Analysis of Clouds and Rain Losses on Terahertz Band for Non-Terrestrial Networks

Bushra Khan and Joonas Kokkoniemi
Centre for Wireless Communication, University of Oulu, 90014 Oulu, Finland
emails: {bushra.khan, joonas.kokkoniemi}@oulu.fi

***Abstract*—In today's world, high-speed and reliable internet access is a global necessity. Despite this, millions of users suffer on a daily basis due to limited service on airplanes and in remote areas. Microwave frequencies have long reachability, but due to the limited available bandwidth, they cannot serve a large number of users with high data rates and reliability guarantees. Therefore, this research focuses on providing high-speed internet access using millimeter wave (mmWave)/terahertz (THz) frequencies to address the aforementioned shortcomings of microwave frequencies. Our primary goal is to investigate the effects of various channel parameters on mmWave/THz frequencies, including point-to-point (P2P) path loss and atmospheric losses. The analysis reveals that airplane-to-satellite (A2S) links can achieve better signal-to-noise ratio (SNR) across the 100-1000 GHz frequency range by avoiding the adverse atmospheric effects at higher altitudes, whereas ground-to-satellite (G2S) links can still perform similarly up to 300 GHz but with higher atmospheric losses.**

***Index Terms*—Atmospheric attenuation, in-flight connectivity, non-terrestrial networks, remote areas, satellite communications systems, terahertz channel.**

I. Introduction

Advancements in wireless communication technology have led the telecommunications sector to pursue the dream of providing services to a variety of new use cases with diverse Quality of Service (QoS) constraints. Current communication systems face a number of challenges for modern wireless applications, the most significant of which is the exponentially increasing demand for bandwidth as data-intensive applications evolve. Existing telecommunication systems are based on radio and microwave frequencies, which are inadequate to handle various QoS requirements and can overload the system during peak user activity [1]. Another challenge is to provide services to underserved and remote areas with reliability guarantees [2]. In general, geographical limitations and a lack of infrastructure impede attempts to link remote areas, which limits their access to wireless services. Furthermore, the time-critical nature of certain applications faces latency issues, such as online gaming, teleconferencing, autonomous car operations, etc.

The terahertz (THz) frequency band, ranging from 0.1 to 10 THz, is a strong candidate for sixth-generation (6G) and beyond wireless communication systems and provides various advantages over lower-frequency bands used in today's systems, such as fifth-generation (5G) [3]. Terahertz wireless systems can achieve multigigabit throughput performance utilizing existing modulation techniques and enhanced channel bandwidth of the order of gigahertz (GHz) [4]. Therefore, to meet the ever-growing need for bandwidth, the use of THz frequencies is deemed essential, which can enable high-speed internet connectivity to remote areas and objects in the atmosphere and also reduce the latency as compared to the existing technologies.

The unique characteristics of THz communication enable many applications in the field of wireless communications. An emerging use case for THz communications is to provide internet connectivity throughout flight. According to the International Civil Aviation Organization's preliminary compilation of annual global statistics, the total number of passengers transported on scheduled services increased to 2.3 billion in 2021, which is 28 percent higher than the previous years [5]. Furthermore, the average flight duration is between three and seven hours, and quite a few have a longer duration. Despite the fact that airplanes are still among the few places where the average person does not have access to the Internet, mainly due to the utilization of technologies with limited available bandwidth and their operating frequencies, i.e., ku (12–18 GHz) and ka (26.5–40 GHz) bands. To ensure that each passenger onboard has continuous access to online services while in the air, regardless of their geographic location, in-flight internet relies on satellite links, which can provide consistent and reliable connectivity at higher altitudes. Another key scenario is the provision of high-speed internet access to remote locations, such as high-altitude regions, isolated islands, and large rural areas, where it is impractical or financially infeasible to deploy conventional networks. To overcome these issues, non-terrestrial networks (NTNs) such as satellite systems, high-altitude platforms (HAPs), and other airborne networks are preparing to adopt millimeter wave (mmWave)/THz frequencies, which are pivotal in the evolution of 6G technology and provide higher data rates and bandwidth, especially by extending connectivity in remote locations [6].

