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Radio Wave Propagation Conditions for Terrestrial Radiocommunications in the EHF Band

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Designing an effective radiocommunication system which operates at EHF band is not an easy task. To achieve this goal it is important to take the meteorological effects into account. It is noteworthy that a combined impact of many weather factors should be considered when transmission frequency exceeds 10 GHz. The understanding of these mechanisms as well as their mitigation is a key to design and build efficient wireless communication systems operating at EHF. Therefore, in this study an influence of different weather conditions on effectiveness of the transmission is discussed. In addition, some possible solutions of reducing these meteorological effects are mentioned. Finally, the simulation results which confirm the usefulness of the EHF band are presented. It is important to note here that the main concern for this study is the fixed and mobile short-range terrestrial radiocommunication and all considerations included in this article are focused mainly on this part of the wireless communication.

Keywords: EHF band, radio wave propagation, attenuation, link availability, millimetre wave communication systems

1. INTRODUCTION

The utilization of extremely high frequencies is a very promising option in modern radiocommunications whose major merit is the possibility of implementing very wide channels and reaching high data rates with relatively simple modulation schemes. On the other hand, shifting the transmission into the band of 30 – 300 GHz is hardly a straightforward task and requires a substantially different approach comparing to the situation when lower frequencies are being used. Another obstacle is a fact that propagation in the EHF band has not been fully researched yet and in some areas further work is still necessary. Nevertheless, the available analyses enable to indicate several most important factors that influence this kind of propagation, which also constitute the basis for designing radiolinks operating in the EHF Band. Among those factors that adversely affect the discussed propagation are: non-line-of-sight (NLOS) propagation and lack of the first Fresnel Zone clearance, diffraction due to uneven terrain, frequency selective fading due to multipath and attenuation and scattering due to vegetation.

It is easy to realize that all the above aspects are relevant to the transmission in lower frequency bands as well as in very high; when analyzing the EHF band transmission, the two most important factors are those that are virtually negligible at low frequencies, namely attenuation due to atmospheric gases and attenuation and depolarization due to precipitation (most notably rain). The first one should be treated as a constant, inevitable factor, depending on a given climatic zone and system parameters. Despite that, the current research show that the communication is realizable due to several attenuation windows that can be identified throughout the EHF Band, which is a similar situation to the optical transmission through fibers. The latter factor is variable and its negative effects are diminished by the assumed built-in link margin, which influences link availability. Rain and other kind of precipitations generally increase link attenuation, which results in the fact the radio link budget might not be balanced. To prevent from this situation, every real link is designed with a particular link margin which should eliminate a negative influence of the precipitation and determine the percentage of time in which radiolink is available. For practical reasons, existing links are not designed with the assumption of full availability (100 percent of time), because the required link margin would have to be too large.

Generally, due to increasing demand of broadband wireless communication services, in addition to the frequency congestion and management problems at lower frequency bands, design engineers have directed their attention towards the use of the EHF band for communication. This is caused by the recent demand for multimedia communication and high data rate capabilities.

2. MAJOR SOURCES OF THE RADIO WAVES DEGRADATION IN THE EHF BAND

Radio wave propagation negative influences at EHF bands include rain attenuation, rain and ice depolarization, gaseous absorption, cloud attenuation, melting layer attenuation, troposphere scintillation, and antenna wetting. These effects are related to the troposphere and weather conditions. Rain attenuation, gaseous absorption, cloud attenuation and melting layer attenuation are absorptive effects producing both signal attenuation and increase in antenna thermal noise. Troposphere scintillation is not absorptive but can produce attenuation as well as enhancement.

Terrestrial millimetre wave communication systems are mainly exploited in clear line-of-sight (LOS) environments to avoid high penetration losses due to buildings and foliage, multipath and diffraction effects as well. For these communication systems, in order to facilitate planning, installation and high-quality fiber-like system performance, it is vital to quantitatively and qualitatively characterize the terrestrial mm-wave propagation channel conditions.

In general, distortions of the radio waves at frequencies higher than 10 GHz are caused mainly by:

– Non-line-of-sight (NLOS) propagation and lack of the first Fresnel Zone clearance;
– Diffraction due to uneven terrain;
– Frequency selective fading due to multipath;
– Attenuation and scattering due to vegetation;
– Attenuation due to atmospheric gases;
– Attenuation and depolarization due to precipitation (rain, snow, fog, clouds etc).

These propagation effects are discussed below.

2.1. NLOS, DIFFRACTION AND FRESNEL ZONES

Diffraction allows radio signals to propagate around the curved surface of the Earth, beyond the horizon, and to propagate behind obstructions. The phenomenon of diffraction can be explained by Huygen's principle, which states that all points on a wavefront can be regarded as point sources and give rise to secondary wavelets. Combination of all the wavelets produces a new wavefront in the direction of propagation.

