Kokkoniemi *et al. J Wireless Com Network* (2021) 2021:88
https://doi.org/10.1186/s13638-021-01974-8

EURASIP Journal on Wireless Communications and Networking

RESEARCH

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A line-of-sight channel model for the 100–450 gigahertz frequency band

Joonas Kokkoniemi*, Janne Lehtomäki and Markku Juntti

*Correspondence: joonas.kokkoniemi@oulu.fi
Centre for Wireless Communications (CWC), University of Oulu, P.O. Box 4500, 90014 Oulu, Finland

Abstract

This paper documents a simple parametric polynomial line-of-sight channel model for 100–450 GHz band. The band comprises two popular beyond fifth generation (B5G) frequency bands, namely, the D band (110–170 GHz) and the low-THz band (around 275–325 GHz). The main focus herein is to derive a simple, compact, and accurate molecular absorption loss model for the 100–450 GHz band. The derived model relies on simple absorption line shape functions that are fitted to the actual response given by complex but exact database approach. The model is also reducible for particular sub-bands within the full range of 100–450 GHz, further simplifying the absorption loss estimate. The proposed model is shown to be very accurate by benchmarking it against the exact response and the similar models given by International Telecommunication Union Radio Communication Sector. The loss is shown to be within ±2 dBs from the exact response for one kilometer link in highly humid environment. Therefore, its accuracy is even much better in the case of usually considered shorter range future B5G wireless systems.

Keywords: Absorption loss, THz channel modeling, THz communications, THz propagation

1 Introduction

The high-frequency communications aim at finding large contiguous bandwidths to serve high data rate applications and services. Especially the millimeter wave (mmWave) frequencies (30–300 GHz) are among the most prominent to provide high data rate connectivity in fifth generation (5G) and beyond (B5G) systems [1–4]. In this context, the 5G systems will utilize the below 100 GHz frequencies, whereas the B5G systems, including the visioned sixth generation (6G) systems, will look for spectral resources also above 100 GHz [3]. These frequencies would theoretically allow very large bandwidths, but there are still many challenges to reach the above 100 GHz band efficiently with compact and portable devices. To overcome the challenges in conquering these frequencies, there have been and are ongoing a lot of research efforts towards understanding the propagation channels, beamforming challenges, and transceiver hardware. For instance, EU Horizon 2020 projects TERRANOVA [5] for the low THz frequencies 275–325 GHz, and ARIADNE [6] for the D band (110–170 GHz). Also, the first standards for the THz communications are appearing, such as IEEE 802.15.3d [7]. Thus, the utilization of the +100 GHz frequencies for the near future wireless communication systems looks very promising.

One of the most important research topics on new frequency bands, knowledge of the operational channels is in the focal point to understand the fundamental physical limits of the transmission platform. This paper considers the line-of-sight (LOS) propagation in the sub-THz and low-THz frequencies at frequency range from 100 to 450 GHz.[1] The main goal of this paper is to give tools to model the molecular absorption loss with a simple model that has minimal loss in accuracy to full line-by-line models. The molecular absorption loss is caused by the energy of the photons being absorbed by the free energy states of the molecules [9]. The absorption loss is described by the Beer–Lambert law, and it causes exponential frequency selective loss on the signals as a function the frequency. The lowest absorption lines lie at low mmWave frequencies [10], but the first major absorption lines appear above 100 GHz.

The molecular absorption loss is most often modeled by line-by-line models for which the parameters are obtained from spectroscopic databases, such as high-resolution transmission molecular absorption database (HITRAN) [10]. The work herein utilizes the spectroscopic databases by obtaining the parameters for the major absorption lines, and we simplify those by simple polynomials that only depend on the water vapor content in the air. These are then applied to the Beer–Lambert's law to obtain distance dependent absorption loss. The free space propagation is modeled by the square-law free space path loss (FSPL). Thus, the produced model is a simple and a relatively compact way to estimate the total free space loss on the above 100 GHz frequencies. The main use case of the produced model is to be able to omit the complicated spectroscopic databases that take efforts to implement and use flexibly. This is especially the case with the common wireless communications problems where detailed information on the source of the loss is not required, but just an easy way to model it.

Starting from the 100 GHz frequency, we model six absorption lines at about 119 GHz, 183 GHz, 325 GHz, 380 GHz, 439 GHz, and 448 GHz. This adds two lines at 119 GHz and 183 GHz to our previous model ([8]) in order to address the D band propagation. Water vapor is the main cause of the absorption losses in the above 100 GHz frequencies and all but one of the above six lines are caused by it. Absorption at 119 GHz is caused by oxygen, and it is comparably weak. Although weak, it has been included in the model, since it is part of the D band and it causes a small attenuation on long distance links.

