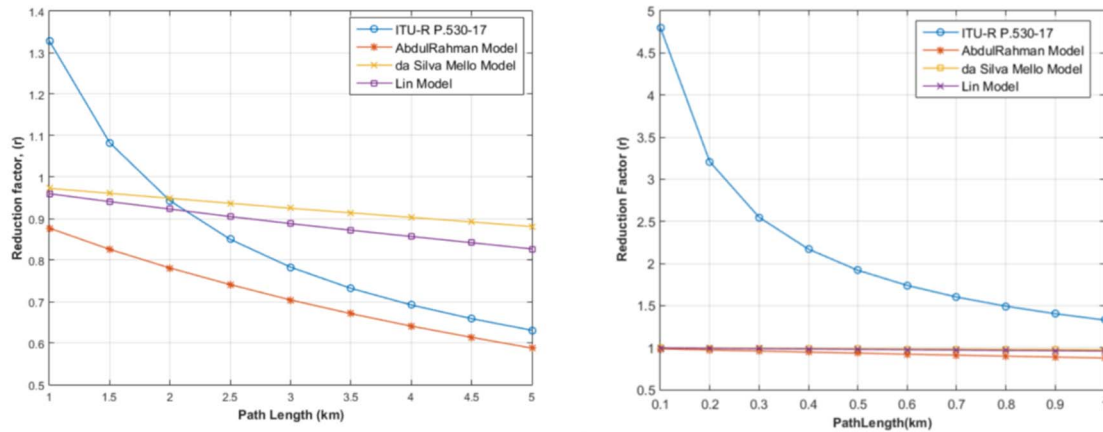


Figure 15: Path reduction factor as a function of link length calculated according to different prediction models [i.17]

A model proposed by China Research Institute of radio wave propagation and Xidian University [i.21], which includes both rain attenuation and wet antenna attenuation, indicates that the values of path reduction factor higher than 1 in short links (less than 1 km) reported by some measurement campaigns [i.24] could be indeed due to the wet antenna effect.

In fact by applying the proposed model to different rain attenuation datasets of the ITU-R SG3 data base (DBSG3) the resulting path reduction factor (here referred as rainfall rate adjustment factor) is always less than 1, according to the physical fact that the rainfall rate becomes more uniform as the path length and rainfall rate decrease.

The rainfall rate adjustment factors generated by the Chinese model, using as input the measured rain attenuation data for the terrestrial links in the ITU-R DBSG3 database, are displayed in Figures 16 and 17 in terms of link length and rainfall rate, respectively.

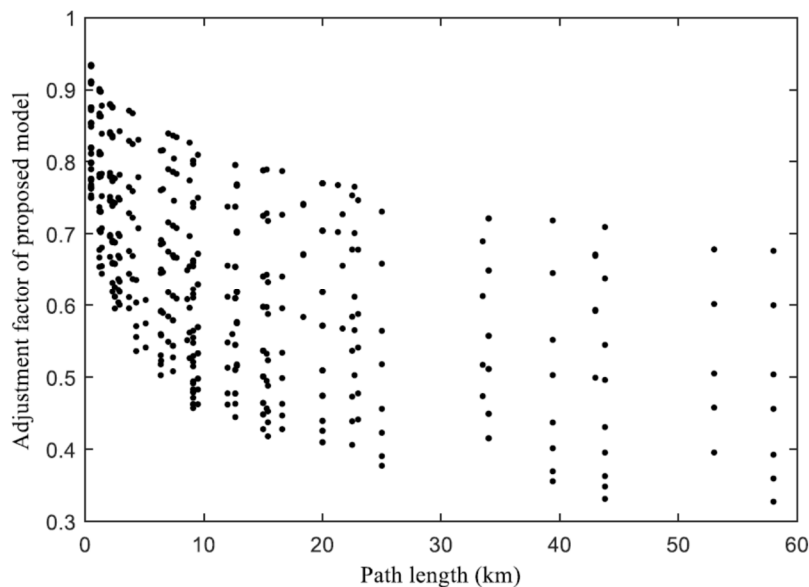


Figure 16: Rainfall rate adjustment factor as a function of link length according to Chinese prediction model [i.21]