Fresnel Zones represent successive regions (figure 1) where secondary waves have a path length from the transmitter to receiver which is $n\lambda/2$ greater than the total path length of a line-of-sight path. Fresnel zones are elliptical in shape with the transmitting and receiving antenna at their foci. The successive Fresnel zones alternatively provide constructive and destructive interference to the total received signal. The radius of the nth Fresnel zone circle, denoted by r_n, can be expressed by:

$$r_n = \sqrt{\frac{n \cdot \lambda \cdot d_1 \cdot d_2}{d_1 + d_2}}, \tag{1}$$

where: r_n – nth Fresnel zone radius [m],
d_1 – distance to the transmitter [m],
d_2 – distance to the receiver [m],
λ – wavelength of the transmitted signal [m].

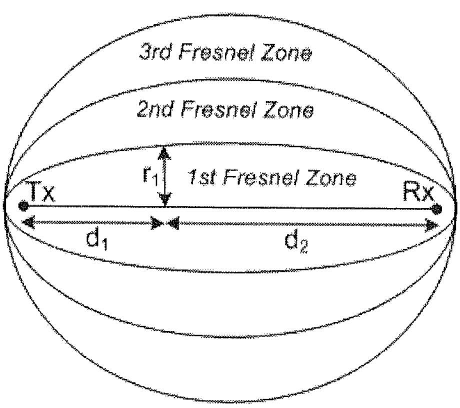

Fig. 1. The Fresnel Zones representation

Diffraction losses occur when secondary waves are blocked such that only a part of the energy is diffracted around the corner. The total received signal energy is given by the vector summation of energy contributions from all unobstructed Fresnel zones. The diffraction losses caused by obstacles can be calculated and taken into account as shown in [1]. In general, however, the attenuation can be approximated, as:

$$L_{diff} = \frac{-20 \cdot h}{r_1} + 10, \tag{2}$$

where h [m] denotes a difference between the highest terrain obstacle and the Line-Of-Sight propagation path (this value is negative when the obstacle stands out above the LOS line), r_1 [m] represents a radius length of the first Fresnel zone (see eq. 1) calculated in the place of the obstacle occurrence.

The given above expression shows that the most important, when considering radio wave propagation, is the first Fresnel zone in which most of the electromagnetic field energy is propagated.

It is important to note that, according to ITU-R recommendation [2], for millimetre radio systems the NLOS propagation is not valid due to large diffraction losses experienced when obstacles cause the propagation path to become NLOS. For these situations, multipath reflections and scattering will be the most likely signal propagation methods.

2.2. MULTIPATH PROPAGATION

In wireless telecommunications, multipath is the propagation phenomenon that results in radio signals reaching the receiving antenna by two or more paths. Causes of multipath include atmospheric ducting, ionospheric reflection and refraction, and reflection from terrestrial objects, such as mountains and buildings. It is important to note that many of these effects are highly unlikely in the case of the short-range terrestrial millimetre systems.

The effects of multipath include constructive and destructive interference, and phase shifting of the signal. This causes Rayleigh fading. The standard statistical model of it gives a distribution known as the Rayleigh distribution. Rayleigh fading with a strong line of sight content is said to have a Rician distribution.

In the case of millimetre radio systems, however, this effect is not as destructive as others described in this study. It is so because for EHF band mechanisms related with absorbing and scattering are much more dangerous than multipath propagation. Additionally, during millimetre transmission the LOS conditions are essential as well as narrow antennas beams are exploited in most cases, which leads to conclusion that multipath propagation is unlikely. In most cases this effect would only reduce a quality of a wireless connection but would not decrease its availability. It is, however, possible to take this effect into account because there are ITU-R recommendations [3, 9] which present this issue. Unfortunately, it is done only to a certain extent which is caused by the lack of the measurement data for frequencies higher than 15 GHz.

2.3. EFFECTS OF VEGETATION

When a radio wave reaches a rough surface, the reflected energy is spread in all directions due to scattering. At millimetre-wave frequencies, the dimensions of tree leaves and tree branches are large as compared to the wavelength. The tree leaves and branches also usually contain water and hence result in absorption and scattering of electromagnetic waves as they propagate through vegetation. Foliage can not only introduce attenuation and broadening of the beam but also depolarization of the electromagnetic wave. The transmission losses through vegetation are affected by various parameters such as the dielectric constant, density, physical size and shape. ITU-R provides an appropriate recommendation [4] and the effects of vegetation can be taken into account.

Attenuation in vegetation can be important in the case of terrestrial millimetre wave propagation. However, the wide range of conditions and types of foliage makes it difficult to develop a generalized prediction procedure. There is also a lack of suitable experimental data. According to ITU-R recommendation, however, some solutions are possible. It is important to note that they are valid only for frequencies lower than 60 GHz. There is no data available for higher bands.