The use of the THz frequency band for NTNs has been the subject of recent research studies [1], [7]–[10]. Millimeter-wave/terahertz frequency bands are highly susceptible to weather conditions and environmental factors. These conditions will have a significant impact on signal strength and reliability. Thus, developing and implementing a THz communications system requires a thorough understanding of radio propagation channels in weather conditions such as water vapor absorption, clouds, fog, and rain, which are critical in NTN scenarios. The main focus of this research is to determine the effects of clouds and rain attenuation in order to provide insights for optimizing

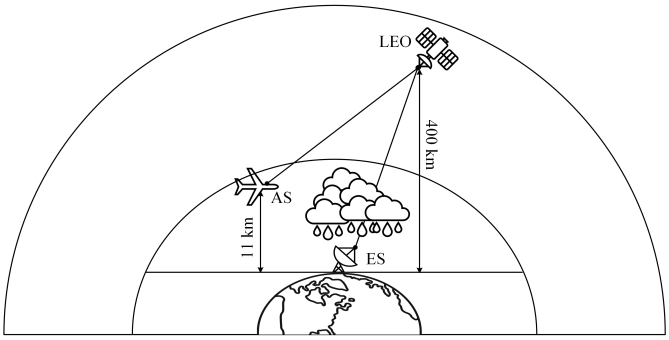


Fig. 1: System model for G2S and A2S communication links. This model shows the Tx, Rx, and the propagation channel involving clouds and rain.

wireless communication links.

The rest of the paper is structured as follows: Section II describes the system model, in which wireless communication links and free-space path loss are discussed. Section III dives deep into the propagation effects, including atmospheric absorption and atmospheric attenuation. Performance evaluation of the THz band is provided in Section IV, and, finally, Section V concludes the paper.

II. System Model

The THz channel modeling approach for ground-to-satellite (G2S) and airplane-to-satellite (A2S) communication systems includes Earth and airplane stations as transmitters (Tx) and Lower Earth Orbit (LEO) satellite stations as receivers (Rx), as illustrated in Fig. 1. The power emitted by the transmitter is referred to as transmitted power, P_T and the receiver sensitivity is determined by the minimum power that the receiver can successfully receive, called received power P_R. The corresponding antenna gains, i.e., the transmitter and receiver gains G_T and G_R depend on their aperture efficiency η and antenna diameter D. The gain of the antenna can be expressed as $G = \eta(\frac{\pi D}{\Lambda})^2$, where λ is the wavelength of the transmitted signal. The important feature of the system model is the distance R between the Earth station (ES) and the LEO satellite in the G2S link and the airplane station (AS) to the LEO satellite in the A2S link, which is several hundreds of kilometers, as well as the terahertz frequencies f at which it operates.

In the design of wireless communication systems, the point-to-point (P2P) path loss model is one of the essential and critical factors to understand how the signal strength decreases as it propagates through the medium. The path loss model includes free space path loss (FSPL), which is important for high-frequency communication systems such as terahertz bands, satellite links, and other non-terrestrial networks.

A. Free Space Path Loss

The free space path loss represents the attenuation of signal power as it propagates through the free space (vacuum) without any interference, reflection, or absorption losses.

FSPL = $\left(\frac{4\pi R}{\lambda}\right)^2 = \left(\frac{4\pi R f}{c}\right)^2$, where R is the distance between the transmitter and receiver and λ is the wavelength of the

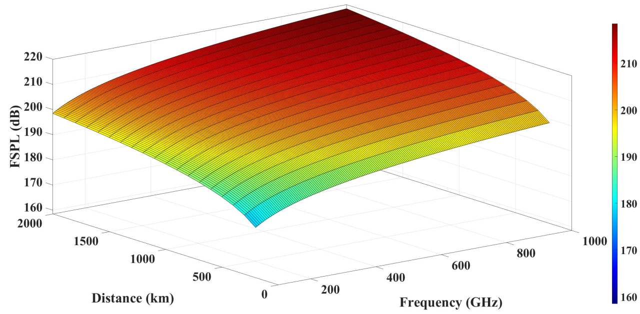


Fig. 2: FSPL as a function of distance between the ground and the LEO station at different altitudes and the frequencies ranging from 100 to 1000 GHz, illustrating the attenuation of signal with higher frequency and longer distance in free space.

transmitted signal. Fig. 2 shows that the path loss increases as the distance between the transmitter and the receiver increases, and the increase in frequency also increases the FSPL.