There exist a lot of research on the line-by-line models and models for calculating the absorption spectrum, such as [9, 11–14]. There are also some existing works on parametric absorption loss models. International Telecommunication Union Radio Communication Sector (ITU-R) has provided a model to calculate gaseous attenuation up to 1000 GHz in ITU-R P.676-8 [15]. This model is line-by-line based, and its output is therefore matched with those of the full spectroscopic databases. There is, however, a difference to the proposed model in this paper: ITU-R uses a modified full Lorentz line shape function that is not in general recommended for the millimeter frequencies [11] due to heavy tailed frequency domain absorption distribution. A better choice is a model

[1] This paper is an invited extended version of the conference paper presented in the EuCNC'19 conference [8].

that takes into account lower wing absorption by using line shape such as van Vleck–Weisskopf or van Vleck–Huber [11]. Furthermore, the full model by ITU-R still requires large numbers of tabulated parameters (553) that render its utilization similarly slow as the full databases. In [15], a polynomial-based approximation is also given. It is valid up to 350 GHz, but it is somewhat usable up to about 450 GHz. Newer version of this model, ITU-R 676-11, also exists but that version does not have a polynomial model. We use the older version in this paper as we present a similar (but more simpler) polynomial model.

Compared to the proposed model, the ones presented in [15] have several weaknesses. The ITU-R models [15] include lines even up to 1780 GHz, but it is only specified to be valid for frequencies up to 350 GHz. The simplified model in the newer version is also limited to 350 GHz. The model also includes nine polynomials. If some of these terms are removed, they may also affect frequencies in different bands due to additive nature of the absorption lines. For example, the term involving 1780 GHz has to be kept or the attenuation levels between the peaks absorption frequencies at lower frequencies is incorrect. However, the ITU-R models are still fairly accurate below 450 GHz. Because of the Full Lorentz line shape model, they overestimate the absorption line wing absorption. As detailed above, we will give a model with the extended frequency range and more accurate estimate for the absorption loss in simple form. This model can also be reduced to a simpler one (due to utilization of a fit parameter) for a desired sub-band within the full range of the model (100–450 GHz).

We have given a simplified molecular absorption loss model in the past in [16]. It was intended for the 275–400 GHz band. We also gave an extended version of that in [8] for frequencies from 200–450 GHz. This paper is an extended version of [8] with new lines focusing on the D band. As mentioned above, the main goal of this paper is to provide easy and accurate tools to estimate the LOS path loss above 100 GHz. The proposed model is shown to be very accurate by numerical results in Sect. 3, where it is benchmarked against the line-by-line models as well as the ITU-R parametric models.

The rest of this paper is organized as follows: Sect. 2 derives the proposed absorption loss model, Sect. 3 gives some numerical examples, and Sect. 4 concludes the paper.

2 Simplified molecular absorption loss model

2.1 Molecular absorption loss

The main goal of this paper is to provide a tool to easily model the molecular absorption loss. It is formally described by the Beer–Lambert law, which gives the transmittance, i.e., the fraction of energy that propagates through the medium at link distance d. This exponential power law depends on the link distance and absorption coefficient by [9, 11]

$$\tau(f,d) = \frac{P_r(f)}{P_t(f)} = e^{-\Sigma_j \kappa_a^j(f) d}, \tag{1}$$

where $\tau(f,d)$ is the transmittance, f is the frequency, d is the distance from transmitter (Tx) to receiver (Rx), $P_t(f)$ and $P_r(f)$ are the Tx and Rx powers, respectively, and $\kappa_a^j(f)$ is the absorption coefficient for the jth type of molecule or its isotope at frequency f. The absorption coefficient is usually calculated with databases of spectroscopic parameters, such as the HITRAN database [10], GEISA [17], or JPL [18]. Detailed calculation of the absorption coefficient with line-by-line models can be found, e.g., in [9, 11, 16]. To summarize the line-by-line models based on the spectroscopic databases, the molecular absorption coefficient is calculated by calculating the effective cross-sectional area of the individual molecules for absorption. This area depends on the absorption line shape functions for which the parameters are obtained from the spectroscopic databases. Finally, the cross-sectional areas of different types of molecules are multiplied with the respective number densities to obtain the total absorption loss coefficient. We derive the simplified absorption loss coefficient expressions based on the theory described above.

2.2 Simplified absorption loss model

The polynomial absorption loss model is obtained by searching the strongest absorption lines on the band of interest and extracting the parameters for those from the spectroscopic databases. The temperature and pressure dependent coefficients are fixed. As the absorption on the frequencies above 100 GHz is mainly caused by the water vapor, the volume mixing ratio of water vapor is left floating. The parametric model is characterized by the absorption coefficients y_i at absorption lines i. The above Beer–Lambert model becomes

$$\mathrm{PL}_{\mathrm{abs}}(f,\mu) = e^{d\left(\sum_i y_i(f,\mu)+g(f,\mu)\right)}, \tag{2}$$

where f is the desired frequency grid, y_i is an absorption coefficient for the ith absorption line, $g(f,\mu)$ is a polynomial to fit the expression to the actual theoretical response (detailed below), and μ is the volume mixing ratio of water vapor. It is determined from the relative humidity ϕ at temperature T and pressure p by

$$\mu = \frac{\phi}{100}\frac{p_w^*(T,p)}{p}, \tag{3}$$

where $\phi p_w^*(T,p)/100$ is the partial pressure of water vapor and p_w^* is the saturated water vapor partial pressure, i.e., the maximum partial pressure of water vapor in the air. This can be obtained, e.g., from the Buck equation [19]

$$p_w^* = 6.1121(1.0007 + 3.46\times 10^{-6}p)\exp\left(\frac{17.502T}{240.97+T}\right), \tag{4}$$

where the pressure p is given in hectopascals and T is given in degrees of centigrade.