In order to estimate the total field loss, the diffracted, ground reflected and through-vegetation scattering components are first calculated and then combined. The diffracted components consist of those bent over the top of the vegetation and those bent around the sides of the vegetation. These components and the ground reflected component are calculated using ITU-R Recommendations. The through or scattered component is calculated using a model based upon the theory of radiative energy transfer (RET). Detailed information can be found in the given above recommendation. The combined loss caused by all of these factors can be calculated as follows:

$$L_{veg} = -10\log_{10}\left\{10^{\left(\frac{-L_{sidea}}{10}\right)} + 10^{\left(\frac{-L_{sideb}}{10}\right)} + 10^{\left(\frac{-L_{top}}{10}\right)} + 10^{\left(\frac{-L_{ground}}{10}\right)} + 10^{\left(\frac{-L_{scat}}{10}\right)}\right\}, \tag{3}$$

where: L_{veg} – total loss due to vegetation,

L_{sidea} – loss due to diffraction around side a of vegetation,

L_{sideb} – loss due to diffraction around side b of vegetation,

L_{top} – loss due to diffraction over top of vegetation,

L_{ground} – loss due to ground reflected component,

L_{scat} – loss due to scattered component.

Example charts given by the recommendation are shown in the figure 2. Unfortunately, these results are only for the case of 40 GHz (5 GHz and 10 GHz – not the EHF band). For different frequencies, however, calculations can be done as well with exploiting equations given in the above recommendation.

Another issue, considering the vegetation influence on millimetre wave propagation, is depolarization effect. Measurements at 38 GHz suggest that depolarization through vegetation may well be large, i.e. the cross-polar signal may be of a similar order to the co-polar signal when both transmitted through the vegetation. However, for the larger vegetation depths, required for this to occur, the attenuation would be so high that both the co-polar and cross-polar components would be below the dynamic range of the receiver.

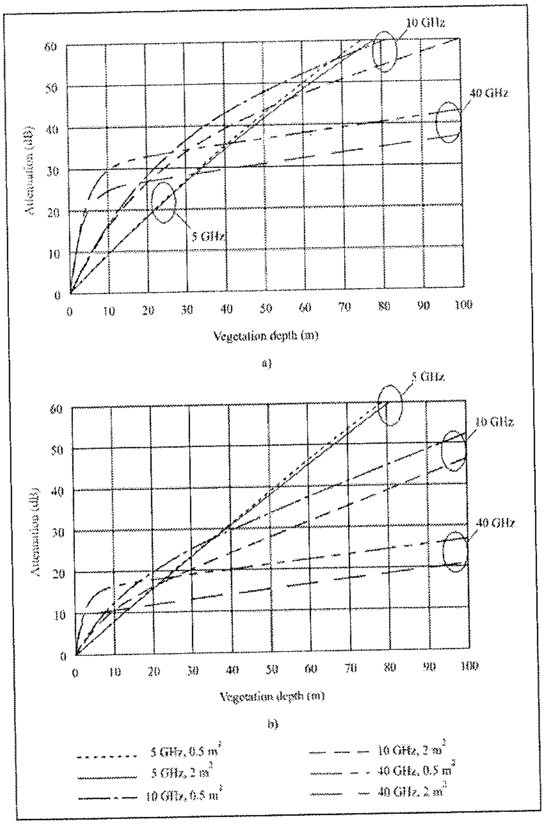

Fig. 2. Total loss due to vegetation for 0,5 m^2 and 2 m^2 illumination area, a) in leaf, b) out of leaf [4]

According to the recommendation it is also important to take into account some dynamic effects of the vegetation. It has been observed that where a link passes through foliage the received signal amplitude varies rapidly when the vegetation moves which is caused mainly by wind. Measurements at 38 GHz and 42 GHz have demonstrated that there is a strong correlation between the amplitude fluctuation rate and the wind speed.

When considering the effects of vegetation it is clear that the environment will not remain static. A receiver site may have one or more trees along the signal path that do not give a sufficient mean attenuation to take the received signal level below the system margin. However, it has been found that as the trees move, the signal level varies dynamically over a large range making the provision of a service unlikely. Several measurements of the attenuation levels during transmission through trees, as a function of time, have been made [4] and show an average reduction of the signal level of about 20 dB per tree. Considerable signal variability was found, with frequent drop-outs of up to 50 dB attenuation lasting for around 10 ms.

The ITU-R recommendation provides some data related to the dynamic effects of wind. Modelled time series and the standard deviations of signal amplitude for wind speeds, ranging from 0 to 20 m/s, are presented in figure 3 in comparison with measured data.

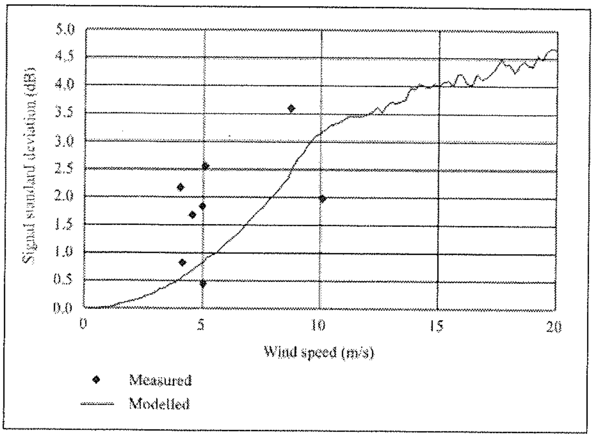

Fig. 3. Standard deviation of measured and modeled 40 GHz time series as a function of wind speed [4]

It should be noted that despite the fact that this type of model shows an inherent frequency dependence, the path length differences through trees are small and the fading across a typical 40 MHz bandwidth will appear flat. Rapid fading is due to the time variability of the medium.