III. Atmospheric Losses

Atmospheric losses L_atm significantly affect the performance of wireless communication systems, particularly satellite communications operating at higher frequencies. These losses incur a huge reduction in signal power when electromagnetic waves (EM waves) propagate through the atmosphere. It is related to the weather conditions, i.e., a clear atmosphere, cloudy and rainy weather, etc. As a result, there are several phenomena that contribute to overall signal attenuation, including atmospheric absorption, cloud attenuation, and rain attenuation.

A. Atmospheric Absorption

Atmospheric absorption L_A refers to the signal attenuation of EM waves caused by the interaction with oxygen and water vapor molecules present in the atmosphere of the Earth. According to [1], [11], [12], atmospheric absorption is primarily quantum in nature, involving vibrational and rotational energy state transitions of molecules. These transitions occur when molecules absorb specific frequencies of electromagnetic waves, causing changes in their energy states. The Beer-Lambert law is used to quantify the absorption of EM waves through the atmosphere as their intensity decreases exponentially with distance, which is expressed as follows:

$$L_\text{A} = e^{\Sigma_i \kappa_\text{a}^i(f) d}, \quad (1)$$

where $\kappa_\text{a}^i(f)$ is the absorption coefficient in cm^{-1} of ith absorbing molecule at frequency f and d is the path length in km. In vertical paths, the absorption coefficient $\kappa_\text{a}(f,d)$ is computed along with the signal propagation path and is dependent on distance and frequency. In this research, four molecules, i.e., ozone (O_3), oxygen (O_2), oxygen atom (O), and water vapors (H_2O), are used from the High Resolution Transmission (HITRAN) molecular absorption database to compute the absorption coefficient using the line-by-line model. Here, the water vapor molecule is responsible for the vast majority of the total absorption loss. In G2S communication, EM waves experience absorption loss, which increases to

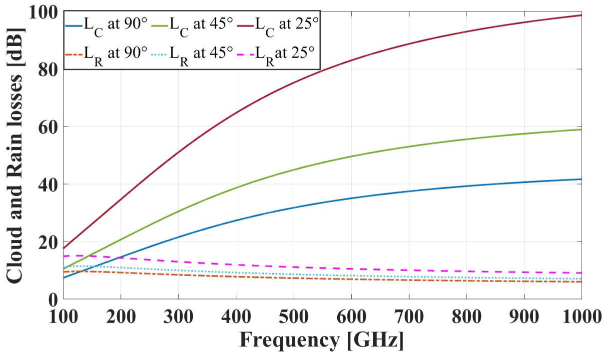


Fig. 3: Attenuation of clouds and rain varies with elevation angle.

hundreds of decibels after 300 GHz, indicating a significant decrease in signal power except for a few frequencies, as shown in Table II. After such a massive reduction, the signal is indistinguishable from noise and nearly nonexistent.

B. Cloud Attenuation

Cloud attenuation has a major effect on satellite communication systems operating at frequencies higher than 10 GHz [13], [14]. It takes place in the troposphere, the lowest layer of the atmosphere, which extends from sea level to approximately 15 km above the earth. It contains most of the atmosphere's water vapor, clouds, and weather phenomena. This layer is crucial for understanding how clouds attenuate EM signals. Clouds are formed from suspended water droplets, ice crystals, or a combination of the two, causing scattering and absorption losses.

The International Telecommunication Union-Radiocommunication Sector (ITU-R) provides a model P.840–6 that predicts cloud or fog attenuation [15]. In light of this, the particular attenuation inside the cloud or fog is $\gamma_c = K_i M$, where γ_c represents the cloud-specific attenuation in dB/km, $K_i = \frac{0.819f}{\epsilon_2(\eta^2+1)}$ is the specific attenuation coefficient in (dB/km)/(g/m^3), where $\eta = \frac{\epsilon_1+2}{\epsilon_2}$, with ϵ_1 and ϵ_2 determined by the Rayleigh scattering, which uses a double-Debye model for the dielectric permittivity of the water, $\epsilon(f)$ is used to calculate the values of K_i for frequencies up to 1000 GHz [15] and M is the liquid water content (LWC) in g/m^3. The total attenuation caused by the cloud is L_C, where d represents the vertical thickness of the clouds.