The six polynomials for the six major absorption lines at the 100–450 GHz band are the following[2]:

$$y_1(f,\mu) = \frac{A(\mu)}{B(\mu) + \left(\frac{f}{100c} - p_1\right)^2}, \tag{5}$$

[2] Please note that in our conference version [8], to which this paper is an extension to, there was a typo that is rectified in this paper. The terms $(f/100c - p_x)^2$ were not squared therein. This causes the model therein to give an incorrect output. However, this happens at so notable level that it should be obvious if one tries to implement the model and compares to our results. The numerical results in [8] were made with correct expressions.

$$y_2(f,\mu) = \frac{C(\mu)}{D(\mu) + \left(\frac{f}{100c} - p_2\right)^2}, \tag{6}$$

$$y_3(f,\mu) = \frac{E(\mu)}{F(\mu) + \left(\frac{f}{100c} - p_3\right)^2}, \tag{7}$$

$$y_4(f,\mu) = \frac{G(\mu)}{H(\mu) + \left(\frac{f}{100c} - p_4\right)^2}, \tag{8}$$

$$y_5(f,\mu) = \frac{I(\mu)}{J(\mu) + \left(\frac{f}{100c} - p_5\right)^2}, \tag{9}$$

$$y_6(f,\mu) = \frac{K(\mu)}{L(\mu) + \left(\frac{f}{100c} - p_6\right)^2}, \tag{10}$$

$$g(f,\mu) = \frac{\mu}{0.0157}(2 \times 10^{-4} + af^b), \tag{11}$$

where, c is the speed of light (m/s), the frequency f is given in Hertz, and

$$\begin{aligned}
A(\mu) &= 5.159 \times 10^{-5}(1-\mu)(-6.65 \times 10^{-5}(1-\mu) + 0.0159),\\
B(\mu) &= (-2.09 \times 10^{-4}(1-\mu) + 0.05)^2,\\
C(\mu) &= 0.1925\mu(0.1350\mu + 0.0318),\\
D(\mu) &= (0.4241\mu + 0.0998)^2,\\
E(\mu) &= 0.2251\mu(0.1314\mu + 0.0297),\\
F(\mu) &= (0.4127\mu + 0.0932)^2,\\
G(\mu) &= 2.053\mu(0.1717\mu + 0.0306),\\
H(\mu) &= (0.5394\mu + 0.0961)^2,\\
I(\mu) &= 0.177\mu(0.0832\mu + 0.0213),\\
J(\mu) &= (0.2615\mu + 0.0668)^2,\\
K(\mu) &= 2.146\mu(0.1206\mu + 0.0277),\\
L(\mu) &= (0.3789\mu + 0.0871)^2,
\end{aligned}$$

where $p_1 = 3.96$ cm^{-1}, $p_2 = 6.11$ cm^{-1}, $p_3 = 10.84$ cm^{-1}, $p_4 = 12.68$ cm^{-1}, $p_5 = 14.65$ cm^{-1}, $p_6 = 14.94$ cm^{-1}, $a = 0.915 \times 10^{-112}$, $b = 9.42$. The lines y_1, y_2, y_3, y_4, y_5, and y_6 correspond to strong absorption lines at center frequencies 119 GHz, 183 GHz, 325 GHz, 380 GHz, 439 GHz, and 448 GHz, respectively. This is also visible in the line expressions as the parameters p_1 to p_6 give the line center frequencies in wavenumbers. These parameters are accurate for the whole frequency band 100–450 GHz. However, slightly improved performance between the absorption lines below 200 GHz can be achieved by using value 2×10^{-5} in the place of 2×10^{-4} in (11). This only has minor impact on very long link distances, such as one kilometer and beyond link distances.

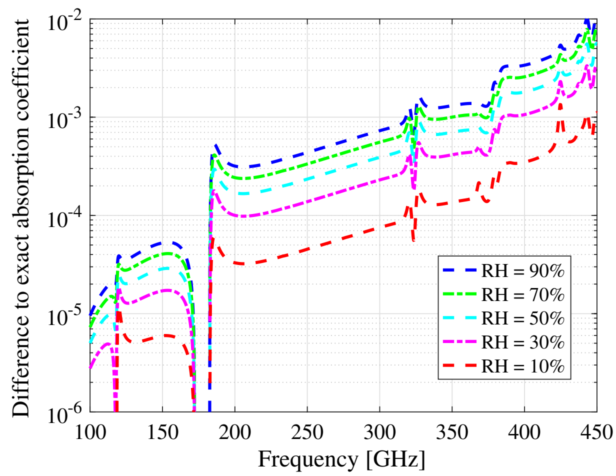

Fig. 1 An error of the proposed absorption coefficient. An error of the absorption coefficient of the proposed model to the exact one as a function of the frequency for different humidity levels before adding the fit polynomial $g(f, \mu)$