Unfortunately, results and solutions given by the ITU-R recommendation are sufficient only in the particular cases but not in general. It is so due to the lack of the measured data for frequencies higher than 40 GHz. The situation is not hopeless, though, because it is often, when considering EHF systems in the terrestrial environment, that degradation of the radio waves is caused mainly by different, more destructive factors, and the influence of the vegetation is marginal. Therefore, in most cases a coarse estimation, shown in the ITU-R recommendation, can be sufficient.

2.4. GASEOUS ABSORPTION

Compared to other absorptive factors, gaseous absorption from oxygen and water in the atmosphere is small. However, gaseous absorption must be considered in link budget analysis since it is always present and its effect increases for higher frequencies, humidity and temperature. Specific attenuation due to gaseous influence varies as a function of frequency. ITU-R recommendation on how to predict absorption due to atmospheric gases is available [5].

In general, the clear cloudless atmosphere also absorbs radio signals, but below 30 GHz absorption losses are small except around the 22 GHz (resonance frequencies of water vapour) and they vary appreciably with water vapour content (figure 4).

Above 30 GHz (EHF band), however, the gaseous absorption issue becomes more destructive. Another resonance frequencies of water vapour can be observed at around 183 GHz. Additionally, at 60 and 119 GHz the resonance frequencies of oxygen are also present (figure 4). Between these marked thresholds in the EHF band atmosphere attenuation windows exist, as shown in table 1.

There are many atmospheric gases and pollutants that have absorption lines in the millimetre bands (such as SO_2, NO_2, O_2, H_2O, and N_2O), however, the absorption loss is present mainly due to water vapour and oxygen.

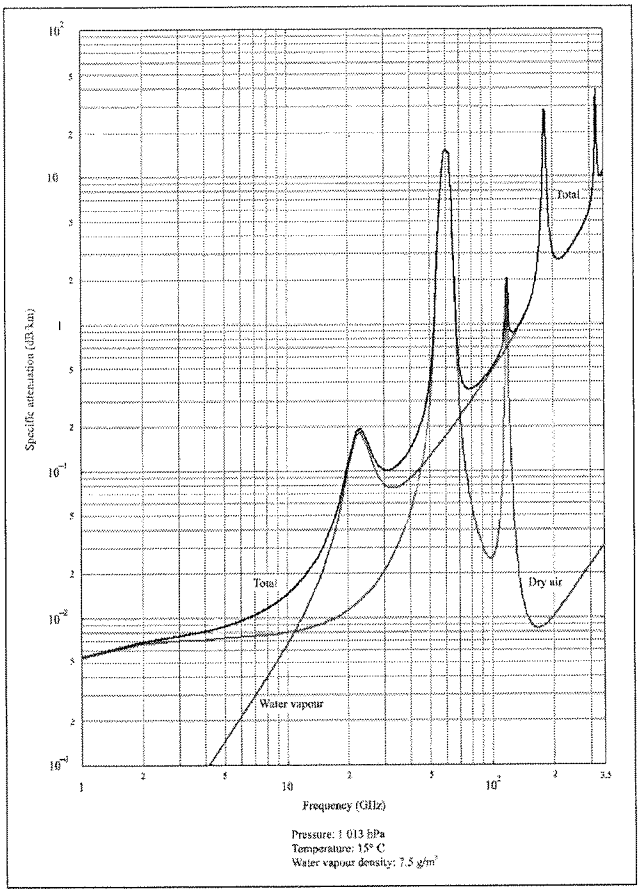

Fig. 4. Specific attenuation due to atmospheric gaseous absorption [5]

Table 1.

Attenuation windows of the atmosphere for the EHF band

Window ID	**Frequency range [GHz]**	**Clear air attenuation (Sea level, 15°C, RH* = 50%) [dB/km]**
W1	25 to 50	0,1 to 0,5
W2	70 to 115	0,5 to 2
W3	125 to 160	2 to 5
W4	200 to 250	5 to 10
*) RH – relative humidity [%]		

The ITU-R recommendation shows how to take the gaseous absorption effect into account. For a horizontal path or for slightly inclined paths close to the ground the attenuation, L_{abs} [dB], may be written as:

$$L_{abs} = \gamma \cdot d = (\gamma_o + \gamma_w) \cdot d\,, \tag{4}$$

where: d – path length [km],

γ_o – dry air attenuation [dB/km] (figure 4),

γ_w – water vapour attenuation [dB/km] (figure 4).

The mentioned above recommendation includes also some equations which allow to approximate the attenuation in the range of 1 to 350 GHz for both horizontal paths as well as inclined ones. This estimate is sufficient in the case of the terrestrial millimetre wave propagation.

It is important to note that the gaseous absorption effect is not only related with humidity (water vapour density) and frequency but also with a pressure and temperature of the air. The recommendation enables to exploit the knowledge of these factors and calculate the proper attenuation. The results in the case of standard values of these parameters and for the horizontal paths are presented in the figure 4. The *Total* attenuation depicted in this figure represents the one calculated according to the expression (4).