$$L_\mathrm{C} = d\gamma_\mathrm{c}, \tag{2}$$

The World Meteorological Organization (WMO) provides a general classification of various types of clouds in which the average values of the vertical thickness, liquid water content, base height, and temperature are listed in Table I [16], [17]. With the help of these properties, a detailed analysis of cloud attenuation and precipitation, including steady and heavy rain, is illustrated in Fig. 4. The vertical thickness of the cloud and the LWC are the primary causes of cloud attenuation. As these two parameters increase, so do the losses, as shown in Fig. 4a. In addition, at low elevation angles, the signal travels through a large portion of the atmosphere, increasing the possibility of encountering more clouds. As a result, it will increase the effects of LWC, resulting in significant cloud attenuation, as demonstrated in Fig. 3.

TABLE I: Classification of Clouds Based on their Average Properties

Types	**LWC** (g/m^3)	**Vertical Thickness** (km)	**Base Height** (km)	**Temperature** ($°C$)
Cirrus	0.03	0.9	6 to 12	< -25
Cirrocumulus	0.03	0.3		
Cirrostratus	0.10	0.9		
Altocumulus	0.20	0.7	2 to 6	between 0 to -20
Altostratus	0.41	0.5		
Nimbostratus	**0.65**	**0.8**	**0 to 3**	**0 to -25**
Stratocumulus	0.30	0.5	0.3 to 1.35	between 0 to -10
Stratus	0.42	0.6	0 to 0.6	
Cumulus	1.00	2.0	0.3 to 1.5	
Comulonimbus	**0.51**	**3.0**	**0.2 to 2**	**0 to -10**

C. Rain Attenuation

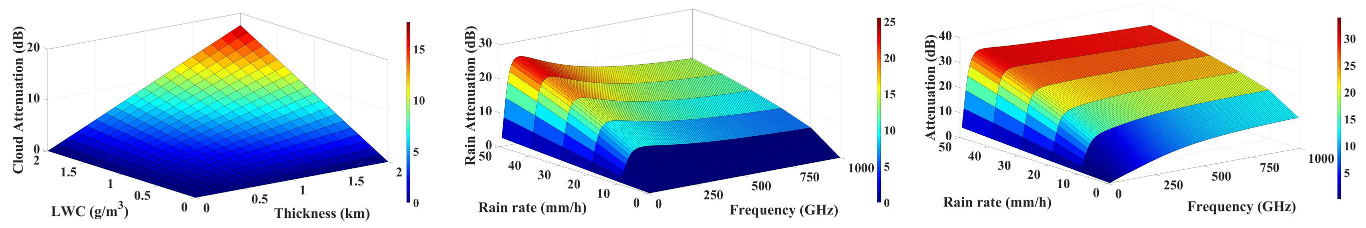
Rain attenuation occurs as a result of raindrop scattering and electromagnetic wave absorption. The ITU-R P.838-3 model determines the specific attenuation of a signal based on the length of the signal path, the frequency, and the rate of rainfall. The specific attenuation, $\gamma_r = kr^\alpha$, is calculated using the power law relationship, where r is the rainfall rate in mm/h, k and α are the coefficients that depend on frequency f, polarization, and type of rain [18]. The rain attenuation is L_R, while the path length through the rain is d.

$$L_\mathrm{R} = d\gamma_r, \tag{3}$$

The rain attenuation was calculated using the model mentioned above, with a rainfall rate of 0-50 mm/h (light rain to very heavy rain), a path length of 1 km, and an elevation angle of Zenith. As the frequency exceeds 100 GHz, the attenuation of the rain appears to be constant. However, this effect is more noticeable at higher rainfall rates, where attenuation increases with the intensity of rainfall, as shown in Fig. 4b. Furthermore, the impact of elevation angle on rain attenuation is shown in Fig. 3, which shows that losses are relatively less at higher elevation angles than at lower elevations. In addition, to demonstrate the effect of cloud and rain on the signal, at the same time, the properties of the nimbostratus cloud are used, with a rain rate ranging from 0 to 50 mm/h over a distance of 1.5 km. Fig. 4c illustrates how losses increase with increasing frequency and rain rate.