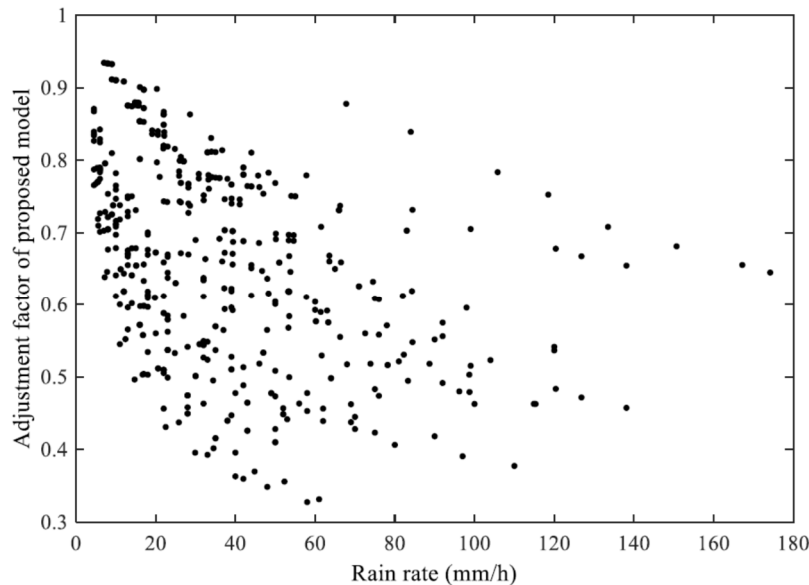


Figure 17: Rainfall rate adjustment factor as a function of rain rate according to Chinese prediction model [i.21]

The expression of the rainfall rate adjustment factor r_p is derived based on the following equation:

$$A_R = \gamma_{Ref} L = k(R_p r_p)^\alpha L$$

where k and α are the coefficients of the power law equation expressing the specific attenuation, R_p , is the rain rate exceeded for $p\%$ of the time and L the link length. In practice the correction factor is applied to the rain rate instead than to the link length, with a straightforward relation to the path reduction factor r :

$$r = (r_p)^\alpha$$

6.2 The SC EXCELL model

Recommendation ITU-R P.530-18 [i.4] as well as Lin, Abdulrahman and Da Silva Mello models are all derived by different regression techniques trying to fit real measured data.

Another approach to modelling is to start from a mathematical description of rain to get a proper statistical prediction. One example of this way of proceeding is the SC EXCELL model [i.18], which describes rain as a set of rain cells with an exponential decay of the rain rate and rotational symmetry, where the probability of occurrence of each rain cell is uniquely identified by its peak rain rate R_M (mm/h) and its effective dimension ρ_0 (km):

$$R(\rho) = R_M e^{-\frac{\rho}{\rho_0}}$$

The peak value and the steepness of decay of a rain cell are dependent on the type of rainfall: on one side convective rain is expected to have high peak and fast decay, on the other side stratiform rain would show low peak and slow decay. It is important to note that this exponential behaviour has been inferred by proper analysis of rain maps derived from meteorological radars, which constitutes the physical basis of the mathematical model.

The description of the rain environment is completed by introducing the probability of occurrence N of the rain cells, which is a function of the two parameters univocally defining each cell (R_M and ρ_0) as well as of the local rainfall Complementary Cumulative Distribution Function (CCDF) of rain rate.

Thanks to its physical soundness in representing the rainfall environment, the SC EXCELL method does not require any calibration procedure on existing data, as is typically the case of most of the semi-empirical models considered.

The performance of the SC EXCELL prediction model has been evaluated [i.18] against the global DBSG3 database of ITU-R, which includes concurrent rain rate and rain attenuation statistics collected in several sites worldwide, showing an improvement in the prediction accuracy with respect to the method currently recommended by Recommendation ITU-R P.530-18 [i.4].

6.3 Comparison of models

In order to compare the different available models for the prediction of rain attenuation, a statistical analysis based on the collection of long term rain data is valuable.

In the framework of the propagation experiment at Politecnico of Milan [i.6] full year data have been collected for the links at E and D band.

The Complementary Cumulative Distribution Function (CCDF) of the rain attenuation measured and estimated at 73 GHz and 83 GHz over 1 year observation period (from February 2017 to January 2018) are shown respectively in Figure 18 and Figure 19, whilst the CCDF of the rain rate measured by the disdrometer over the same period is shown in Figure 20.