2.5. RAIN ATTENUATION

Rain attenuation is the most degrading effects of the atmosphere. Rain on a radio path causes fading, or "rain attenuation". Rain attenuation is a function of frequency, elevation angle, polarization angle, rain intensity, raindrop size distribution and raindrop temperature. This is the interference between raindrops and electromagnetic signals travelling through the atmosphere, which causes the radio waves distortions. When this phenomenon occurs, the transmission is weakened by absorption and scattering of the radio wave. Raindrops absorb and scatter radio wave energy, resulting in amplitude fluctuation and phase randomness in the received signal which degrades the reliability and performance of the communication link.

Any raindrop in the path of the signal, which is comparable to the half of the wavelength in diameter, will cause attenuation. Rain also depolarizes signals, converting energy from one polarization to another. The severity of rain attenuation and depolarization depends on how hard it is raining (described by the "rain rate" in millimetres of accumulation per hour), not on the total rain accumulation. Thus, areas subject to intense thunderstorms experience more severe propagation problems from rain than areas with a high average rainfall but few thunderstorms.

The ITU-R recommendation [6] provides a "semi-empirical" model for the rain attenuation calculations. The parameter, L_{rain} [dB], is obtained from the rain rate R [mm/h] using the power-law relationship:

$$L_{rain} = d_{eff} \cdot k \cdot R^{\alpha}\,. \tag{5}$$

Values for the coefficients k and α are determined as functions of frequency, f [GHz], in the range from 1 to 1 000 GHz. These coefficients can be rewritten either as k_H and α_H in the case of the horizontal polarization or as k_V and α_V in the case of the vertical polarization. The

ITU-R recommendation provides expressions which enable to calculate specific rain attenuation for different types of the polarization. Numerical values for the coefficients k and α at given frequencies as well as equations for calculations are given in the recommendation. The effective radio link length d_{eff}, which denotes a statistically calculated distance within rain, is a value which depends on the actual radio link length and the rainfall rate. Appropriate equations can be found in the recommendation.

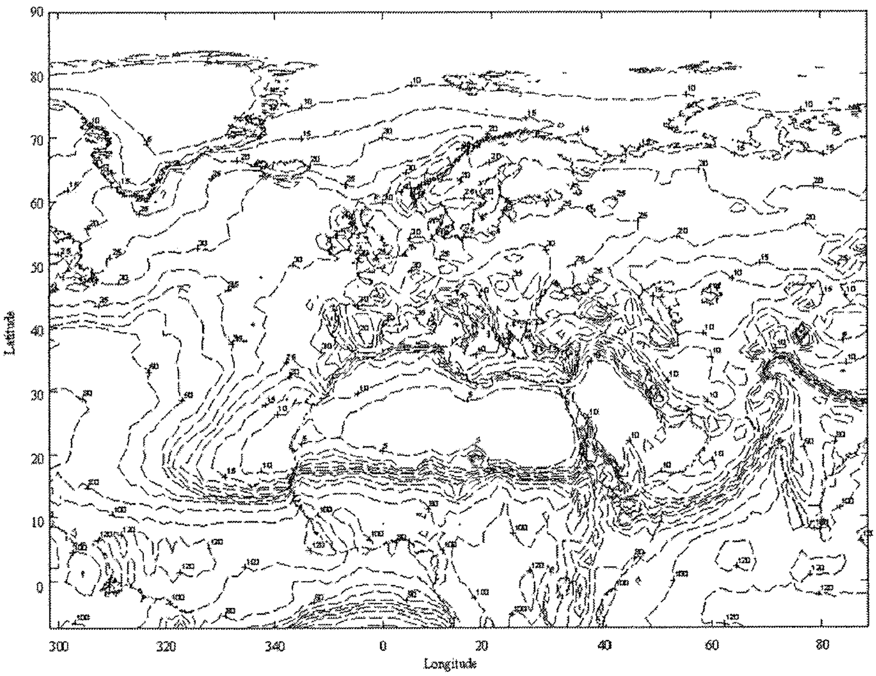

Fig. 5. Rain rate [mm/h] exceeded for 0,01% of the average year [7]

In order to compute the value of the specific rain attenuation, the rain rate must be obtained. It can be done with exploiting another ITU-R recommendation [7] which gives a solution for this issue. It presents how to derive the rainfall rate, exceeded for $p\%$ of the average year, for the desired latitude and longitude. Figure 5 presents the rainfall rates for latitudes and longitudes which are within the scope of this article. It is easy to note that in the case of Poland this value, exceeded for 0,01% of the average year, numbers about 25 mm/h. For Europe rainfall rate changes in the range of 15 (northern Europe) to 40 (southern Europe) mm/h.

2.6. CLOUD AND FOG ATTENUATION

Despite the fact that the effect of cloud attenuation is the main concern for the satellite communication it is described here because fog attenuation can still influence the terrestrial millimetre propagation to some degree. Radio waves are depolarized and attenuated by clouds and fog but this mechanism is difficult to predict or model because it is not described by anything analogous to rain rate that can be measured on the ground. The small size of cloud/fog particles relative to wavelength makes cloud attenuation a function of cloud/fog temperature and water content along the propagation path. The ITU-R provides the recommendation which shows a method for predicting cloud and fog attenuation [8].