IV. Numerical Results

This section contains the numerical analysis for a G2S and A2S link that takes into account both FSPL and atmospheric losses under various weather conditions. In this study, we focus on frequencies between 100 and 1000 GHz with elevation angles of 90 and 45 degrees. However, future work will expand to include lower frequency bands as well. Furthermore, the satellite is 400 kilometers above the Earth's surface in the Lower Earth Orbit, and the maximum altitude of the airplane is 11 kilometers. The antenna diameters for airplanes, ground stations, and satellites are 0.5, 1, and 1.2 meters, respectively.



(a) Impact of cloud vertical thickness and liquid Water Content (LWC) on signal attenuation.

(b) Attenuation losses due to rain with Varying rainfall rates over a 1 km path length.

(c) Signal attenuation caused by Nimbostratus cloud taking into account the effect of clouds and rain.

Fig. 4: Cloud and rain effects on signal attenuation over different path lengths are determined by cloud thickness, liquid water content, and rainfall rates.

A. Link Budget calculation

To evaluate the performance of the communications system, we need to determine the signal-to-noise ratio (SNR). It helps analyze the quality and reliability of the received signal. It is determined by the total received power and the noise power as

$$\text{SNR} = \frac{P_R}{N}. \tag{4}$$

To calculate the total received power over the distance R, we take both the antenna gains G_T and G_R, the wavelength λ, and the atmospheric losses L_atm, which encompass atmospheric absorption, cloud loss, and rain loss, with free space path loss as the total propagation loss of the system model

$$P_R = \frac{P_\text{T} G_\text{T} G_\text{R} \lambda^2}{(4\pi R)^2 L_\text{atm}}. \tag{5}$$

The last element of the link budget calculation before calculating the SNR is the noise power. In a G2S link, both the thermal N_TH and the atmospheric noise N_A are combined to calculate the total noise power N [1]. However, in the A2S link, only thermal noise is considered because the atmosphere becomes extremely thin at the aircraft's altitude, thereby avoiding the effects of atmospheric noise

$$N_\text{Th} = k_\text{b} T_\text{nf} W, \tag{6}$$

$$N_\text{A} = k_\text{b} T W \left(1 - \exp\left(-\int_a^b k_\text{a}(f, r) dr\right)\right), \tag{7}$$

$$N = N_\text{Th} + N_\text{A}, \tag{8}$$

where k_b is the Boltzmann constant 1.38×10^{-23} J/K, $T_\text{nf} = T_\text{o}(10^{(N_\text{f}/10)} - 1)$ which is the equivalent system noise temperature in Kelvin (K), T_o is the base temperature in Kelvin, N_f is the noise figure that quantifies the system noise contribution in dB, and W is the bandwidth in GHz. In (7), k_a is the absorption coefficient of the atmosphere depending on the operating frequency f in GHz, T represents the temperature profiles of the atmosphere, r is the distance between each slab that incorporates the small portions of the atmosphere, which is 1 km, and a and b is the travel distance between Tx and Rx.

We assume a transmitted power of 1W and a bandwidth of 1 GHz, so that the results are per unit of transmit power and per GHz of bandwidth for easy scaling. The aperture efficiency of the antenna is 70%, N_f is 10 dB, and the frequencies, such as 140 GHz (from the D band, which is a potential candidate for 6G), 250 GHz (from the extremely high frequency (EHF) band for various uses, including Earth Exploration-Satellite Service (EESS), fixed and mobile services), and 410 GHz, 670 GHz, and 880 GHz, were chosen for their lower absorption losses compared to the rest of the frequency range. In A2S links, the airplane is closer to the satellite than the ground station. Despite having the same transmitted power, the shorter path length results in lower free-space path losses.

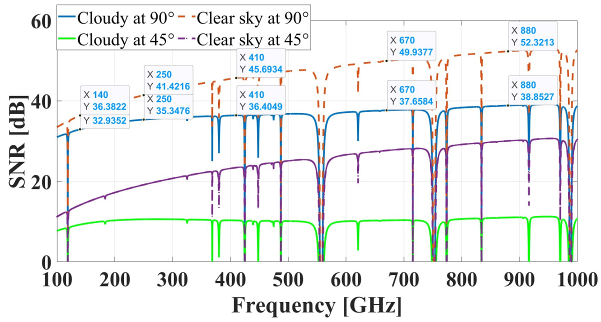


Fig. 5: SNR comparison for A2S links at 45° and zenith in cloudy and clear skies.