The above absorption lines were estimated based on the simple Lorentz line shape. The reason is the simpler form as compared to more accurate, but at the same time more complex line shapes, such as the van Vleck–Huber line shape [12, 20]. This produces an error as the Lorentz line shape over estimates the absorption line wing absorption. Therefore, the fit polynomial $g(f, \mu)$ is introduced. This fit polynomial also takes care of the wing absorption in the case the model is only utilized partially. That is, if one only utilizes some of the lines to model a sub-band within the full 100–450 GHz band, the fit polynomial in (11) as in full model should always be included. It was obtained by curve fitting to the difference between the exact response and the response of the above y_i lines. It would be possible to calculate the exact difference theoretically, but would only apply to the in-band absorption lines and this would not consider the out-of-band wing absorption, mainly from lines above 450 GHz. The total absorption loss with the above model is shown to produce very accurate estimate of the loss in the numerical results.

The water vapor volume mixing ratio is taken into account in the fit polynomial $g(f, \mu)$ based on the volume mixing ratio calculated from water vapor according to (3). Whereas it is highly accurate, this estimate will cause some error that is dependent on the water vapor level. Figure 1 shows the error of the absorption coefficient to the exact one based on the above absorption loss model and before applying the fit polynomial. This error was calculated at 25 degrees centigrade and in various volume mixing ratios of water vapor $\mu = [0.0031\ 0.0094\ 0.0157\ 0.0220\ 0.0282]$ that correspond to relative humidities $\phi = [10\%\ 30\%\ 50\%\ 70\%\ 90\%]$, respectively, at 298.15 K (25 degrees centigrade) temperature and at standard pressure 101,325 Pa. In this figure, taking into account the exponential y-axis, the error is small. However, the error increases as a function of frequency. This is due to the increasing and accumulating wing absorption from the higher frequency lines. This is the error the fit polynomial $g(f, \mu)$ rectifies by adjusting the absorption lines shapes. The value 0.0157 in $g(f, \mu)$

comes from the design atmospheric conditions of 25 degrees centigrade and 50% relative humidity at standard pressure. It should be noticed that the error is the smallest for lower humidities due to the fact that there is less water in the air, and thus, the overall difference between the exact and estimated absorption coefficient is small.

2.3 FSPL and the total loss

The total loss in pure LOS path requires the molecular absorption loss and the loss due to free space expansion of the waves. The FSPL is given by the Friis transmission equation:

$$\mathrm{PL}_{\mathrm{FSPL}}(d,f) = \frac{(4\pi df)^2}{c^2}. \tag{12}$$

We focus herein only on the free space propagation and thus the total LOS path loss is given by the FSPL and the molecular absorption loss as

$$\mathrm{PL}(d,f) = \frac{(4\pi df)^2 \exp(\kappa_\mathrm{a}(f,\mu)d)}{c^2} G_{\mathrm{Rx}} G_{\mathrm{Tx}}, \tag{13}$$

where G_{Rx} and G_{Tx} are the antenna gains. When using the polynomial models above, the absorption coefficient $\kappa_\mathrm{a}(f,\mu)$ is

$$\kappa_\mathrm{a}(f,\mu) = \sum_i y_i(f,\mu) + g(f,\mu), \tag{14}$$

where the $y_i(f,\mu)$ are the above polynomial absorption lines (and as also shown in (2)), or subset of those depending on the modeled frequency band within the frequency range from 100–450 GHz. For instance, a D band propagation model would only require lines $y_1(f,\mu)$ and $y_2(f,\mu)$. Another popular band for high-frequency communications is the 275–325 GHz band. Then, only the line $y_3(f,\mu)$ would be enough. The fit polynomial $g(f,\mu)$ is always required and because of it we can use very low complexity models for the possible sub-bands, further pronouncing the complexity benefits as compared to the ITU-R polynomial model. It will be shown in the numerical results that these subsets give very accurate estimate of the loss also in partial bands without a need to implement all the lines in the model.

3 Numerical results and discussion

In this section, we first present some performance analysis for the proposed molecular absorption loss model. This is done by analyzing the error produced by the model to the exact model, as well as comparing it to the ITU-R parametric and full models. After that, we analyze the accuracy of the model with reduced polynomials. Lastly, we give link budget calculations for some common +100 GHz frequency bands.