The propagation loss due to clouds and fog may be a factor of importance especially for microwave systems well above 10 GHz. For clouds or fog consisting entirely of small droplets, generally less than 0.01 cm, the Rayleigh approximation is valid for frequencies below 200 GHz and it is possible to express the attenuation in terms of the total water content per unit volume. Thus the cloud/fog attenuation can be written as:

$$L_{fog} = K_l \cdot M \cdot d \,, \tag{6}$$

where: L_{fog} – attenuation [dB] caused by the cloud/fog,
K_l – specific attenuation coefficient [(dB/km)/(g/m^3)],
M – liquid water density in the cloud or fog [g/m^3],
d – propagation path length within the cloud/fog [m].

At frequencies of the order of 100 GHz and above, attenuation due to fog may be significant. The liquid water density in fog is typically about 0.05 g/m^3 for medium fog (visibility of the order of 300 m) and 0.5 g/m^3 for thick fog (visibility of the order of 50 m).

A mathematical model based on Rayleigh scattering, which uses a double-Debye model for the dielectric permittivity of water, can be used to calculate the value of the specific attenuation coefficient for frequencies up to 1000 GHz. This solution can be also found in the above mentioned recommendation. For the purpose of this study, however, figure 6, which shows the values of K_l at frequencies from 5 to 200 GHz and temperatures between –8° C and 20° C, is presented. It is important to note that for cloud attenuation, the curve corresponding to 0°C should be used.

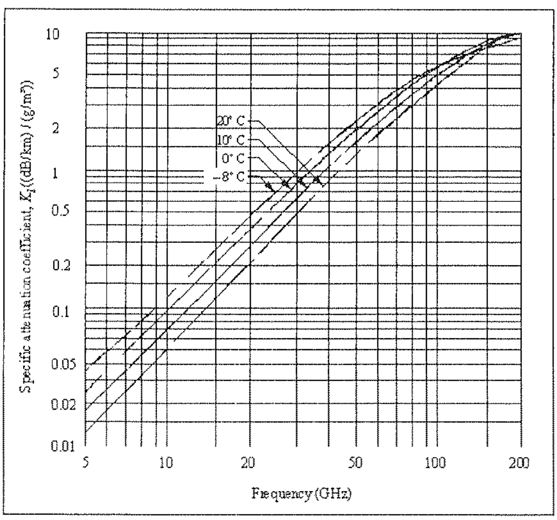

Fig. 6. Specific attenuation coefficient at various temperatures as a function of frequency [8]

2.7. COMBINED EFFECT OF PROPAGATION INFLUENCES

The factors described above are the individual propagation impairments that affect radio wave propagation. These effects have been studied individually for lower frequencies. Little data are available for frequencies above 30 GHz. However, with a few assumptions, which can be done due to specific of the millimetre and LOS propagation in the short-range terrestrial environment, a solution can be found. The propagation effects are related and can occur simultaneously. Hence, a model which describes the combined effect of propagation impairment is needed. There is a recommendation provided by ITU-R [9], which solves this issue.

In general, for frequencies above 10 GHz the total transmission loss for a radio system is given as:

$$L\,[dB] = 10 \cdot \log\left(\frac{4 \cdot \pi \cdot d}{\lambda}\right)^{\alpha} + L_{add}\,[dB]\,, \tag{7}$$

$$L_{add}\,[dB] = L_{diff} + L_{abs} + L_{rain} + L_{veg} + L_{fog}\,, \tag{8}$$

where: L_{add} – total excess attenuation [dB],

L – total attenuation [dB],

d – propagation path length [m],

λ – wavelength [m],

α – free space exponent.

The free space exponent in the case of the real free space equals 2. The ITU-R recommends, however, to use 2.2 as the value of this parameter in order to estimate the basic propagation loss for frequencies higher than 10 GHz when considering the short range propagation in urban areas. Due to the higher value of the free space exponent, an additional link margin is obtained, which can be useful in avoiding multipath propagation effects.

Other mechanisms such as antenna-wetting, depolarization due to rain or ice, dispersion, and troposphere scintillation influence also the propagation of radio waves. These effects, however, will not be discussed here because their importance as a destructive factors, comparing with the previously presented, is small.

3. COMPENSATION OF THE RADIO WAVES DISTORTIONS IN THE EHF BAND

To diminish distortions of the radio signals, system designers must incorporate compensation techniques in their designs. The main task of it is to mitigate the negative propagation influences caused by the effects described before. At higher frequencies compensation is an essential process for maintaining a proper quality of the service. It is important to add that most of the mechanisms inflecting the radio waves changes dynamically, therefore the compensation methods should be adaptive and even preventive.

The most common compensation techniques exploited in modern radiocommunication systems are as follows:

– Built-in Link Margin

In general, a link or system margin is allocated to a communication system in order to provide specific link availability. Since link margins are fixed, it is not possible to achieve an increase in capacity or availability using this technique.