In particular the curves compared in the figures describe:

- the model provided by Recommendation ITU-R P.530-18 [i.4] considered with rain rate exceeded for 0,001 % of the time both measured locally ($R_{0,001\%} = 41,9$ mm/h) and derived by Recommendation ITU-R P.837-7 [i.26] and Recommendation ITU-R P.838-3 [i.3];
- the SC EXCELL model;
- the Lin model;
- the data measured by the disdrometer.

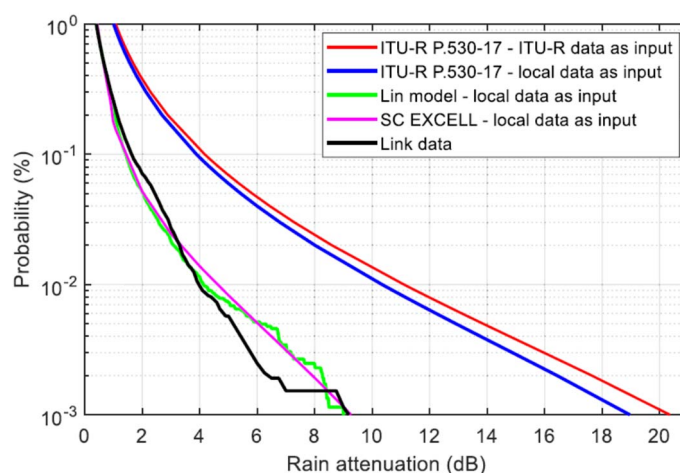


Figure 18: Comparison between the rain attenuation CCDF measured using the link and estimated by prediction models; $f = 73$ GHz, Milan [i.6]

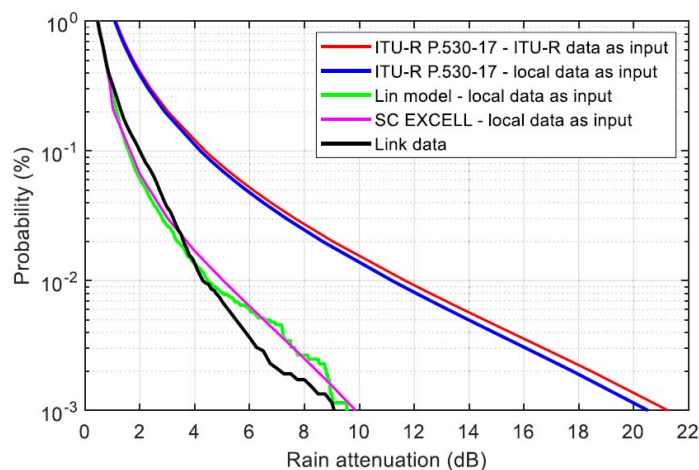


Figure 19: Comparison between the rain attenuation CCDF measured using the link and estimated by prediction models; $f = 83$ GHz, Milan [i.6]

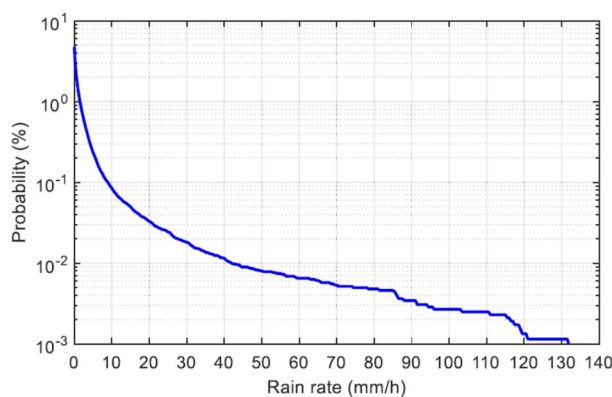


Figure 20: CCDF of the rain rate as measured by the disdrometer in Milan in the period February 2017 - January 2018 [i.6]

As is clear from Figure 18 and Figure 19, in comparison with the measured data both the SC EXCELL and Lin models provide accurate predictions, whilst the Recommendation ITU-R P.530-18 [i.4] model largely overestimates the measured data. This is likely due to the very high values of the path reduction factor r , which, for the above tests, ranges between 2,34 ($f = 83$ GHz) and 2,5 ($f = 73$ GHz).

It is worth noticing that the increased accuracy of both SC EXCELL and the Lin model is also partially due to the fact that they receive as input the full rain rate CCDF, while, on the contrary, the ITU-R model makes use only of $R_{0,01}$ %.