3.1 Error performance analysis

We compare the path loss values of the proposed molecular absorption loss model versus the ITU-R models in Figs. 2, 3 and 4 for the relative humidity levels from 10% to 90%, respectively, at 25 degree centigrade for a one-kilometer link. A high link distance was

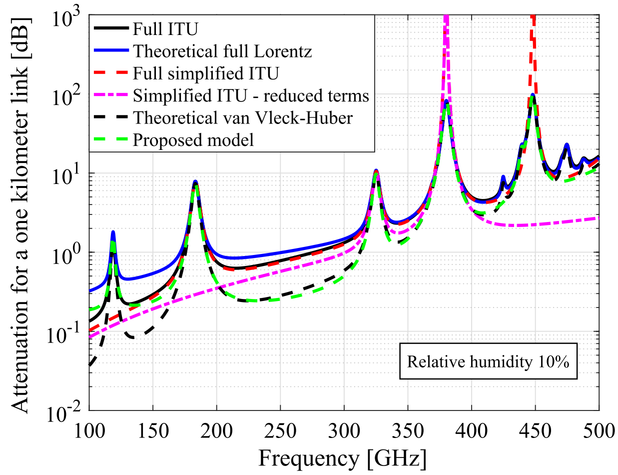

Fig. 2 Molecular absorption loss at 1 km distance and 10% relative humidity. Molecular absorption loss at 1 km distance at 25 degrees centigrade and 10% relative humidity ($\mu = 0.0031$)

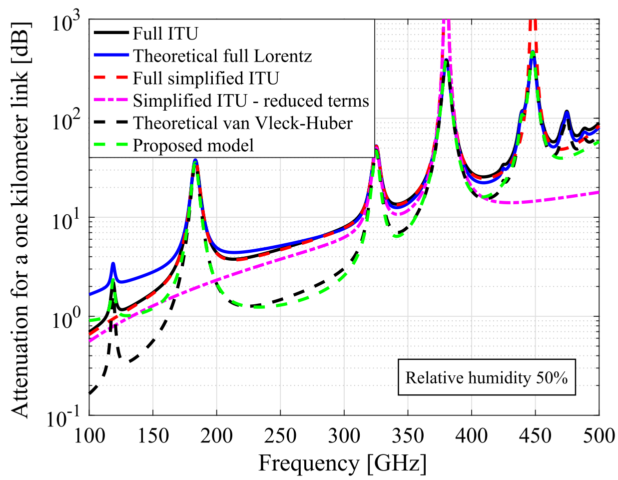

Fig. 3 Molecular absorption loss at 1 km distance. Molecular absorption loss at 1 km distance at 25 degrees centigrade and 50% relative humidity ($\mu = 0.0157$)

used to emphasize the differences between the models. This is because the impact of the molecular absorption loss decreases for short distances due to exponential power law.

As it was predicted above, the Lorentz line shape (along with the full Lorentz line shape) overestimates the wing absorption. This is not a major issue at higher parts of the THz band due to more lines and line mixing. However, at the lower frequencies this is a problem because the Lorentz line shape does not attenuate the absorption wing response fast enough towards the zero frequency. As a consequence, the ITU-R models give higher path loss figures in general for below 500 GHz frequencies. The difference to the actual response varies from few dBs to tens of dBs depending on the link distance and humidity level. Notice that the simplified reduced version of the ITU-R model does not include all the lines leading to incorrect results.

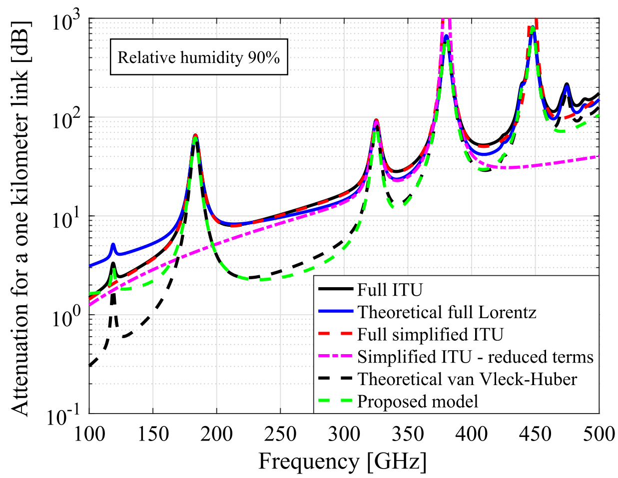

Fig. 4 Molecular absorption loss at 1 km distance and 90% relative humidity. Molecular absorption loss at 1 km distance at 25 degrees centigrade and 90% relative humidity ($\mu = 0.0282$)

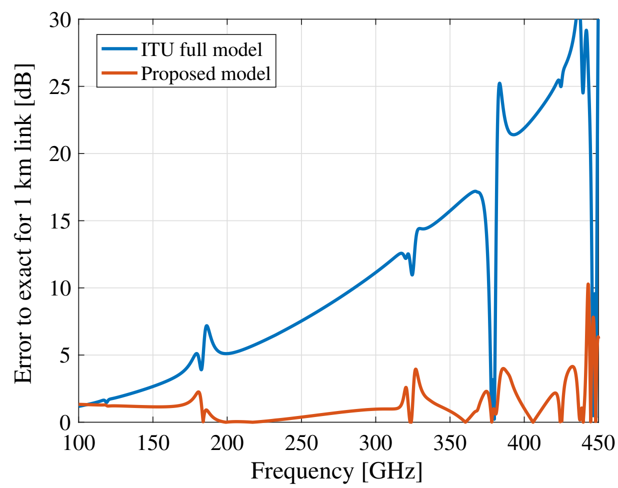

Fig. 5 Error of the model and comparison with ITU-R model. Absolute errors given by the ITU-R full model and the proposed model to the exact theory for a one kilometer link