– Diversity

At frequencies above 10 GHz, diversity techniques can be used e.g. to mitigate rain fade. Although diversity can be used to mitigate fading, the requirement of complex system design and separate antenna system (such as MIMO) may not justify the benefit.

– Uplink Power Control (UPC)

Uplink power control is a technique where the uplink EIRP is adjusted on an adaptive basis based on continuous measurement of the downlink carrier power. The amount of uplink power is estimated from the measured downlink fade.

– Adaptive Modulation and Coding

The AMC technique is used in wireless communications to match the modulation and coding parameters to the conditions of the radio link. Adaptive modulation systems require, however, some channel information at the transmitter in order to improve rate of transmission, and/or bit error rate.

4. THE PRACTICAL ASPECTS OF THE PROPAGATION CONDITIONS FOR FREQUENCIES HIGHER THAN 5 GHz

In this part of the article some simulation results are presented in order to show a propagation conditions for frequencies above 5 GHz in a more practical way. The given above frequency band can be divided into two different ranges. The former one is called *Super High Frequencies* (SHF) and is comprised of frequencies in the range of 3 to 30 GHz, which in general, are beyond the scope of this article but are presented for the comparison purposes. The latter one is called *Extremely High Frequencies* (EHF) and consists of frequencies above the SHF band up to 300 GHz.

The ITU-R recommendation [2], however, provides a considerably different division. Two separate propagation models, for the short range terrestrial radio systems at the standard SHF band, are available. In the case of frequencies up to 15 GHz a LOS propagation within street canyons can be considered. Proper equations for calculating the transmission loss are given in the recommendation. It is important to add that this model allows to estimate the attenuation in some range only (upper and lower bound of attenuation can be computed) and results are dependent on some inputs: distance, base station antenna height, mobile station antenna height and a level of traffic. The latter parameter is characterized by an effective height of the road (details can be found in the recommendation). Some standard values of these parameters were chosen and proper calculations were made. Results are presented in table 2. These results clearly show that the main destructive influence on propagation has the heavy road traffic which can cause additional attenuation of even 20 dB comparing with the light one. Additionally, a general rule can be created with reference to antennas height. Higher base station antennas do not reduce the propagation loss as clearly as higher mobile ones. It is important to add, at this point, that the presented here model do not take any meteorological phenomena into account in contrast to the next one.

Table 2.

Propagation attenuation for LOS situations within street canyons

ID	Conditions	Frequency [GHz]					
		5	7	8	11	13	15
		Attenuation [dB] (for the path length equals 1 km)					
1.	hm* = 1.8 m, hb** = 10 m, light traffic (hs*** = 0,5 m)	102-122	103-123	104-123	107-125	108-127	109-127
2.	hm = 1.8 m, hb = 20 m, light traffic (hs = 0,5 m)	100-119	103-121	104-122	107-124	108-125	109-126
3.	hm = 1.8 m, hb = 30 m, light traffic (hs = 0,5 m)	100-118	103-120	104-121	107-123	108-124	109-125
4.	hm = 1 m, hb = 20 m, light traffic (hs = 0,5 m)	104-124	104-124	104-124	107-126	109-127	110-128
5.	hm = 3 m, hb = 20 m, light traffic (hs = 0,5 m)	100-117	103-120	104-120	107-123	109-124	110-125
6.	heavy traffic (hs > hm)	117-137	120-140	121-141	124-144	125-145	127-147

*) hm – mobile terminal antenna height [m];
**) hb – base station antenna height [m];
***) hs – effective height of the road [m].

There is another propagation model provided by the mentioned before ITU-R recommendation. It can be exploited in the case of designing the short range terrestrial millimetre radio systems and also for those terrestrial solutions which operates in LOS conditions and at frequencies higher than 10 GHz. In general, it is described by the equation (7) and the whole model components were shown in the paragraph 2 of this article. Calculations results for those frequencies which are in the interest of this article and fit in the range of 10 GHz and more are presented in table 3.

The given table clearly shows that the atmospheric gases cause noticeable overall attenuation increment only at the band 52-55 GHz. The additional 4 dB may turn out to be an important component of the total transmission loss. It is noteworthy, however, that atmospheric gases are not the main concern when considering the given above frequencies.

As expected, rain appears to be the most destructive factor inflecting badly the transmission, even at the SHF band. Additionally, this kind of meteorological phenomenon is difficult to predict. Moreover, its influence on the radio wave propagation varies in the wide range which is a result of different rain rates that can occur. There is only one proper solution for this issue. Designer of the wireless SHF/EHF systems needs meeds to remember about this problem during their work. They should consider exploiting a proper link margin or different methods for mitigating the destructive influence of this factor.

The fog influence on the propagation is marginal at most frequencies. Its impact begins to be a problem only at the EHF band but even though the loss of 2 dB is much smaller than 11 dB in the case of the rain. Moreover, that level of attenuation is achievable only for a very thick fog.

The above results present as well the difference between standard free space transmission loss ($\alpha = 2$) and the one which utilizes coefficient $\alpha = 2.2$. More than 10 dB higher attenuation

Table 3.