A similar behaviour has been found when considering two links both operating at 156 GHz [i.19]:

- one in Milan within the same propagation experiment considered above, with data collected between 01/02/2018 and 31/01/2020;
- one in Athens, over a 100 m distance, with data collected between 01/10/2019 and 31/05/2021.

In this case a modified version of the Recommendation ITU-R P.530-18 [i.4] a model has been considered as well, where the path reduction factor is limited to 1; with this modification the model fits very well to the measured data, as can be seen in Figure 21 and Figure 22.

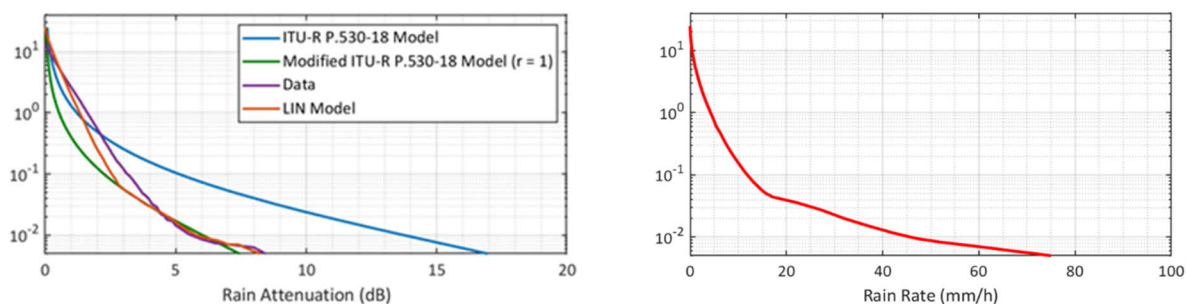


Figure 21: Comparison between the rain attenuation CCDF measured using the link and estimated by prediction models, $f = 156$ GHz; CCDF of rain rate (link in Milan, 325 m) [i.19]

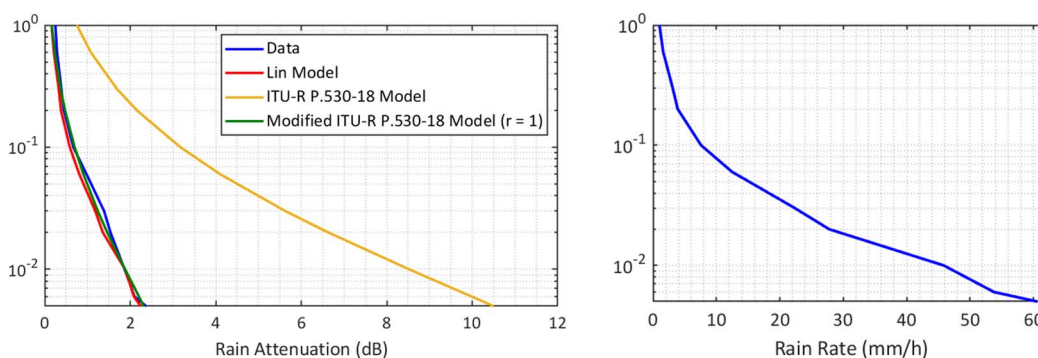


Figure 22: Comparison between the rain attenuation CCDF measured using the link and estimated by prediction models, $f = 156$ GHz; CCDF of rain rate (link in Athens, 100 m) [i.19]

Considering that Athens and Milan are subject to different meteorological conditions and that the two links have different path lengths, the results shown in this analysis give a significant indication on the need to adopt a physically sound value for the path reduction factor in very short links, considering a value close to 1 when the rain rate can definitely be considered constant along the path.

7 Field trial measurements

This clause provides some samples of measurements done in field trials in order to give an indication of the behavior of mm-wave radio links with respect to propagation impairments.

As it was described in clause 5.1, the effect of rain deposition over the antenna radome is a cause of attenuation in the propagation of radio waves.

A field trial has been conducted in Sweden from December 2021 to June 2022 on a 200 m E-band hop in order to evaluate the possibility to counteract this effect by means of a water-repellent radome coating [i.23]: the hop has been equipped with two parallel links, one with a traditional radome and the second with the protective coating. Link length is short so to minimize the attenuation effect due to rain along the link, highlighting the wet-antenna effect.