There are a couple of further observations to be made. The ITU-R models are based on the full Lorentz model, but the database specific one does overestimate the response even more. This is due to reason that the ITU-R model is a modified version of the full Lorentz model that increases its accuracy. Second observation is that the proposed model is rather accurate, but not perfect. In Figs. 2 to 4, the difference is the largest below 200 GHz. However, the large part of the apparent difference comes from the logarithmic y-axis. Figure 5 gives the true worst case error herein. This figure shows the error of the path loss for one kilometer link at 25 degrees centigrade and at 90% relative humidity. It can be seen that the error is very good across the band, but the lower frequencies do give comparably slightly larger error due to in general lower absorption loss. However, the figures herein are for one kilometer link and the error

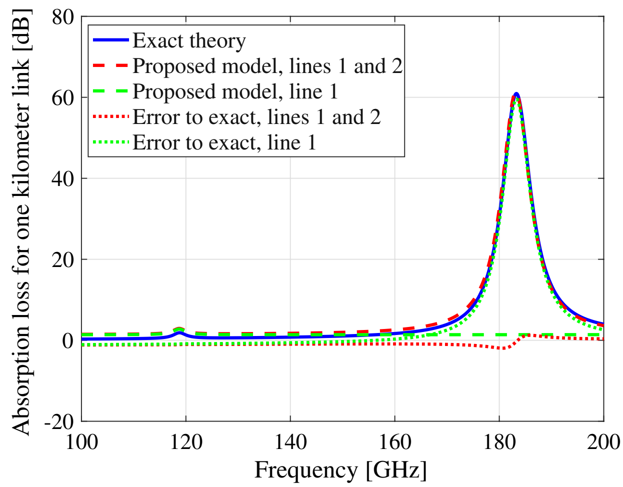

Fig. 6 Performance of the proposed model with reduced terms, low band. Reduced versions of the proposed model giving absorption losses up to about 160 GHz (1 term) and 200 GHz (2 terms)

will decrease with decreasing distance due to exponential behavior of the absorption loss. Thus, the resultant error of roughly ±2 dB is very good for such extremely high link distances considering the high frequencies and their general applicability to low range communications. Furthermore, the error also decreases in less humid environment and this is in general true for ITU-R models as well. For instance at 10% relative humidity at 25 degrees centigrade, the differences are rather modest. Regardless of this, in more humid environments there is a notable difference between the models, especially above the 200 GHz frequencies.

As a last note on the error performance, all the models herein are rather accurate and it is an application specific issue how accurately the absorption loss needs to be calculated. If the link distance is high or the communications band is in the vicinity of the absorption line, the importance of the correct loss is high. However, on low distance links and in the middle of the low loss regions of the spectrum the absorption loss is modest and large error is not made if the absorption loss is omitted altogether.

3.2 Performance of the model with reduced terms

If one targets only some sub-band within the 100–450 GHz band, the proposed model can be further simplified by only using subset of the polynomials y_i. Figures 6 and 7 compare the performance of the proposed model with reduced terms against the exact theory. Figure 6 shows performance of the proposed model when using the first two lines at about 119 GHz and 183 GHz separately and jointly (shown as lines 1 and 2 in the figure). In the other words, one should utilize the absorption coefficient as $\kappa_a(f,\mu) = y_1(f,\mu) + g(f,\mu)$ or $\kappa_a(f,\mu) = y_1(f,\mu) + y_2(f,\mu) + g(f,\mu)$ for lines 1 and 1 and 2 jointly, respectively. This reduction corresponds roughly to the frequency range of the D band. It can be seen that the proposed model with reduced terms performs very well on estimating the absorption loss. The same occurs in the case of Fig. 7 that shows the performance of the next two lines (lines 3 and 4) corresponding to frequencies 325 GHz and 380 GHz. These two line alone gives a very good estimate of the loss

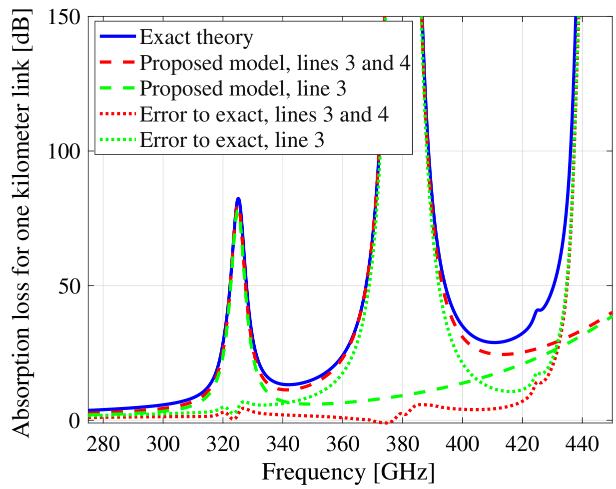

Fig. 7 Performance of the proposed model with reduced terms, high band. Reduced versions of the proposed model giving absorption losses up to about 330 GHz (3rd line only) and 390 GHz (lines 3 and 4 only)