Propagation attenuation for frequencies above 10 GHz and for terrestrial LOS propagation scenarios

Conditions	Frequency [GHz]																
	11	13	15	18	23	26	28	38	52-55 GHz band			71-76 GHz band			81-86 GHz band		
									52	53.5	55	71	73.5	76	81	83.5	86
	Attenuation [dB] (for the effective path length equals 1 km)																
Free space (α=2)	113.3	114.7	116	117.5	119.7	120.7	121.4	124	126.8	127	127.2	129.5	129.8	130.1	130.6	130.9	131.1
Free space (α=2.2)	124.6	126.2	127.6	129.3	131.6	132.8	133.5	136.4	139.4	139.7	140	142.4	142.7	142.9	143.7	144	144.2
Attenuation by atmospheric gases (ρ = 1013 hPa, T = -5°C, humidity = 5 g/m³)	0.016	0.02	0.026	0.048	0.138	0.1	0.087	0.112	0.739	1.65	4.578	0.424	0.34	0.308	0.294	0.298	0.305
Attenuation by atmospheric gases (ρ = 1013 hPa, T = 0°C, humidity = 5 g/m³)	0.015	0.019	0.025	0.046	0.137	0.098	0.084	0.107	0.709	1.601	4.455	0.404	0.324	0.293	0.28	0.283	0.29
Attenuation by atmospheric gases (ρ = 1013 hPa, T = 7.5°C, humidity = 7.5 g/m³)	0.018	0.023	0.032	0.063	0.196	0.137	0.114	0.133	0.725	1.595	4.345	0.478	0.409	0.387	0.39	0.401	0.416
Attenuation by atmospheric gases (ρ = 1013 hPa, T = 15°C, humidity = 12.5 g/m³)	0.024	0.033	0.048	0.098	0.315	0.219	0.18	0.198	0.808	1.663	4.32	0.667	0.616	0.611	0.647	0.675	0.708
Attenuation by atmospheric gases (ρ = 1013 hPa, T = 20°C, humidity = 12.5 g/m³)	0.023	0.032	0.046	0.096	0.314	0.214	0.175	0.189	0.778	1.62	4.213	0.636	0.586	0.581	0.614	0.64	0.67
Attenuation by rain (rain rate = 15 mm/h)	0.474	0.701	0.939	1.325	2.045	2.506	2.82	4.355	6.105	6.257	6.403	7.596	7.732	7.858	8.079	8.177	8.267
Attenuation by rain (rain rate = 25 mm/h)	0.882	1.267	1.666	2.303	3.445	4.153	4.624	6.832	9.181	9.377	9.563	11.04	11.2	11.35	11.61	11.72	11.82
Attenuation by rain (rain rate = 40 mm/h)	1.561	2.184	2.825	3.829	5.568	6.608	7.287	10.34	13.36	13.6	13.83	15.57	15.75	15.92	16.2	16.33	16.44
Attenuation by fog (T = 0°C, visibility = 300 m)	0.006	0.008	0.01	0.015	0.024	0.03	0.034	0.06	0.102	0.107	0.111	0.164	0.172	0.18	0.196	0.204	0.212
Attenuation by fog (T = 0°C, visibility = 50 m)	0.056	0.078	0.103	0.147	0.235	0.297	0.342	0.597	1.018	1.066	1.114	1.637	1.718	1.799	1.96	2.039	2.118
Attenuation by fog (T = 15°C, visibility = 300 m)	0.004	0.005	0.007	0.01	0.016	0.02	0.023	0.041	0.074	0.078	0.082	0.128	0.136	0.143	0.159	0.167	0.175
Attenuation by fog (T = 15°C, visibility = 50 m)	0.036	0.051	0.067	0.097	0.156	0.199	0.23	0.413	0.74	0.779	0.819	1.279	1.355	1.433	1.59	1.67	1.75

shows that additional factors like multipath propagation and diffraction have quite a huge impact on the transmission in this case of the wireless SHF/EHF terrestrial communication. Values of the free space loss ($\alpha = 2.2$), for frequencies lower than 15 GHz, can be easily compared with results given in the table 2. The conclusion – attenuations are comparable. Both models seem to be compliant with each other which can, to a certain degree, confirm their correctness.

5. CONCLUSION

The recent increase in demand for multimedia wireless communication services have caused designers to develop more and more highly efficient systems operating in the EHF band. The personal communications network, the mobile broadband systems, local multipoint distribution system, fixed radio links, next generation Internet, and wireless local loop telephony, are often systems meant to operate in the EHF band. The availability of tremendous amount of bandwidth, the potential for high frequency reuse, and the reduced size of transmitting and receiving antenna elements and electronic components, make EHF band uniquely suited for these services. Implementation of these systems requires, however, a detailed knowledge of all factors influencing the radio wave propagation. Hence, there is a need for estimating not only the individual propagation effects but also the combined propagation influence for systems operating at EHF band. In general, the transmitted signals can be distorted by the multipath propagation as well as the weather conditions. It is important, therefore, to consider not only the influence of the typical propagation phenomena such as: reflection, diffraction and scattering but also an interaction of the radio waves with meteorological phenomena and atmosphere itself as well.

6. REFERENCES

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