Figure 23 shows the fading statistics over the two months period, with a significant improvement on all fades, large and small. For example, if considering the 0,01 % worst fades (corresponding to the 99,99 % percentile), it can be seen that the link with water-repellent coating has fades that are 6 dB less than those of the link without special coating.

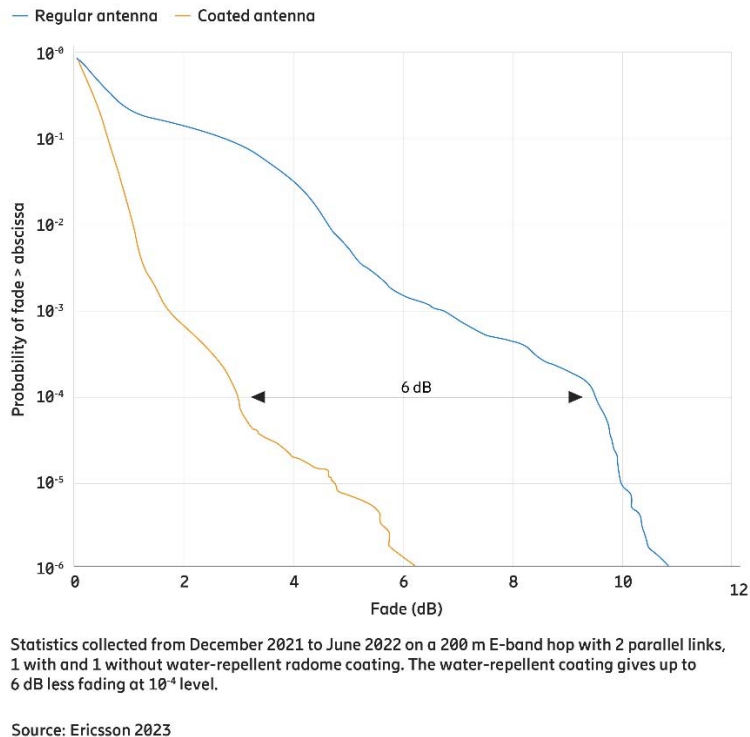


Figure 23: Statistics collected from December 2021 to June 2022 on a 200 m E-band hop with two parallel links, one with and the other without water-repellent radome coating [i.23]

In the same field trial, the behavior with respect to snow and ice has been analysed as well. Snow affects microwave links differently to water, as can be seen in Figure 24: when snow is dry, the impact is limited, but wet snow introduces much higher losses. In case snow melts, the link experiences increasing degradation until suddenly it slides off the antenna and the received power is restored to its nominal level, but if instead snow freeze again ice can form on the radome provoking attenuation with the possible need of manual removal of the ice from the antenna.

The antenna with water repellent coating has remained unaffected.

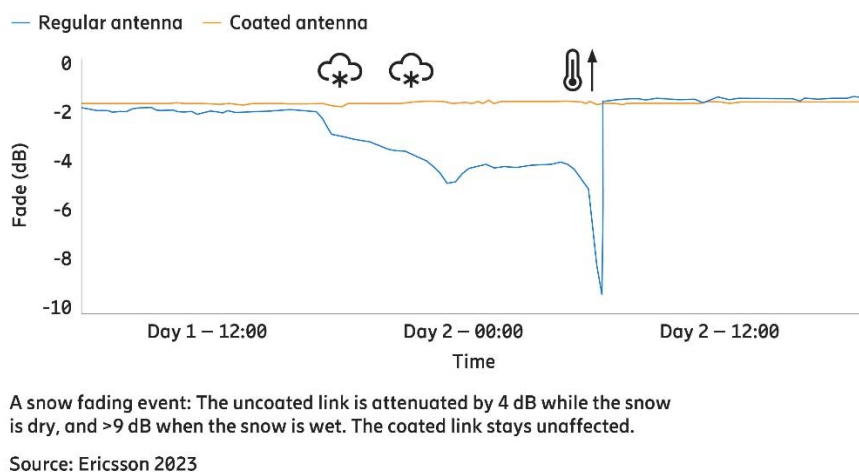


Figure 24: A snow fading event: The uncoated link is attenuated by 4 dB while the snow is dry, and > 9 dB when the snow is wet - The coated link stays unaffected (Source: [i.23])

A similar behavior has been noted on the same hop by employing two parallel D-band links, one with traditional radome and the other with a water protecting coating.