Table 1 Link budget calculations for the D band channels. Values in brackets are the exact theoretical values

Parameter	D_1	D_2	D_3	D_4
Center frequency (GHz)	132.00	144.75	157.75	170.90
Bandwidth (GHz)	3	7.5	12.5	7.8
Transmit power (dBm)	0			
Tx/RX antenna gain (dBi)	48.3	49.1	49.9	50.6
Noise figure (dB)	10			
Noise floor (dBm)	−69.2	−65.2	−63.0	−65.0
Link distance (m)	1,000			
Path loss (dB)	135.1 (135.2)	136.0 (136.1)	137.0 (137.1)	139.4 (139.4)
Rx power (dBm)	−38.5 (−38.5)	−37.8 (−37.8)	−37.3 (−37.4)	−38.2 (−38.2)
SNR (dB)	30.6 (30.6)	27.4 (27.3)	25.6 (25.6)	26.8 (26.8)

up to about 330 GHz and 390 GHz for the line 3 and joint lines 3 and 4, respectively. These correspond to utilizing an absorption coefficient as $\kappa_a(f,\mu) = y_3(f,\mu) + g(f,\mu)$ and $\kappa_a(f,\mu) = y_3(f,\mu) + y_4(f,\mu) + g(f,\mu)$. As such, the line 3 would be mostly enough for the popular transition frequencies between the mmWave and THz bands. Namely 275–325 GHz. However, with these two lines, the model remains accurate from about 200 GHz up to the above-mentioned 390 GHz. Therefore, the proposed model is flexible and easily reducible for multiple frequency bands within the full range from 100 to 450 GHz for some specific applications that occupy only certain sub-band.

3.3 Link budget calculations

To show some examples on use cases for simple channel model, we give link budget calculations for the D band and THz band below. We assume long distance backhaul connection, a one kilometer LOS link. For the D band, we have chosen the free bands for wireless communications therein according to European Conference of Postal and

Table 2 Link budget calculations for the THz band channels. Values in brackets are the exact theoretical values

Parameter	T_1	T_2	T_3	T_4
Center frequency (GHz)	265.68	282.96	300.24	317.52
Bandwidth (GHz)	8.64			
Transmit power (dBm)	0			
Tx/RX antenna gain (dBi)	54.4	54.9	55.5	55.9
Noise figure (dB)	10			
Noise floor (dBm)	-64.6			
Link distance (m)	1,000			
Path loss (dB)	142.2 (142.4)	142.9 (143.2)	144.2 (144.7)	153.6 (154.7)
Rx power (dBm)	-33.4 (-33.7)	-33.0 (-33.4)	-33.3 (-33.8)	-41.7 (-42.9)
SNR (dB)	31.2 (30.9)	31.6 (31.2)	31.3 (30.8)	22.9 (21.7)

Telecommunications Administrations (CEPT) Electronic Communications Committee (ECC) Recommendation 18(01) [21]. Those are detailed in Table 1. For the THz band, we utilize every second channel of 802.15.3d standard with 8.64 GHz channelization [7]. These channels are given in Table 2. The transmit powers at the high-frequency bands have not been regulated other than by maximum radiation intensities [22] that are typically in the range of $55 f_G^{-0.177}$ W/m^2 depending on the source and application, where f_G is frequency in GHz. Thus, we use 0 dBm transmit power for all bands in order to have rather conservative radiated power with respect to the radiation limits and what the current THz capable devices are able to output. A one kilometer link at +100 GHz frequencies requires very large antenna gains. We assume parabolic reflector antennas to provide very large gain. The gain of such antenna is given by

$$G_{\mathrm{a}} = A_e \left(\frac{\pi d_a}{\lambda} \right)^2, \tag{15}$$

where A_e is the aperture efficiency, d_a is the diameter of the parabolic reflector, and λ is the wavelength. We assume aperture efficiency of 70% herein and a 225 mm diameter for the parabolic antenna. This diameter is equivalent to that of the Cassegrain antennas developed in TERRANOVA project [23]. This size parabolic antenna gives about 55 dBi gain at 300 GHz frequency [23] and as also shown below in Table 2 based on (15) with the above parameters. The antenna gains per band, average path loss per channel, and the received powers and SNRs are given in Tables 1 and 2. The average path losses per band (indexed in Tables 1 and 2) compared to the theoretical path losses from theoretical path loss given by molecular absorption loss in (1) and FSPL given in (12) are given in Fig. 8. For these calculations, no other losses, such as antenna feeder losses, are assumed. The main aim here is to estimate performance of the simplified path loss model.