Propagation losses due to clouds and rain increase in adverse weather conditions compared to clear skies. To demonstrate cloud losses, we used a cumulonimbus cloud with a vertical thickness assuming 3 km in the case of G2S and 1 km in the case of A2S and a LWC of 0.51 g/m^3, resulting in a significant reduction in SNR at higher frequencies. However, the rainfall rate is the most important factor in rain attenuation, which reduces the SNR. Table II, summarizes the detailed calculation of the link budget for the G2S link under clear skies and cloudy weather conditions, highlighting the effects of clouds and rain attenuation. Fig. 5, illustrates the SNR for the A2S link under clear skies and cloudy weather conditions, excluding rain attenuation as it is not relevant in this case. The findings show that in clear sky/cloudy conditions, the A2S link outperforms the G2S link at higher frequencies, highlighting the benefits of high-altitude communications by avoiding atmospheric attenuation. For example, at 410 GHz, the SNR of the A2S link is 45.69/36.40 dB, while the SNR of the G2S link is 28.02/-7.62 dB at the zenith angle under clear skies and cloudy weather, respectively.

V. Conclusion

This study examines atmospheric attenuation for the G2S and A2S communication links. It emphasizes that for G2S

TABLE II: Detailed Link Budget Calculation for 1 W Transmitted Power and 1 GHz Bandwidth

Parameter	Values										Unit
Transmitted Power	30										dBm
Frequency	140		250		410		670		880		GHz
Noise Level	-74.31		-74.08		-73.43		-73.42		-73.42		dBm
Transmitted Gain	63.36		68.40		72.69		76.96		79.33		dB
Received Gain	61.78		66.81		71.11		75.37		77.74		dB
Elevation Angle	90	45	90	45	90	45	90	45	90	45	degrees
Distance	400	5048	400	5048	400	5048	400	5048	400	5048	km
FSPL	187.41	209.43	192.44	214.46	196.74	218.76	201.01	223.03	203.37	225.40	dB
Absorption Loss	0.50	1.43	1.65	4.73	22.47	64.25	79.62	227.66	52.54	150.23	dB
Cloud Loss	**10.34**	**14.62**	**18.22**	**25.76**	**27.86**	**39.40**	**36.83**	**52.09**	**40.40**	**57.14**	**dB**
Rain Loss	**9.64**	**11.47**	**8.86**	**10.49**	**7.77**	**9.17**	**6.73**	**7.92**	**6.26**	**7.35**	**dB**
Total Path Loss	207.90	236.96	221.19	255.47	254.85	331.60	324.21	510.72	302.59	440.13	dB
Received Power	-52.75	-81.82	-55.97	-90.25	-81.04	-157.79	-141.87	-328.37	-115.51	-253.05	dBm
SNR (cloudy)	**21.55**	**-7.51**	**18.11**	**-16.17**	**-7.62**	**-84.36**	**-68.44**	**-254.95**	**-42.09**	**-179.63**	**dB**
SNR (clear sky)	**41.54**	**18.58**	**45.19**	**20.09**	**28.02**	**-35.77**	**-24.87**	**-194.93**	**4.57**	**-115.13**	**dB**

links, factors such as atmospheric absorption, clouds, and rain cause massive signal losses, particularly when dealing with a longer slant path or a lower elevation angle. However, the aircraft in A2S links are flying at altitudes above most dense atmospheric layers, where these effects are most noticeable, and they experience comparatively lower atmospheric losses.

The numerical results show that attenuation from clouds and rain, particularly at higher frequency bands, has a considerable influence on signal performance and causes variations in signal-to-noise ratio, while free-space path loss remains a major issue. Integrating cloud and rain loss models at different elevation angles reveals that particular attenuation increases with frequency, reducing overall connection reliability. Due to the aforementioned limitations, frequencies greater than 300 GHz are considered unsuitable for ground to satellite communications. However, in airplane-to-satellite communication systems, the high altitude of airplanes allows for the efficient use of frequencies greater than 300 GHz. This makes terahertz bands an attractive option for higher altitudes, meeting the growing need for higher bandwidth and low-latency services.

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