8 Implications to radio link budget evaluation

A good model of the attenuation due to rain is very important in order to define the fade margin of a radio link with sufficient accuracy. When considering link budget at mm-wave, technological limitations on both transmitter maximum power and receiver sensitivity make the optimization of rain fade margin even more important. Based on the results discussed in clause 5, the evaluation of specific attenuation due to rain in the mmWave range has to consider not only the rain rate but also the microphysics of rain, in particular the DSD, which is highly dependent on the type of rain in a particular rain zone and season. Recommendation ITU-R P.838-3 [i.3], being based on a specific DSD model, should be extended to consider other DSD models as applicable to the different rain types and zones.

As shown in clause 6, the currently adopted model within Recommendation ITU-R P.530-18 [i.4] tends to overestimate the rain attenuation in particular when considering link lengths shorter than 1 km, due to a not physically sound consideration of the path reduction factor. In fact when rain rate can be considered constant along the path, the path reduction factor should be reasonably slightly less than or equal to 1. This physical consideration is corroborated by long term measurements performed at both E and D band in Milan and Athens, but also by several other similar studies done in other parts of the world.

A proper adaptation of the model in Recommendation ITU-R P.530-18 [i.4] limiting the path reduction factor to 1 could be a good way forward to have a more physically based accurate prediction model usable for radio link budget evaluation with short links.

Separated consideration of the wet antenna effect is important as well, since it is a different attenuation mechanism from the strictly propagation related ones.

As a final consideration, the range of applicability of a proper terrestrial rain attenuation prediction model for mmWave systems (30 - 300 GHz) should not be limited to 100 GHz, as it is currently the case in Recommendation ITU-R P.530-18 [i.4], since the same physical attenuation mechanisms are active in this frequency range.

9 Conclusion

According to the analysis taken in the previous clauses, when evaluating attenuation due to rain in the mmWave range (30 - 300 GHz) where the wavelength is comparable to the rain drop size, there are several aspects to be considered:

- specific attenuation due to rain γ_R (dB/km), which is dependent not only on frequency and rain rate but also on the particular Drop Size Distribution (DSD);
- total attenuation due to rain along the radio link (dB), which is dependent on the spatial variation of the specific attenuation along the link;
- attenuation due to rain but not related to the propagation path (dB), such as the wet antenna effect.

As for the specific attenuation, several models of DSD have been developed based on both experimental rain data and analytical models of rain attenuation mechanisms. All the analyses converge on the fact that the DSD model is highly dependent on the type of rain in the specific rain zone and in the specific season.

Recommendation ITU-R P.838-3 [i.3] is based on the Laws-Parsons drop size distribution model [i.20] which describes typical continental temperate rainfall of stratiform kind. When considering a convective type of rain, typical of tropical regions, a different modelling of DSD is needed and different results would be obtained.

As for the total link attenuation, several models of the path reduction factor have been developed in order to take into account the spatial inhomogeneity of rain along the link. All models describe a path reduction factor which decreases below 1 with increasing link length, where the link length is much larger than the length over which the rain rate can be considered homogeneous. Instead when dealing with short links, below about 1 km, where rain rate can be considered constant along the path, the path reduction factor should be reasonably slightly less than or equal to 1.

Recommendation ITU-R P.530-18 [i.4] is based on a model which gives a path reduction factor increasing well over 1 with a decreasing link length, which seems to be not physically sound and gives as a consequence an overestimation of the attenuation due to rain along the link. A proper adaptation of the model limiting the path reduction factor to 1 could be a good way forward to have a more accurate prediction model for short links.

The wet antenna attenuation, due to the thin water film deposited by rain over the antenna of the radio equipment, is a cause of attenuation that should be separated from the propagation loss due to rain along the link. This effect could be the cause of some measurements apparently giving a path reduction factor much higher than unity with short links.

Finally it is important noting that there is no physical reason why the range of applicability of a terrestrial rain attenuation prediction model for mmWave systems should be limited to 100 GHz, as it is currently the case in Recommendation ITU-R P.530-18 [i.4]; as a matter of fact in the mmWave frequency range (30 - 300 GHz) the main attenuation mechanisms are absorption and Mie scattering and only when going towards higher frequencies, well over the mmWave range, the geometric optics scattering model becomes valid.

History

Document history		
V1.1.1	May 2025	Publication