Based on the link budget calculations, the proposed simplified model gives a very good performance without a need for complex line-by-line models. The link budget calculations are among the most important applications for estimating the required antenna gains and transmit powers for novel wireless systems. A simple channel gain estimate helps to quickly calculate the expected channel loss within the overall link

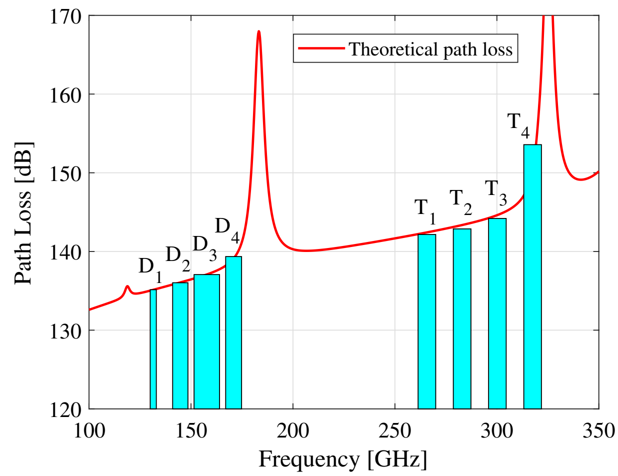

Fig. 8 Path losses for the bands considered in the link budget calculations. The exact path loss as a function of frequency versus the average losses per band given in Tables 1 and 2

budget. We can see that the expected accuracy of the proposed simplified model gives SNR values that are at most 1.2 dB off the real value. This level of difference in the real systems is insignificant due to all the other loss mechanisms, and, the link distance here is quite large for high-frequency communications. Although these link distances are very much possible as shown, e.g., in [23, 24], where 1 km link distance with the above-mentioned 55 dBi Cassegrain antennas was demonstrated. Their total loss with antenna gains at 300 GHz was about 40 dBs, whereas in Table 2 we see a loss of about 33 dBs. This shows that even with very simple calculations, one can get very close to real-life measurements even without taking into account feeder losses, or other possible atmospheric losses, such as fog loss and small particle scattering in the air. Therefore, the proposed simplified loss model can very reliably estimate the atmospheric losses and the accuracy of the total link budget mostly falls into properly modeling all the parts of the wireless system that have impact on the total received power.

3.4 Discussion

As a summary and discussion from above, the higher mmWave and low THz frequencies are among the most potential frequencies to utilize ultrahigh rate communications in the future wireless systems. The proper modeling of the channel behavior therein is very important due to absorption loss and how it behaves in comparison with the FSPL. In short distance communications (few meters) below 300 GHz, it is not absolutely crucial to model the absorption due to dominating FSPL. Its importance increases with link distance, but also with frequency. In the other words, the link budget and the components in it are application dependent. The tools provided herein give and easy way to model the absorption loss and estimate its impact on the link budget.

4 Conclusion

We derived a LOS channel model for 100–450 GHz frequency range in this paper. The main goal was to find a simple and easy to use model for the molecular absorption loss. The derived model was shown to be very accurate and predict the channel loss very well in the target frequency regime. This model can be reduced to simpler forms in the case of limited frequency range within 100–450 GHz. Considering the upcoming B5G systems, the interesting frequency bands include the D band (110 GHz to 170 GHz) and the low THz frequencies (275 GHz to 325 GHz). The molecular absorption loss is an important part of the link budget considerations at +100 GHz bands. Therefore, the model presented here gives a simple tool to estimate the total link loss in various environmental conditions and link distances. As it was shown in the numerical results, the derived model can be used to predict the expected SNR within D band and THz band with below 2 dB error compared to the exact theoretical model. Therefore, this simple tool gives high enough accuracy for any LOS system analysis, but also in the broader sense, analysis of the large scale fading in the sub-THz regime.

5 Methods/experimental

This paper is a purely theoretical model on simple way to estimate the absorption loss. Although theoretical, the original data obtained from the HITRAN database [10] are based on experimental data. The goal in this article is to simplify the complex database approach into simple polynomial equations with only few floating parameters, such as humidity and frequency. As such, the model produced in this paper is suitable for LOS channel loss estimation for various wireless communications systems. Those include back- and fronthaul connectivity and general LOS link channel estimation. The work is heavily based on the HITRAN database and the theoretical models for absorption loss as well as simple LOS free space path loss models.

Abbreviations

5G: Fifth generation; 6G: Sixth generation; B5G: Beyond fifth generation; FSPL: Free space path loss; HITRAN: High-resolution transmission molecular absorption database; ITU-R: International Telecommunication Union Radio Communication Sector; LOS: Line-of-sight; mmWave: Millimeter wave; Rx: Receiver; Tx: Transmitter.

Authors' contributions

JK derived the molecular absorption loss model. All the authors participated in writing the article and revising the manuscript. All authors read and approved the final manuscript.

Funding

This work was supported in part by the Horizon 2020, European Union's Framework Programme for Research and Innovation, under Grant Agreement No. 761794 (TERRANOVA) and No. 871464 (ARIADNE). It was also supported in part by the Academy of Finland 6Genesis Flagship under Grant No. 318927.

Data availability

Not applicable.

Declarations

Competing interests

The authors declare that they have no competing interests.

Received: 7 January 2020 Accepted: 30 March 2021
Published online: 09 April 2021

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